DEVELOPMENTS IN

SPACE RESEARCH 50

HIGHLIGHTS OF USRA'S ACHIEVEMENTS

ESSAYS BY DAVID CUMMINGS

USRA ADVANCING SPACE RESEARCH AND EXPLORATION FOR 50 YEARS

DEVELOPMENTS IN

SPACE RESEARCH

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Published by USRA
Columbia, Maryland

Developments in Space Research: Highlights of USRA's Achievements
by David Cummings

ISBN: 978-0-9980623-1-0

ISBN 9780998062310

9 780998 062310

Design by: B. Creative Group, Inc.
Baltimore, Maryland
Printed in USA by: GraphTec

ACKNOWLEDGEMENTS

I WISH TO THANK Dr. Jeffrey Isaacson, the USRA President and CEO, for suggesting that I write some essays that would feature highlights of USRA during its first fifty years. His support has been essential to the successful completion of the book.

I am very much indebted as well to Mr. Kevin Schmadel, USRA's Vice President of Corporate Affairs and Communications, for his support, encouragement, and many suggestions that helped shape the book.

I wish also to express my appreciation for contributions made by a number of other individuals and groups, including:

Ms. Erin Senoz, USRA's Manager of Media and Communications, for her many design ideas that enriched the book;

Mr. Mark Swiatek of Swiwrite, Ltd., for his editorial assistance;

B. Creative Group, Inc., which provided the overall layout and design for the book;

The USRA scientists and others who provided input and/or reviewed sections of the book, notably Dr. Assaf Anyamba, Dr. Zaven Arzoumanian, Dr. David Bell, Dr. Robert Cassanova, Dr. Alexander Chernov, Dr. Peter Denning, Dr. Ted Dunham, Dr. Tapasi Ghosh, Dean Martin Glicksman, Dr. Vicki Johnson, Dr. Chryssa Kouveliotou, Professor Louis Lanzerotti, Dr. Jacqueline Le Moigne, Dr. Stephen Mackwell, Dr. William Meyer, Dr. Christian Otto, Dr. Neal Pellis, Ms. Elizabeth Pentecost, Mr. Martin Ruzek, and Dr. James Van Alstine.

Finally, I wish to thank Mrs. Sue Cummings, my wife, for her support and encouragement.

DAVID CUMMINGS
USRA EXECUTIVE DIRECTOR
1976–2007

EXPLORE

FOREWORD

AT THE BEGINNING OF 1966, James Webb, the Administrator of NASA, began to act on his desire to more thoroughly engage the university community in the activities of NASA. One of Webb's initiatives was to contact Dr. Frederick Seitz, President of the National Academy of Sciences, to discuss how NASA might involve the university community in the analyses of samples soon to be returned from the Moon. That discussion led to considerations of how NASA might collaborate with the university research community as the agency undertook explorations in a broad range of space-related disciplines.

Dr. Seitz organized extensive discussions within the university research community, and the eventual result of Webb's request was the formation of the Universities Space Research Association (USRA) on 12 March 1969. The new independent non-profit corporation was chartered to carry out research, development, and educational activities associated with space science and technology, through cooperative efforts with universities, the Federal Government and other organizations.

Soon after I became USRA's seventh President and CEO in 2014, I asked Dr. David Cummings to identify and document some of the highlights of USRA's achievements over the past decades. Dr. Cummings joined USRA in 1976 as its Executive Director and thus has had a wide view of, and in some cases direct participation in, the various activities taking place at USRA.

This book contains twenty of Dr. Cummings's essays. The essays cover a variety of space-related disciplines and, in my view, provide excellent examples of how USRA has been fulfilling its chartered purpose over the past decades. With this past as prologue, I look forward to the new achievements, yet to occur, as USRA takes on new challenges, in new ways, in the coming decades.

I hope you enjoy Dr. Cummings's essays.

JEFFREY A. ISAACSON
USRA PRESIDENT AND
CHIEF EXECUTIVE OFFICER
MARCH 2019

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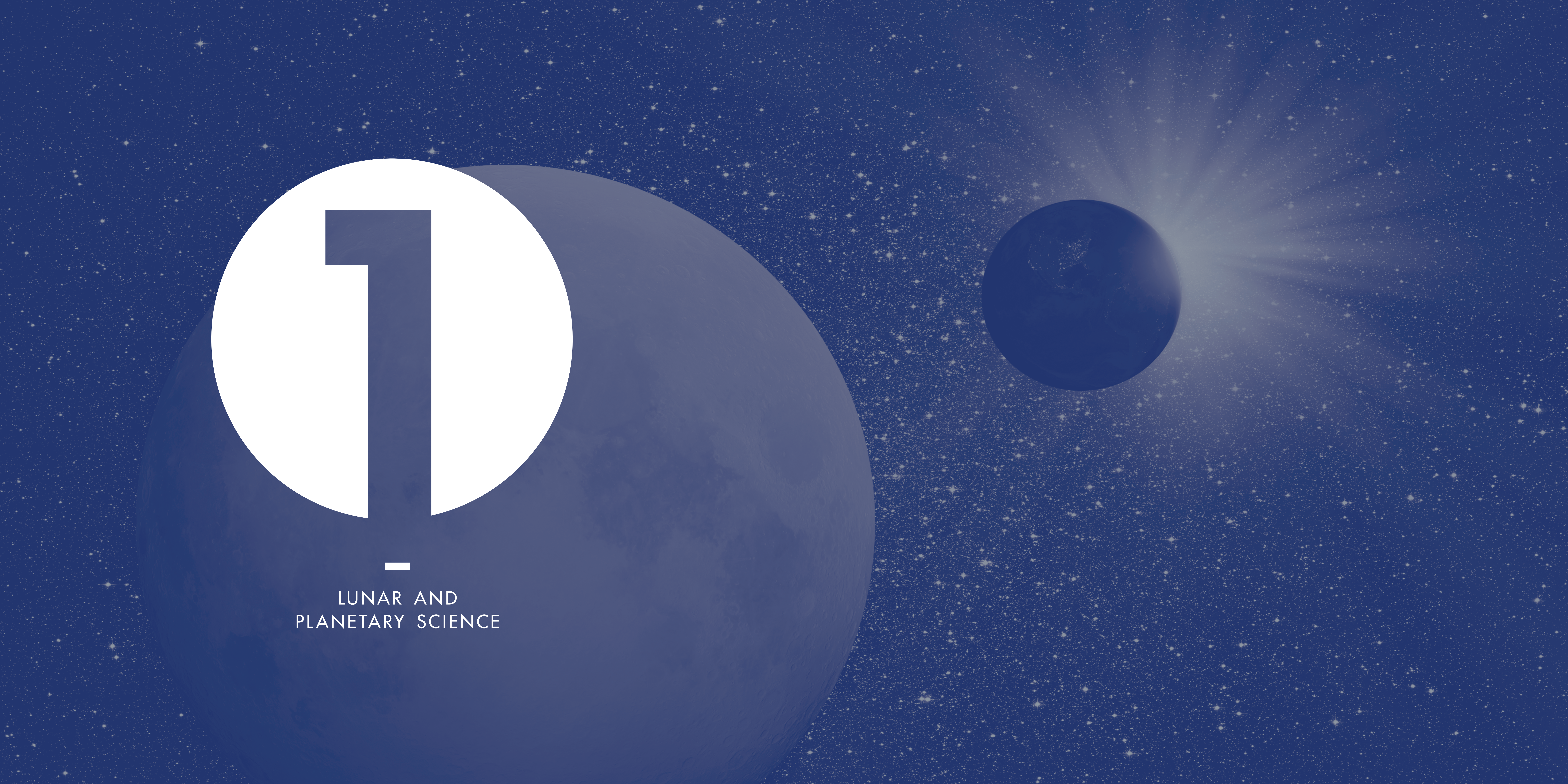
LUNAR AND PLANETARY SCIENCE



THE IMPACT OF CHICXULUB

How Scientists at the Lunar and Planetary Institute helped force a reevaluation of the geological doctrine of gradualism.

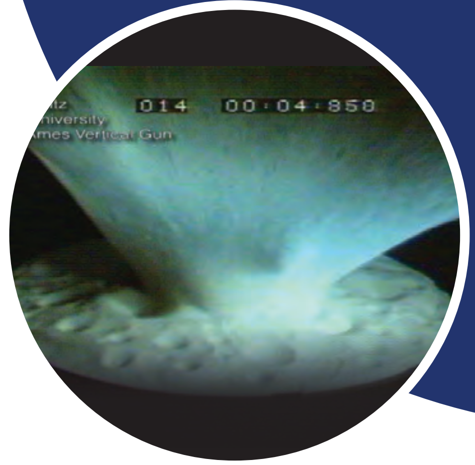
WITH THE IMPENDING RETURN OF THE LUNAR SAMPLES from the Apollo exploration of the Moon, NASA Administrator James Webb asked the National Academy of Sciences (NAS) to help build up a significant involvement by the university community in the development of NASA's research programs. As a result, the NAS, with support from NASA, created the Lunar Science Institute (LSI) in 1968, as well as an independent national consortium, the Universities Space Research Association (USRA), to manage the LSI and other institutes and programs as needed.

Under the leadership of its first director, Dr. William W. Rubey, the LSI began a wide-ranging lunar research program that was characterized by close working relationships with scientists from NASA and the university research community. Much of the research was focused on the analysis of the lunar samples that were being returned during the Apollo explorations and what these samples and other data from the Apollo program could reveal about the geology and geophysics of the Moon.

One topic of interest was the formation and structure of lunar basins and craters. In 1976, the LSI sponsored a Symposium on Planetary Cratering Mechanics that was held in Flagstaff, Arizona, and the Institute compiled the material for the follow-on book, *Impact and Explosion Cratering*. Participants at the conference discussed a range of issues related to the formation of craters, including the extent to which crater shapes are determined by the make-up of the target body, from where in the vertical distribution of the target body do materials in the ejecta distribution come, how shock waves produced by the impact might create magnetism in the minerals of the rocks at the impact site, and many other topics related to the mechanics of cratering.

Additional research occurred in 1977, when Dr. Peter Schultz, a staff scientist at the LSI, began the management of the science associated with the operation of the Vertical Gun Range at NASA's Ames Research Center.[1] The facility allows the study of craters produced by the vertical gun, which produces a gunpowder explosion that compresses hydrogen gas, which in turn propels a marble-size pellet down a 14-foot barrel into a target. High-speed cameras record the development of the impact and its aftermath.

In 1978, the LSI was renamed the Lunar and Planetary Institute (LPI), reflecting the growing, common interests of the lunar and planetary research communities. One such area of common interest involved large impacts on some of the terrestrial planets that produced basins with outlying rings, so called multi-ring basins. In the fall of 1980, the LPI sponsored a "Conference on Multi-ring Basins: Formation and Evolution." Schultz and Dr. Carroll Ann Hodges of the US Geological Survey convened the conference. Topics discussed at the conference included the possible mechanisms for creating the multi-ring structures, the time sequence of events during the formation, the density distribution of material within the structures, the profile of the underlying layers of material, and the range of the ejecta from the basins. The LPI published a book comprised of the research papers that were presented.[2]

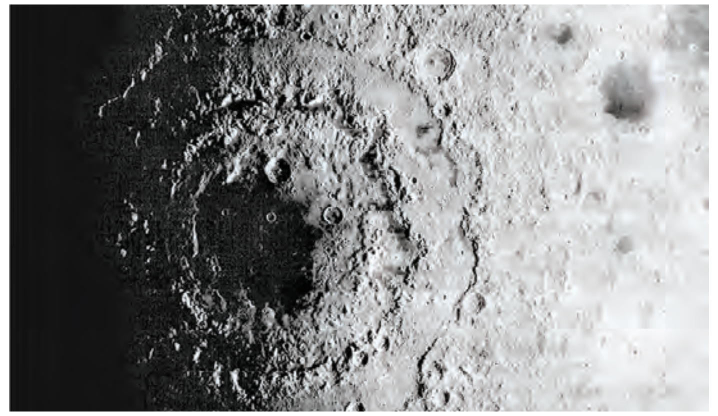


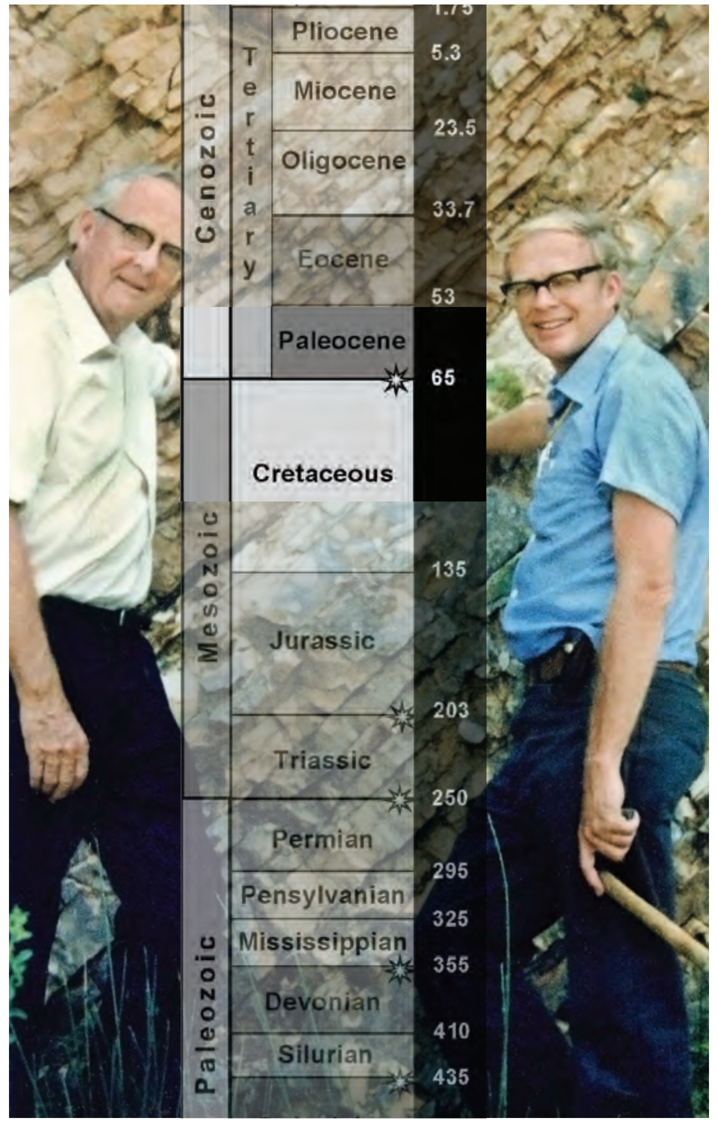
High-speed photo of an impact from the NASA Ames Vertical Gun taken by Peter Schultz. This photo was taken in 2005 after Schultz had moved to Brown University. It was simulating the Deep Impact projectile onto the surface of comet Temple 1. *(NASA)*

WILLIAM RUBEY
FOUNDING DIRECTOR OF THE LSI

Peter Schultz, in the yellow shirt, is shown with the Institute's Summer Interns of 1978.

THE ALVAREZ GROUP PROPOSED THAT THE IRIDIUM CAME FROM AN ASTEROID THAT IMPACTED THE EARTH 65 MILLION YEARS AGO. LPI'S STUDIES OF MULTI-RING BASINS ON THE MOON PROVIDED BACKGROUND FOR THE SUBSEQUENT ANALYSIS OF WHAT CAME TO BE KNOWN AS THE CHICXULUB CRATER.





RIGHT: Luis and Walter Alvarez standing at a site of the exposed iridium layer in Gubbio, Italy. *(Image: Adapted by Erin Senoz from Wikipedia)*

INSET RIGHT (PAGE 7): Charts prepared by Dr. Ron Blakey of Colorado Plateau Geosystems, Inc.

LEFT: The 1967 Orbiter IV photograph of the Moon's Mare Orientale multi-ring basin system. *Credit: NASA*

THE ALVAREZ HYPOTHESIS

That same year, Professor Luis Alvarez, a Nobel-laureate physicist at the University of California, Berkeley, and the Lawrence Berkeley Laboratory, his son Dr. Walter Alvarez, a geologist, Dr. Frank Asaro, a nuclear chemist, and Dr. Helen Michel, a paleontologist, together published an article in *Science* magazine titled "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction."[3] The group reported on finding large increases of the element iridium in deep-sea sediments that were exposed in Italy, Denmark, and New Zealand. The iridium was deposited in a thin clay layer that separated two distinct geological periods, the Cretaceous and the Tertiary (now called the Paleogene). This boundary between the Cretaceous and Paleogene periods is also the boundary between the Mesozoic and Cenozoic eras. Dinosaurs were prevalent during the Mesozoic era and extinct during the Cenozoic.

The Alvarez group proposed that the iridium came from an asteroid that impacted the Earth 65 million years ago, which is the time that marked the end of the Cretaceous period in geological history. They estimated the diameter of the asteroid at about 10 kilometers and that the impact would have injected about 60 times the asteroid's mass into the Earth's stratosphere, where it would be distributed worldwide and remain for several years. They proposed that the resulting darkness would suppress photosynthesis and cause the extinctions noted in the geological record. The Cretaceous-Paleogene boundary corresponds to one of the greatest mass extinctions in Earth's history. At least 75 percent of the species on Earth were extinguished. In the oceans, more than 90 percent of the plankton was extinguished, which led to the collapse of the oceanic food chain.[4]

LPI CONFERENCES

From its beginning, the LPI has sponsored annual conferences, now called the Lunar and Planetary Science Conferences, which are attended by hundreds of lunar and planetary researchers from around the world. In addition, the Institute sponsors workshops and topical conferences. A year after the publication of the paper by the Alvarez group, the LPI sponsored a topical conference titled "The Conference on Large Body Impacts and Terrestrial Evolution: Geological, Climatological, and Biological Implications." The conference was co-sponsored by the US National Academy of Sciences and held in Snowbird, Utah.

A SNOWBIRD CONFERENCE PAPER SPARKS CONTROVERSY

Peter Schultz was a part of the program committee for this first "Snowbird Conference," as they came to be called.[5] Among the more than 60 papers presented at the four-day conference was a paper by the Alvarez group and two papers co-authored by Schultz. The majority of papers presented aimed to further explore the idea that had been presented by Luis Alvarez and his colleagues. One was not. The abstract of the paper by Professor Thomas J. M. Schopf of the University of Chicago read in part:

> *The first step in any scientific program is to determine the problem to be solved. The often popular view that thousands of species of dinosaurs went extinct in the space of a year or two, worldwide, is not true. The firm evidence is that during the last 2 to 3 m.y. of the latest Cretaceous ... a total of about 16 species ... which had been living along the margins of a large seaway (which once extended from the Gulf of Mexico to the Arctic Circle) died off as the seaway dried up. Elsewhere in the world, local populations of dinosaurs had evidently died out before the latest Cretaceous both in Mongolia and in southern Europe. Possibly a species persisted in northern Europe into the latest Cretaceous. Seen in this light, the extinction of the dinosaurs is a perfectly understandable phenomenon – indeed no different than the fate of millions and millions of previous species. The reason why the extinction of the dinosaurs has attracted so much non-scientific attention by scientists and others is that (1) it doesn't cost anyone anything, (2) it sounds impressive, (3) it's basically a rather unimportant scientific problem though a rather important popular problem, and (4) hard paleontological data are difficult to obtain.*[6]

THE WESTERN INTERIOR SEAWAY

BEFORE 75 MILLION YEARS AGO

AT THE END OF THE CRETACEOUS PERIOD, 65 MILLION YEARS AGO

LEFT: 1983 David Kring, Peter Schultz, and the 1983 LPI Summer Interns.

RIGHT: 2009 David Kring examines lunar rock samples.

The seaway referenced by Schopf is called the Western Interior Seaway, and his position was well established in the field of Paleobiology. In 1975, the dinosaur expert Dr. Robert T. Bakker had written in a *Scientific American* article that the likely reason for the extinction of the dinosaurs:

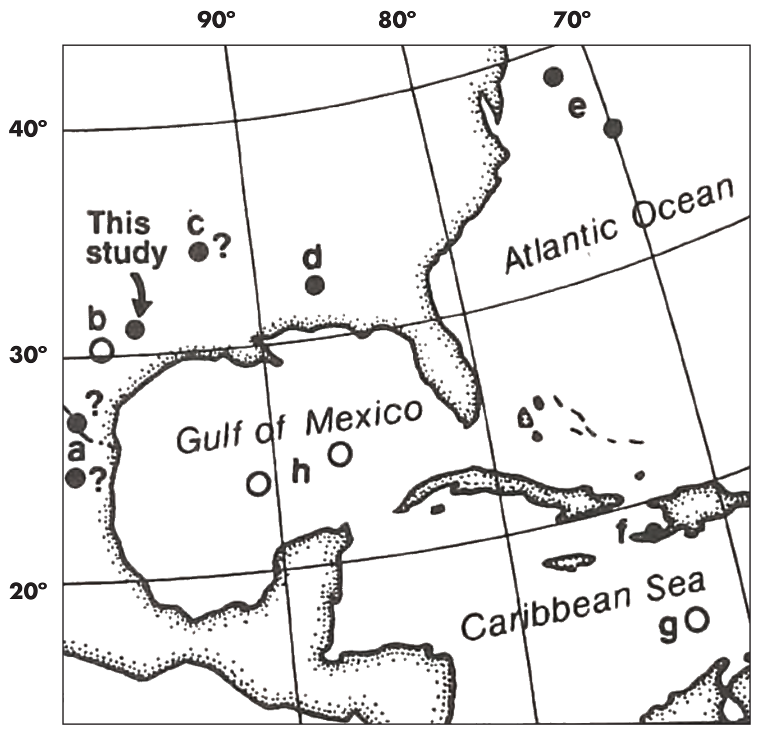
> *… is the draining of shallow seas on the continents and a lull in mountain-building activity in most parts of the world, which would have produced vast stretches of monotonous typography. Such geological events decrease the variety of habitats that are available to land animals, and thus increase competition. They can also cause the collapse of intricate, highly evolved ecosystems; the larger animals seem to be the more affected. At the end of the Permian similar changes had been accompanied by catastrophic extinctions among therapsids and other land groups. Now, at the end of the Cretaceous, it was the dinosaurs that suffered catastrophe; the mammals and birds, perhaps because they were so much smaller, found places for themselves in the changing landscape and survived.*[7]

Schopf's skepticism about the impact hypothesis as the cause of the extinctions at the end of the Cretaceous period was shared by many paleobiologists. In a 1981 paper titled, "Out with a Whimper, Not a Bang," W. A. Clemens, J. David Archibald, and Leo J. Hickey pointed out:

> *… the global pattern of relatively few extinctions in the tropics with increasing frequency of exterminations to the north is just the reverse of what would be expected [under the Alvarez hypothesis]. Dormancy and carry-over mechanisms evolved in response to climatic stress and are assumed to have been, then as now, less well developed in the tropics. In addition, plants eliminated from northern floras are those of more tropical affinity, like palms. … This multiplicity of patterns of extinction strongly argues against any hypothesis invoking some kind of catastrophic, short, sharp shock as the causal factor of the terminal Cretaceous extinctions. These paleobiological data suggest the Cretaceous-Tertiary transition was a period of several tens of thousands if not hundreds of thousands of years in duration, characterized by interaction of a complex of physical and biological factors producing a high net rate of decrease in biotic diversity within both the terrestrial and marine biotas.*[8]

This was just the beginning of widespread resistance by paleontologists to the ideas of the Alvarez group. The acrimony was at times rather bitter, as suggested by the following quotation from Bakker:

> *The arrogance of these people is simply unbelievable. They know next to nothing about how real animals evolve, live, and become extinct. But, despite their ignorance, the geochemists feel that all you have to do is crank up some fancy machine and you've revolutionized science. The real reason for the dinosaur extinctions have to do with temperature and sea level changes, the spread of diseases by migration and other complex events. In effect, they're saying this: we high-tech people have all the answers, and you paleontologists are just primitive rockhounds.*[9]



Closed circles represent sites with coarse-grained deposits at the K-T boundary. Open circles represent sites where there is a disconformity at the K-T boundary, presumably a gap in the sediment record caused by tsunami erosion.[13]

THIS INITIAL DISCOVERY [IN 1982] OF WHAT CAME TO BE CALLED THE CHICXULUB CRATER WAS UNKNOWN TO LUNAR AND PLANETARY SCIENTISTS FOR THE NEXT TEN YEARS.

We can hope that Bakker's charge of arrogance was overblown, but it was true that many geochemists were applying new technologies that had been developed for the analyses of lunar samples.

RESEARCH CONTINUES DESPITE CONTROVERSY

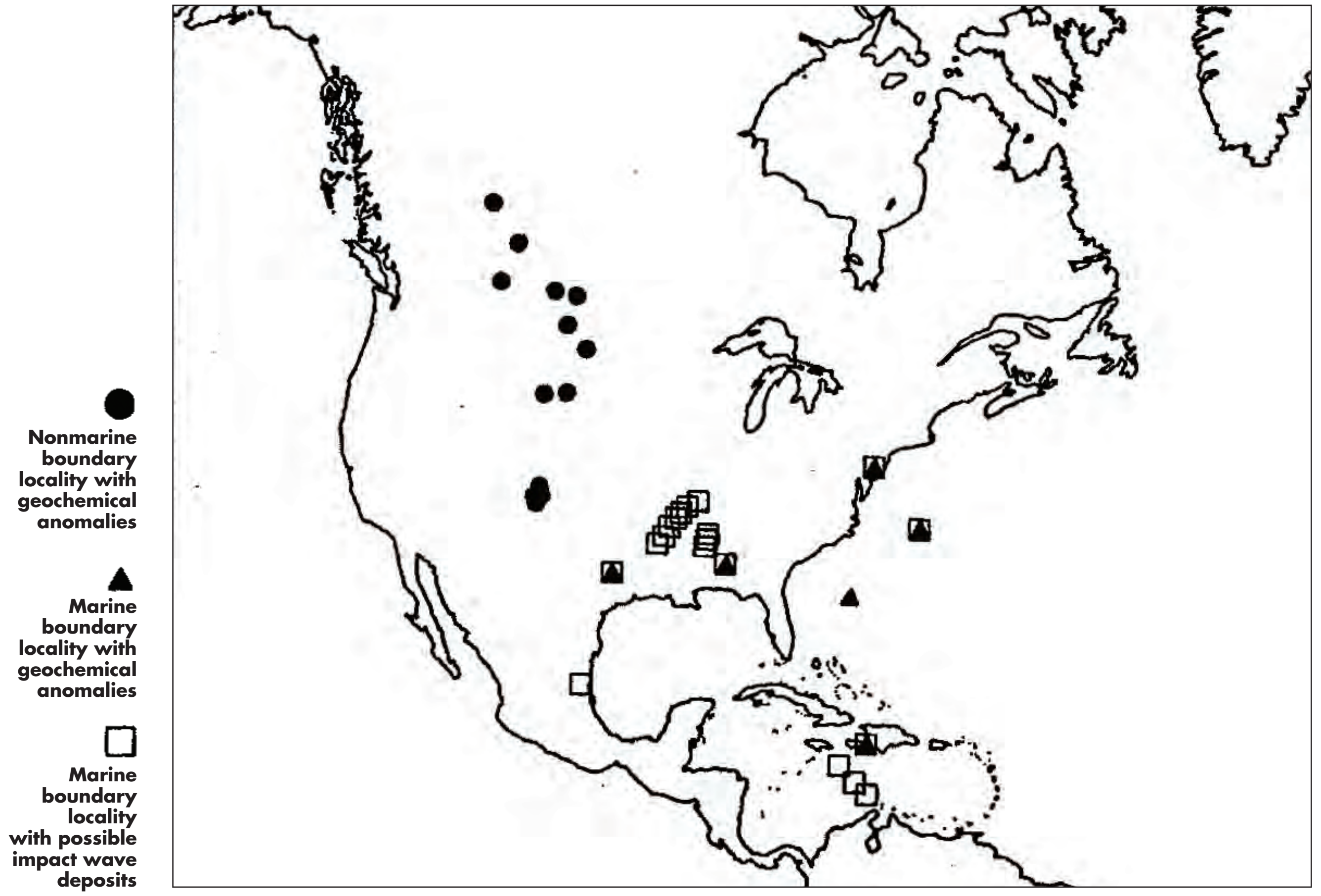
Meanwhile at the LPI, scientists were keeping their heads down as the controversies raged; continuing their research on crater formation, conducting workshops and conferences, and training new planetary scientists. The 1983 class of LPI Summer Interns contained an undergraduate from Indiana University, David Kring, who would later become involved in investigations that led to the identification of the crater that was caused by the kind of impact the Alvarez group had envisaged.

The discovery of the crater site was actually made at about the same time as the research by the Alvarez group, and it was announced the weekend before the first Snowbird Conference was held. Geophysicists Glen T. Penfield and Antonio Camargo-Zanoguera, working for the Mexican national oil company, Petróleos Mexicanos, or PEMEX, gave a paper at the 51st annual meeting of the Society of Exploration Geologists in which they described a large, buried, circular structure on the northwestern margin of the Yucatán peninsula of Mexico.

> *A recent survey collected approximately 50,000 km of high sensitivity aeromagnetic data at 500 m altitude over the Campeche bank and Yucatan platform. In conjunction with gravimetric studies and data from three Pemex wells, this survey indicated the presence of two concentric zones of igneous material beneath the central Yucatan platform. The central zone, characterized by numerous high amplitude (approaching 1000 γ), short wavelength magnetic anomalies, and a gravity high, has a diameter of approximately 60 km and is centered near the town of Progreso on the northern Yucatan coast. Well data indicates the presence of massive andesites of Jurassic or Cretaceous age. Modeling the magnetic and gravity data indicates in excess of 3 km of high-density highly magnetic material in this central zone. The depth to the top of the zone is on the order of 1100 m below the ground surface.*

EVER SINCE THE ANNOUNCEMENT OF THE IMPACT HYPOTHESIS BY THE ALVAREZ GROUP, MANY RESEARCH GROUPS HAD BEEN SEARCHING FOR THE IMPACT SITE.

AMERICAN MARINE AND NONMARINE K/T BOUNDARY LOCALITIES[15]



Concentric with this area is an outer zone characterized by low amplitude (5 to 20 γ), short wavelength magnetic anomalies, and a gravity low surrounded by a weak gravity high. This outer zone is approximately 200 km in diameter, and the well data suggest the presence of intercalated volcanics and limestones.[10]

Among the possible explanations for the structure, Penfield and Camargo listed, “a mid-plate igneous plume, or astrobleme,” the latter being the scar left on the surface of the Earth by the impact of an asteroid or comet.

Penfield and Camargo were exploring for oil deposits when they had done their survey and analysis of PEMEX data. Such exploration was the primary interest of the members of the Society of Exploration Geologists, and their meeting was not attended by geologists and geophysicists who were involved in the exploration of the Moon and planets of our solar system. Thus, the initial discovery of what came to be called the Chicxulub crater was unknown to lunar and planetary scientists for the next ten years.

In the fall of 1984, the LPI held a conference in Kona, Hawaii, titled the “Origin of the Moon,” and the Institute subsequently published a book with the same title. An outcome of this conference was a consensus view by the lunar and planetary research community that the Moon was created by a collision of a Mars-size planetary body with the Earth very early in the history of the Earth. The presentations and discussions at the conference helped to open the minds of researchers to the inevitability of impacts. In a paper for the conference, Professor William Hartmann of the University of Arizona wrote,

An example of the problem of class-predictable events in planetary science is the probable Cretaceous-ending asteroid impact. Since the 1960s, asteroid statistics have implied such events every few 10^7 – 10^8 years, but we could not convincingly tie specific geologic effects to specific impacts. In the absence of such evidence, impacts of this size tended to be ignored; as scientists, we should have pursued the geologic and climatic consequences of these class-predictable events instead of waiting for iridium-rich layers to take us by surprise.[11]

KEVIN BURKE
LPI DIRECTOR, 1982 – 1988

Ever since the announcement of the impact hypothesis by the Alvarez group, many research groups had been searching for the impact site, although other research groups were looking for or studying large volcanic sources that might explain the extinctions at the end of the Cretaceous. In the spring of 1987, the LPI held its 18th annual Lunar and Planetary Science Conference in Houston, and reports of some of the searches and studies were given at the conference. Drs. Alan R. Hildebrand and William V. Boynton of the Lunar and Planetary Laboratory of the University of Arizona reported on their analysis of rare-earth-element abundances in the Cretaceous-Tertiary (K/T) impact fall-out layers at various sites around the globe. They suggested that the impact site was in the eastern Pacific Ocean basin.[12]

A year later, however, a group of researchers led by Dr. Joanne Bourgeois of the University of Washington discovered an enormous tsunami deposit at sites near the Brazos River in Texas that were dated at the end of the Cretaceous period. The authors wrote:

Conditions for depositing such a sandstone layer at these depths are most consistent with the occurrence of a tsunami about 50 to 100 meters high. The most likely source for such a tsunami at the Cretaceous-Tertiary boundary is a bolide-water impact.[13]

THE SECOND SNOWBIRD CONFERENCE

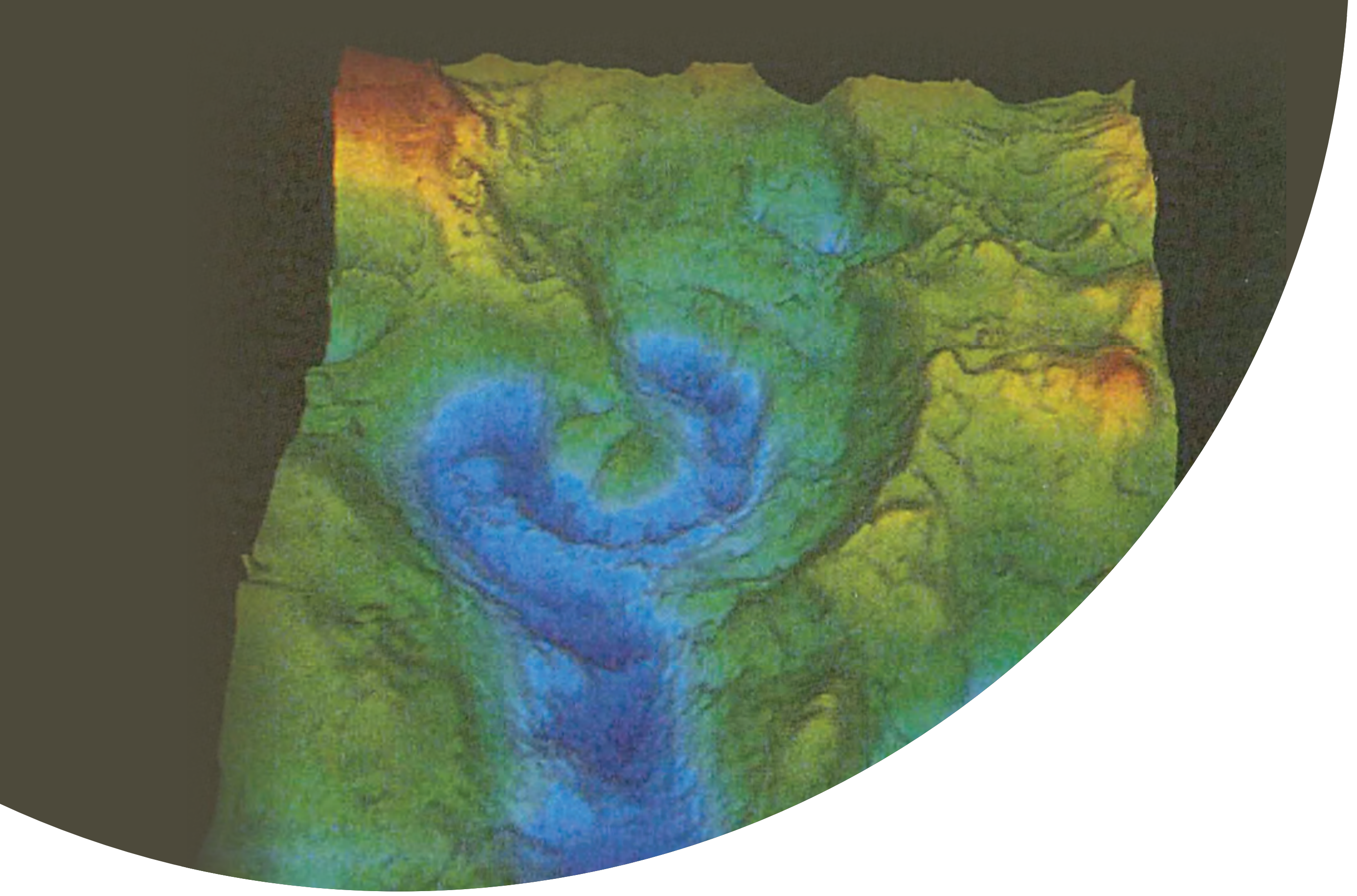
In the fall of 1988, the LPI co-sponsored with the National Academies of Science the second Snowbird conference, which had the title “Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality.” Various possible mechanisms for the end of the Cretaceous period were discussed at the conference, including the gradual transition favored by most paleontologists, as well as more catastrophic causes such as Earth impacts by asteroids or comets or large-scale volcanism episodes. Among the 60 talks and 67 posters given at the conference was a paper by Dr. Peter Francis, a visiting scientist at the Institute and Dr. Kevin Burke, who was the Director of the LPI. These LPI researchers discounted volcanism as a cause unless large episodes might have triggered ocean current circulation patterns that would cause global climatic changes. The Alvarez group gave a presentation, in which they wavered a bit about the certainty of an asteroid impact as the sole cause of the end of the Cretaceous period, perhaps because they yet knew of no suitable impact crater to support their hypothesis. Paleontologists Drs. J. David Archibald and Laurie Bryant reported on their examination of the vertebrate record, concluding:

The extinction patterns among the vertebrates do not appear to be attributable to any single cause, catastrophic or otherwise. The earliest Paleocene fauna can be understood as a Late Cretaceous fauna simply altered by withdrawal of the Western Interior Sea and by the formation of extensive swamps that replaced well-drained terrestrial environments.[14]

In a paper at the conference, Hildebrand and Boynton continued to favor an oceanic impact but now argued that the putative impact occurred in the ocean near North America.

All available evidence is consistent with an impact into oceanic crust terminating the Cretaceous Period. Although much of this evidence is incompatible with endogenic origin, some investigators still feel that a volcanic origin is possible for the K/T boundary clay layers. Following the dictum that remarkable hypotheses require extraordinary proof this latter view may still be reasonable, especially since the commonly cited evidence for a large impact stems from delicate clay layers and their components (i.e., no catastrophic deposits), and the impact site has not yet been found.

Impact sites have been suggested all over the globe, but are generally incompatible with known characteristics of the boundary clay layers. We feel the impact is constrained to have occurred near North America by:



Reprocessed gravity data over Northern Yucatán reveal three major rings and parts of a fourth ring, spaced similarly to those observed at multiring basins on other planets.[20]

the occurrence of a 2 cm thick ejecta layer only at North America locales, the global variation of shocked quartz grain sizes peaking in North America ... and possibly uniquely severe plant extinctions in the North American region. Also the ejecta layer may thicken from north to south.... A new constraint on the impact location comes in the form of impact wave deposits; giant waves are a widely predicted consequence of an oceanic impact.

Impact wave deposits have not been found elsewhere on the globe, suggesting the impact occurred between North and South America.[15]

In a paper for the follow-on book for the second Snowbird Conference, a group of researchers from the LPI, led by Dr. Virgil L. “Buck” Sharpton, argued against a single oceanic impact.

Understanding the crustal signature of impact ejecta contained in the Cretaceous Tertiary (K/T) boundary layer is crucial to constraining the possible site(s) of the postulated K/T impact event. The relatively unaltered clastic constituents of the boundary layer at widely separated outcrops within the Western Interior of North America are not compatible with a single oceanic impact but require instead an impact site on a continent or continental margin. On the other hand, chemical compositions of highly altered K/T boundary layer components in some marine sections have suggested to others an impact into oceanic crust. We suspect that post-depositional alteration within the marine setting accounts for this apparent oceanic affinity. If, however, this is not the case, multiple simultaneous impacts, striking continent as well as ocean floor, would seem to be required.[16]

THE DENOUEMENT

Finally, in the spring of 1990, Hildebrand connected with Penifeld, and the two of them, together with Kring, Mark Pilkington, Antonio Camargo-Zanoguera, Stein B. Jacobsen, and William Boynton collected the magnetic and gravity-field data, some of the core samples from previous PEMEX drillings, and the data from analysis of ejecta from sites around the Caribbean. In the fall of 1991, they published a paper in the journal *Geology* titled “Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico.” In the paper, they concluded:

The Chicxulub crater is the largest probable impact crater on Earth. Its position and target-rock composition satisfy many of the characteristics required for the K/T crater, and it may have a K/T boundary age. This impact may have caused the K/T extinctions.[17]

Hildebrand and his colleagues found shocked quartz grains in Chicxulub rocks, indicative of an impact, but they were unable to precisely date the Chicxulub crater.

The next year, a team led by Sharpton that included Drs. Graham Ryder (1949–2002) and Benjamin Schuraytz of the LPI, Brent Dalrymple of the US Geological Survey, and Luis Marín and Jaime Urrutia-Fucugauchi of the Universidad Nacional Autónoma de México (UNAM) published a paper based on their analyses of PEMEX core samples. They measured enhanced concentrations of iridium in some of the sections of the core samples, and they were able to determine the age of some of the melt-rock samples as 65.2±0.4 million years at the 95% confidence level.[18] For many researchers, this measurement, coupled with an independent and identical result the same year[19] by Paleontologist Carl C. Swisher III ended any remaining uncertainty about whether or not the buried Chicxulub structure was the long-sought impact crater that had been postulated by the Alvarez group in 1980.

THIS EXTRAORDINARY EVENT HAS LED TO NEW KINDS OF THINKING IN EVERY BRANCH OF SCIENCE IT HAS TOUCHED...IN GEOLOGY, IT FORCED A REEVALUATION OF THE CENTRAL GEOLOGICAL DOCTRINE OF “UNIFORMITARIANISM” OR “GRADUALISM,” WHICH FOR 150 YEARS HAD DISCOURAGED ANY THINKING ABOUT CATASTROPHIC EVENTS.

GRAHAM RYDER

PAUL SPUDIS

DAVID KRING

VIRGIL L. “BUCK” SHARPTON

Sharpton and Dr. Paul Spudis (1952–2018) at the LPI, and their colleagues at the University of Houston, UNAM, and PEMEX continued to study the Chicxulub structure through a cooperative research agreement between the LPI and the Instituto de Geofisica of UNAM. Building on their accumulated knowledge of lunar and planetary crater structures over many years, Sharpton and his colleagues published an article in *Science* magazine in the fall of 1993 with the following abstract:

The buried Chicxulub impact structure in Mexico, which is linked to the Cretaceous-Tertiary (K-T) boundary layer, may be significantly larger than previously suspected. Reprocessed gravity data over Northern Yucatán reveal three major rings and parts of a fourth ring, spaced similarly to those observed at multi-ring basins on other planets. The outer ring, probably corresponding to the basin's topographic rim, is almost 300 kilometers in diameter, indicating that Chicxulub may be one of the largest impact structures produced in the inner solar system since the period of early bombardment ended nearly 4 billion years ago.[20]

THE THIRD SNOWBIRD CONFERENCE

The impact site had been located and its structure continued to be examined by additional drillings, some of which were conducted through the collaborations between the LPI and UNAM. However, the argument as to whether or not the impact caused the extinctions at the end of the Cretaceous persisted.

In 1994, the LPI sponsored the third Snowbird Conference, which was actually held in Houston, Texas, and titled “New Developments Regarding the K/T Event and Other Catastrophes in Earth History.” The follow-on publication was co-edited by Ryder, David Fastovsky, and Stefan Gartner and was titled *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History.*

At the conference, the impact data were well presented by the Alvarez, Hildebrand, and Sharpton research groups. The dissenters, while admitting the reality of the impact, were reaching other conclusions about the KT extinctions. For example, Dr. J. David Archibald wrote, “Single-cause theories of extinction, such as a bolide impact and its corollaries, fail to explain the pattern of vertebrate extinctions at the KT boundary.”[21] José Guadalupe Lopez-Oliva & Gerta Keller added, “Our study indicates that the biotic effects of the KT boundary event on planktic foraminifera in the northeastern Mexico sections were not as catastrophic as predicted from a large bolide impact on Yucatan.”[22] In a separate paper, Keller argued:

One of the most important recent developments in KT boundary studies is the growing awareness that (1) the mass extinction associated with this event is not the result of a single catastrophe, (2) that extinctions occurred over an extended time period and were selective

THE CHICXULUB RESEARCH EFFORT CONTINUES WITH DRILLINGS AND STUDIES BY MANY WHO ARE STILL INTERESTED.

> *rather than random within organismal groups as well as between different groups, and (3) that the biotic effects were most severe and sometimes limited to tropical-subtropical regions while high-latitude faunas and floras escaped virtually unscathed.*[23]

The LPI's Graham Ryder wrote an article for the follow-on book that responded to the conclusions made by many of the paleontologists:

> *Many counter-revolutionary papers (i.e., those that deny an impact cause) over the last decade … give the impression that it is those who invoke an impact who have required a particular paleontological significance, for instance that impact proponents claim abrupt extinction. Yet it was never the case that an impact was inferred and that then there was a search for associated extinctions. It is an ironic reversal that some paleontologists chose to reduce the significance of the boundary after the impact was inferred. Rather than evaluate the record in the light of an impact, they chose to construct straw men.*[24]

The LPI co-sponsored the fourth Snowbird Conference, which was held in Vienna, Austria, in 2000. It was titled "Catastrophic Events and Mass Extinctions: Impacts and Beyond." There was continued discussion of the Chicxulub impact at the conference, but the main focus was on whether or how short-term, high-energy impacts influence biological evolution on Earth.

CONTINUED RESEARCH

In 2006, David Kring, who had been an LPI intern in 1983, returned to the Institute as a scientist. Kring had obtained his PhD at Harvard and then joined the staff at the University of Arizona, where he had worked on K-T impact research, including drillings at Chicxulub, among other things.

In 2010, Kring joined 40 other senior researchers from 12 countries in the publication of a review article for *Science* magazine titled "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary."[25] Following their world-wide, exhaustive research, the authors concluded:

> *The Cretaceous-Paleogene boundary ~65.5 million years ago marks one of the three largest mass extinctions in the past 500 million years. The extinction event coincided with a large asteroid impact at Chicxulub, Mexico, and occurred within the time of Deccan flood basalt volcanism in India. Here, we synthesize records of the global stratigraphy across this boundary to assess the proposed causes of the mass extinction. Notably, a single ejecta-rich deposit compositionally linked to the Chicxulub impact is globally distributed at the Cretaceous-Paleogene boundary. The temporal match between the ejecta layer and the onset of the extinctions and the agreement of ecological patterns in the fossil record with modeled environmental perturbations (for example, darkness and cooling) lead us to conclude that the Chicxulub impact triggered the mass extinction.*[26]

In 1990, Walter Alvarez reflected on the significance of the research topic that he and his father and others at Berkeley had started.

> *However, this extraordinary event has led to new kinds of thinking in every branch of science it has touched. In biology, it required thinking about non-Darwinian mechanisms of evolution. In geology, it forced a reevaluation of the central geological doctrine of "uniformitarianism" or "gradualism," which for 150 years had discouraged any thinking about catastrophic events. In chemistry, it focused on iridium, an almost comically obscure element, and created a demand for very fast analytical capabilities at the parts-per-trillion level. And new problems have been opened up in ecology, geophysics, astrophysics and atmospheric science, as well.*[27]

The Chicxulub research effort continues with additional drillings and studies by Kring and others at the LPI. As noted by Alvarez, it is an important investigation affecting many branches of science. The LPI has played a significant role in the development of this research, consistent with the vision of NASA Administrator Webb and others who created USRA to be an entity in and through which universities could cooperate with each other, the federal government, and other organizations to develop knowledge.

ENDNOTES

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THE ORIGIN OF THE MOON AND A SCIENTIFIC COMMUNITY

How a USRA institute helped develop the research discipline of lunar and planetary science.

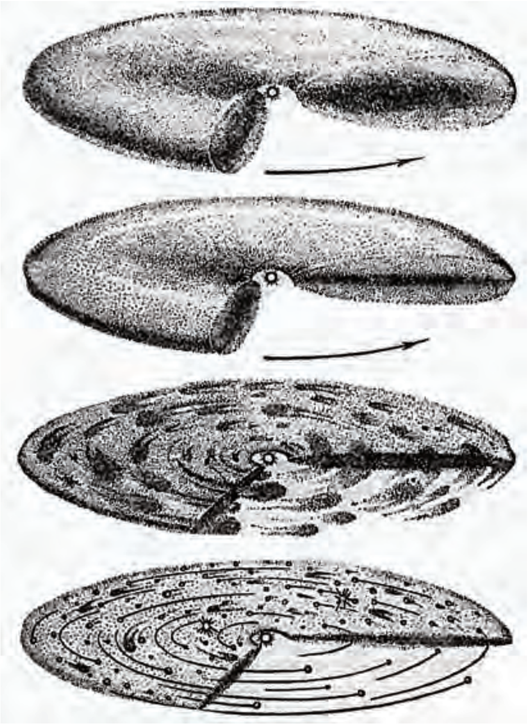
Credit: Voraorn Ratanakorn, Shutterstock

THE SCIENTIFIC DISCIPLINES OF ASTRONOMY and geology rest upon centuries of research from which ideas and technologies have been developed, tested, and widely shared. In contrast, the newer discipline of lunar and planetary science was much less well developed, and prior to the Apollo exploration of the Moon, it lacked a vigorous research community.

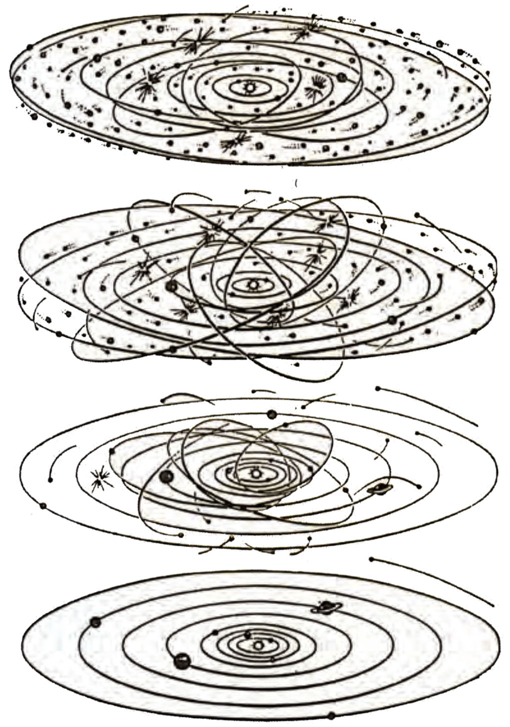
From time to time, geologists or astronomers put forward ideas about the Moon, but there was little or no follow up from others. An example was the work of Dr. Grove Karl Gilbert (1843–1918), a distinguished American geologist who in the summer of 1892 made observations of the Moon with the 26½ inch telescope of the U. S. Naval Observatory and concluded that the craters of the Moon were not volcanoes, as was commonly thought, but were caused by impacts of other solar system bodies.[1]

Gilbert's work was ignored for decades. The astronomer Dr. Ralph Belknap Baldwin (1912–2010), who also made careful observations of the Moon's surface and came to the same conclusions in 1941, was unaware of Gilbert's work. Baldwin's assertion—that the great lunar basins such as Imbrium, Serenitatis, and Tranquillitatis were caused by giant impacts—wasn't accepted by many distinguished astronomers, and he had a difficult time finding a journal willing to publish his initial work.[2,3] Prior to the Apollo exploration of the Moon, there wasn't a significant community of researchers who identified themselves as lunar scientists or planetary scientists. The lack of such a community, and the absence of the dialog that would have taken place within it, left standing a few, old hypotheses about the origin of the Moon.

G.K. GILBERT
Credit: USGS



Formation of asteroid-sized intermediate bodies from the dust component of the solar nebula according to the models of Russian researchers.
Credit: Elsevier



Gradual accretion of intermediate bodies into planets, per the Russian models.
Credit: Elsevier

OTTO SCHMIDT

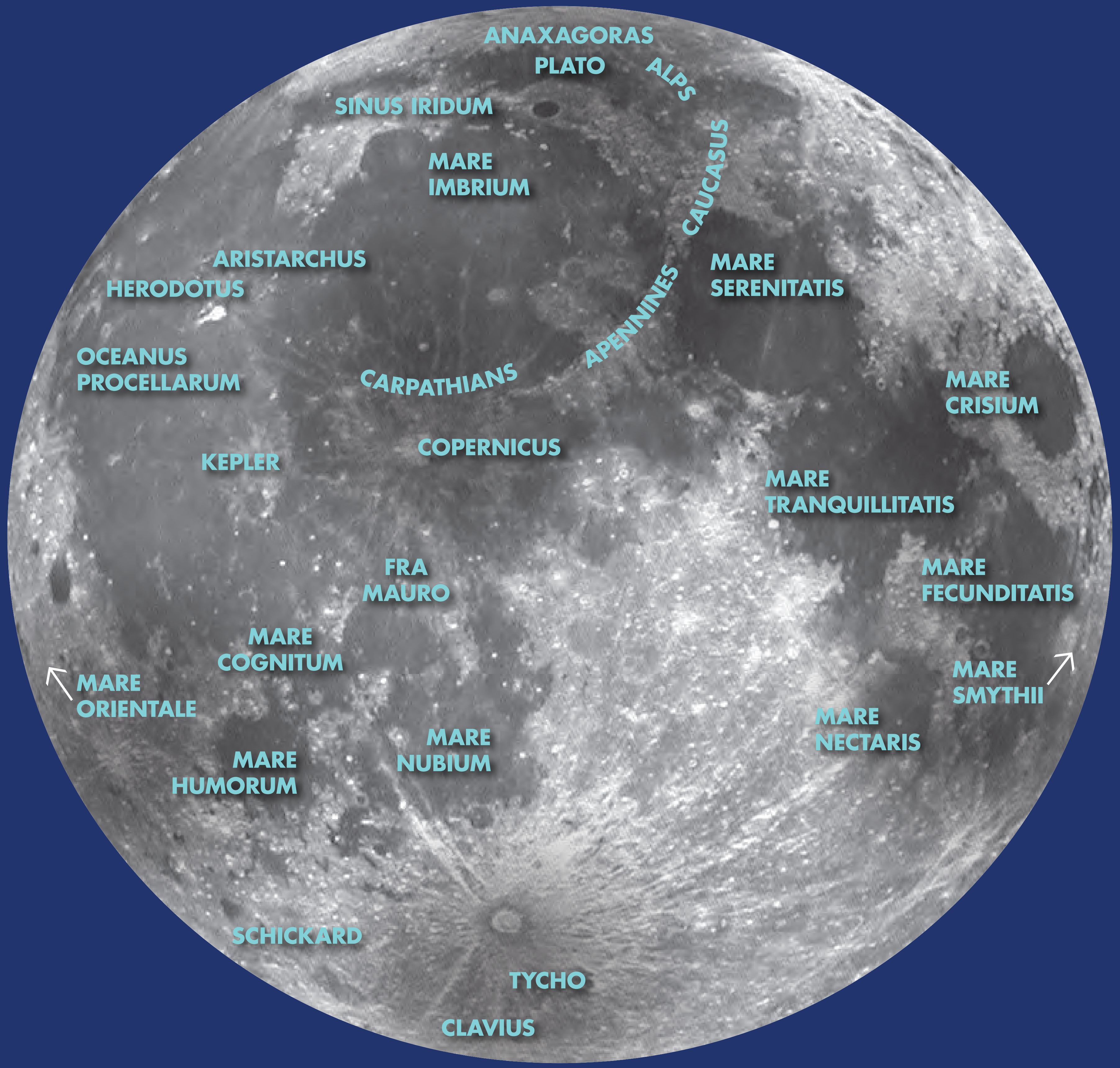
VICTOR SAFRONOV

MOON HYPOTHESIS ONE

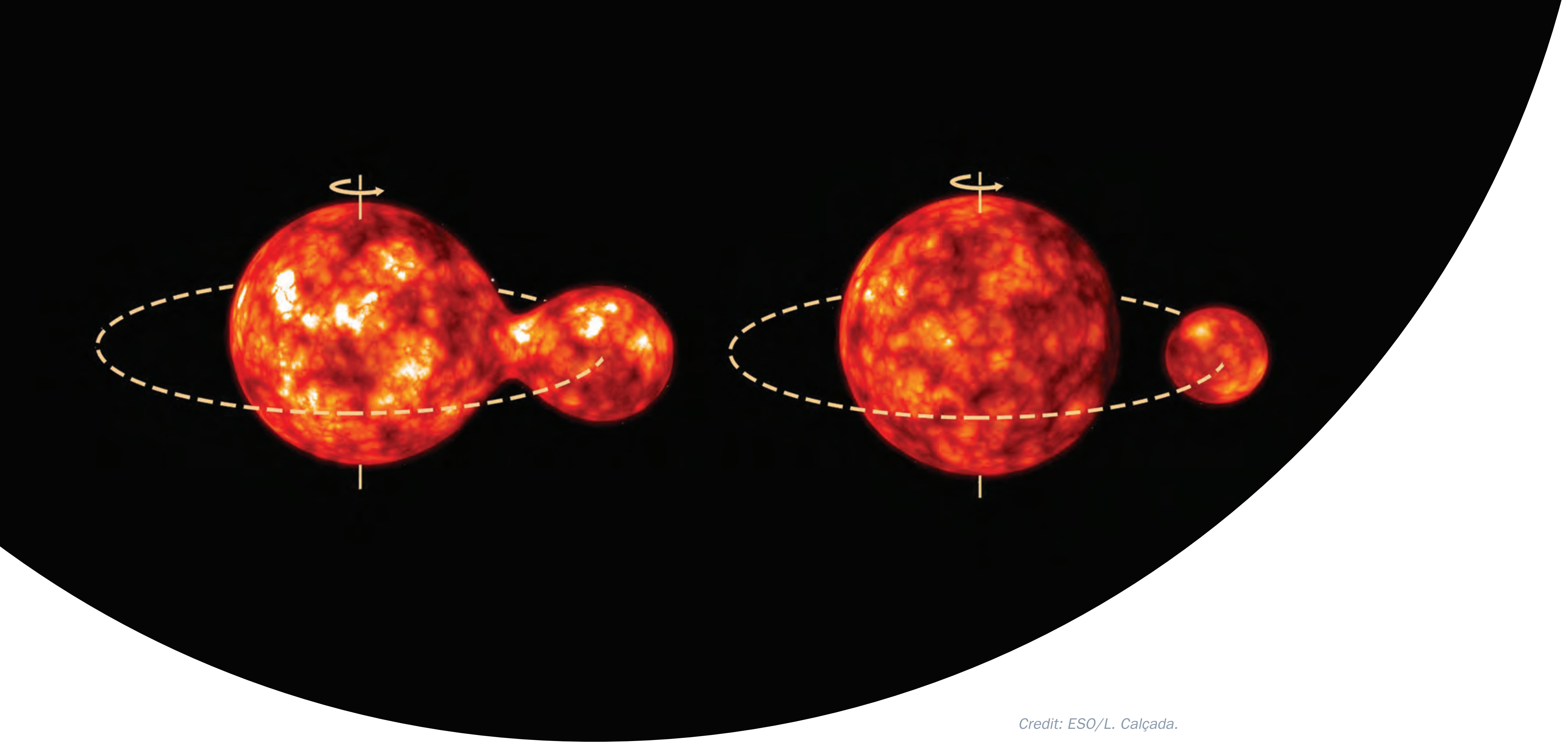
Perhaps the leading one of these hypotheses was called "co-accretion" or "binary accretion." A version of this idea that influenced planetary scientists following the Apollo exploration of the Moon was developed at the Institute of Theoretical Geophysics in Moscow by Otto Yulevich Schmidt (1891–1956) and his colleagues. Schmidt studied the formation of the Moon and other planetary satellites in the context of the larger process that formed the solar system. He believed that:

> *The satellites are formed in one single process together with the planets. During the process of planet formation, when particles encountered the bigger planet embryos, some of them lost their velocity to such an extent in collisions that they were captured from the swarm and began to revolve around the planets. In this way a condensation, a swarm of particles, was formed near the planet embryo and revolved about it on elliptical orbits. These particles also collided amongst themselves, thus changing their orbits. In these swarms, processes similar to the formation of planets took place on a smaller scale. The majority of the particles fell on to the planet and were absorbed by it, but some of them formed a swarm around the planet and accumulated to form independent embryos, the future satellites. The exception is the ring of Saturn which consists of small particles that have not been able to agglomerate on account of the tidal action of Saturn in whose immediate vicinity they are (an unformed satellite). As the orbits of the particles forming a satellite were averaged, the satellite acquired a symmetrical, almost circular orbit in the equatorial plane of the planet and could not fall on it. In this way satellites appeared around the planets. Thus we see that the formation of the satellites was a by-product of the formation of the planets…*[4]

Schmidt's model was refined by his students, and perhaps the best known among them by US scientists was Dr. Victor Sergeevich Safronov (1917–1999). Scientists referred to the model developed over the years at the Institute of Theoretical Geophysics as the "Russian model" or the "Safronov model" for the formation of the solar system. An important feature of the model held that the accretion of the planets and their satellites occurred in two stages: first, the formation of asteroid-sized intermediate bodies from the dust component of the solar nebula; and second, the aggregation of those bodies to form the planets and their satellites.[5]



Credit: Lunar and Planetary Institute and Erin Senoz



Credit: ESO/L. Calçada.

GEORGE H. DARWIN

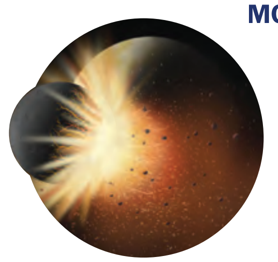
MOON HYPOTHESIS TWO

A second commonly held view about the origin of the Moon was called "fission," or more properly, "rotational fission." George Howard Darwin (1845–1912), the second son of Charles Darwin, was primarily responsible for developing this theory. He and others understood that the tides observed on Earth were caused by the Moon, and to a lesser extent the Sun. He reasoned that if the early Earth were a molten, viscous mass with an orbiting Moon, then the main body of the Earth would rotate beneath stationary tidal bulges, just as today's Earth rotates beneath tidal bulges in the ocean's surface. If the early Earth was a viscous liquid, there would be frictional losses of energy within the Earth as it rotated beneath the tidal bulges, and this loss of energy would come from the rotational kinetic energy of the Earth, so that the Earth's rate of spin about its axis would be reduced. Because of the conservation of angular momentum in the Earth-Moon system, the loss of spin angular momentum of the Earth would be compensated by an increase in orbital angular momentum of the Moon about the Earth-Moon center of mass. This increased orbital angular momentum of the Moon would be accomplished by an increase in the Earth-Moon separation distance. Darwin then argued that if in the early life of the Earth-Moon system the Moon was moving away from the Earth, there must have been an earlier time when the Earth and Moon were closer together, and therefore, "if the moon and the earth were ever molten viscous masses, then they once formed parts of a common mass."[6]

If the common mass of the proto-Earth and Moon had the same angular momentum as the current Earth-Moon system, it would have been rotating with a period of between four and five hours. Darwin argued that a resonance between tides caused by the Sun and the natural oscillation of a liquid proto-Earth could cause a rupture that would result in the Moon revolving around the Earth.

MOON HYPOTHESIS THREE

A third idea for the formation of the Moon was the "capture" hypothesis. When one planetary body passes near another one, it cannot go into orbit around the second body unless its kinetic energy is reduced. This has become familiar during the age of planetary exploration, when the kinetic energy of a spacecraft is reduced by the firing of retro-rockets to allow the spacecraft to go into orbit around a planet. In 1955, a German school teacher, Dr. Horst Gerstenkorn (1923–1981), developed a detailed theory for how an approaching planetary body could have been captured by the Earth to become the Moon.[7] In the scenario developed by Gerstenkorn, the pre-captured Moon passed around the Earth in a retrograde trajectory, i.e., moving opposite to its current prograde sense, which is in the same rotational direction as the rotation of the Earth, and with the plane of its motion inclined to the plane of the Earth's equator by 31 degrees. In this first pass, at a closest approach of 26 Earth radii, Gerstenkorn calculated that there was enough energy lost by tidal friction to allow the Moon to be captured by the Earth. Because of its retrograde motion, the conservation of angular momentum dictated that the Moon would get closer to the Earth, instead of farther away, as the Earth's spin was reduced owing to tidal friction, and that the inclination of the plane of the Moon's orbit would increase. When the Moon came as close to the Earth as 4.7 Earth radii, the inclination of the Moon's orbit relative to the Earth's equator passed 90 degrees, and the Moon began to orbit the Earth in a prograde sense. The captured Moon was now in a highly inclined prograde orbit, and angular momentum was conserved by lowering the inclination of the orbit while the Moon continued to get closer to the Earth. The Moon reached its closest approach at a geocentric distance of about 2.9 Earth radii, following which angular momentum was conserved by both a continued decline in the inclination of the Moon's orbit and an increase in its distance from the Earth. Eventually, the Moon achieved its present, near circular orbit.[8]



MOON HYPOTHESIS FOUR

A fourth idea for the origin of the Moon might be called "collisional fission" or "collisional capture" or, as we shall see below, the "giant impact" hypothesis. Until the 1970s, few scientists considered this possibility, though the idea had its modern origin in the early- to mid-1940s, when the eminent Princeton astronomer, Professor Henry Norris Russell (1877–1957) wrote to Professor Reginald Aldworth Daly (1871–1957), "that it might be worthwhile to study the question whether the main part of the moon's substance represents a planetoid which, after striking the earth with a glancing, damaging blow, was captured."[9]

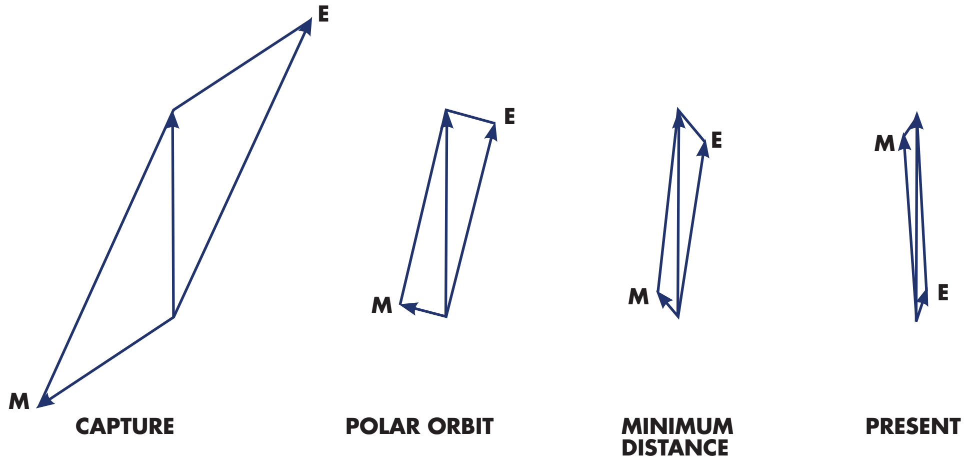
Daly at the time was an emeritus professor of geology at Harvard, and he followed up on Russell's suggestion and published the results of his study in 1946. Daly conjectured that:

> *A 'planetoid,' captured because of tangential, slicing, collision with the liquid earth, brought with it so much angular momentum as to ensure its perpetuation as a separate, revolving body – the moon we know. ... initially liquid fragments were exploded out of the planet, well beyond Roche's limit. Many of these were gravitationally aggregated by the pull of master fragment or captured 'planetoid' to make the substance of our moon, and the somewhat diminished earth felt a prolonged rain of other earth-fragments, large and small.*[10]

Daly's paper was ignored for forty-six years, another example of the lack of a vibrant lunar science research community during that time. In a belated review of the paper in 1992, Ralph Baldwin and Donald Wilhelms noted that:

> *Daly's paper explicitly discussed the idea that a collision between the brand-new Earth and a planet-sized body led to the formation of the Moon. Yet his paper is not discussed in any of the modern works on the origin of the Moon...*[11]

The angular momentum vectors for the Earth's rotation (E) and the Moon's orbital motion (M) during the capture of the Moon by the Earth in Gerstenkorn's theory. The vector sum is constant and is represented by a vertical arrow. Four stages in the evolution of the Earth-Moon system are shown.
Credit: Field, 1963



REGINALD DALY

ROCHE'S LIMIT

The Earth exerts tidal forces on the Moon in the same way that the Moon exerts tidal forces on the Earth. When the Moon was in a formative state, so that its various parts were held together loosely by mutual gravitational attraction, there was a minimum distance that the Moon could approach the Earth without being torn apart by the tidal forces from the Earth. That distance is called the Roche limit, named for the French astronomer, Édouard Roche, who first derived it in 1848. The concept of a Roche limit applies to all bodies in the solar system. For the Earth, the Roche limit is a little less than a distance of 3 Earth radii from the Earth's center.

REGINALD DALY'S IDEA THAT A COLLISION BETWEEN THE BRAND NEW EARTH AND A PLANET-SIZED BODY LED TO THE FORMATION OF THE MOON WAS IGNORED FOR 46 YEARS.

HAROLD UREY

RALPH BALDWIN

THE MOON IN THE 1960S

By the mid 1960s, strong objections had been raised to the co-accretion, rotational fission, and capture hypotheses for the formation of the Moon. The high angular momentum of the Earth-Moon system was not easily explained by the co-accretion theory. Theoretical analysis indicated that internal friction in a liquid proto-Earth would not allow the tidal resonances required for rotational fission,[12] and even if rotational fission did occur, the ejected Moon would continue to move away from the Earth rather than settle in orbit around it.[13] Gerstenkorn's capture hypothesis seemed unlikely. It required an enormous initial (positive) angular momentum for the Earth prior to the capture of a body that was bringing angular momentum with an opposite sign to what would become an Earth-Moon system with a very high (positive) angular momentum. There were counter arguments to these objections, however, and all three primary models were at least marginally viable as the Apollo exploration of the Moon drew near. But, as Professor Harold Clayton Urey (1893–1981) noted in 1963, "there is no model for the origin of the moon that is not complicated and does not appear to be very highly improbable."[14]

In 1965, Ralph Baldwin further lamented:

> *We are thus left on the multipointed horns of a dilemma. There is no existing theory of the origin of the moon which gives a satisfactory explanation of the earth-moon system as we know it.*
>
> *The moon is not an optical illusion or a mirage. It exists and is associated with the earth. Before 4.5 billion years ago, the earth did not exist. Somehow in this period of time, the two bodies were formed and became partners. But how?*[15]

All hoped that the upcoming exploration of the Moon would reveal how the partnership was formed.

THE FORMATION OF LSI AND USRA

In 1966, as astronauts were preparing for the first mission to leave Earth orbit, the NASA Administrator James Edwin Webb (1906–1992) began to look for a new mechanism to engage university researchers in the missions of NASA. Webb knew that since the creation of NASA in 1958, university researchers had built their scientific instruments on their campuses, brought them to NASA for testing, launch, operation, and data capture, and then analyzed and published their data in the normal mode of academic research. Webb foresaw that future NASA missions, such as those of the Apollo program, would be much more operationally complex and require a stronger means of engagement with university researchers.

President Lyndon Johnson announcing the formation of the Lunar Science Institute on 1 March 1968.

Webb turned to the National Academy of Sciences (NAS) to identify the proper mechanism or organization to give NASA the intellectual and technical support of university researchers, while at the same time minimizing the burden on university scientists who had the responsibility to teach and train graduate students. The president of the NAS, Dr. Frederick Seitz (1911–2008), took on the task, and after lengthy deliberations, the Lunar Science Institute (LSI) was formed near the Manned Spacecraft Center (later named the Johnson Space Center) south of Houston.

President Lyndon Johnson announced the creation of the LSI on 1 March 1968. Rice University was appointed as interim institutional manager for the LSI while the academic community deliberated with the NAS over an organizational structure to oversee the institute. In February 1969, the NAS, with the support of NASA, organized the Universities Space Research Association (USRA) to manage the LSI, and other facilities and programs as the need arose. USRA was incorporated as a nonprofit association of 48 major research universities on 12 March 1969, and now numbers more than 100 such universities as members.[16]

EXPLORATION OF THE MOON

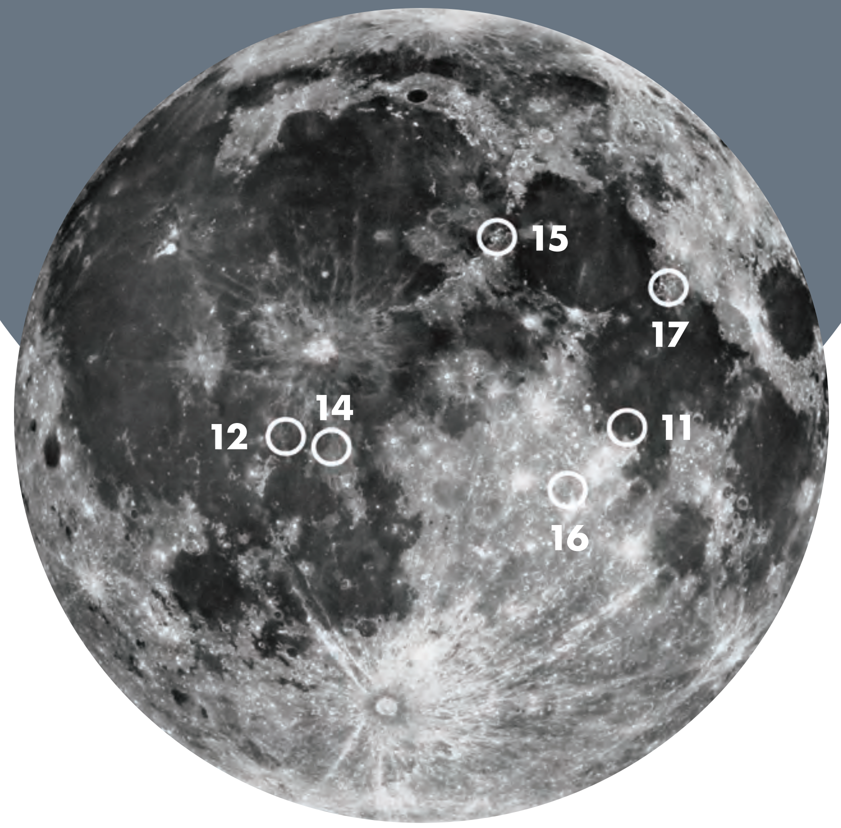
The first director of the LSI, William Walden Rubey (1898–1974) soon began to assemble staff and visiting scientists to carry out lunar research and assist other researchers around the world in the analysis of lunar samples and, more generally, in the conduct of a discipline that would come to be defined as lunar and planetary science. Time was short for developing the LSI into a viable entity to assist both NASA and the university research community. The first Apollo landing would take place on 20 July 1969.

Between July 1969 and December 1972, six Apollo explorations brought 382 kilograms (842 pounds) of lunar samples (rocks and soil) to Earth laboratories for analysis by scientists from all over the world. In addition, data from surface packages left on the moon, including seismometers, heat-flow sensors, and retro-reflectors, began to be analyzed. Among the major results of the analyses of lunar data were:

- The age of the Moon was determined to be 4.6 billion years, similar to the age of the Earth and other objects in the solar system.[17]
- The ages of the basaltic lavas from the lunar maria varied from site to site and were younger than the ages determined for the rocks in the lunar highlands by at least 0.5 billion years. The younger basalts must have been produced by melting via radioactive heating deep below the surface of the Moon subsequent to its formation. Liquid lava is about 10% less dense than solid basalt, so the basaltic lava would have risen to the surface of the Moon and filled preexisting basins that had been created by giant impacts.[18]
- Most of the samples taken from the lunar highlands were anorthosites, an unusual rock type that's not likely to be produced as a condensate from the primitive solar nebula of gas and dust. It can only be formed by fractional crystallization.[19]
- There had been melting of the outer 100 km or more of the Moon, with the result that lunar material had "differentiated," with lighter layers on top of heavier ones.[20]
- The rate of impacts by bodies causing craters on the Moon was much higher during the first 0.5 billion years following the Moon's formation than the average rate of impacts over the life of the Moon.[21]
- Lunar samples were significantly deficient in volatile elements,[22] including water in the mineral structure of the rocks,[23] and enriched in most of the refactory elements, compared to their presumed abundance in the primitive solar system.[24] The lunar samples were also deficient in iron and iron-loving elements, so-called siderophiles.[25]
- The outward heat flow measured at the Apollo 15 and Apollo 17 sites suggested a global heat flux of about 18 ergs/cm^{2}sec.[26] The outward heat flow through the surface of the Earth has been recently estimated at 47±2 x 10^{12} watts,[27] which corresponds to an average outward heat flux over the Earth's surface of about 92 ergs/cm^{2}sec.
- Lunar magnetic data suggested that the Moon had a fluid core 3-4 billion years ago.[28]

THE SIX APOLLO LANDING SITES

(Credit: Lunar and Planetary Institute/Erin Senoz)



WILLIAM HARTMANN

DONALD DAVIS

ALASTAIR CAMERON

WILLIAM WARD

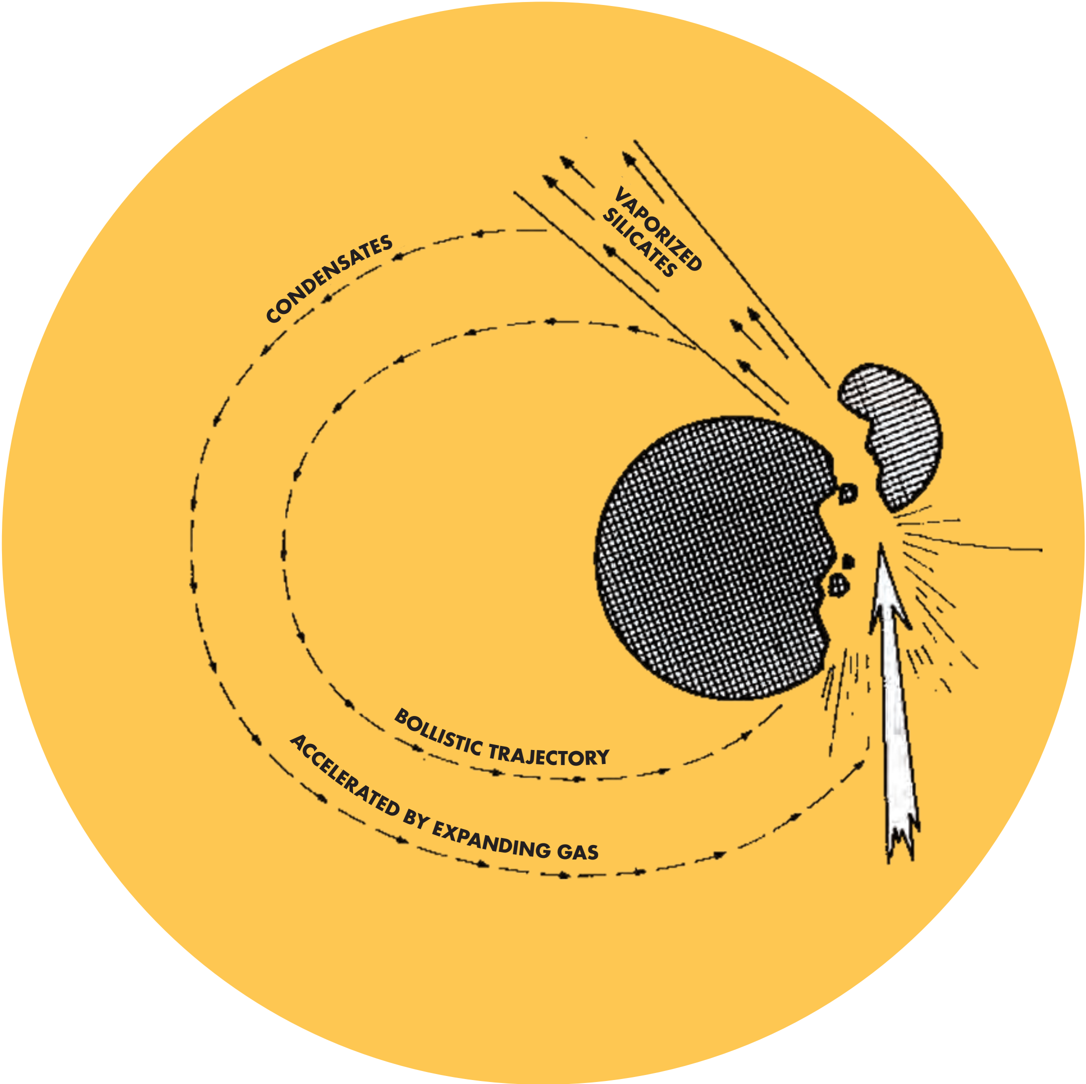


FIGURE: The collisional ejection model: Expansion of ejected silicate vapor accelerates condensates into orbit around the Earth.
Credit: From figure 10 in Wood, J. A.

TOP (LEFT TO RIGHT): William Hartmann, *Arizona Public Media.* **Donald Davis,** *Planetary Science Institute.* **Alastair Cameron,** *Yeshiva University.* **William Ward,** *University of Missouri, Kansas City.*

OPPOSITE: *Robert Clayton, University of Chicago.*

THE "GIANT IMPACT" MODEL

Analyses of the lunar samples and other Apollo data gave a clearer picture of the structure of the Moon, but the question of the origin of the Moon still wasn't settled. Generally, the protagonists of pre-Apollo theories adjusted their theory to accommodate the lunar data.

Among the original theories, rotational fission was largely dropped from consideration. The developing lunar science community continued to be unaware of Reginald Daly's hypothesis, but collisional fission began to be discussed, though initially in the context of variations of other theories. In 1975, however, the collisional fission or "giant impact" idea began to be treated as an independent theory to explain the lunar geochemical data. In that year, Drs. William K. Hartmann and Donald R. Davis published a paper in which they pointed out that, "collision of a large body with the Earth could eject iron-deficient crust and upper mantle material, forming a cloud of refractory, volatile-poor dust that could form the Moon."[29]

Hartmann and Davis made a virtue of a seemingly ad hoc theory, concluding that:

> *This model has an important philosophically satisfying aspect. There has always been difficulty in accounting for all properties of all satellite systems by a single evolutionary theory. Jupiter and Saturn have "miniature" solar systems with retrograde outriders. Uranus has its spin and satellites' angular momentum vectors radically altered. Earth is a "dual" planet with a relatively huge satellite. Mars has only two tiny moons. Venus and Mercury have none. This heterogeneity becomes more satisfyingly accountable if it is viewed as the product of events involving statistics of small numbers. Does the second-largest planetesimal in each system hit the planet after 10^7 years or 10^8 years? Is it large or small? Does it hit the planet dead center? Retrograde? A glancing blow prograde? Or is it captured? Or is it destroyed by a planetesimal-planetesimal collision so that it has no appreciable effect on the planet other than to produce many small craters? Or does it hit a preexisting satellite of the planet, perhaps converting it to several small satellites? Only one of these kinds of fates can befall the second-largest planetesimal. And this fate, the product of small-number statistical chance encounters, may determine whether the planet acquires a tilted axis, a massive circumplanetary swarm of dust, a captured satellite, or perhaps loses a larger satellite, gaining small fragmentary satellites.*
>
> *This model can thus account for the iron depletion, refractory enrichment, and volatile depletion of the Moon, and at the same time account for the Moon's uniqueness; the Moon may have originated by a process that was likely to happen to one out of nine planets.*[30]

THE QUESTION OF THE ORIGIN OF THE MOON STILL WASN'T SETTLED.

Drs. Alastair Graham Walter Cameron (1925–2005) and William R. Ward had independently developed ideas for a giant impact theory, which they discussed at the Seventh Lunar Science Conference in 1976.

> *A key constraint on the origin of the Earth-Moon system is the abnormally large value of the specific angular momentum of the system, compared to that of the other planets in the solar system. At an early stage, when the Moon was close to the Earth, most of the angular momentum resided in the spin of the Earth. This spin was presumably imparted by a collision with a major secondary body in the late stages of accumulation of the Earth, with the secondary body adding its mass to the remainder of the protoearth. The collisional velocity must have been close to 11 km/sec, and if the impact parameter was one earth radius, then the mass of the impacting body was comparable to that of Mars. It is probable that the largest accumulative collision should have involved a mass of this order, but the size and location of the impact parameter would have been a matter of chance. It is likely that both bodies would have been differentiated and possibly molten at the time of impact.*[31]

In their paper, Cameron and Ward made another important point, namely that after the collision:

> *The mantle material of both bodies in the region of the collision would shock-unload predominantly in the forward direction relative to the collision velocity and much of the material would vaporize. The subsequent motion of this material is not just a set of ballistic trajectories; the early motion of the material is entirely governed by gas pressure gradients in the vapor which is expanding into a vacuum.*[32]

In other words, much of the material that would re-condense to form the Moon would be helped off Earth by being entrained in an expanding hot gas envelope. It would not fall back to Earth, as many had assumed.

ROBERT CLAYTON

OXYGEN ISOTOPES

It had been assumed almost since the return of the first lunar samples that a theory for lunar formation had to account for the Moon's iron depletion, refractory enrichment, and volatile depletion. A group from the University of Chicago, led by Professor Robert N. Clayton, developed an additional constraint on theories for the formation of the Moon that was based on the isotopes of oxygen. Most of the oxygen in the universe is in the form ^{16}O, with 16 atomic mass units in its nucleus. There are minute amounts of two stable isotopes of oxygen, ^{17}O and ^{18}O, in the universe, as well. Because of developments in technologies driven by the Apollo exploration of the Moon, lunar and planetary researchers could now measure with high accuracy the ratios of $^{17}O/^{16}O$ and $^{18}O/^{16}O$ in a given sample of material.

At his talk at the Sixth Lunar Science Conference in Houston in the spring of 1975, Clayton argued that:

> *Due to the inhomogeneous distribution of the stable isotopes of oxygen at the time of condensation and accretion in the solar nebula, it is possible to identify bodies which formed from a common region of the nebula and distinguish them from bodies formed in other regions. On this basis, the moon is in the same group as the earth and the differentiated meteorites (achondrites, mesosiderites, pallasites, irons), and is unrelated to the ordinary chondrites or the carbonaceous chondrites. … The fact that the moon and the earth lie on the same mass-fractionation line would not be surprising except for the observation that most of the other analyzed samples of the solar system do not.*[33]

GEORGE WETHERILL

WETHERILL'S SYNTHESIS AND SIMULATIONS

In 1975, Dr. George West Wetherill (1925–2006) of the Carnegie Institution of Washington presented a "tentative synthesis" for the formation of the solar system and planets that prominently featured planetesimals in his version of the Safronov model:

1. The nebular period had a duration of 100-150 m.y., following which time condensation of solid matter took place.
2. Planetesimals up to ~100 km in radius accreted rapidly (~10^4 yr) … as a consequence of gravitational instability of solid matter in the central plane of the nebula.
3. The interiors of at least some of these planetesimals were at temperatures of 500-1600 °C within ≤ 10^7 years, resulting in metamorphism and/or igneous differentiation.
4. Some of the planetesimals cooled quickly (~ 10^7 to 10^8 yr) either because of their original small size or because of disruption during an early heavy bombardment associated with the formation of Jupiter and Saturn.
5. Most of these planetesimals and their debris accreted further to form planets and large satellites on a very uncertain time scale of 10^4 to 10^8 years. The importance of gravitational energy of accretion as a heat source is critically dependent on the length of this time scale.
6. The larger surviving planetesimals and planetary objects combined to evolve internally in the subsequent planetary era.[34]

From the work of Victor Safronov and his colleagues at the Geophysical Institute in Moscow, the existence of planetesimals in the early solar system was assumed. At issue was the probability of a collision with the Earth of a Mars-size body as envisaged by Hartmann, Davis, Cameron, and Ward. During his talk at the Seventh Lunar Science Conference, Wetherill said that what was needed was an accretional model that could give, "fairly definite predictions concerning the size distribution, orbits, and evolution of large bodies in the early solar system."[35]

Using digital computers with ever increasing power, Wetherall and his colleagues began to develop such an accretion model.

In October of 1984, the Lunar and Planetary Institute (formerly the Lunar Science Institute) held a conference in Kona, Hawaii, that marked a turning point in the effort to understand how the Moon was formed. At that conference, Wetherall gave a review paper[36] in which he reported on his most recent computer simulations of terrestrial planet formation.

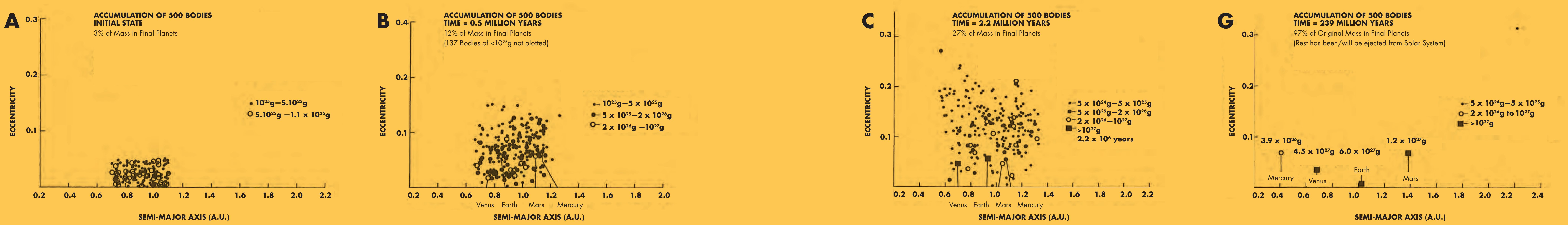
In his computer simulations, Wetherill's initial state consisted of 500 bodies with a range of masses determined based on the theoretical work of Safronov and others. The initial eccentricity of the elliptical orbit of each body about the Sun was assigned a random value between 0 and 0.05, the initial inclination a random value between 0 and 0.025 degrees, and the initial semi-major axis a random value between 0.7 and 1.1 astronomical units.[37] As the computer simulation proceeded, Wetherill explained:

> *The evolution of the system is assumed to result from close two-body encounters between planetesimals in crossing orbits… When the encounter distance between two planetesimals becomes less than the sum of their physical radii, the bodies are assumed to merge to form a larger body with mass equal to the sum of the masses. Otherwise, an encounter between two bodies results in gravitational perturbation to new orbits. As the calculation progresses the number of bodies becomes smaller.… Eventually, only bodies in noncrossing orbits will remain, the calculation is then terminated, and the surviving bodies are considered to be the final planets resulting from that particular accumulation calculation.*[38]

Wetherill found that his simulations generally resulted in the formation of four or less small planetary bodies with masses greater than 10^{26}g (1.4 lunar masses). In half of his simulations the number of "large" planets (>2 x 10^{27}g) is three instead of the observed two (Earth and Venus).[39]

The question of interest at the conference was "How likely was it that during the formation of the planets the Earth was impacted by a Mars-size object?" Wetherill reported that for 12 accumulation calculations:

> *Typically, one or two impacts of bodies more massive than Mars occur for each accumulation, and about three more massive than Mercury. …These giant impacts occur most frequently after the accumulation has proceeded for 1–15 m.y. In this time interval from 15% to 70% of the mass of the Earth had already formed. …Rather than considering giant impacts as a somewhat radical suggestion, if one is skeptical about the reality of the phenomenon, a good starting point would be to consider it a normal phenomenon that one should, at least naively, expect during planetary formation.*[40]



FIGURES: Figures are from Wetherill (1986). *Credit: From figure 10 in Wood, J. A.*

PHOTO: *Photo of Wetherill courtesy of Dr. Alan P. Boss and AAS.*

From his computer simulations, Wetherill concluded that:

> *For a wide range of initial conditions, terrestrial planet accumulation was characterized by giant impacts, ranging in mass up to 3 times the mass of Mars, at typical impact velocities of ~9 km/sec. These large planetesimals and the impacts they produce are sufficient to explain the unexpectedly large angular momentum of the Earth-Moon system.*[41]

Wetherill also noted that:

> *It is particularly interesting that these large planetesimals provide in a natural way the giant impacts proposed by Hartmann and Davis (1975) and Cameron and Ward (1976) as a way of forming the Moon. …Although it would be presumptuous to conclude that these large planetesimals and impacts were inevitable consequences of planet formation, their probable occurrence imposes obligations of explicitly considering their consequences in any discussion of the early history of the Earth and the Moon.*[42]

Genesis Rock returned by the Apollo 15 mission
Credit: NASA

The paper by Wetherill seemed to lay to rest concerns about the implausibility of an impact on the Earth by a Mars-size body early in the life of the solar system.

COMPARISON OF THE GIANT IMPACT MODEL WITH THE DATA

In the follow-on book for the Kona conference on the origin of the Moon, William Hartmann reviewed the fit between the "giant impact" theory and the properties and constraints on lunar origin.

WETHERILL'S PAPER SEEMED TO LAY TO REST CONCERNS ABOUT THE IMPLAUSIBILITY OF AN IMPACT ON THE EARTH BY A MARS-SIZE BODY EARLY IN THE LIFE OF THE SOLAR SYSTEM.

- **IRON DEFICIENCY AND GROSS SIMILARITY TO EARTH'S UPPER MANTLE:**
… After Apollo, lunar rock geochemistry led to the consensus that the lunar material crudely resembles Earth's mantle …
- **VOLATILE DEPLETION:**
The volatile depletion pattern of the Moon has always been difficult to explain in detail. However, at a first-order level, it appears consistent with a strong heating of most lunar material, probably in pulverized form to allow volatile escape, perhaps to temperatures of 1400–1800 K, and possibly additional chemical processing. … The hypothesis of an impact ejecting hot, finely disseminated material thus appears to be a step forward in understanding lunar volatiles …, but the chemistry of impact processing clearly requires further study.
- **ANGULAR MOMENTUM CONSIDERATIONS:**
As Cameron and Ward (1976) emphasize, a giant impact provides a plausible mechanism to explain the unusually high value of angular momentum in the Earth/Moon system, relative to other planets. … Indeed, a large impact is the ideal mechanism to produce Earth's final spinup to the effective period of 4.1 hours, matching the angular momentum of the present system …
- **OXYGEN ISOTOPE RATIOS:**
… lunar samples … fall on the chemical mass fractionation line characteristic of Earth materials and are indistinguishable from Earth … In summary, the O-isotope data require that the Moon formed from material that originated in the same terrestrial "feeding zone" that contributed material to the Earth, and not as far away as the "feeding zone" of Mars.
- **BULK IRON CONTENT:**
– … The estimated bulk elemental iron content of the Earth's mantle and the Moon are:
– Earth mantle: 7% iron by weight …
– Moon: 7–9% iron by weight …
– … The similarity is predictable if the Moon formed from ejected upper mantle material (especially if some projectile iron were added), but is an odd coincidence in other theories.
- **DENSITY:**
The mean densities of the Moon (3.344 ± 0.002 g/cm^3) and [Earth's] upper mantle (3.3 to 3.4 g/cm^3) are virtually identical.… This is directly explained if the Moon formed from ejected upper mantle material, but is an odd coincidence in other theories.[43]

THE CONFERENCE WAS REVOLUTIONARY. THE TRADITIONAL IDEAS FOR LUNAR ORIGIN WERE TOSSED ASIDE BY ALMOST ALL ATTENDEES IN FAVOR OF THE GIANT IMPACT HYPOTHESIS.

JEFFREY TAYLOR
Credit: Jeffrey Taylor

A REVOLUTIONARY CONFERENCE

The Kona Conference didn't answer all the questions surrounding the origin of the Moon. For example, it still remained to be determined whether the ejected material that formed the Moon largely originated in the Earth's mantle or was mainly composed of material from the impactor. Despite lingering uncertainties, continued research on the origin of the Moon has been heavily influenced by the Kona Conference, which caused a revolution in thinking, as one of the organizers of the conference, Professor G. Jeffrey Taylor, remembered fourteen years afterwards:

> *The conference was revolutionary. The traditional ideas for lunar origin were tossed aside by almost all attendees in favor of the giant impact hypothesis. Beyond the giant impact hypothesis being a good idea, several factors came into play to raise it to its pedestal. The three old ideas (fission from the Earth, capture, and binary accretion) had their adherents, but most of us were dissatisfied with all of the old hypotheses. Each had serious flaws. Computer methods had improved significantly, so simulations of the giant impact could be done. Our understanding of impact processes was stronger than ever because of experiments and studies of large terrestrial craters. Finally, and perhaps most important, our ideas of how planets accumulated had achieved a new paradigm that depicted planets accumulating from objects that were themselves still accumulating, leading to several large bodies near each other. In this view, a giant impact was almost certain to happen. At the end of the three-day conference, the traditional hypotheses were discarded by most of us -a revolution in our thinking! …The giant impact idea… provides the context in which we think about planet formation, much the way plate tectonics provides the context in which we try to understand the geology of the Earth.*[44]

Gigantic asteroids in space about to crash on planets 3D rendering elements of this image furnished by NASA
Credit: sdecoret Shutterstock

THE LPI MADE POSSIBLE THE STRONG COLLABORATION BETWEEN NASA AND THE INTERNATIONAL UNIVERSITY RESEARCH COMMUNITY THAT RESULTED NOT ONLY IN A NEW UNDERSTANDING ABOUT THE ORIGIN OF THE MOON, BUT ALSO IN THE DEVELOPMENT OF A NEW RESEARCH DISCIPLINE.

Credit: Patrik Valis, Shutterstock

IT'S NOT OVER

In sporting events, one often hears "it's not over until it's over." With scientific research, the corresponding phrase would be "it's not over." There's always the chance that further research will change a perception, or at least aspects of a perception, that had previously enjoyed widespread acceptance in a research community. And now a vibrant lunar and planetary research community exists to advance the discussion on this and many other topics.

An enormous amount of credit must go to NASA for the development of the discipline of lunar and planetary science. NASA planned and executed the Apollo lunar explorations that brought back samples for study by researchers around the world. NASA has developed and carried out many other planetary missions and, most importantly, NASA has funded and continues to fund researchers who make up the lunar and planetary research community.

The Lunar and Planetary Institute also deserves credit. Over the years, the management and staff of the LPI have worked closely with NASA managers to achieve the research goals of the lunar and planetary program, helping to advance lunar science by orchestrating a perhaps unique collaboration between NASA science managers and the university research community. The annual Lunar Science Conferences (later Lunar and Planetary Science Conferences) sponsored and managed by the LPI played a big role in the development of the lunar and planetary community, as did the many topical conferences and workshops held by the Institute each year. USRA and the LPI developed facilities to support visiting scientists selected predominantly from universities in the US and abroad. Many of these scientists and their students came to the Institute to conduct their research, using the collections of research-quality lunar photography, other imagery, and maps maintained at the Institute, as well as a library of lunar sample information, a geophysical data facility, and a superb lunar and planetary science publications library.

IN SUMMARY

The LPI made possible the strong collaboration between NASA and the international university research community that resulted not only in a new understanding about the origin of the Moon, but also in the development of a new research discipline.

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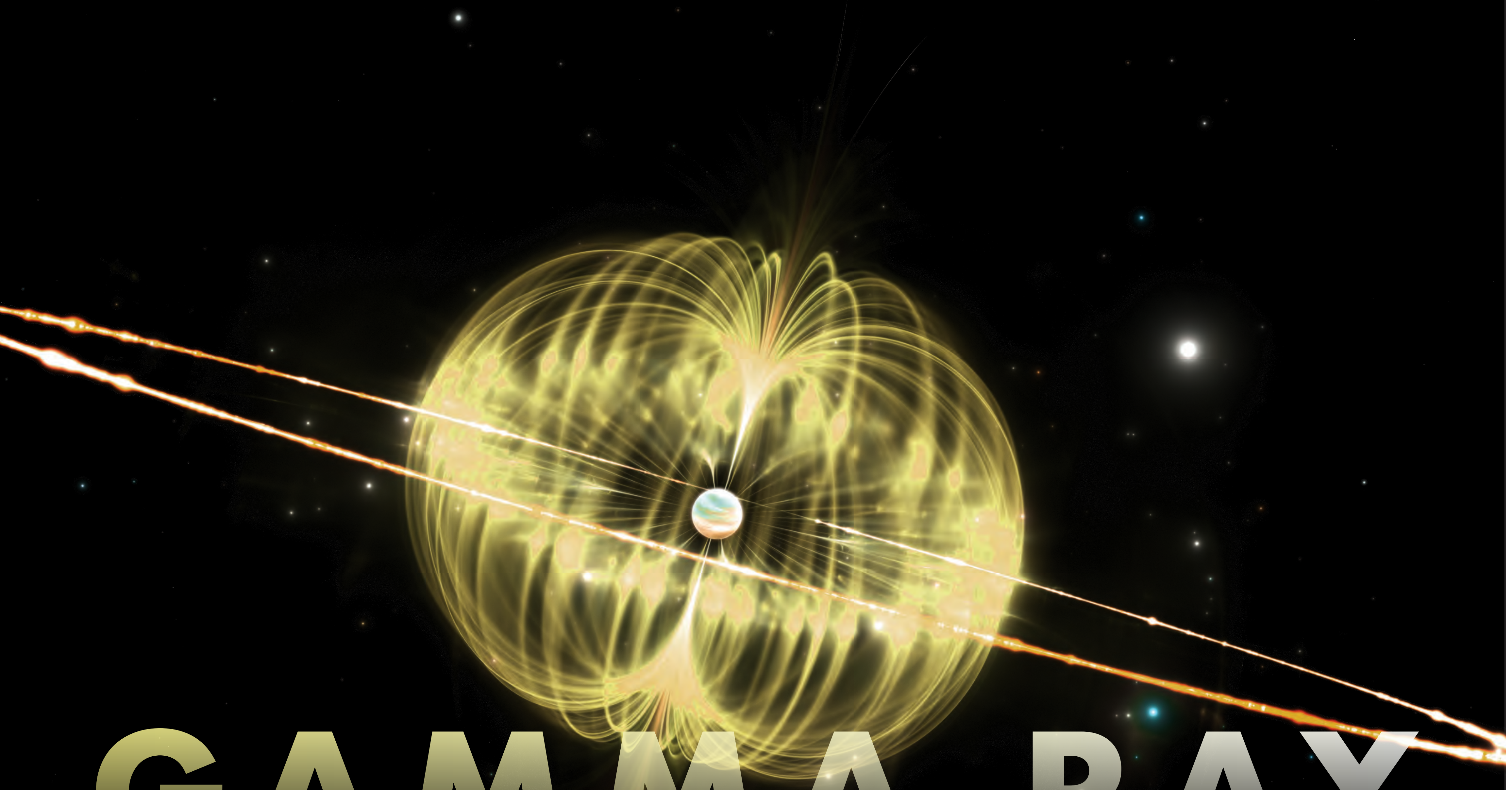
ASTRONOMY AND ASTROPHYSICS



GAMMA-RAY BURSTS AND MAGNETARS

How USRA scientists helped make major advancements in high-energy astrophysics.

DURING THE 1960S, THE SECOND ADMINISTRATOR OF NASA, JAMES E. WEBB, sought a university-based organization that could serve the needs of NASA as well as the space research community. In particular, Webb sought to have university researchers assist NASA in the planning and execution of large, complex projects. The result of Webb's vision was the Universities Space Research Association (USRA), which was incorporated as a non-profit association of research universities on 12 March 1969.

As described in the previous essay, USRA's first major collaboration with NASA was the Apollo Exploration of the Moon. The vehicle by which USRA assisted NASA and the space research community was the Lunar Science Institute, later renamed the Lunar and Planetary Institute.

COLLABORATING WITH NASA TO RESEARCH GAMMA RAYS

Another major project was undertaken in 1983, when USRA began to support NASA in the development of the Space Telescope Project at NASA's Marshall Space Flight Center (MSFC). USRA also began to support the Naval Research Laboratory (NRL) as they worked on the Oriented Scintillation Spectrometer Experiment, which was one of four major experiments to be launched on NASA's Gamma Ray Observatory (GRO).

Professor Frank J. Kerr (1918 – 2000) of the University of Maryland was appointed by USRA to manage its programs in astronomy and astrophysics. Kerr was a highly-regarded radio astronomer, originally from Australia. He had been the Director of the Astronomy Program at the University of Maryland, and at the time of his USRA appointment in 1983, he was Provost of the Division of Physical and Mathematical Sciences and Engineering at the University.

In support of MSFC and NRL, USRA brought astronomers to work closely with NASA researchers in the development of instrumentation and the preparation for analyses of data for various projects, including the MSFC's Burst and Transient Source Experiment (BATSE), which was another of the experiments being planned for the GRO.

Gamma-ray bursts had been detected in the late 1960s and early 1970s by the Vela satellites, which had been placed in orbit around the Earth to watch for possible violations of the 1963 treaty that banned nuclear weapon tests in the atmosphere, in outer space and under water. While the satellites were emplaced to monitor compliance with the treaty by the Soviet Union, researchers at the Los Alamos National Laboratory quickly realized that the gamma-ray bursts did not come from Soviet nuclear explosions. In 1973, they reported that the analysis of Vela satellite data over the three-year period July 1969 – July 1972 demonstrated that bursts of gamma rays as short as 0.1 second and as long as 30 seconds did not come from the Earth or the Sun.[1]

Gerald Fishman with one of the BATSE detectors.
Credit: NASA

FRANK KERR

IF THESE SOURCES REALLY ARE ASSOCIATED WITH DISTANT GALAXIES, THEN THE BATSE RESULTS IMPLY THAT GAMMA-RAY BURSTS ARE SOME OF THE BRIGHTEST EXPLOSIONS SINCE THE BIG BANG.

CHRYSSA KOUVELIOTOU
BATSE TEAM

UNDERSTANDING THE SOURCE OF GAMMA RAYS

So where did they come from? The energy carried by a photon is proportional to the frequency of the photon, or inversely proportional to its wavelength. Gamma rays have the highest frequency and shortest wavelength of all the photons. Their wavelength is comparable to the size of an atomic nucleus. The energy of a gamma ray is hundreds of thousands times the energy of a photon in the “visible” range, i.e., a photon that humans can “see”. The Earth’s atmosphere protects human and other life from the otherwise lethal effects of gamma rays and other high frequency radiation, so that gamma rays can only be observed from space. Because of their high energy, gamma rays cannot be easily focused, which means that localizing gamma-ray sources is difficult.

BUILDING THE RESEARCH TEAM

To find the source of gamma-ray bursts, Dr. Gerald Fishman of NASA proposed the BATSE as part of the GRO (later re-named the Compton Gamma Ray Observatory (CGRO), in honor of physicist Arthur Holly Compton). The CGRO was one of NASA’s “Great Observatories;” a series of large space observatories designed to examine the Universe from the infrared to gamma-ray regime.[2]

Fishman turned to USRA to help him build a team that would work on various aspects of BATSE. In January 1991, USRA hired Dr. Chryssa Kouveliotou to work with Fishman and others on the BATSE team at MSFC in Huntsville, Alabama. Dr. Kouveliotou was an expert on gamma-ray bursts, being the first student with a PhD thesis on the subject. She took a leave of absence from the University of Athens, Greece, to help develop BATSE data analysis software and to analyze and interpret these data.

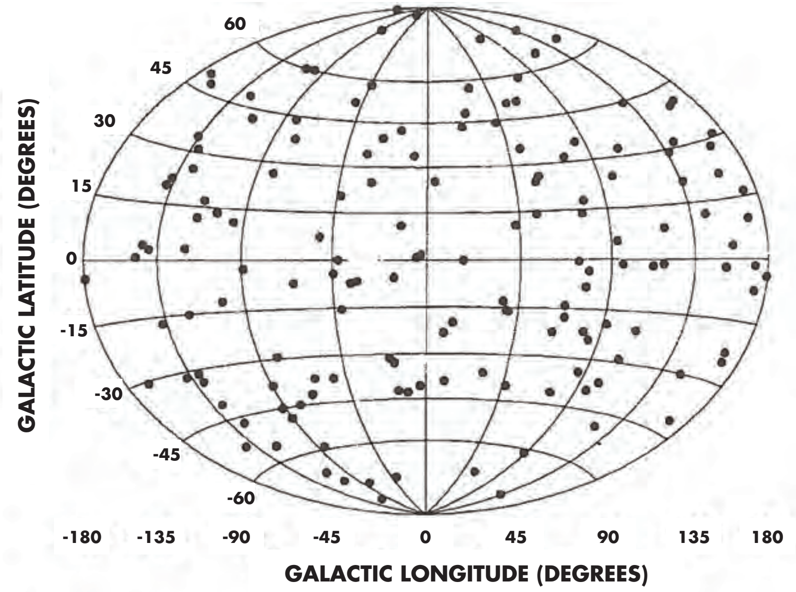
There wasn’t much time for development work. CGRO and BATSE were launched on board the space shuttle Atlantis on 5 April 1991. The BATSE instrument was activated on 21 April 1991, and it began to record gamma-ray bursts at a rate of about one per day.

GAMMA-RAY WORKSHOP

To further explore the question about where gamma-ray bursts were coming from, as well as other questions about gamma-ray bursts, USRA and NASA co-sponsored the first Huntsville Gamma-Ray Burst Workshop in the fall of 1991. Over 130 scientists from around the world attended and discussed their research in the context of the recently acquired BATSE data. Prior to BATSE, scientific consensus was that the sources for gamma-ray bursts were in our own galaxy, the Milky Way. In the simplest scenario, this would predict that a plot of the positions of the gamma-ray bursts would show most of them near the disk of the Milky Way. Perhaps the most important point to come out of this first Gamma-Ray Burst Workshop was that gamma-ray bursts seemed to be coming from sources that are randomly and evenly distributed across the sky, i.e., the distribution seemed to be isotropic. These results challenged the galactic nature of the events and argued for an extragalactic origin of the phenomenon.

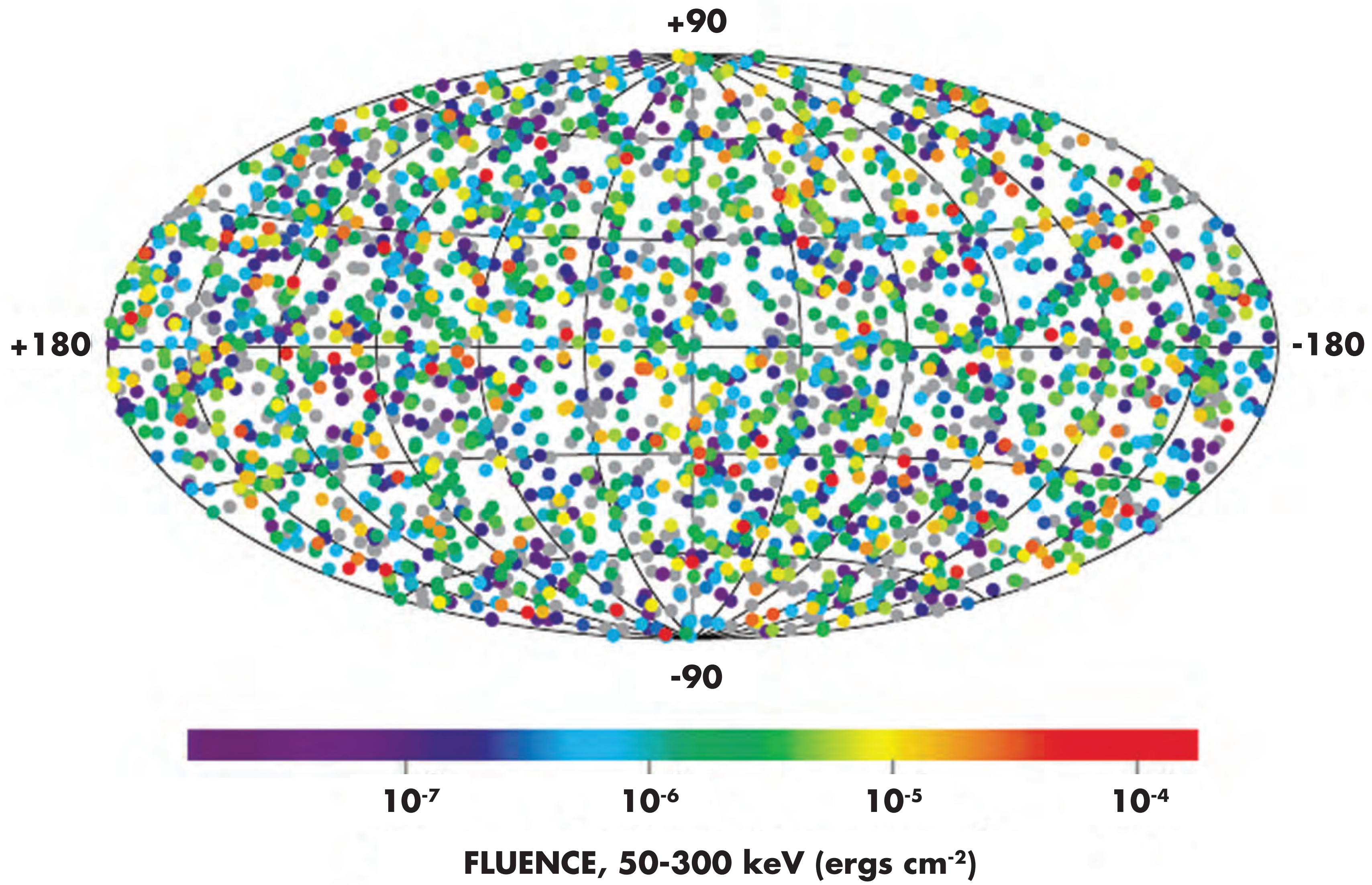
The first paper by members of the BATSE team, including Kouveliotou (who had emigrated to the US and remained a USRA scientist) was published in *Nature* on 9 January 1992.[3] The team ran tests on the data from 153 gamma-ray bursts that occurred between 21 April 1991 and 31 October 1991. The results demonstrated analytically that there is no statistically significant deviation from isotropy.[4]

BATSE detectors onboard the CGRO
Credit: NASA



Credit: Nature (1992) by Meegan, C.A.

2704 BATSE GAMMA-RAY BURSTS



Credit: NASA

The Crab Nebula is an example of a massive star that exploded in our galaxy as a supernova.
Credit: NASA

DISTANCE TO SOURCES OF GAMMA-RAY BURSTS

As more gamma-ray bursts were observed over the life of the CGRO, the isotropic distribution was confirmed. During the entire mission, BATSE observed 2,704 gamma-ray bursts.[5]

The BATSE results suggested that the sources of the gamma-ray bursts must be "at cosmological distances," i.e., at distances beyond our Milky Way galaxy, and the event distribution should follow the isotropic distribution of distant galaxies. If the sources really were associated with distant galaxies, then the BATSE results implied that gamma-ray bursts are some of the brightest explosions since the Big Bang. Some researchers argued at the time, however, that the sources might be neutron stars in a halo around our galaxy.

The theory is plausible, in part, because of the extraordinary characteristics of neutron stars. A neutron star is the remnant of a massive star that has used up its inner nuclear fuel, the burning of which kept it supported against the force of its self-gravity. Once the nuclear fuel has been spent, the stellar core collapses into an incredibly dense ball in which electrons and protons are squeezed together into neutrons and other sub-atomic species. As the core collapses, the down-rushing, outer layers of the star collide with the neutron core, and then rebound, producing an explosive outpouring of energy called a "supernova." The Crab Nebula is an example of this process; a massive star that exploded in our galaxy as a supernova and was observed by Chinese astronomers in 1054 CE. The neutron star left behind by the Crab supernova is about 30 kilometers across, has a spin rate of about 30 revolutions per second, and is located near the center of the nebula.

The halo theory posits that, depending on the energy of the explosion and whether the explosion was asymmetric, a supernova could impart a high-velocity kick sufficient to propel a neutron star from the Milky Way galaxy. These ejected neutron stars could form a nearly isotropic halo around the galaxy, and in principle, these ejected neutron stars could produce the distribution of gamma-ray bursts seen by BATSE.

The principal proponent of this theory was Professor Donald Lamb of the Enrico Fermi Institute of the University of Chicago. In 1997, Lamb wrote:

> *We do not yet know the distance scale to gamma-ray bursts. Here I discuss several observational results and theoretical calculations which provide evidence about the distance scale. First, I describe the recent discovery that many neutron stars have high enough velocities to escape from the Milky Way. These high velocity neutron stars form a distant, previously unknown Galactic "corona." This distant corona is isotropic when viewed from Earth, and consequently, the population of neutron stars in it can easily explain the angular and brightness distribution of the BATSE bursts…*[6]

Later the same year, X-ray and optical observations showed that some gamma-ray bursts were indeed associated with distant galaxies. In one case, the gamma-ray burst was from a star in a galaxy about 7 billion light-years distant;[7] and in another case, about 12 billion light-years.[8] The implication of observing gamma-ray bursts at these great distances is that their sources must generate, in a matter of seconds, more energy than the Sun could emit over billions of years, assuming that the gamma-rays are emitted at the same rate, in all directions.

CLASSES OF GAMMA-RAY BURSTS

Given this huge energy flow, perhaps the most interesting question is "How are these distant gamma-ray bursts produced?" But the BATSE team realized that there are varieties of gamma-ray bursts, so they first tried to identify some of the categories. Kouveliotou was the lead author for the team on a paper published in 1993 titled *Identification of Two Classes of Gamma-ray Bursts.*[9] In it, she and her BATSE colleagues demonstrated that the short bursts of gamma-rays, defined as those with durations less than 2 seconds, had a larger proportion of higher energy photons than the bursts with longer durations. The short bursts were said to have "hard energy spectra," while the bursts of longer duration were said to have "soft energy spectra."

In addition, there were a small number of gamma-ray bursts that were found to repeat at irregular intervals. They typically had a very short (a fraction of a second) high-energy burst followed by a longer, fainter glow of lower-energy X-rays. They became known as Soft Gamma Repeaters (SGRs).[10] Kouveliotou suggested that SGRs represent a completely different phenomenon from either of the other two categories of gamma-ray bursts, and she set out to understand them.

MAGNETARS

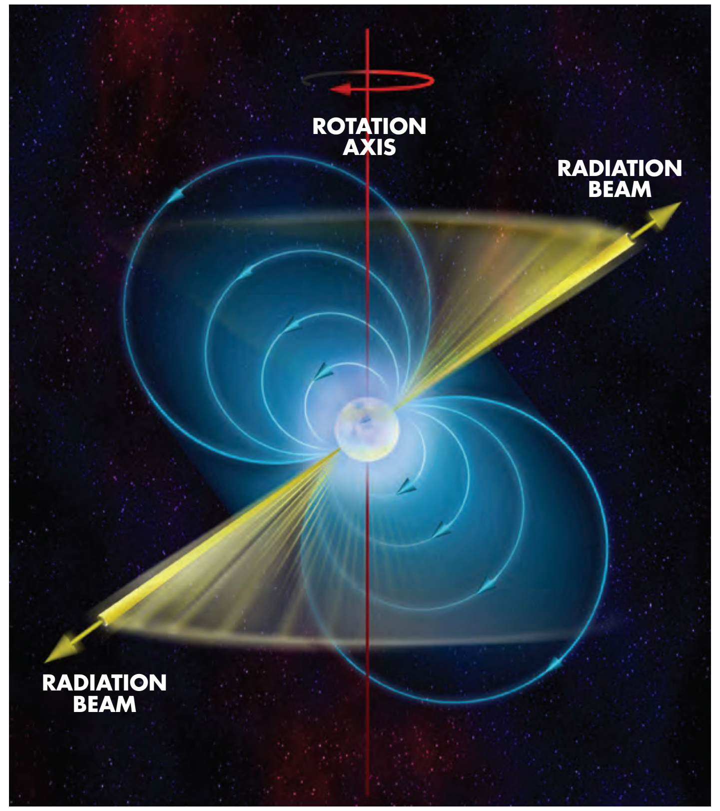
In 1992, the same year that the BATSE team published its paper showing the isotropic distribution of gamma-ray bursts, Professors Robert Duncan of the University of Texas and Christopher Thompson of the University of Toronto published a paper titled, "Formation of Very Strongly Magnetized Neutron Stars: Implications for Gamma-ray Bursts."[11] In this paper, they introduced the term 'magnetar' to designate a highly magnetized neutron star, i.e., a neutron star with a magnetic field of 10^{14} – 10^{15} gauss, which is 100 – 1000 times greater than the magnetic field strength of a typical neutron star. It is unimaginably larger that the magnetic field strengths of our everyday experience, for example, the less than 1 gauss field strength of the Earth, and the typically 100 gauss field strength of a magnet used to post notes on the door of a refrigerator.

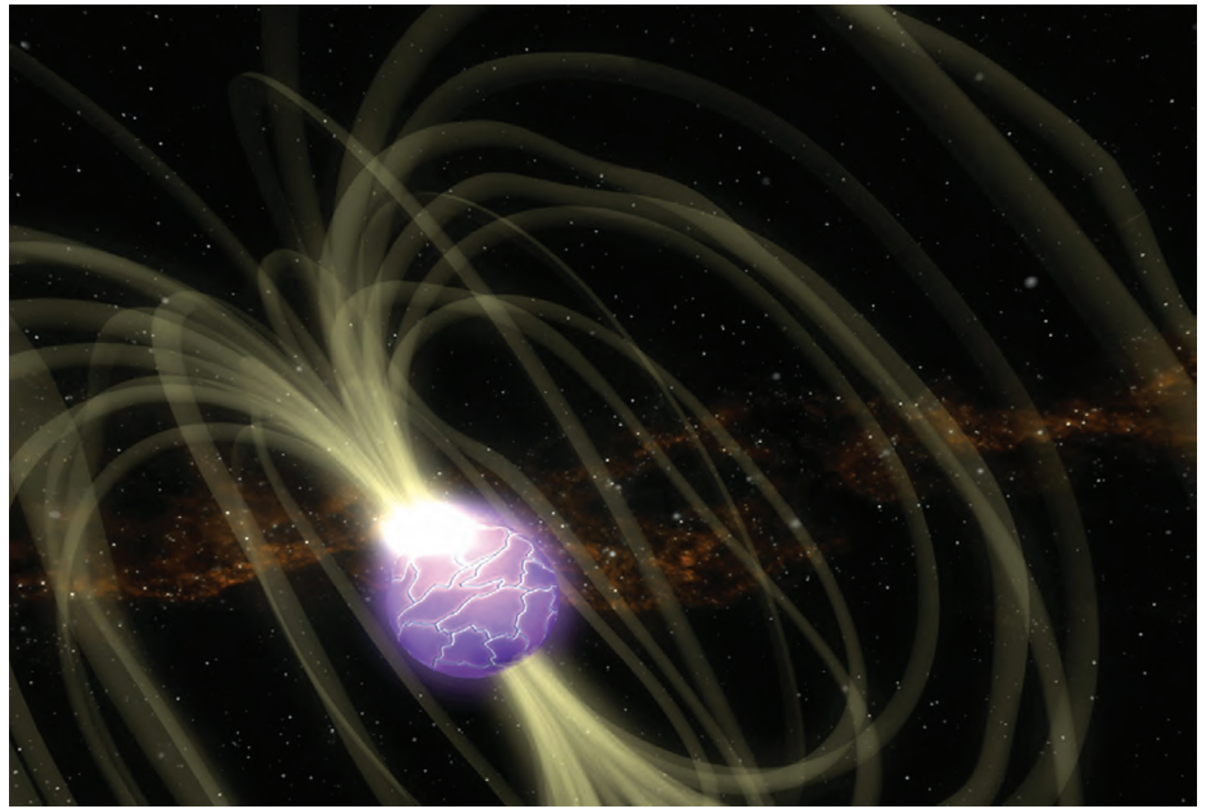
In 1996, Thompson and Duncan published another paper in which they suggested that the outbursts of SGRs are the result of large fractures of a magnetar's crust,[12] a "starquake" similar to the sudden energy released by earthquakes, but trillions of times more powerful.

To check the Thompson and Duncan magnetar theory, Kouveliotou needed to be able to measure the SGR's magnetic field strength. The standard process for measuring the magnetic field strength at the magnetic pole of a spinning neutron star is based upon the assumption that the star is slowing down because its energy is being radiated away. The idea is that if the magnetic axis is not aligned with the rotation axis, a distant observer sees a time-changing magnetic field, which corresponds to an electric field. The combination of oscillating electric and magnetic fields results in the radiation, called magnetic dipole radiation. Based upon this assumption, the neutron star surface magnetic field strength at the pole of the spinning, magnetized neutron star can be determined if the period of rotation and the rate of change of the period can be determined.[13]

ROBERT DUNCAN AND CHRISTOPHER THOMPSON INTRODUCED THE TERM 'MAGNETAR' TO DESIGNATE A HIGHLY MAGNETIZED NEUTRON STAR.

THE ORIGIN OF GAMMA-RAY BURSTS REMAINS A SUBJECT OF INTENSE SCIENTIFIC ENQUIRY, BUT MOST ASTROPHYSICISTS AGREE THAT THE ORIGIN OF SOFT GAMMA REPEATERS HAS BEEN SOLVED BECAUSE OF THE WORK OF KOUVELIOTOU, THOMPSON, AND DUNCAN.





LEFT: Neutron star emitting radiation along its magnetic axis while rotating along another axis. *(Bill Saxton, NRAO/AUI/NSF).*

RIGHT: Artistic rendering of a magnetar, with its surface cracks and strong magnetic field. *(NASA/GSFC Conceptual Image Lab)*

Fortunately, these rotation rates can be determined for some spinning neutron stars when the spin axis of the neutron star is not aligned with the magnetic axis. To a distant observer, the radiation from such a neutron star appears in pulses for the same reason that pulses of light appear to come from a lighthouse. The lighthouse lamp emits a steady beam, but the lamp rotates so that the observer sees flashes of light from the lighthouse. Similarly, a spacecraft that can detect X-rays in a certain energy range will see pulses of X-rays coming from a so-called "X-ray pulsar" because the neutron star emitting the radiation is rotating.

KOUVELIOTOU'S RESEARCH

Kouveliotou and her BATSE teammates studied radiation from an SGR that was one of three discovered in 1979, designated as SGR 1806-20 (the numbers give the astronomical coordinates that locate the object in the sky). Kouveliotou and her colleagues started the investigation by using data from the Rossi X-ray Timing Explorer (RXTE), a US satellite launched on 30 December 1995 that was designed specifically to study time-varying X-ray emission from cosmic sources. In November 1996, they used RXTE to measure the change in the X-ray emission from SGR 1806-20. They found that the X-ray emission came in pulses, and they carefully measured the time between the pulses. They found that the period of rotation for the neutron star was 7.476551 seconds. They conducted the same analysis on archived data from the Japanese Advanced Satellite for Cosmology and Astrophysics (ASCA) spacecraft. In this analysis, they found the period of SGR 1806-20 observed in 1993 to be 7.4685125 seconds. The period determined from the 1993 data was slightly shorter than the period from the 1996 data, thus the spinning neutron star was observed to be slowing down at the rate of 0.0026 seconds per year.[14]

Kouveliotou determined the magnetic field strength of SGR 1806-20 by using her spin rate values with a formula that was based on the assumption that the neutron star was slowing down because it was radiating electromagnetic energy in the manner of a spinning dipole. She found the magnetic field strength of SGR 1806-20 to be approximately 8×10^{14} gauss, much larger than the magnetic field associated with any other known X-ray pulsar, confirming that the X-ray pulsar powering SGR 1806-20 was a magnetar.

The origin of gamma-ray bursts remains a subject of intense scientific enquiry, but most astrophysicists agree that the origin of SGRs has been solved because of the work of Kouveliotou, Thompson, and Duncan. SGRs are produced by "starquakes," the cracking and re-forming of the crust of highly-magnetized neutron stars that are in the Milky Way galaxy or in a nearby galaxy.

Astrophysicists also agree that magnetars are important because of the extreme environment they create. The US National High Magnetic Field Laboratory (MAGLAB) has produced magnetic field strengths up to 4.5×10^5 gauss. The magnetic field strength of SGR-1806-20 is larger than that by a factor of 1.8 trillion. In an article for Scientific American written in 2003, Kouveliotou, Thompson, and Duncan briefly discussed the extreme environment of magnetars:

> *In such strong fields, bizarre things happen. X-ray photons readily split in two or merge together. The vacuum itself is polarized, becoming strongly birefringent, like a calcite crystal. Atoms are deformed into long cylinders thinner than the quantum-relativistic wavelength of an electron.*[15]

For his contributions to gamma-ray astronomy through BATSE, Fishman was awarded the Rossi Prize of the High Energy Astrophysics Division of the American Astronomical Society in 1994. He also won the Shaw Prize, which some consider to be the Asian equivalent of the Nobel Prize, in 2011.

For her work in proving the existence of magnetars, Kouveliotou shared the 2003 Rossi Prize with Thompson and Duncan. Kouveliotou was elected to the US National Academy of Sciences in 2013.

IN SUMMARY

The pioneering research of these scientists exemplify USRA's role in realizing James Webb's vision: to bring together the best minds in academe, government agencies and other organizations in the development of knowledge in space science and technology.

ENDNOTES

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4. In the accompanying figure, which was presented in the BATSE team's paper, the format of the plot allows for a two-dimensional presentation of the whole sky, from the north to the south galactic pole in latitude and a full 360 degrees in galactic longitude. The figure shows the positions of the 153 gamma-ray bursts.
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EXPLORING THE GALACTIC CENTER

A case study of how USRA answered a question posed by James Webb in 1966.

ON 14 JANUARY 1966, NASA ADMINISTRATOR JAMES WEBB (1906–1992) wrote a letter to the prominent Harvard physicist, Professor Norman F. Ramsey Jr. (1915–2011), asking him to establish an advisory group that would:

> *Review the resources at our NASA field centers, and such other institutions as would be appropriate, against the requirements of the next generation of space projects and advise NASA on a number of key problems, such as:*
>
> 1. *How can we organize these major projects so that the most competent scientists and engineers can participate?*
> 2. *How can academic personnel participate and at the same time continue in strong academic roles?*
> 3. *What mechanism should be used to determine the scientific investigations which should be conducted?*
> 4. *How does a scientist continue his career development during the six to eight years it requires to develop an ABL [Automated Biological Laboratory] or a large astronomical facility?*
> 5. *Should we change the orientation of some of our NASA Centers?*
> 6. *What steps should be taken in scientific staffing, both inside and outside NASA, over the next few years to assure that we have the proper people at the proper places to do the job?*
> 7. *How can we obtain the competent scientists to take the key roles in these major projects?*[1]

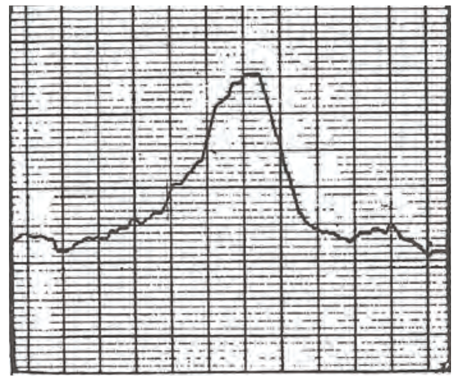
Ramsey assembled his advisory group, and they worked through the spring and summer on their report, which they delivered to the Administrator on 15 August 1966. Their first recommendation was that the NASA Administrator appoint a General Advisory Committee to bring to bear "maximum competence" on "the formulation and execution of long-term programs of NASA."[2]

This recommendation, and many of the others in the report, were not what NASA was looking for, and so the Administrator turned to the National Academy of Sciences to find answers for at least some of the questions posed to Ramsey. The result of the extended deliberations between the Academy and the university community was the formation of USRA.[3]

JAMES WEBB
Credit: NASA

NASA LOOKED TO THE NATIONAL ACADEMY OF SCIENCES TO FIND ANSWERS TO SOME OF THE QUESTIONS POSED. AFTER EXTENDED DELIBERATIONS, USRA WAS FORMED.

ERIC BECKLIN
Credit: American Institute of Physics



GALACTIC CENTER

A strip-chart recording of a right-ascension scan of the galactic center region at 2.2 μ. *(From Fig. 2 of Becklin and Neugebauer, 1968, p. 147.)*

AT THE SAME TIME JAMES WEBB POSED THE QUESTIONS ON HOW TO INVOLVE UNIVERSITIES IN NASA'S RESEARCH PROGRAMS, ERIC BECKLIN, A GRADUATE STUDENT AT CALTECH, DISCOVERED THE LOCATION OF THE CENTER OF THE MILKY WAY.

DISCOVERING THE CENTER

At about the time that James Webb approached the president of the National Academy of Sciences with questions on how best to involve university students and faculty in NASA's research programs, a graduate student at Caltech discovered the location of the center of the Milky Way Galaxy. The student was Eric Becklin, and his thesis advisor was Professor Gerry Neugebauer (1932–2014), who was one of the pioneers of infrared astronomy.

Becklin and Neugebauer had used an infrared photometer with the 24-inch telescope on Mt. Wilson to scan the small region of the sky in the Sagittarius constellation that was thought to be the dynamical center of the rotating Milky Way Galaxy. Becklin later told the story of his discovery:

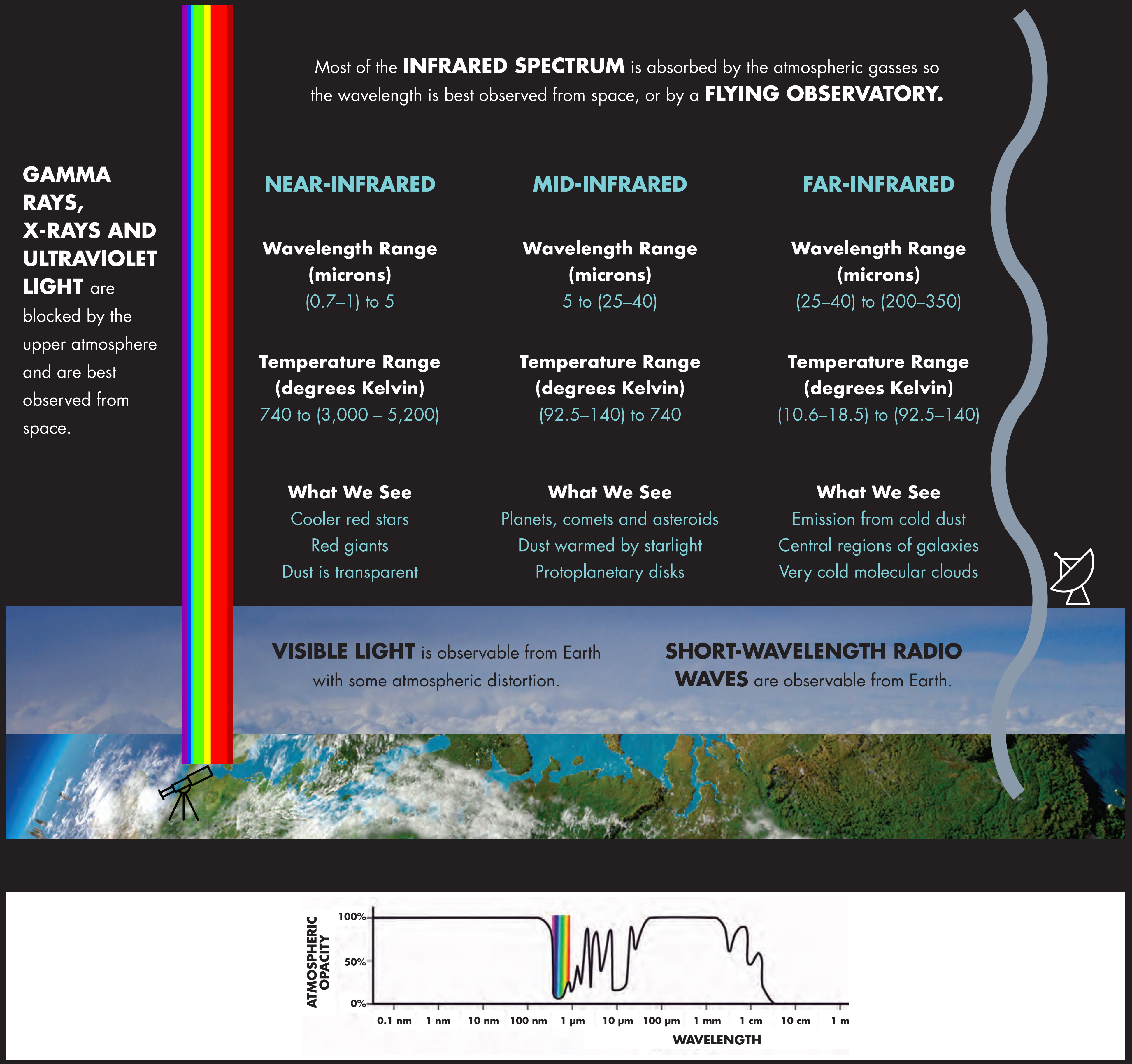
> *Back then, people weren't even sure where the center was. There was some vague understanding. There was a radio source called "Sagittarius A," a very strong radio source, but there was even debate whether that was really the center or not.*
>
> *There is so much dust between us and the galactic center, it is completely opaque. You do not see the stars in the galactic center. The most powerful telescopes cannot see it.*
>
> *Infrared radiation gets through the dust, because its wavelengths are longer…*
>
> *It was in August of 1966. I was up at Mt. Wilson. It was a beautiful night on the small 24-inch telescope. And, as we were looking with the infrared detector, we were seeing more and more stars.*
>
> *This is the signal in the infrared, and each star gives you more signal, and we were building up, as we were getting closer to the center, more and more stars. And we were actually seeing through the dust, for the first time, and then came to a peak, and then back down again, and I knew, immediately, that that was the center of our Milky Way, and that I was the first person to actually see the stars in the very core of our galaxy.*[4]

The photons recorded by Becklin had a wavelength of 2.2 microns (μ), also written 2.2 micrometers (μm), which is 2.2 x 10^{-6} meters. This wavelength is in the "near infrared" part of the electromagnetic spectrum, i.e., near to the visible range, which runs from about 0.38 microns (violet light) to 0.75 microns (red light). The "mid infrared" part of the electromagnetic spectrum corresponds to photons with longer wavelengths, and the "far infrared" with still longer wavelengths. The accompanying table shows the infrared spectral regions, wavelength ranges, temperatures of the sources of the radiation, and what can be seen in the three ranges.

Earth's atmosphere absorbs photons in much of the infrared wavelengths. As shown in the accompanying figure, however, the atmosphere is partially transparent to the wavelength that Becklin used at the Mt. Wilson Observatory, i.e., at 2.2 microns.

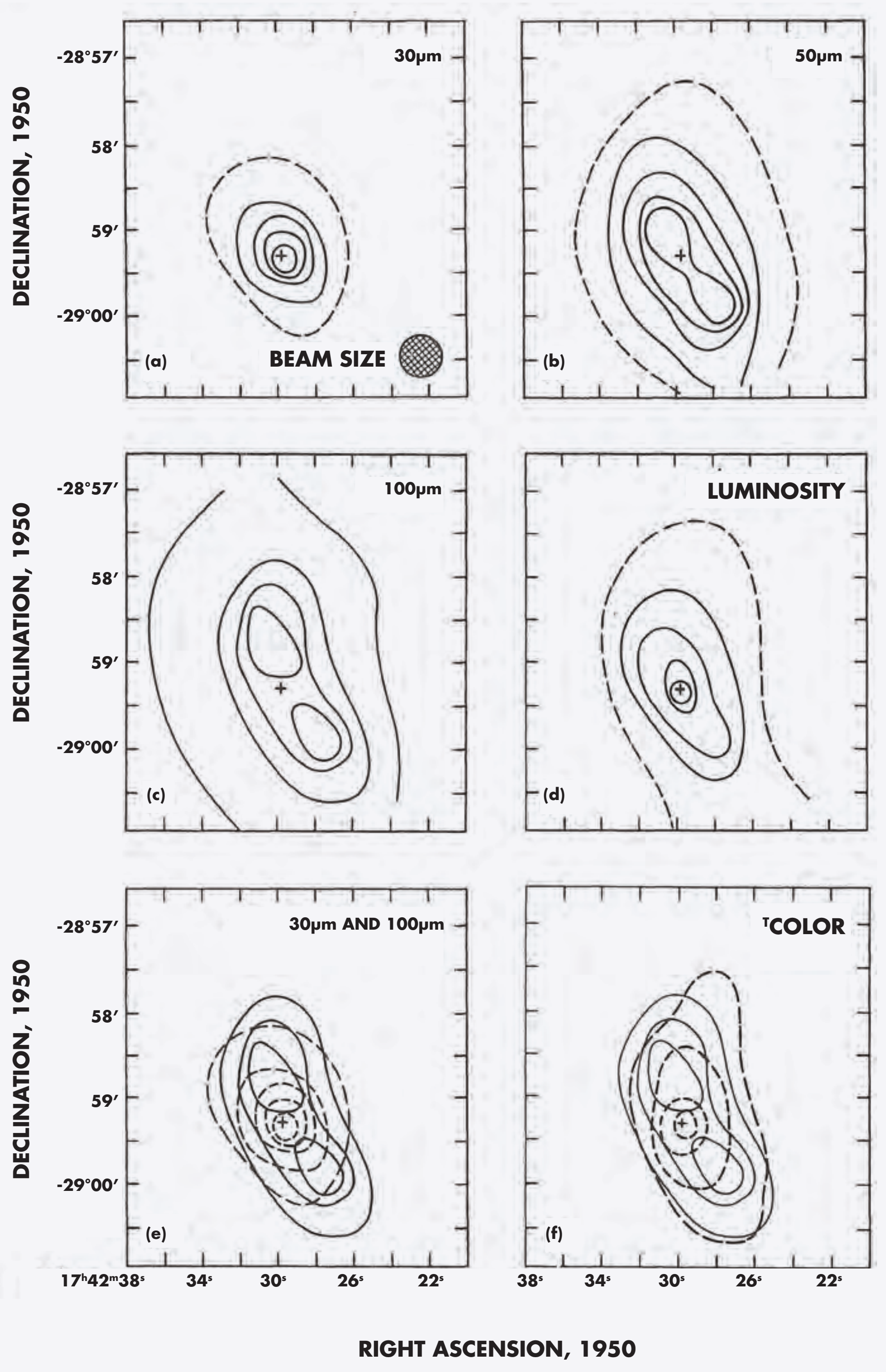
Near infrared radiation coming from a distant source in the universe is not affected by intervening dust. As can be seen from an all-sky mosaic of the Milky Way shown on page 47, this is not true of the visible light, which is blocked by dust.

Eric Becklin had located the center of our galaxy, and he and Neugebauer at Caltech, as well as other researchers elsewhere, began to map the central region of the Galaxy in wavelengths that corresponded to atmospheric "windows,"



Adapted by Erin Senoz from images provided by NASA and Infrared Processing and Analysis Center (IPAC) and Shutterstock.

Figure 2 in Becklin et al., 1982, p. 137. The cross denotes the centroid of the galactic center emissions at 34 microns as derived from ground-based measurements.



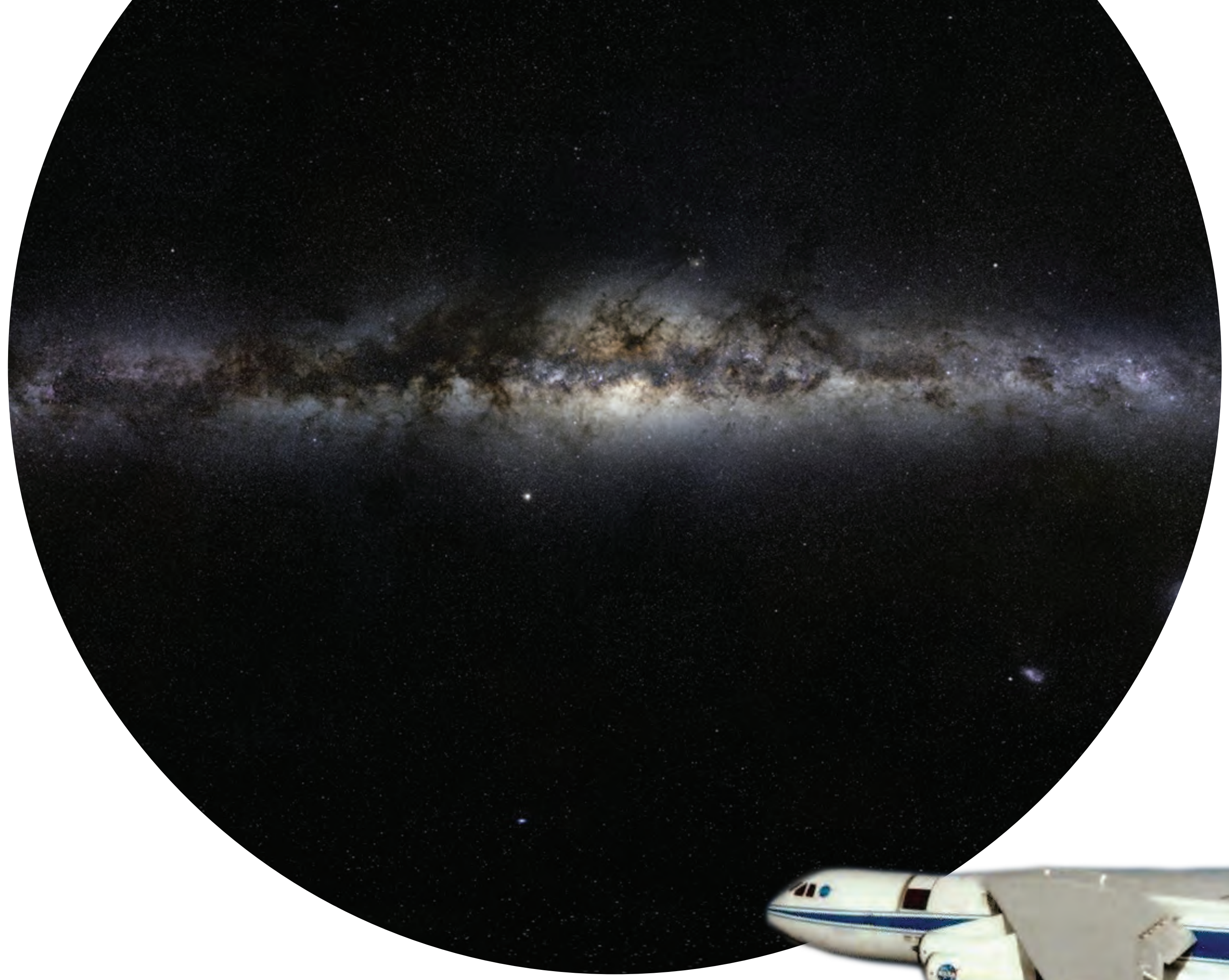
e.g., 2.2 microns and 10 microns. In 1975, Becklin and Neugebauer published a paper[5] in which they used an infrared photometer with the 200 inch Hale telescope at the Palomar Observatory. In the article, they showed maps of the central 1 minute of arc of the Milky Way Galaxy with resolutions of a few seconds of arc.[6] In this central 1 minute of arc, they identified 19 sources of infrared radiation at 2.2 microns and 9 sources at 10 microns.

Becklin and his colleagues were beginning to see the structures at the center of the Milky Way Galaxy, but they knew that to determine the nature of the sources of radiation they would need to make high-resolution observations at longer infrared wavelengths. Unfortunately, the Earth's atmosphere is mostly opaque at these wavelengths. The solution to this problem was to make observations from the Earth's stratosphere, above 99% of the atmospheric water vapor, which causes the blockage of far infrared radiation. By 1975, NASA had developed a means of doing that with the Gerard P. Kuiper Airborne Observatory (KAO).

The KAO was a modified Lockheed C-141 military cargo plane, outfitted with a 36-inch reflecting telescope in the front part of the plane. A retractable door above the telescope was closed for landings and take offs and opened only when the plane reached the desired altitude for observation, normally between 41,000 and 45,000 ft.

Becklin and his colleagues at Caltech soon were able to schedule flights on the KAO, and in 1975 they viewed the Galactic center at a resolution of about 1 minute (60 seconds) of arc. The Caltech team measured the flux of infrared radiation in three wavelength bands simultaneously, 30, 50, and 100-microns, from a single field of view. From this data they mapped the far infrared surface brightness and the color temperature[7] in a small region at the galactic center. They concluded that their data provided:

> *Very strong support for the idea that the far-infrared radiation is thermal emission from dust. In particular, the wavelength dependence of the source size is a natural result of a temperature gradient in the dust that is produced by heating by a centrally concentrated energy source.*[8]



An all-sky mosaic of the Milky Way recorded from Earth-based observatories over several months of 2008 and 2009. (Courtesy of the European Southern Observatory (ESO), Serge Brunier and Frederick Tapissier.) The image is oriented so that the plane of the Milky Way is horizontal, and the bulge of the Galactic Center is in the center.

Kuiper Airborne Observatory

FURTHER RESEARCH USING KUIPER AIRBORNE OBSERVATORY (KAO) FLIGHTS

By 1982, Becklin had moved to the University of Hawaii. He was the lead author on a paper that reported on KAO flights conducted in 1979. Becklin and his colleagues made measurements of the central 4 arc minutes of the Galaxy at 30, 50, and 100-microns. They found that the 30-micron radiation peaks strongly at the center of the Galaxy, while the 50 and 100-micron radiation patterns form lobes on either side of the 30-micron peak. At the galactic center, there is a local minimum in the 100-micron surface brightness. Assuming that in this part of the far infrared spectrum, the source of the radiation is dust, they concluded that the dust density decreases inward over the central 10 light years or so of the Galaxy. In this central region, they found that the total luminosity of the sources heating the dust, which radiates the far-infrared emission, is between ten million and thirty million times the luminosity of the Sun.[9]

If the stars in the central region of the Galaxy were all like the Sun, there must be 10 to 30 million of them in a volume that is perhaps 10 light years across. For comparison, the Sun's nearest neighbor is about 4 light years away. Based on the data shown in the figure on page 46, Becklin and his colleagues concluded that the galactic center is located in a central cavity, about 5 light years in radius, within a larger ring of dust and gas.[10]

This conclusion was confirmed by experiments conducted by a group of researchers from Cornell University on KAO flights in 1995.[11] They found a "minispiral" structure surrounded by a circumnuclear ring of dust and gas at the center of the Galaxy. The lobes of 50 and 100-micron radiation found by Becklin and his colleagues correspond to concentrations of radiating dust in the line of sight from either end of the ring, seen somewhat "edge on."

The 1995 flights by the Cornell group were among the last for the KAO, which was decommissioned in October of that year. NASA discontinued the KAO flights to save money that would be used for the development of the successor to the KAO, the Stratospheric Observatory for Infrared Astronomy (SOFIA).

BECKLIN AND HIS COLLEAGUES CONCLUDED THAT THE GALACTIC CENTER IS LOCATED IN A CENTRAL CAVITY, ABOUT 5 LIGHT YEARS IN RADIUS, WITHIN A LARGER RING OF DUST AND GAS. THIS CONCLUSION WAS CONFIRMED BY EXPERIMENTS CONDUCTED ON KAO FLIGHTS, WHERE RESEARCHERS FOUND A "MINISPIRAL" STRUCTURE SURROUNDED BY A CIRCUMNUCLEAR RING OF DUST AND GAS AT THE CENTER OF THE GALAXY.

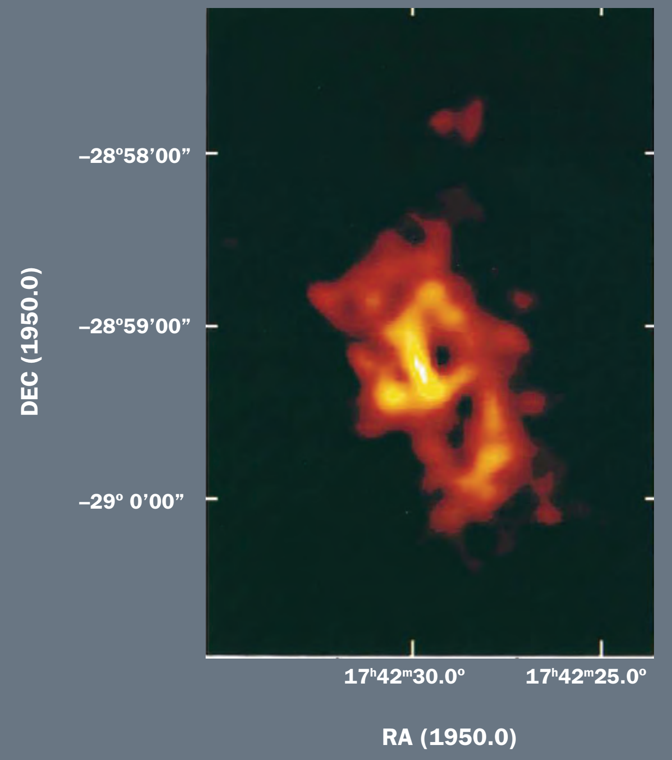


Figure 1 from Latvakoski et al., 1999, p. 763.

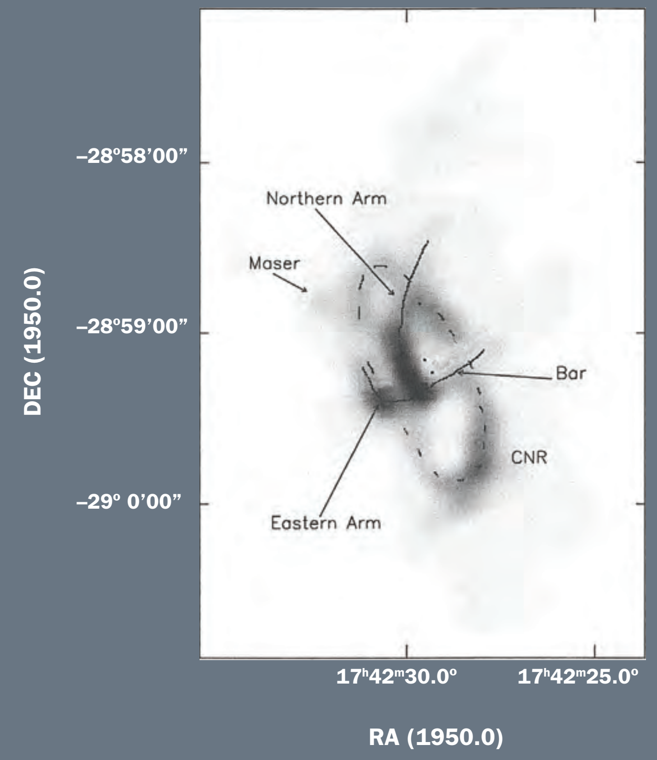
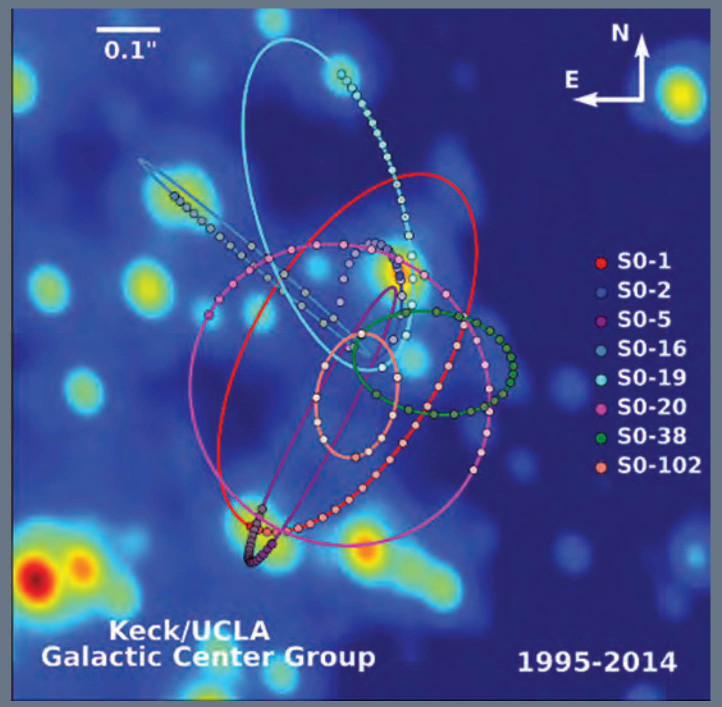


Figure 3 from Latvakoski et al., 1999, p. 764.



Tracks of stars that orbit Sgr A*
(From UCLA Galactic Center group website)

SOFIA on a test flight with the telescope door open.

USRA WINS NASA COMPETITION FOR SOFIA

In April of 1996, NASA issued a request for proposals in a competitive solicitation for (1) the provision of an airplane that could be modified to become SOFIA; (2) the modification of the airplane; and (3) the management of science for the observatory once it was operational. USRA persuaded Eric Becklin, now at UCLA, to be the science leader for SOFIA. The USRA Project Manager was Tom Bonner, who had earlier worked for NASA at the Langley Research Center and had experience in the modification of aircraft.

The USRA-led team, with partners United Airlines and Chrysler Technologies Airborne Systems (CTAS), won the NASA competition. United Airlines provided a Boeing 747 SP and CTAS, which was purchased by L3 Communications, conducted the extensive modification of the aircraft at its plant in Waco, Texas. SOFIA would house a 2.5-meter telescope that was provided by the German Aerospace Center (DLR). After several years of development and testing, the SOFIA observatory was operational in 2010.

LEFT: Inside view of SOFIA during checkout of the observatory with FORCAST attached to the SOFIA telescope

TOP RIGHT: Eric Becklin inside SOFIA, with the telescope and its instrument mount.

BOTTOM RIGHT: Terry Herter in the foreground and Eric Becklin in the background during testing of FORCAST.

PARTNERING IN RESEARCH

While SOFIA was under development, Becklin continued his research on the center of the Galaxy. With colleagues at UCLA, in particular Professor Andrea Ghez, Becklin conducted observations of the central stellar cluster of the Galaxy at 2.2 microns using the 10-meter W. M. Keck telescope near the summit of Mauna Kea in Hawaii.

Ghez had developed methods for minimizing distortions of infrared images that result from turbulence in the atmosphere. With these techniques and the large aperture of the Keck telescope, the UCLA team tracked the motions of a group of stars orbiting what had been called Sgr A* (pronounced Sagittarius A star), which is at the dynamical center of the Galaxy.

The orbits around Sgr A* of some of the stars tracked by the UCLA Galactic Center Group are shown in the figure on page 49. The orbital period for SO-2, for example, has been measured to be 16.17 years. Given an estimate of the semi-major axis of the orbit, one can use the measured orbital period and Kepler's laws to determine the attracting mass at Sgr A*.

In 1998, Becklin and the UCLA Galactic Center Group reported that the motions of the stars around Sgr A* indicated that the stars were orbiting a mass of about 2.6 million solar masses. The luminosity at 2 microns in the small region around Sgr A* was only about 40 times the luminosity of the Sun at the corresponding wavelength band. The UCLA group concluded that, "given the high mass-to-light ratio observed, the central mass concentration is certainly composed primarily of dark matter."[12]

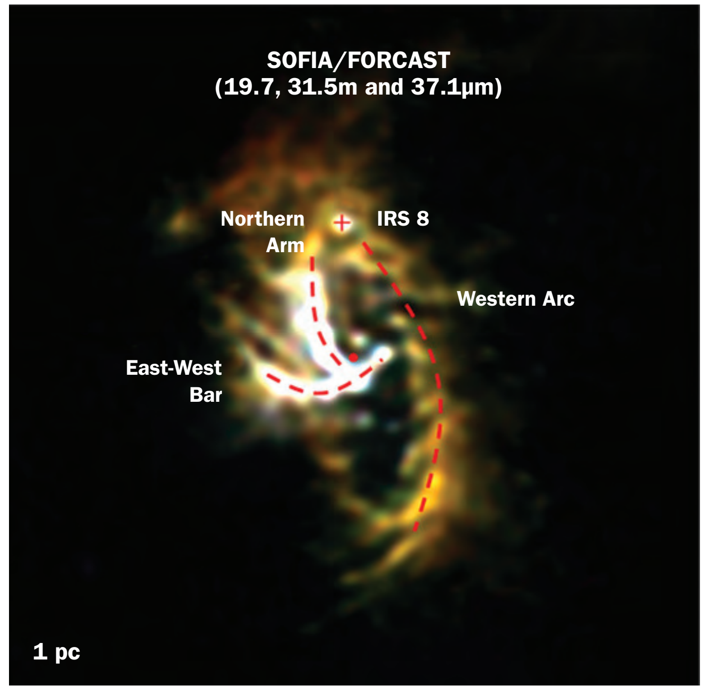
The group considered and ruled out several other possibilities and concluded that the Milky Way Galaxy harbors a black hole with a mass of 2.6 x 10^6 solar masses. Subsequent measurements of the motions of the stars around Sgr A* have yielded a value for the mass of the Milky Way's black hole of more than 4 x 10^6 solar masses.[13]

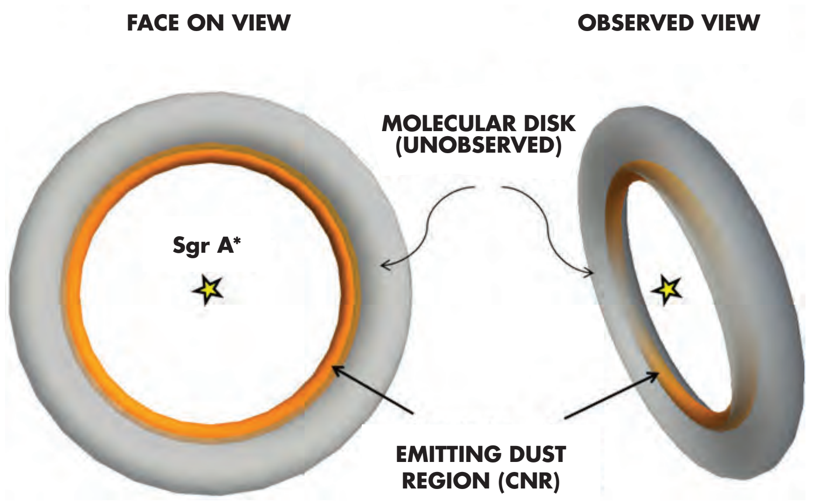
In 1995, Dr. Ted Dunham of NASA's Ames Research Center was asked what SOFIA could do that the KAO couldn't:

> *SOFIA's mirror is 3 times bigger than the KAO's, so its area is 9 times bigger. This means that it collects 9 times as much light as the KAO does. In addition, because the mirror is bigger its angular resolution is better because of diffraction, an effect related to the wave nature of light. The big problem in infrared astronomy is the very bright background from thermal emission from the telescope and atmosphere. The better resolution of the telescope means that if you are looking at a point source, like a star, you have to look at 9 times less background sky area than with the KAO. When you combine the larger collecting area and the smaller background area, it turns out that it takes 81 times less observing time to do the same observation with SOFIA than with the KAO! An observation that would take half a KAO flight can be done with SOFIA in 2 or 3 minutes!*
>
> *Of course, a lot of observations will be made that take an hour from SOFIA. These are totally impossible from the KAO–they would take 10–15 whole flights! Another way of looking at this is that you can do in one SOFIA flight what we now do with the KAO in a whole flight year!*
>
> *The kinds of things that people will do with SOFIA that can't be done with the KAO will be in looking at star forming regions in more detail, looking at how stars form in other galaxies (that's right on the edge of the KAO's capability), better understanding of what is going on in the center of the galaxy, looking at the planets in our solar system in more detail and at some wavelengths where they are undetectable with the KAO, and a bunch of other things that I forgot and haven't even thought of yet. It will be a very interesting time when SOFIA starts flying.*[14]

FEW PEOPLE WERE MORE PLEASED AND EXCITED WHEN SOFIA STARTED FLYING THAN ERIC BECKLIN.

USRA'S MANAGEMENT OF SOFIA SCIENCE HAS ALLOWED UNIVERSITY FACULTY TO PARTICIPATE WHILE STILL CARRYING ON THEIR PRIMARY FUNCTION OF TRAINING GRADUATE STUDENTS.





Figures 3 (left) and 4 (right) from Lau et al., 2013, p. 41

RYAN LAU

EXTENDING THE RESEARCH WITH THE FAINT OBJECT INFRARED CAMERA (FORCAST) FOR SOFIA

Soon after the award of the contract for SOFIA, USRA issued calls for proposals for instruments that would be attached to the telescope. One of the instruments that won the competition was the Faint Object Infrared Camera for the SOFIA Telescope (FORCAST) from Cornell University, with Professor Terry Herter as the Principal Investigator. FORCAST can record infrared radiation from 5 to 40 microns.

On flights in June of 2011, SOFIA/FORCAST observed the Circumnuclear Ring at the Galactic center.

To some degree these early flights confirmed and provided more detail to the Cornell observations of the galactic center via the KAO. The Circumnuclear Ring was found to have a radius of about 4.5 light years and to be inclined by 67 degrees from the plane perpendicular to the line of sight to Sgr A*. The density of the ring was found to be about 10,000 particles per cm^3, with density clumps of 5 to 9 times the background that are typically half a light year in length along the inner edge of the ring.[15]

The lead author for the paper that reported the observations of the Galactic Circumnuclear Ring was Ryan Lau, a graduate student of Terry Herter at Cornell University. Lau obtained his PhD in 2014, and his thesis title was "Probing the Extreme Environment of the Galactic Center with Observations from SOFIA/FORCAST."

Soon after defending his dissertation, Lau published an article in which he and his colleagues used SOFIA/FORCAST observations to answer a question about the source of dust in galaxies.[16] It's generally been thought that dust is created in supernova explosions, where there is a contact surface between the driver gas and dust coming out of the supernova and the ambient gas of the surrounding interstellar medium. A shock wave proceeds from the contact surface into the ambient gas and dust, but another shock wave proceeds from the contact surface back into the driver gas and dust. The question was whether this reverse shock wave would destroy most of the dust grains that had been produced by the supernova explosion. As noted by Lau and his colleagues:

> *Recent studies have argued that [supernovae] may be net destroyers of dust in present-day galaxies … but net producers of dust in the earliest-forming galaxies in the universe … . However, no direct observational evidence currently exists of the quantities of SN-condensed dust surviving the passage of the reverse shock through the ejecta.*[17]

Lau and his colleagues provided the missing evidence by using SOFIA/FORCAST to study the dust in the remnant of an old core-collapse supernova near the center of the Galaxy. They estimated that something like 7% to 20% of the dust produced by this 10,000-year-old supernova survived the reverse shock and was delivered to the interstellar medium.

In the Acknowledgements section of his thesis, Ryan Lau addressed a remark to Eric Becklin, who had discovered the location of the Galactic center almost 50 years before.

> *I was very honored to have worked with you on our Galactic center observations of the Circumnuclear Ring– thank you for all the support and guidance.*[18]

IN CONCLUSION

Almost 50 years after James Webb asked, "how can academic personnel participate [in major NASA efforts] and at the same time continue in strong academic roles," USRA provided a case-in-point answer by managing the science for US participation in SOFIA in a way that allowed Terry Herter to develop FORCAST and focus on science and the training of graduate students such as Ryan Lau. Surely, James Webb would have approved.

ENDNOTES

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6. Arc seconds - A great circle in the sky contains 360 degrees. Each degree contains 60 minutes of arc, and each arc minute contains 60 seconds of arc. A second of arc, therefore, is a very tiny length in the sky, but it corresponds to almost 10 light years of distance when viewing the center of the galaxy. The standard abbreviation for an arc minute is ', and the abbreviation for an arc second is "
7. Color temperature -To determine the color temperature, one measures the energy flux of a source at two different wavelengths. The color temperature is the temperature of the source if it were a black body that radiated energy corresponding to the energy flux in the two wavelengths that were measured. Becklin and his colleagues used the wavelengths of 50 and 100 microns to determine the color temperature, and they found temperatures up to about 100 Kelvins in the central region of the galaxy.
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15. Lau, R.M., Herter, T.L., Morris, M.R., Becklin, E.E. and Adams, J.D., 2013. SOFIA/FORCAST imaging of the circumnuclear ring at the Galactic center. *The Astrophysical Journal, 775*(1), pp.37–52, p.51.
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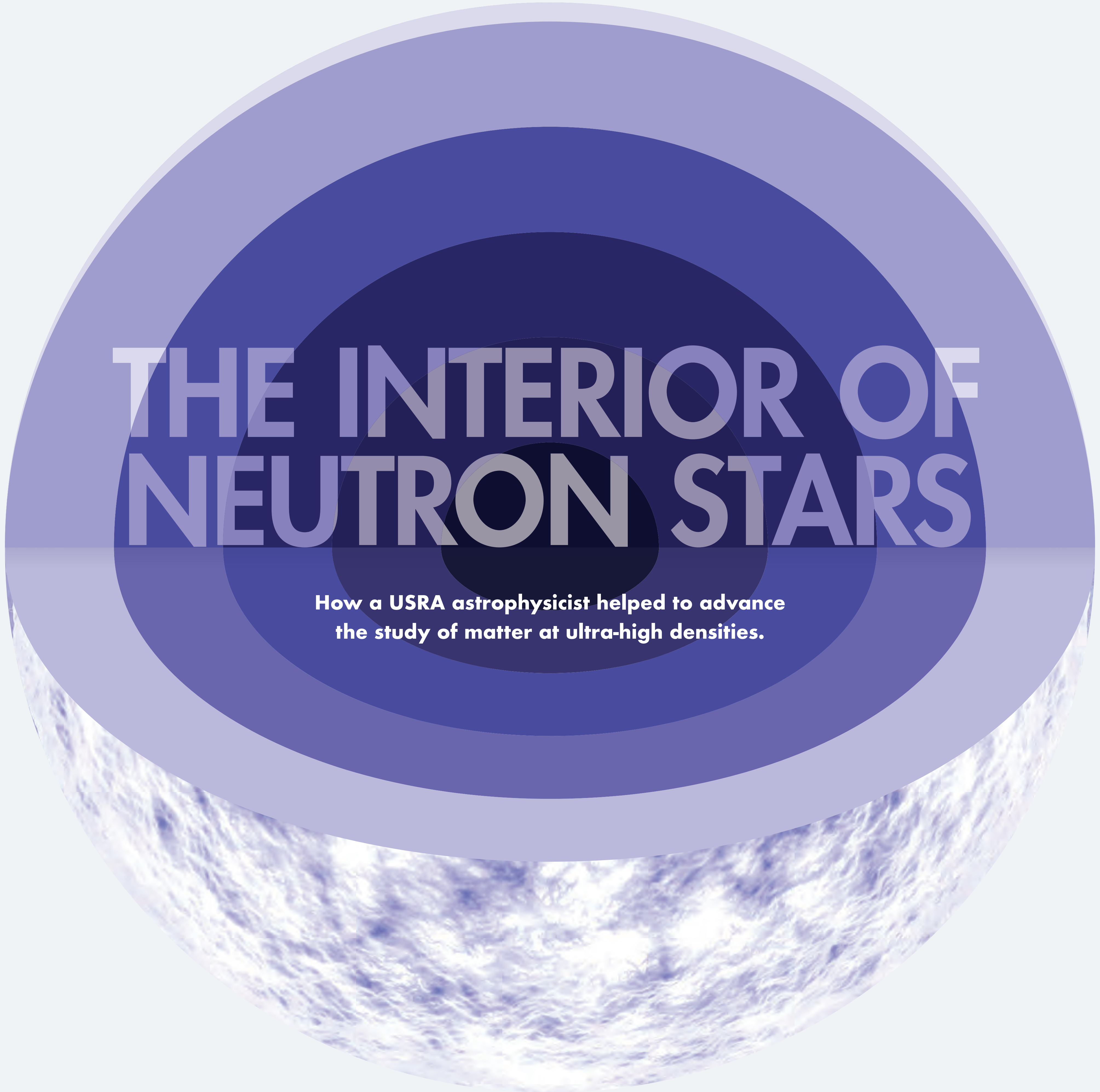
THE INTERIOR OF NEUTRON STARS



How a USRA astrophysicist helped to advance the study of matter at ultra-high densities.

I**N 1934, THE ASTRONOMERS WALTER BAADE (1893–1960)** of the Mt. Wilson and Palomar Observatories and Fritz Zwicky (1898–1974) of Caltech used estimates of the amount of radiation emitted during a supernova to calculate the energy loss, and hence the mass loss, of the star that exploded. They found that "the phenomenon of a super-nova represents the transition of an ordinary star into a body of considerably smaller mass."[1] Further, they concluded that this object would be very compact and be composed mostly of neutrons, hence the term "neutron star."

> *With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. ... As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such.*[2]

The first observational evidence of neutron stars came more than three decades later, when in the summer of 1967, Susan Jocelyn Bell discovered what came to be known as "pulsars." Bell was pursuing her PhD under Professor Anthony Hewish[3] at the University of Cambridge in the UK. As she began to analyze data from a large rectangular array of antennas that she had helped construct at the Mullard Radio Astronomy Observatory, she soon discovered a pulsating celestial radio source with a very steady period (1.3372795 ± 0.0000020 seconds).[4]

Similar celestial objects were soon identified, and Bell, Hewish and others at Cambridge began to name them LGM-1, LGM-2, etc., where LGM stood for Little Green Men. The naming was intended as a bit of humor based on the possibility that the observed pulsations might be signals from intelligent beings beyond Earth. The Cambridge team did consider and rule out a number of "intelligence-related" possibilities, such as "man-made transmissions which might arise from deep space probes, planetary radar or the reflexion of terrestrial signals from the Moon."[5]

The Cambridge group suggested that the regular pulsations might be caused by radial oscillations (in and out movements) of a star at the end state of its evolution, i.e., a white dwarf or a neutron star.[6]

SUSAN JOCELYN BELL (1967)

THE FIRST OBSERVATIONAL EVIDENCE OF NEUTRON STARS CAME IN 1967 WHEN "PULSARS" WERE DISCOVERED.

THOMAS GOLD
Credit: AIP

PULSARS AS ROTATING NEUTRON STARS

However, Professor Thomas Gold (1920–2004) of Cornell University immediately recognized that the most probable source of the pulsations was a rotating neutron star:

> *The constancy of frequency in the recently discovered pulsed radio sources can be accounted for by the rotation of a neutron star. Because of the strong magnetic fields and high rotation speeds, relativistic velocities will be set up in any plasma in the surrounding magnetosphere, leading to radiation in the pattern of a rotating beacon. … No other theoretically known astronomical object would possess such short and accurate periodicities as those observed.*[7]

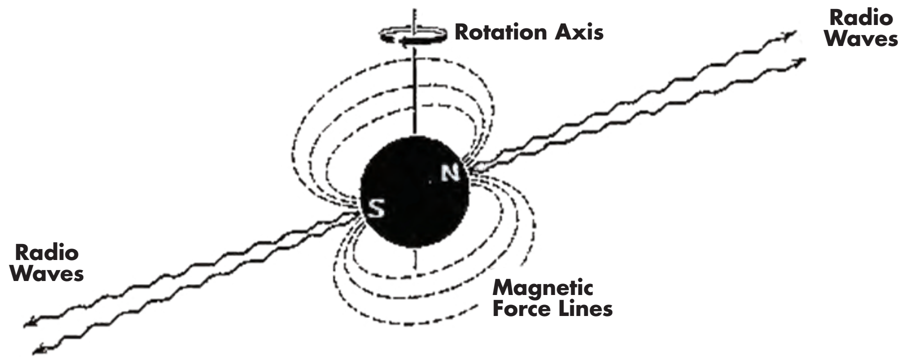
In 1974 Professor Joseph H. Taylor, then of the University of Massachusetts, Amherst and his student Russell A. Hulse, discovered a pulsar with a companion star, i.e., a pulsar in a binary system. The discovery earned them the 1993 Nobel Prize in Physics, because it had opened new possibilities for the study of gravitation:

> *The first pulsar was discovered in 1967 at the radioastronomy laboratory in Cambridge, England … What was new about the Hulse-Taylor pulsar was that, from the behaviour of the beacon signal, it could be deduced that it was accompanied by an approximately equally heavy companion at a distance corresponding to only a few times the distance of the moon from the earth. The behaviour of this astronomical system deviates greatly from what can be calculated for a pair of heavenly bodies using Newton's theory. Here a new, revolutionary "space laboratory" has been obtained for testing Einstein's general theory of relativity and alternative theories of gravity. So far, Einstein's theory has passed the tests with flying colours. Of particular interest has been the possibility of verifying with great precision the theory's prediction that the system should lose energy by emitting gravitational waves in about the same way that a system of moving electrical charges emits electromagnetic waves.*[8]

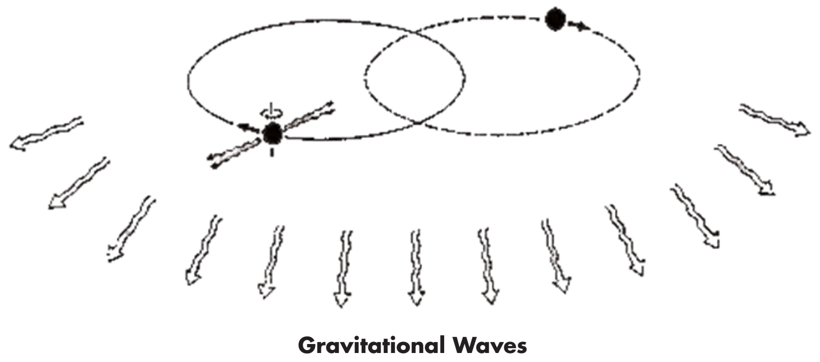
THE INTERIOR OF NEUTRON STARS

During the next few decades, much astronomical research focused not only on tests of general relativity, but also on what might be learned about the environment of neutron stars. In the fall of 2001, a young research astronomer, Dr. Zaven Arzoumanian, joined USRA. Arzoumanian had obtained his PhD from Princeton in 1995 under the guidance of Professor Joseph H. Taylor. His PhD dissertation was titled "Radio Observations of Binary Pulsars: Clues to Binary Evolution and Tests of General Relativity." When Arzoumanian joined the high-energy astrophysics group of USRA astronomers working at NASA's Goddard Space Flight Center (GSFC), he began to work with USRA and NASA colleagues on a multi-wavelength study of the interactions between neutron-star systems and their surroundings.

PULSAR



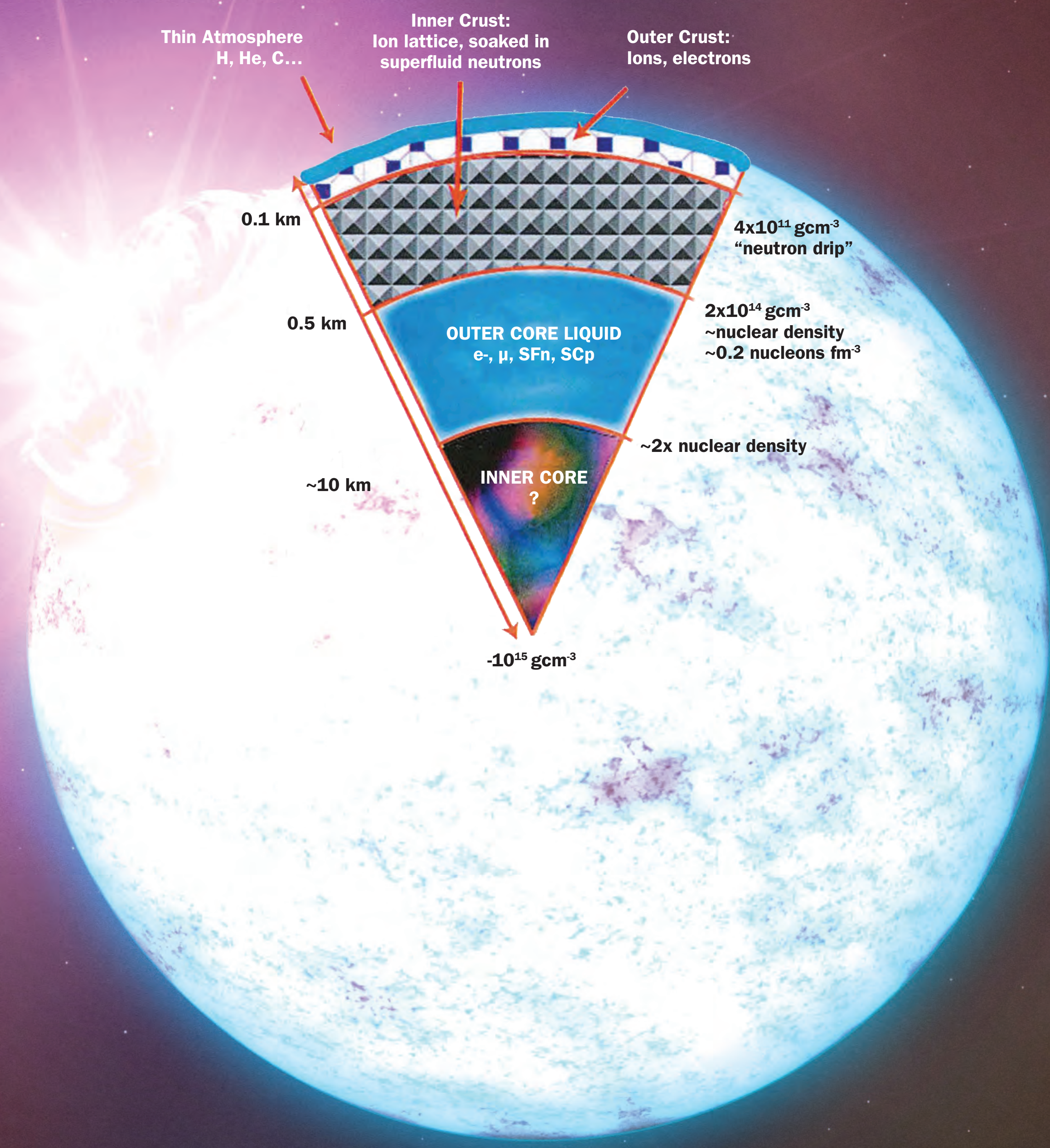
BINARY PULSAR



LEFT: The radio waves from a pulsar are emitted in two bunches which sweep across space at the same rate as the pulsar rotates.
RIGHT: From a binary pulsar, gravitational waves are also emitted.
Credit: Nobel Prize press release, 1993
TOP: Thomas Gold, *Credit: AIP*

CURRENT THEORETICAL UNDERSTANDING OF THE INTERIOR COMPOSITION OF NEUTRON STARS. UNCERTAINTY INCREASES WITH DEPTH.

From figure 1 in Arzoumanian et al., 2009.
Background image: NASA's Goddard Space Flight Center/Scott Wiessinger, USRA



During the next few years Arzoumanian's interests expanded to include the question of the interior composition of neutron stars. He and his colleagues at GSFC, USRA, and at various universities submitted papers to the Astronomy and Astrophysics Decadal Survey for 2010, in which they argued for the importance of X-ray timing of neutron stars as probes of extreme physics:

> *Neutron stars embody extremes inaccessible anywhere else in the Universe, but two insights provide the fundamental physics context:*
>
> - *According to current understanding, neutron stars represent the strongest gravitational environment in which matter of any kind can stably exist. An incremental addition of matter would drive a massive neutron star beyond the point at which it could support its own weight, and the star would collapse to a black hole.*
> - *The state of cold, stable matter at ultra-high density remains one of the most important unsolved problems in subatomic physics. Neutron stars represent a density-temperature regime that can be explored in no other way.*
>
> *A neutron star's interior structure is captured, in a global sense, by the still-uncertain equation of state (EOS) of bulk matter. The EOS relates density to pressure within a star or, through General Relativity, its mass M to radius R. Most EOSs predict that R will shrink as M grows and the self-gravitational force increases, but different assumptions about interior composition produce different detailed mass-radius relations. Thus, measurements of M and R probe dense matter. The conditions resulting from the enormous pressure at the center of the star may include i) dissolution of individual neutrons into an undifferentiated soup of quarks and gluons; ii) a phase transition to a "Bose condensate" of pions or kaons; or iii) a phase transition to yet-more-exotic matter made up of hyperons.*[9]

WHAT DID HE SAY?

A PHYSICS PRIMER FOR THE CURRENT UNDERSTANDING OF THE INTERIOR OF NEUTRON STARS

ZAVEN ARZOUMANIAN

"SOUP OF QUARKS AND GLUONS"

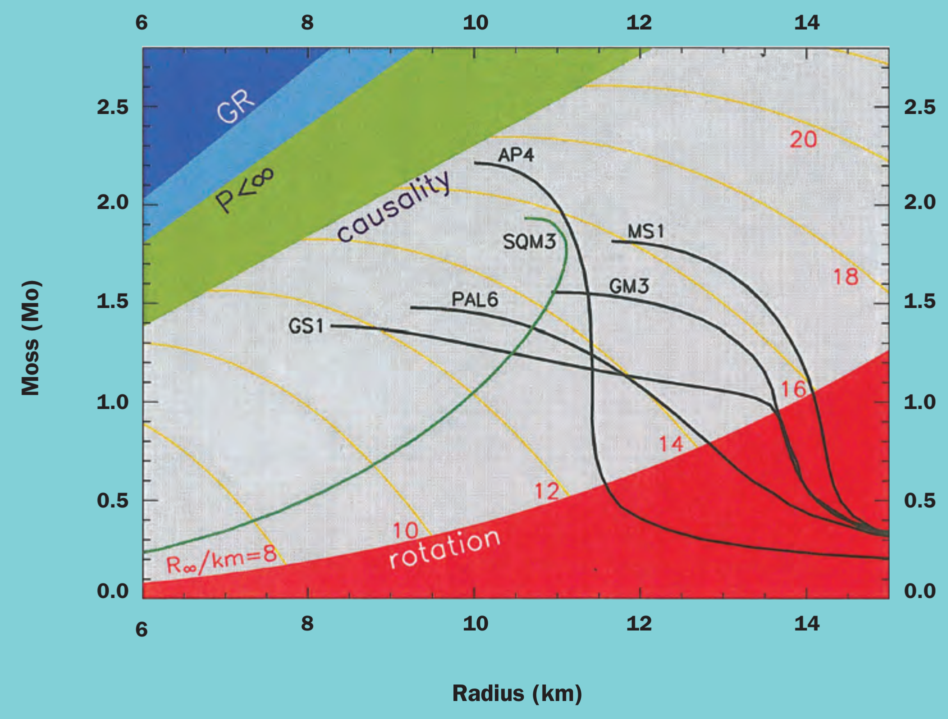
In electrodynamics, photons mediate the interactions between charged particles. In the strong force, which binds quarks into neutrons and protons, gluons mediate the interactions between quarks. Unlike electrodynamics, however, the strong force of attraction increases with separation distance, so that quarks are not normally observed as "free" particles, i.e., "outside" of neutrons or protons. It is thought, however, that in extremes of temperature and/or density, quarks and gluons can exist in a "soup" or plasma, rather than being confined inside protons and neutrons.

"PHASE TRANSITION TO A BOSE CONDENSATE OF PIONS OR KAONS"

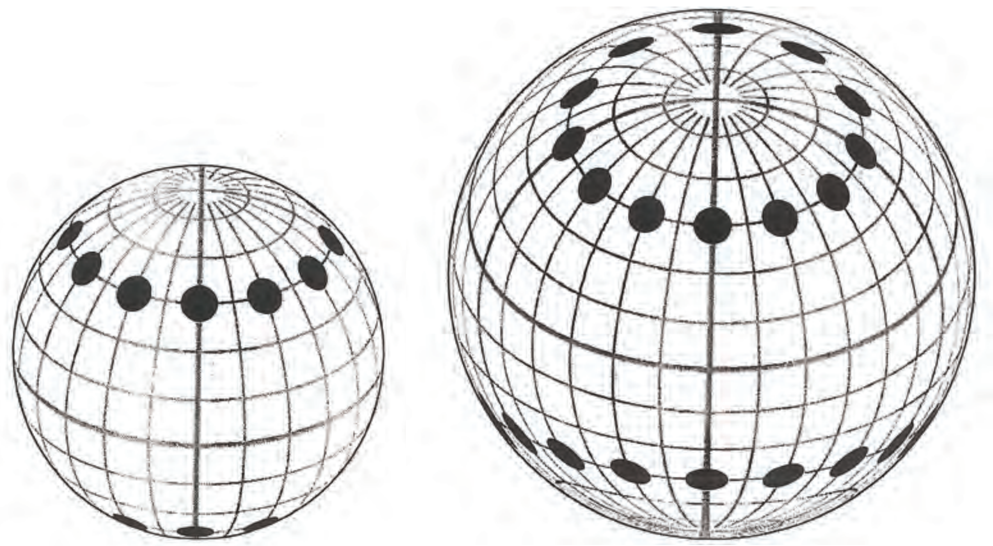
Elementary particles are divided into two classes depending on a quantum mechanical characteristic called "spin." Particles with half-integer spin (1/2, 3/2, ...) are called fermions, and no two of them can co-exist in the same quantum state in a given quantum system, a requirement known as the Pauli Exclusion Principle. Neutrons, and the quarks that compose them, are fermions, and the resistance to contraction resulting from the Pauli Exclusion Principle was thought to be the reason that certain stars that have used up their nuclear energy sources are prevented from further collapse. Static solutions of Einstein's equations for general relativity for spherically symmetric bodies indicated that the maximum mass that could be sustained in this way was about 0.7 solar masses.[10] Since the masses of neutron stars are known to be at least twice this value, researchers have searched for other models for the internal structure of neutron stars, and this has led to the consideration of the other class of elementary particles, namely, bosons. Bosons have zero or integer spin (0, 1, 2, ...) and are not subject to the Pauli Exclusion Principle. Photons and gluons, which carry force between fermions, are examples of bosons. Pions and kaons are also bosons, as they are composed of quarks that have spins summing to integer values. When the temperature of bosonic matter falls below a critical value, a phase change occurs that transforms the matter into a Bose-Einstein condensate. In many Earth-laboratory situations, this critical temperature is quite low, but because the critical temperature is proportional to the two thirds power of the number density of particles, Bose-Einstein condensates can form in the interior of neutron stars, even though the temperature there is quite high.[11] Even fermions can be a part of a Bose-Einstein condensate. In metal lattices, electrons, which are fermions, form what are called Cooper pairs. These pairs can behave like bosons, because the sum of their paired spins is an even number. It has been suggested that in neutron stars, where interparticle distances are extremely small, boson-like paired fermions can cohere to form a Bose-Einstein condensate state of matter. In such a macroscopic quantum state, neutron matter behaves like a superfluid (SFn), and proton matter behaves like a superconductor (SCp).

"PHASE TRANSITION TO YET-MORE-EXOTIC MATTER MADE UP OF HYPERONS"

Protons, neutrons, pions, and kaons are each composed of two quarks of various types. Hyperons are composed of three quarks, one of which is a so-called "strange" quark. Hyperons are fermions but, presumably, could form pairs that behave as bosons and could participate in a phase transition to a Bose-Einstein condensate state of matter.



Model equations of state based on various theoretical approaches and assumed compositions of neutron stars, e.g., AP4[12] assumes a composition of neutrons and protons; GM3[13] assumes neutrons, protons, and hyperons; GS1[14] assumes neutrons, protons, and kaons; and SQM3[15] assumes strange quark matter. The lines denoted GR, $P < \infty$, and causality represent limits to physically realistic structures per Einstein's theory of General Relativity and other considerations. The red region labeled rotation shows a limit derived from the most rapidly rotating pulsar known. Orange curves are contours of radiation radii R_∞ , which is the radius of the star as seen by a distant observer. Because of the curvature of space around a small massive object, the "radiation radius" of a neutron star is larger than its actual radius. Adapted from figure 4.3 in Lattimer, 2005.



A rotating neutron star with a pair of hot spots on either end of magnetic field lines, shown as it would appear in flat space and with light bending in the presence of strong gravity. *From figure 3 in (Nollert et al., 1989, p. 155).*

IT REMAINS TO BE SEEN IF THE NICER INSTRUMENT WILL ADVANCE KNOWLEDGE OF THE INTERIOR OF NEUTRON STARS.

MEASURING THE RADIUS AND MASS OF A NEUTRON STAR

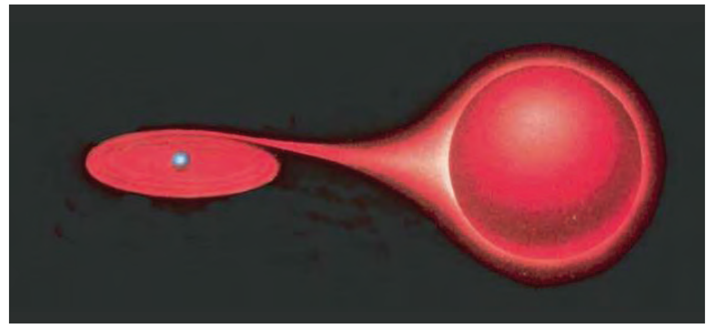
Arzoumanian and others have stressed the importance of finding observational ways to simultaneously constrain both the mass and radius of neutron stars. Constraints on the masses of neutron stars have proven to be possible because of the occurrence of some neutron stars in binary systems, including the Hulse-Taylor system. With careful and extended measurements of the dynamics of these binary systems through pulse timing observations, coupled with relations derived from Einstein's theory of general relativity, it is possible to determine both masses within the system. In addition to the period of the orbital motion, a required measurement might be, for example, the rate of advance of the line connecting the two bodies at their minimum separation distance, the so-called "advance of the periastron." It was this kind of measurement for the planet Mercury in our solar system that provided the first evidence for the validity of Einstein's theory of general relativity.

One would think that the measurement of the radius of an object that is just kilometers across and distant from Earth by thousands of light years would be challenging, to say the least. But the behavior of light in the presence of significantly curved space provides some useful aids. For example, Dr. Hans-Peter Nollert and his colleagues at the University of Tübingen pointed out the advantage to a distant observer of being able to see part of the back of a neutron star. If the neutron star has a "hot spot," as many of them do, at both ends of a dipole-like stellar magnetic field, the hot spot would be evident in the data record of the photons coming from the star–the so called "lightcurve."[16] To a distant observer, the radius of the neutron star would appear larger than it would appear in flat space, and the lightcurve analysis would show the rotating hot spots differently. Analysis of the lightcurve could yield an estimate of the magnified radius of the star as seen by a distant observer, and, through the theory of general relativity, this radius is related to the actual radius and mass of the neutron star.

There are several other possible ways to obtain estimates of the radius of a neutron star, or at least to constrain the radius R and mass M of the star to a small range of values. For example, if the spectrum of emission lines from a hot spot on the surface of a neutron star can be measured, the shift in frequency of the line due to the rotational motion of the star or to its gravitational field can yield independent constraints on R and M.

THE NICER/SEXTANT PROJECT

Arzoumanian and Dr. Keith Gendreau of NASA GSFC won an opportunity to develop a space mission designed to better understand the interior composition of neutron stars. The mission, Neutron Star Interior Composition Explorer/Station Explorer for X-ray Timing and Navigation Technology (NICER/SEXTANT) will study neutron stars and test the use of pulsars for space navigation (see the essay in this book titled "Loosening the Bonds"). As of this writing, the observing instrument for NICER/SEXTANT has been mounted on the International Space Station and is making measurements of X-ray pulsars.



Artist rendition of the formation of a millisecond pulsar through the addition of mass and angular momentum from a companion star. *From figure 6.15 in (Becker, 2009, p. 120)*

One of the science goals of NICER/SEXTANT is to use lightcurve analysis of hotspots on so-called millisecond pulsars (MSPs) to constrain radius measurements to ±5% uncertainty, and thereby to distinguish between the various models of the interior of neutron stars. MSPs are the most rapidly rotating pulsars known, with rotational periods between about 1 and 10 milliseconds. They are thought to be "recycled" pulsars that have been spun up through the accretion of material from a companion star; the accretion bringing both mass and angular momentum to the neutron star.

NICER/SEXTANT has a combination of good energy resolution and accurate timing, a capability that has not been available before for X-ray astronomy. Astronomers from around the world are now able to carry out concurrent observations of the neutron star targets for NICER/SEXTANT in the radio, optical, and gamma-ray wavelength bands. Astronomers will be able to use NICER/SEXTANT to target objects of their own choosing as Guest Observers. Referring to the Guest Observer program, Arzoumanian noted, "It's a pleasure to build a tool that will enable much more science than I could ever do myself."

It remains to be seen if the NICER instrument will advance knowledge of the state of matter at the extreme conditions found in the interior of neutron stars, but the effort and the desire on the part of Dr. Arzoumanian to advance knowledge and share research opportunities is entirely consistent with the chartered purposes of USRA.

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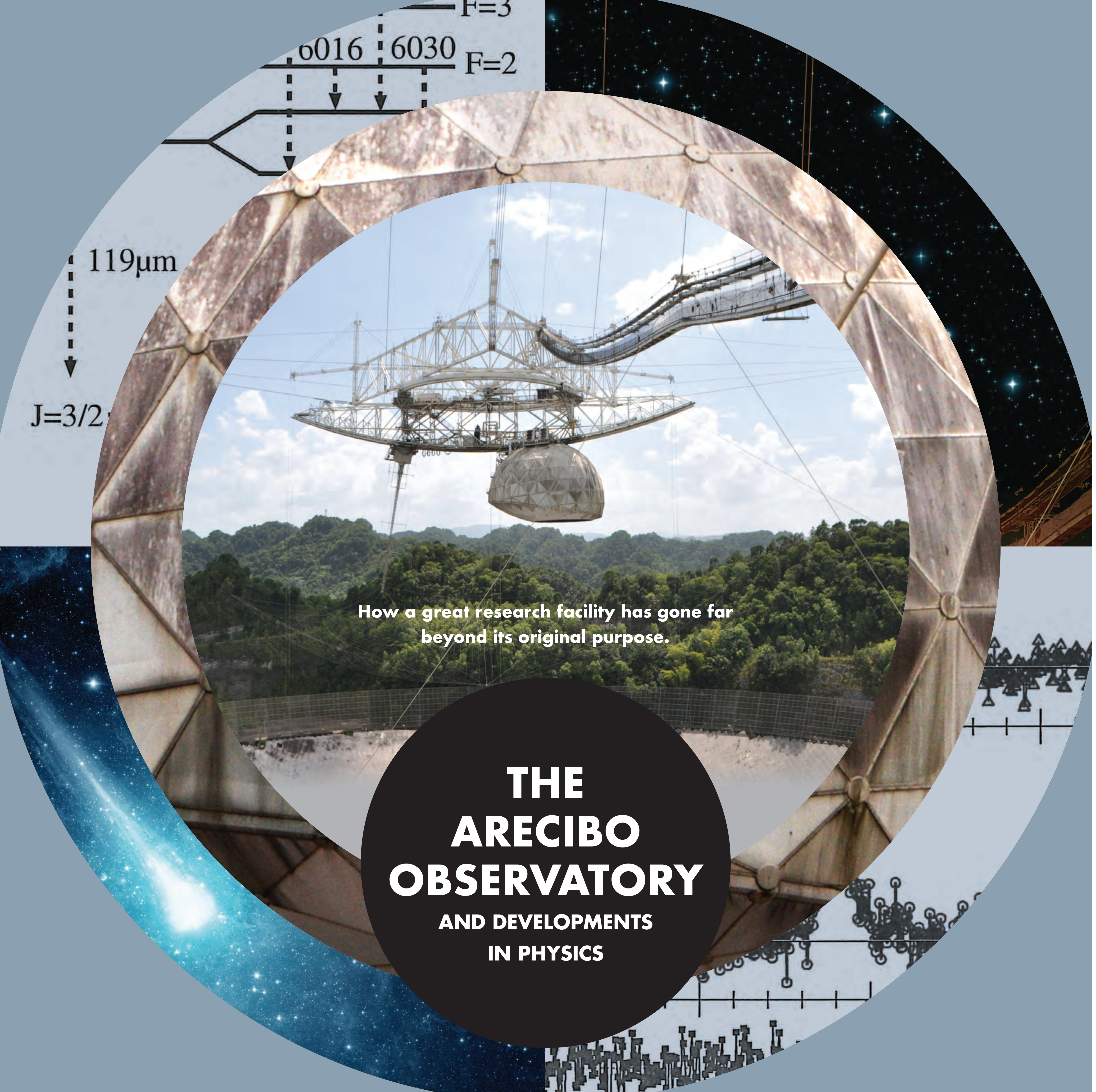


How a great research facility has gone far beyond its original purpose.

THE ARECIBO OBSERVATORY

AND DEVELOPMENTS IN PHYSICS

Credit: Danielle Futselaara

IN 2011, USRA BEGAN MANAGING THE SCIENCE FOR THE ARECIBO OBSERVATORY, which has a decades-long distinguished history of discoveries in ionospheric research, planetary science, and astronomy.

The Arecibo facility was conceived in the late 1950s by Cornell University professor William Edwin "Bill" Gordon (1918–2010), who wanted to use a large radio-wave transmission and receiving system to study the ionosphere. His idea was to send bursts of radio waves into the ionosphere to study its structure by measuring the weak back scatter from various heights with a fixed parabolic dish antenna. If he used the best transmitters and receivers then available, Gordon calculated that he would need a receiving dish 1000 feet (305 meters) across.

At the same time the US Department of Defense (DoD) was interested in better understanding the structure of the ionosphere. The Advanced Research Projects Agency (ARPA) was tasked with developing defenses against the Soviet Union's intercontinental ballistic missiles (ICBMs). Since Soviet ICBMs could be accompanied by decoys, the US defense system needed to quickly distinguish between real warheads and decoys.

Hypervelocity objects encounter increasing drag as they enter the atmosphere. The kinetic energy they lose heats and ionizes the surrounding air, leaving an ionized trail. From studies of meteors, scientists knew that this ionized wake could be detected at radar wavelengths as well as in the visible spectrum. They reasoned that the energy of the wake should be related to the mass of the object that produced it, and thus radar measurements of the ionized wake should yield a means of discriminating between the heavy warheads and the lighter reentry decoys.[1]

William Gordon (left) and William McGuire (right) examine a model of the Arecibo Observatory in 1958. McGuire (1920–2013) was a civil engineer at Cornell and deeply involved in the design of the Arecibo structure.

BUILDING THE DISH

The ARPA agreed to fund the construction of Gordon's large radio dish to gain information about the structure and characteristics of the Earth's ionosphere as it continued to research the possibility of detecting these ionized wakes. More generally, ARPA researchers wanted to understand what happens to an ICBM and its decoys and debris as it re-enters the upper layers of Earth's atmosphere.

The surface area of Gordon's radio dish would be about 18 acres. It wasn't feasible to rotate such a large structure, so Gordon's original idea of a paraboloidal reflector surface meant that it could only look straight up. Through continued discussions with ARPA and other elements of the DoD, Gordon decided on a reflector with a spherical surface

TOP LEFT: Triangular support platform and rotatable feed arm truss suspended 150 m above the reflector. Line feeds corresponding to different frequencies are mounted on the feed arm.
From figure 5 in LaLonde, 1974.

BOTTOM LEFT: Aerial view of the Arecibo facility as it appeared after the original construction was completed in 1963.
From figure 1 in LaLonde, 1974.

RIGHT: The Arecibo dish shown in the surrounding limestone landscape that features sinkholes of various shapes and sizes.

instead, allowing viewing and tracking in a 40-degree cone around the vertical. The observatory could now study more than just the ionosphere.

The original reflecting surface, made of square steel mesh with wires spaced on one half-inch centers,[2] was built into a sinkhole near Arecibo, Puerto Rico. Since radio waves incident on the Arecibo reflector do not converge at a single focal point, as they would with a parabolic reflecting surface, it was necessary to collect the reflected waves along tapered aluminum waveguides, called "line feeds," which could be aimed in different directions. The original line feed, designed for operation at 430 MHz, was 96 feet (29 meters) in length with hundreds of slots through which radiation could enter (or exit when the observatory was being used in the transmission mode)[3]. The line feeds were attached to a bow-shaped feed arm truss, the azimuth arm, that rotates along a circular track. The track is attached to a triangular shaped platform suspended above the reflecting surface by large cables running to three towers back stayed to large concrete anchors.[4] The feed arm truss curvature matches the surface of the Arecibo reflector, so that the line feed always points along the radius of the spherical surface of the dish.

EARLY SCIENTIFIC DISCOVERIES

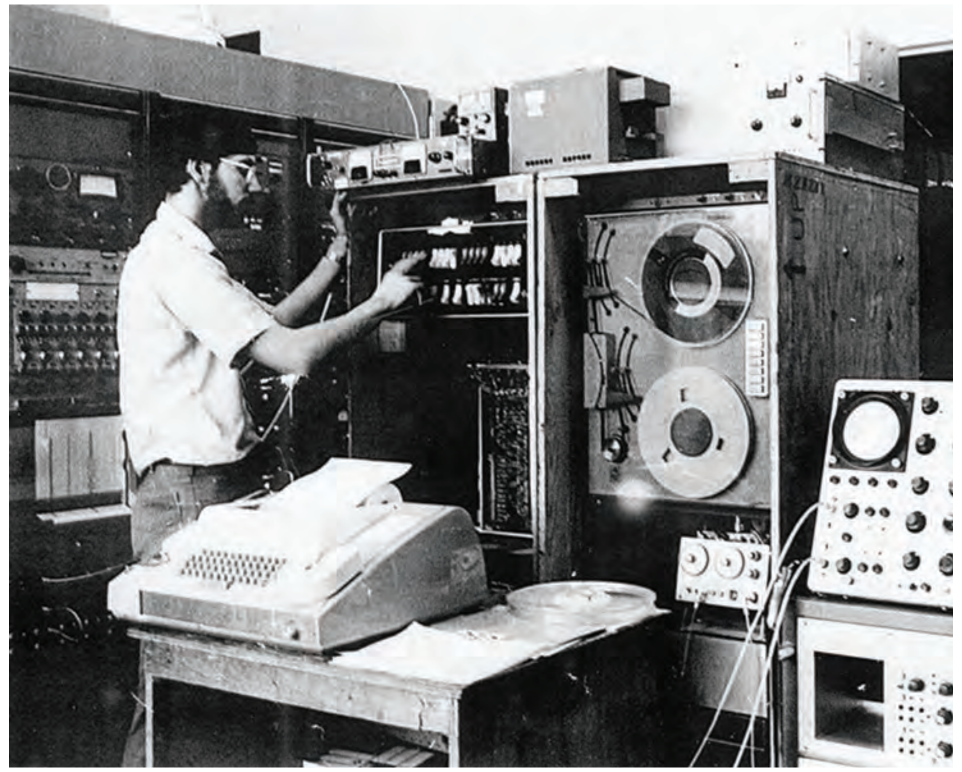
The observatory was completed and commissioned for service by 1 November 1963. The ARPA benefited from some initial experiments by Gordon and his graduate students to characterize the ionosphere, and ionospheric research has always been an important part of the observatory's program. But on 1 October 1969 the sponsorship of the observatory was transferred from ARPA to the National Science Foundation (NSF), in recognition of the broader capabilities of the radio dish.

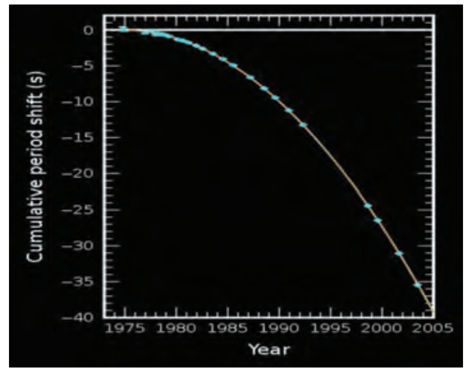
By 1974, the range of astronomy experiments had greatly increased following the replacement of the wire mesh reflecting surface with perforated aluminum panels. Scientific advances in the first two decades of the life of the Arecibo Observatory include:

- The discovery, by Drs. Gordon H. Pettengill and Rolf B. Dyce, that the planet Mercury's rotation period is 59 ± 5 days, rather than 88 days.[5] The period of Mercury's orbit around the Sun is 88 days, and if the planet had been locked in its orbit around the Sun in the same way that the Moon is locked in its orbit around the Earth (always showing the same lunar "face" to the Earth), its period of rotation would have been the same as its orbital period.
- The early characterization of pulsars, first discovered by Jocelyn Bell, then a graduate student at the University of Cambridge. Bell's discovery was published in Nature magazine on 24 February 1968, and five days later, the Arecibo telescope detected the pulsar's radio signature. Dr. Frank Drake[6] noted that the detailed morphology of the individual pulses could help determine the size of the emitting object and the physical mechanism responsible for the radio emission.[7] Bell's pulsar was in the constellation Vulpecula, and other pulsars were soon discovered there and characterized using the Arecibo facilities. Later in 1968, the period of a pulsar in the Crab nebula was measured at Arecibo.[8,9] The short period of this pulsar (33 milliseconds) confirmed that pulsars were rotating neutron stars.
- The discovery by graduate student Russell Hulse and Professor Joseph Taylor of the University of Massachusetts, Amherst, of a pulsar with an orbiting companion of about the same mass.[10] This was an important development in physics as it was the first confirmation of the existence of gravitational waves (albeit an indirect one), and it earned Hulse and Taylor a Nobel Prize in 1993.
- The discovery by Professor Donald C. Backer (1943–2010) of the University of California, Berkeley; his doctoral student, Shrinivas Kulkarni; Professor Carl Heiles of UC Berkeley; and Dr. Michael Davis of Arecibo that a compact component of the radio source 4C21.53[11] was a pulsar with a rotation rate of 1.558 milliseconds.[12] This was the first millisecond pulsar (PSR1937+21)[13] to be detected. It's a neutron star with a mass of about 1.4 times the mass of the Sun rotating at a rate that corresponds to a frequency of 642 Hz, which is between E flat and E above treble C on a piano keyboard. Millisecond pulsars such as PSR1937+21 are thought to be "recycled" pulsars, i.e., pulsars in binary systems in which the orbiting partner of an original pulsar delivers mass and angular momentum to the neutron star, thereby speeding it up.
- The discovery by Professors Willem Baan and Perry Wood, then of Pennsylvania State University, and Aubrey Haschick of the Haystack Observatory of the first hydroxyl (OH) megamaser. Baan and his colleagues used the Arecibo Observatory to measure 18 cm radiation from galaxy IC 4553,[14] also known in the astronomer Halton Arp's Atlas of Peculiar Galaxies as Arp 220.[15]

RUSSELL HULSE

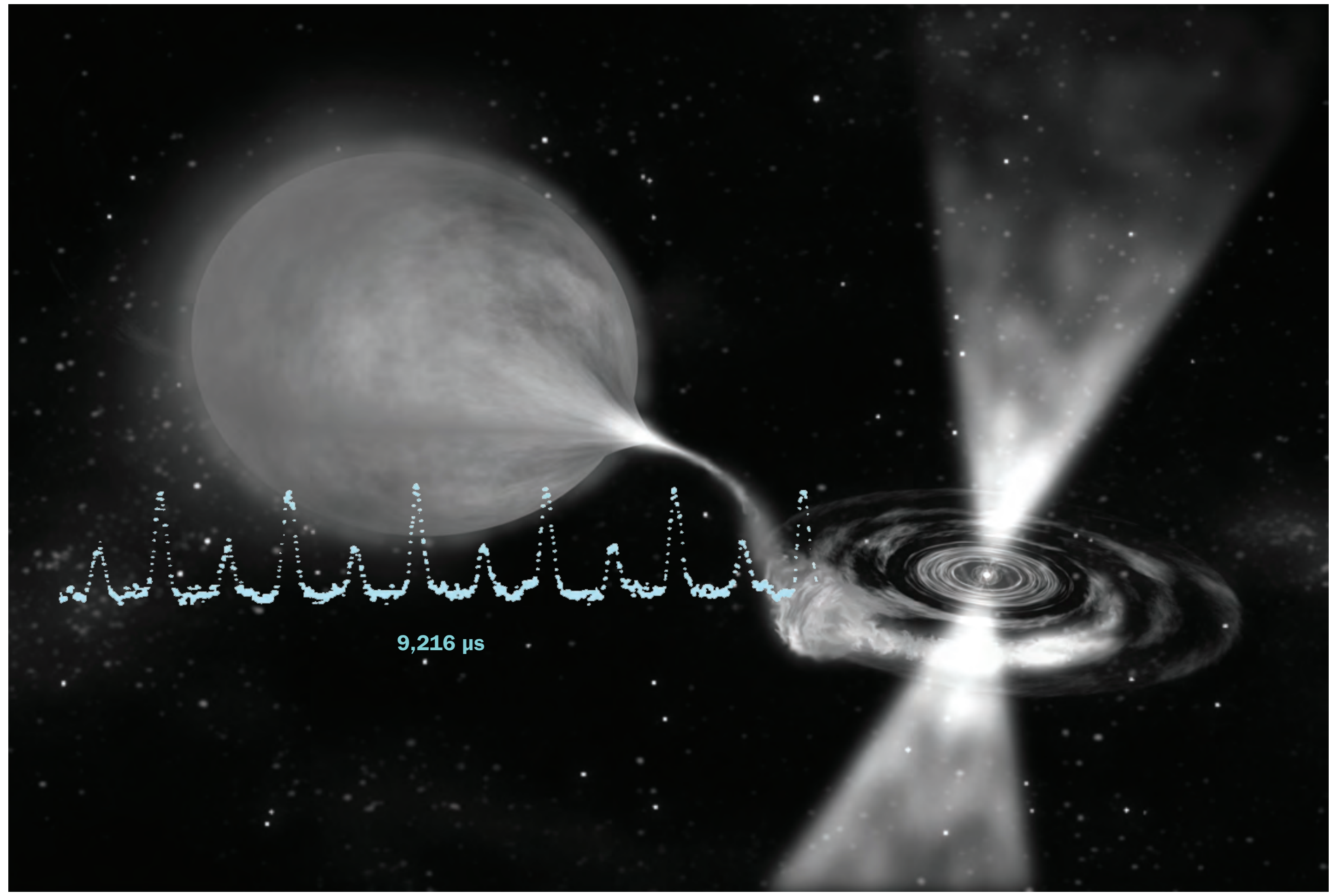
JOSEPH TAYLOR





LEFT: Russell Hulse in the control room at Arecibo in 1974. The photograph is courtesy of Joseph Taylor, obtained from Nadia Drake's article in WIRED. *(Drake, 2013)*

ABOVE: The dots are the observations of the orbital decay of the binary pulsar system discovered by Hulse and Taylor. The curve is the theoretically expected decay for a system emitting gravitational radiation, according to general relativity.
Adapted from figure 1 in Weisberg and Taylor, 2005, p. 28.



INSET IMAGE: The waveform of the first millisecond pulsar to be detected. The trace of 9,216 microseconds shows six periods of the main pulse and an interpulse. From figure 4 of Backer et al., 1982. **BACKGROUND IMAGE:** Artist's depiction of a pulsar accreting mass from a binary companion. *Credit NASA/Dana Berry.*

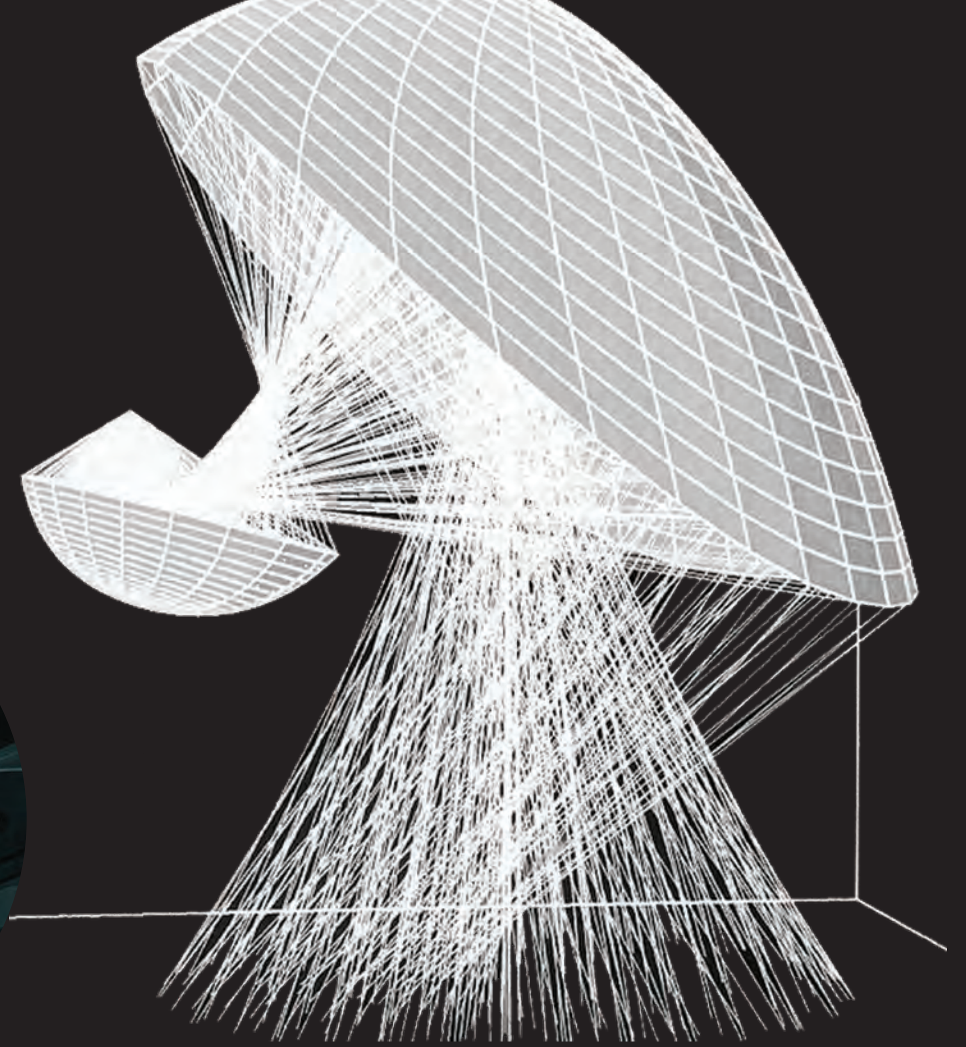
Infrared image of the Arp 220 galaxy. *Credit Space Telescope Science Institute.*

The Arp 220 galaxy is classified as "peculiar" because it seems to have a double nucleus. It appears that at least two galaxies are colliding to form Arp 220. The galaxy is very active, forming new stars at a prodigious rate. The radiation from these new stars heats the dust in the galaxy, and the infrared radiation emitted by the dust is absorbed by OH molecules, causing them to be in higher energy (excited) states. Cascading to the rotational ground state of OH allows the possibility of OH masering (to be discussed in more detail below). Baan and his colleagues estimated that Arp 220 was emitting 70 million times the energy in the OH 1667 MHz line than the known "standard" OH maser in our own galaxy.[16] Arp 220, therefore, is thought to contain many OH masers and the galaxy is termed an OH "megamaser."

ARECIBO GETS AN UPGRADE

In 1997, the second major upgrade of the Arecibo Observatory was completed. Most of the line feeds were replaced with a Gregorian[17] subreflector system, which focuses radio waves from a spherical reflecting surface to a single point, regardless of frequency/wavelength. The Arecibo Gregorian is housed in an 85-foot (26 meter) diameter geodesic protective dome and attached to the azimuth arm of the telescope, along with the 430 MHz line feed.[18] The Gregorian system allows continuous frequency coverage between 300 MHz (λ = 1 m) and 10 GHz (λ = 3 cm), with much better collection efficiency than was possible with the line feeds. Feed horns on a rotatable turret within the Gregorian dome allow researchers to quickly change observing frequencies.

DESPITE THE UNCERTAIN FUTURE, THE OBSERVATORY CONTINUED TO DELIVER NEW DISCOVERIES.



LEFT: ALFA installed in the Gregorian Dome.

RIGHT: Two reflecting surfaces in the Gregorian system allow radio waves from the Arecibo spherical reflector to come to a single focal point.

The Gregorian dome and the 430 MHz line feed attached to the azimuth arm of the Arecibo telescope.

A significant upgrade to the signal processing systems and receiver arrays within the Gregorian dome was the installation in 2004 of the Arecibo L-band Feed Array (ALFA), consisting of a central feed horn surrounded by six additional horns in a hexagonal array. The L band radio waves range is from 1225 MHz (λ = 24.5 cm) to 1525 MHz (λ = 19.7 cm).

By the time USRA began managing the science for Arecibo, the observatory had substantially evolved under the excellent guidance of Cornell University. With the new Gregorian system, the ALFA, and other improvements in "back-end" hardware and software, scientists using the Arecibo Observatory continued to make advances in astronomy and astrophysics. However, the observatory increasingly found itself competing with other NSF astronomy-related priorities. The Foundation budget wasn't growing fast enough to support development of next generation observatories while maintaining support for its existing ones.

THE FUTURE OF ARECIBO IS UNCERTAIN

In 2004, NSF officials decided to reduce funding of their existing observatories by a total of $30 million dollars per year to support development of new facilities. In 2005, the Foundation established a Senior Review committee to recommend the best way to balance support of existing facilities against an ambitious set of new programs. The Senior Review committee recommended decreases in the budgets of all the existing NSF observatories, including Arecibo. For Arecibo, the review recommended:

Decreasing the telescope's annual $12.0 million budget to $9.0 million in FY2009, and securing partnerships for the remaining necessary funding. If alternate funding sources or partnerships could not be obtained by 2011, the review recommended dismantling the facility.[19]

The cloud over Arecibo's future continued to darken. In 2004, the NSF solicitation to manage the facility was $70 million over 5 years. Cornell won the bid to manage the observatory during that 5-year period, which was extended by one year. In 2010, NSF issued another solicitation for the management of the Arecibo Observatory, and this solicitation contained an estimate of funding of $41.2 million, less than 60% of the funding level for the 2004 solicitation. A team led by SRI International,[20] and which included USRA as the science manager, won this bid to manage the observatory.

DELIVERING DISCOVERIES DESPITE SETBACKS

Despite the uncertain future of Arecibo, the observatory continued to deliver new discoveries as USRA took over science management. In 2012, an extra-galactic, millisecond-duration, radio burst was detected using data from the Arecibo pulsar ALFA survey.[21] Radio bursts of this nature, so-called Fast Radio Bursts (FRBs), had been discovered by researchers at the Parkes radio telescope in Australia. The one observed at Arecibo by Dr. Laura Spitler of the Max-Planck-Institute for Radio Astronomy and her colleagues was designated FRB 121102.[22]

Initially, FRBs were thought to involve a one-time cataclysm of some kind. Then, in 2015, during follow-up observations at Arecibo, Spitler and her colleagues found ten additional bursts from FRB 121102,[23] and reported that:

> *These bursts have dispersion measures and sky positions consistent with the original burst. This unambiguously identifies FRB 121102 as repeating and demonstrates that its source survives the energetic events that cause the bursts. Additionally, the bursts from FRB 121102 show a wide range of spectral shapes that appear to be predominantly intrinsic to the source and which vary on timescales of minutes or less.*[24]

Therefore, FRB 121102 is a repeating FRB, the cause of which is more than ever a mystery, as one-time cataclysmic events seem to be ruled out. The mystery wasn't reduced much when in 2016 the Very Large Array[25] in New Mexico was used in conjunction with the Arecibo Observatory to pinpoint the source of the radio bursts.

> *The source appears to be co-located with a low-luminosity active galactic nucleus or a previously unknown type of extragalactic source.*[26]

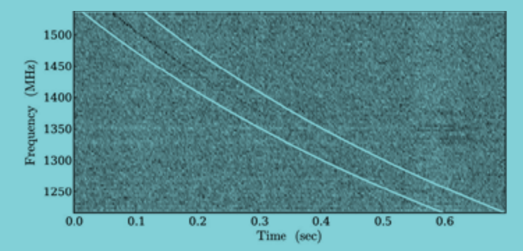
At this writing, the physics of what causes repeating FRBs, the most powerful transient radio bursts yet observed, is not understood.

USING ARECIBO TO STUDY FUNDAMENTAL PHYSICS

Beginning in 2005, researchers using the Arecibo Observatory began to impact the discipline of theoretical physics by seeking to determine whether so called "fundamental constants" are really constant over time.
One of these constants is known as alpha (α) and defined as

$$\alpha = e^2/\hbar c$$

where e is the charge of an electron, $\hbar = h/2\pi$ is Planck's constant divided by 2π, and c is the speed of light. The fundamental constant α is a dimensionless number, with a value of about 1/137. The frequency of radiation by electrons making a transition from one energy level to another in an atom or molecule depends on the value of α.



DISPERSION MEASURE

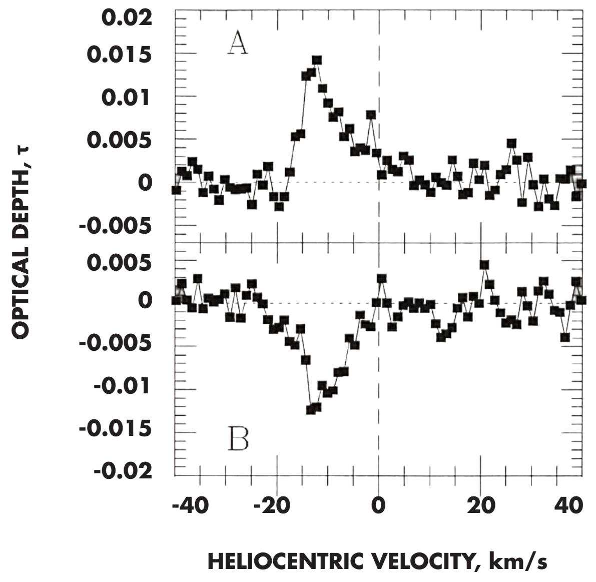
The speed of radio waves travelling through a medium containing free electrons depends on the frequency of the waves. Waves with higher frequencies travel faster than waves with lower frequencies. For a constant density of free electrons in the intervening space between a pulsar and a receiver, theory predicts that the delayed arrival time is proportional to $1/\nu^2$, where ν is the frequency of the wave. The "dispersion measure" (DM) is obtained from the measurement of different arrival times for different frequencies for a given pulse and then fitting the results to the expected theoretical $1/\nu^2$ curve based on models of the electron distribution in the Galaxy and beyond.

The DM is typically defined as

$$DM = D^* n_e \text{ parsecscm}^{-3}$$

where D is the distance to the object in parsecs and n_e is the mean electron density along the path to the object. (A parsec is the distance at which one astronomical unit subtends an angle of one arcsecond. It corresponds to a distance of about 3.26 light years.) The DM, therefore, gives the column density of electrons between the pulsar and a radio antenna. By using models of the distribution of free electrons in our galaxy, in the space between our galaxy and the "host" galaxy, and within the host galaxy, the DM can be used to make a rough estimate of the distance to a radio source. The dark curve in the above figure shows the dynamic spectrum of the FRB 121102 during the 0.7 seconds that it swept across the frequency band of the ALFA system. The white curves show the expected sweep for a $1/\nu^2$ dispersed signal at a DM=557.4 parsecscm^{-3}.
(Adapted from figure 2 in Spitler et al., 2014.)

Optical depth τ versus heliocentric velocity (relative to z = 0.24671) as measured at the WSRT (1.1 km/s resolution). [A] 1720 MHz spectrum, and [B] 1612 spectrum. *Adapted from figure 1 in Kanekar et al., 2004.*



New physical theories allow for the possibility that a fundamental constant such as α might vary over time.

> *The developments of high energy physics theories such as multi-dimensional and string theories provide new motivations to consider the time variation of the fundamental constants. The observation of the variability of these constants constitutes one of the very few hopes to test directly the existence of extra-dimensions and to test these high energy-physics models … But indeed, independently of these motivations, the understanding of the value of fundamental constants of nature and the discussion of their status of constant remains a central question of physics in general: questioning the free parameters of a theory accounts to questioning the theory itself.* [27]

NISSIM KANEKAR

JAYARAM CHENGALUR

TAPASI GHOSH

Professor Nissim Kanekar of the National Center for Radio Astronomy (NCRA) in India has been a leader in the effort to constrain the uncertainty of the variability of α. Since 2003, Professor Kanekar has collaborated with Professor Jayaram Chengalur, also of NCRA, and Dr. Tapasi Ghosh[28] of the Arecibo Observatory in the α-research project.

The team's approach has involved observing certain maser emission and absorption lines of the OH molecule coming from a quasar source, PKS1413+135.[29] The frequency of known spectral lines in this source are redshifted owing to the expansion of the universe, and the redshift or "z value" is about 0.247, where the fractional frequency shift z = $(\nu_{emitted} - \nu_{observed})/\nu_{observed}$. Using this redshift value in a model for the expanding universe indicates that radio waves now being received from PKS1413+135 were emitted some 2.9 billion years ago. Kanekar's project has been to determine if the fundamental constants as determined by transitions in the OH molecule 2.9 billion years ago are different from the fundamental constants as measured today.

The Kanekar team first used the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands to measure the peaks in the conjugate lines (1720 and 1612 MHz) and thereby set a limiting value for the variation over time in a combination of fundamental constants defined as

$$G \equiv g_p[\mu\alpha^2]^{1.849}$$

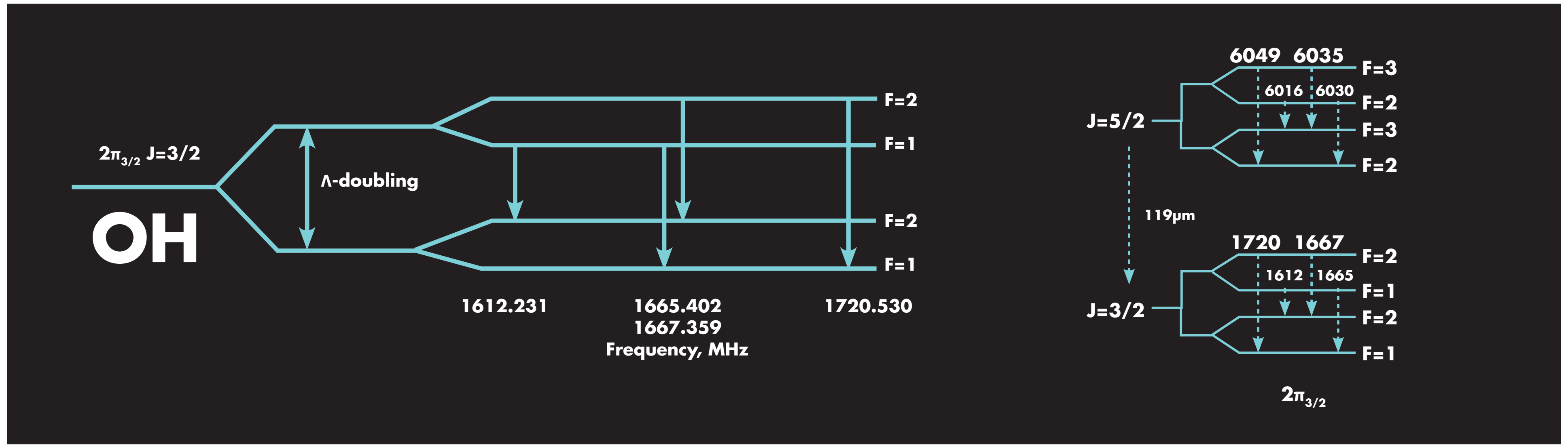
where g_p is the so-called "proton g factor," which is a dimensionless number that relates the proton's magnetic moment to its nuclear spin angular momentum, and μ, which is the ratio of the proton and electron masses (m_p/m_e).[34] They found that

$$\Delta G/G = 3.7[\Delta\alpha/\alpha] + 1.85[\Delta\mu/\mu] + [\Delta g_p/g_p] = (+2.2 \pm 3.8) \times 10^{-5}$$ [35]

MASERING

To appreciate the work of the Kanekar team, it's necessary to understand in some detail how the hydroxyl molecule gives rise to radio waves through a masering process. A diagram of the lowest rotational energy state (denoted as $^2\Pi_{3/2}$ with the total angular momentum quantum number J = 3/2) of the hydroxyl molecule (OH) is shown on the facing page. The interaction of the rotational angular momentum of the molecule and the orbital angular momentum of the electrons splits the energy level into two – the so-called lambda (Λ) doubling. Coupling with the nuclear spin (½) of the hydrogen nucleus causes hyperfine splitting of the two lambda doublet lines, corresponding to different values of F, which is the quantum number for total angular momentum, including nuclear spin.[30]

When an OH molecule changes state, say from the F=1 level of the upper part of the Λ-doublet to the F=2 level of the lower part of the Λ doublet, a photon is emitted with a frequency that is proportional to the energy difference between the two levels, according to the formula ν = ΔE/h. In this case the frequency ν would be approximately 1612 MHz (more precisely 1612.231 MHz) for a transition occurring in a laboratory on Earth. This frequency would be observed as a line on a spectrum of radio waves. Of the four transition lines in the hyperfine structure of the lowest rotational energy level of OH, the two in the middle (F=1 → F=1 and F=2 → F=2) are usually the most intense and are called the "main lines" (1665 MHz and 1667 MHz). The two transitions corresponding to F=1 →F=2 and F=2 →F=1 are called the "satellite lines" (1612 MHz and 1720 MHz). These four lines correspond to a wavelength of about 18 cm, and their emissions were first detected in the interstellar medium by researchers at the Haystack Observatory of MIT's Lincoln Laboratory in 1963.[31]



LEFT: Energy levels for the rotational ground state of OH (not to scale). J denotes total angular momentum exclusive of nuclear spin, while F denotes total angular momentum inclusive of nuclear spin. *Adapted from http://comet.sai.msu.ru/~gmr/Maser_monitoring/masers.htm*

RIGHT: The intra-ladder transition to the ground state of OH. *Adapted from figure 1 in Kanekar, 2008, p. 2718.)*

The number of emissions per unit of time depends on the distribution of OH molecules across the four possible states. Normally, there would be more molecules in the lower energy states than in the higher ones. But if there is a "population inversion," with more OH molecules in the higher energy states than in the lower ones, a maser process can occur in which an incident photon at the transition frequency for a given line induces an emission with the same frequency and phase as the incident photon. If, for example, there is a continuum source of radio waves behind an OH cloud relative to an observer, this maser process would cause an amplification at the frequency of an OH line with a population inversion.

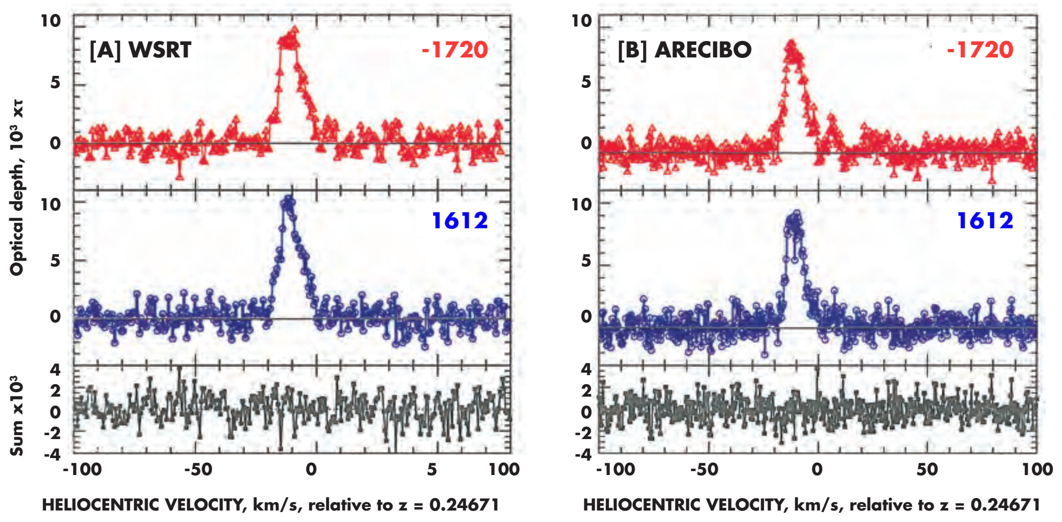
CONJUGATE EMISSION/ABSORPTION LINES

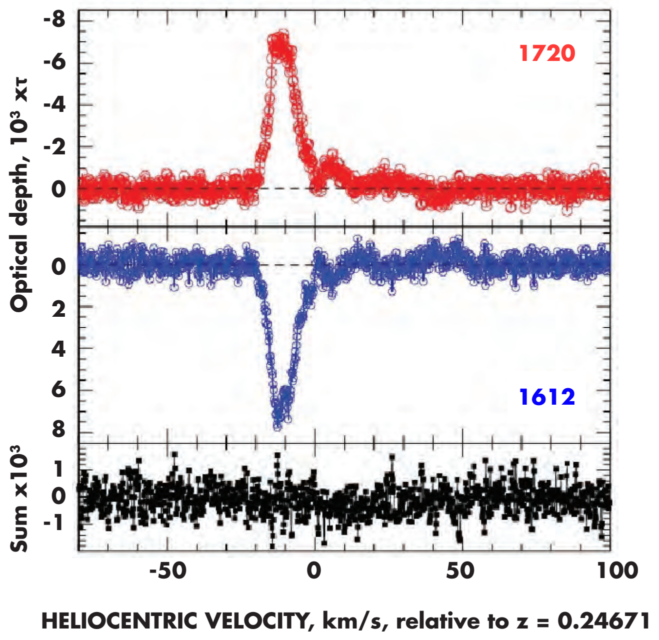
This maser process can also occur if the population distribution is such that there is a larger than normal number of OH molecules in lower energy states than in higher ones. This is called a "population anti-inversion," and when this happens an observer would see absorption of radiation, rather than emission, at the line with an anti-inversion.

It turns out that in certain circumstances, quantum selection rules for state changes in the OH molecule cause population distributions that result in maser emission from one of the satellite lines and maser absorption in the other.

The OH molecules can be "pumped" from the ground state to higher rotational states by the absorption of far-infrared radiation emitted by nearby dust. The molecules so driven to higher energy states cascade back down to the ground state. One route to the ground state, the 119 μm intra-ladder transition, $^2\Pi_{3/2}$ (J=5/2) → $^2\Pi_{3/2}$ (J=3/2) is shown in the accompanying figure. This decay back to the ground state is governed by the quantum mechanical selection rule ΔF = 0, ±1. This means that transitions from the F = 3 sub-levels of the excited state to the F = 1 sub-levels of the ground state are forbidden, while the F = 2 sub-levels can decay to all ground state sub-levels. There are, therefore, more paths from the excited state to the F = 2 sub-levels of the ground state than to the F = 1 sub-levels. In a relatively dense OH gas cloud (optically thick), the populations in the ground state are determined only by the number of possible routes to each sublevel. There will therefore be a population inversion between the F=2 and the F=1 sublevels of the ground rotational state of OH, with the consequent stimulation (masering) of the 1720 MHz line in emission and of the 1612 MHz line in absorption. In this circumstance, the profiles of satellite lines are said to be "conjugate," that is, they have the same shape (though one will be seen in emission and the other in absorption), and one is assured that the emission and absorption is occurring in the same OH gas cloud.[32]

This is important because if emission masering is occurring in one OH gas cloud and absorption masering is occurring in another, and the clouds are moving with different velocities relative to an observer on Earth, then the difference in frequency shifts of the two spectral lines (1720 and 1612 MHz) could be partly or wholly due to different Doppler shifts of the two OH clouds. If you know that the emission and absorption is occurring in the same OH cloud, the systematic velocity offsets between the two spectral lines is not an issue.[33] If one measures the frequencies of these conjugate satellite lines coming from an OH cloud in a distant galaxy, any difference in the frequencies of the satellite lines, as compared to differences measured in





TOP: From figure 1 in Kanekar et al., 2010. Optical depth is shown here (rather than minus optical depth), and the plot in the 1720 line is flipped in sign. The bottom panel shows the sum of the 1720 and 1612 spectra and is consistent with noise, as it should be for conjugate lines.
RIGHT: The latest results using 150 hours of observing time with the ALFA system at Arecibo.

THE ARECIBO OBSERVATORY HAS BEEN USED FOR A VARIETY OF PROJECTS, INCLUDING TO SET CONSTRAINTS ON THE POSSIBLE VARIABILITY OF THE FUNDAMENTAL CONSTANTS OF NATURE.

a laboratory, can be attributed to changes in one or more of the fundamental constants. This is the premise for the strategy that the Kanekar team used when they began to look for OH conjugate lines coming from the quasar PKS1413+135 in 2003.

Using the WSRT, the Kanekar team had demonstrated the conjugate nature of the satellite lines in the OH cloud in front of the quasar PKS1413+135, but the spectral resolution of their measurements was only about 1.1 km/s (measured in terms of velocity-induced shift of spectral lines). This relatively poor spectral resolution led to a large uncertainty in the possible change in G and hence in the fundamental constants g_p, μ, or α over the look-back time of about 2.9 billion years. The change in the fundamental constants could have been positive, negative, or zero.

The team decided to try to make the same measurement again at both the WSRT and the Arecibo Observatory. Between May and July of 2005, they were able to get 58 hours of time at WSRT with a resolution of 0.57 km/s and 40 hours at the Arecibo Observatory, with a resolution of 0.35 km/s.

The team again saw conjugate emission/absorption in the 1720 and 1612 satellite lines, and they found a more precise constraint on $\Delta G/G$, namely

$$\Delta G/G = 3.7[\Delta\alpha/\alpha] + 1.85[\Delta\mu/\mu] + [\Delta g_p/g_p]$$
$$= (-1.18 \pm 0.46) \times 10^{-5}$$ [36]

The team applied the same conjugate-line technique to a nearby galaxy, Centaurus A, and got the expected null result.

The constraint on $\Delta G/G$ does not provide the desired constraint on $\Delta\alpha/\alpha$, but it is perhaps a step toward that end. At any rate, the Kanekar team decided that the best next step would be to try to further narrow the uncertainties in this measurement.

So, between April 2010 and June 2012, they used about 150 hours of observing time with the ALFA system at Arecibo to again measure OH emissions coming from a gas cloud that is positioned in front of the quasar PKS1413+135.

At the meeting of the American Astronomical Society in Grapevine, Texas, in January of 2017, Dr. Ghosh presented the latest results from the team. The new limiting value for the variability of G is:

$$\Delta G/G = (-3.5 \pm 2.5) \times 10^{-6}$$

Their new result has statistical significance at the 2-sigma level of confidence, meaning that there is about a 97.7% chance that the result is real. The team wants to gather more data to increase confidence in their result to at least the 3-sigma level, which would mean that there is about a 99.9% chance that the result is real.[37]

The painstaking work of Professor Kanekar's team will hopefully continue, as these researchers are using the Arecibo Observatory to provide much-needed experimental guidance to others who are developing new theories of physics.

IN CONCLUSION

Bill Gordon anticipated that his radio telescope would be used for a wide variety of projects beyond his own domain of research interest, including the tracking and characterization of asteroids that might pose a hazard to the Earth or the discovery of new astronomical objects such as the repeating fast radio bursts. In addition to these expectations, his namesake telescope at the Arecibo Observatory is now being used to set constraints on the possible variability of the fundamental constants of nature.

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3

HUMAN HEALTH IN SPACE AND ON EARTH

HUMANS IN SPACE

How the research of USRA scientists could help make possible the human exploration of Mars.

LESS THAN SIX MONTHS AFTER PRESIDENT EISENHOWER CREATED NASA IN JULY 1959, the Soviet Union's Luna 1 spacecraft passed the Moon and entered orbit around the Sun, becoming the first space vehicle to leave Earth orbit. Three months later, Luna 2 became the first spacecraft to impact the Moon, and a few weeks after that, Luna 3 obtained the first photographs of the far side of the Moon. This series of firsts was preceded by Sputnik and crested on 12 April 1961, with Yuri Gagarin's orbiting the Earth inside a Vostok spacecraft. For those keeping score, the Soviet Union was winning the space race. Five days later, a paramilitary group sponsored by the US Central Intelligence Agency launched a failed attempt to overthrow Cuba's Fidel Castro. As historian and space policy expert John Logsdon describes the time:

> *The fiasco of the Bay of Pigs reinforced Kennedy's determination, already strong, to approve a program aimed at placing the United States ahead of the Soviet Union in the competition for firsts in space. It was one of the many pressures that converged on the president at the time, and thus its exact influence cannot be isolated. As president, Kennedy could treat few issues in isolation anyway, and there seems little doubt that the Bay of Pigs was in the front of his mind as he called Lyndon Johnson to his office on April 19 [1961] and asked him to find a "space program which promises dramatic results in which we could win.*[1]

A month later, on 25 May 1961, President John F. Kennedy addressed a joint session of congress. In his speech, the President made a bold announcement:

> *(T)his nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish.*[2]

HARRISON SCHMITT
INTERIM USRA DIRECTOR OF DSB, 1984–1987

MAKOTO IGARASHI
USRA DIRECTOR OF DSB, 1987–1991

ALFRED COATS
USRA DIRECTOR OF DSLS, 1991–2001

ADRIAN LEBLANC
USRA DIRECTOR OF DSLS, 2002–2010

THE FIRST TOPIC OF INTEREST TO NASA WAS SPACE MOTION SICKNESS, WHICH AFFECTS 60% TO 80% OF ASTRONAUTS DURING THEIR FIRST FEW DAYS IN THE WEIGHTLESSNESS OF SPACE.

Kennedy's goal was accomplished on 24 July 1969, when the crew of Apollo 11 returned safely to Earth after a brief stay on the Moon. There were five subsequent Apollo explorations of the Moon, and the last, Apollo 17 in December of 1972, involved the only scientist-astronaut, the geologist Dr. Harrison Schmitt. Schmitt and fellow astronaut Eugene Cernan were the last humans to leave their footprints on the Moon.

The US involvement of humans in space continued after the Apollo program with the hope of further human exploration of the solar system, especially the planet Mars. The Skylab space station was intermittently occupied from 1973 to 1979, and the Space Shuttle made its first flight on 12 April 1981.

NASA's study of the effects of the space environment on humans continued after the Apollo and Skylab programs, and in 1983 USRA created its Division of Space Biomedicine (DSB) to focus on the issues of human physiology in space. The DSB was later renamed the Division of Space Life Sciences (DSLS) and was co-located with USRA's Lunar and Planetary Institute near NASA's Johnson Space Center, south of Houston.

The founding Director of the DSLS was the former astronaut Dr. Harrison Schmitt, who was officially an "Interim" director, but he led the Division for its first three years. Schmitt received a BS degree from Caltech in 1957 and a PhD in geology from Harvard in 1964. He was a United States Senator from New Mexico from 1977 to 1983, and he had recently served as Chair of the NASA Advisory Council when he became the first director of USRA's space biomedical research program. Though not a biomedical researcher, Schmitt had first-hand knowledge about the various physiological effects and hazards associated with being in space, which included:

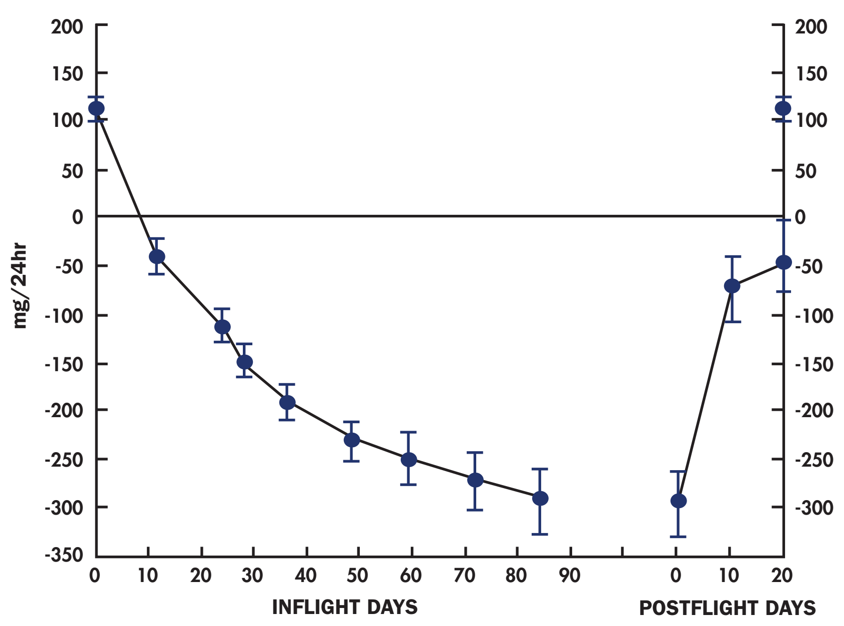
- Exposure to high-energy radiation, particularly solar and galactic cosmic rays
- Fluid shifts toward the head, chest, and upper body
- A loss of mass and strength in the muscles supporting the body against Earth gravity
- A loss of mass and strength in the weight-bearing bones of the body
- A decrease in the number of red blood cells in the body
- A disorientation and disequilibrium known as "space motion sickness" associated with entering a weightless environment[3]

MOTION SICKNESS: FIRST TOPIC OF INTEREST

The first topic of interest to NASA was space motion sickness, which affects 60% to 80% of astronauts during their first few days in the weightlessness of space. Some astronauts are unable to do much work during this period of adaptation to the space environment.

With the help of USRA's John R. Sevier, Deputy Director of the DSB, Schmitt began to bring visiting scientists to NASA's Johnson Space Center, and the DSB started to conduct workshops on topics such as "Pharmacological Approaches to Space Motion Sickness, and Emergency Medicine in Space." USRA formed a Space Adaptation Working Panel to make recommendations to NASA regarding flight and ground investigations that would, among other things, help understand the causes of space motion sickness and lead to the development of effective countermeasures.

TOP: Harrison Schmitt, *Heartland Institute*. **Makoto Igarashi,** *Baylor College of Medicine*



Calcium balance as a function of skylab flight duration (mean ±SE). From figure 2 in Rambaut and Johnston, 1979.

To help guide its efforts, USRA appointed a Science Council of eminent research physicians. The initial chair of the Science Council for the Division of Space Biomedicine was Dr. Bobby R. Alford, who was the Vice President and Dean of Academic Affairs at the Baylor College of Medicine in Houston.

In 1986, the USRA Board of Trustees appointed Makoto Igarashi, MD, of the Baylor College of Medicine as the next Director of the Division. Dr. Igarashi was a distinguished vestibular researcher and had served as Director of the Otopathology Section of the US Naval Aerospace Medical Research Institute before joining the Baylor College of Medicine.

Igarashi's appointment was significant. The human vestibular system had been implicated in the problem of space motion sickness, because part of the system is critically influenced by gravity. Two sacs of the vestibular organ, the utricle and the saccule, contain calcium carbonate crystals, called otoliths, which are embedded in a gel-like substance that also contains the cilia of hair cells. When a person bends her head on Earth, the otoliths respond to gravity and tend to slide "downhill." This causes the cilia of the hair cells in the gelatinous material to bend, which in turn causes a signal to be sent to the brain.

In the weightless environment of space, the otoliths do not move under the influence of gravity, and the cilia of the hair cells do not bend. However, the vestibular apparatus in the semicircular canals of the inner ear and other inputs to the brain (e.g., from the visual system) indicate motion in the same way that they would on Earth. In weightlessness, therefore, the brain receives conflicting signals when the head moves, and this is thought to be the cause of space motion sickness.

In a matter of a few days or less, the brain adjusts to a new "space normal," and the symptoms of space motion sickness go

Image of Astronaut Sunita Williams measuring maximum oxygen intake during a high-intensity workout on the International Space Station. *Courtesy of NASA.*

Astronaut Karen Nyberg conducts an ocular health exam on herself. *Credit NASA.*

LORI PLOUTZ-SNYDER
USRA LEAD SCIENTIST, EXERCISE PHYSIOLOGY & COUNTERMEASURE DEVELOPMENT

away. But for the short-duration Shuttle flights, space motion sickness was a serious impediment, and the next Director of the Division of Space Life Sciences, Dr. Alford C. Coats, was also an expert in vestibular investigations. Dr. Coats was a professor at the Baylor College of Medicine, and, in addition, he was the director of the Cochlear Function and Vestibular Laboratories at the Methodist Hospital in Houston.[4]

OTHER EFFECTS OF THE SPACE ENVIRONMENT

As longer stays of US astronauts became possible on Skylab and the International Space Station (ISS), other effects of the space environment on humans came under closer scrutiny.

The loss of calcium from the bones is problematic for long duration exposure to the space environment, e.g., on a trip to Mars, as well as for astronauts after they return from such missions. In some parts of the skeleton, the rate of destruction of bone cells substantially outpaces the rate of creation of bone cells. The loss of bone cells is particularly acute in the load-bearing parts of the skeleton. The overall average rate of bone loss is approximately 1% to 1.5% per month, and it is not clear whether the bone mineral density stabilizes at a lower level in space or continues to diminish. It is also unclear whether all the bone mineral loss is recovered for individuals who return to Earth.[5] In any case, ultimate recovery might take several years, and there is evidence of changes in bone architecture.

A study in 1979 of the average calcium balance as measured by body inflow and outflow of calcium for astronauts on all three Skylab missions demonstrated the effect of the space environment on total-body calcium levels[6] (see the chart on page 79). In 2007, Dr. Adrian LeBlanc, who was the Director of the DSLS at the time, showed that the total-body calcium levels did not tell the whole story. LeBlanc was the lead author of a review paper that noted, for the Skylab missions:

> *(B)one loss was inhomogeneous; i.e., no loss occurred in the upper extremities, while there were significant losses in the calcaneus [heel bone]; and the regional losses on a percentage basis could be much greater than percentage changes in total body bone mineral.*[7]

In collaboration with researchers from NASA and other organizations, USRA researchers investigated bone loss and helped to develop countermeasures through ground-based spaceflight analogs, including bed rest studies, the development of exercise and dietary prescriptions, pharmacological approaches, and the use of the Digital Astronaut model. For example, LeBlanc of USRA and Dr. Toshio Matsumoto of the University of Tokushima in Kuramoto, Japan, were the principal investigators on an important study to evaluate the effects of bisphosphonates used by astronauts as a countermeasure to space-flight-induced bone loss. Bisphosphonates are medications that block the breakdown of bone and are used to treat osteoporosis. The study found that the use of bisphosphonates in conjunction with routine, in-flight exercise significantly lessened the losses in bone mineral density of the spine, hip, and pelvis in the astronauts.[8]

Partly as the result of the research of USRA staff at the DSLS, exercise devices on the ISS have been improved. However, musculoskeletal and cardiovascular-related risks to astronaut health and performance have not been eliminated. USRA researchers have worked on approaches to exercise that will provide higher intensity workouts of shorter duration and still accomplish the protection from bone loss during long-duration human space missions. USRA-led research was the first to show that exercise alone, using equipment similar to what is available to astronauts on the ISS, is able to fully protect cardiovascular and muscular health during 14 days of bed rest.[9] This higher intensity exercise program was also evaluated during 70 days of bed rest and 6 months of spaceflight.

INFLIGHT ULTRASOUND OF AN ASTRONAUT'S RIGHT EYE, SHOWING GLOBE FLATTENING AND OPTIC DISC EDEMA[14]

THE EFFECT OF WEIGHTLESSNESS ON VISION

The general approach of NASA's Human Research Program is to first identify and understand health and performance risks for human space flight and then to develop countermeasures to remove or reduce the risk to acceptable levels. A risk that was not fully understood at the time of the formation of the DSB/DSLS, but which later became the subject of intense research, is the effect of weightlessness on vision.

The first case of optic disc swelling, known as papilledema, in an astronaut was reported during a six-month mission on the ISS in 2005. The astronaut lost visual acuity during the flight. A post-flight examination of the astronaut was conducted, and an increase in intracranial pressure was suspected as the cause of the papilledema and other abnormalities in the eyes, such as folds in choroidal layers of the surface of the eyes. For patients on the ground, papilledema and choroidal folds are serious signs of some underlying condition that if left untreated can cause loss of vision.

In the summer of 2009, NASA held a Papilledema Summit, which was attended by 41 experts in ophthalmology and related fields. Several cases of papilledema in astronauts were discussed. The panel of experts expressed doubt that increased intracranial pressure is the underlying cause of disc edema and choroidal folds. They noted that patients on the ground with increased intracranial pressure do not experience a loss in visual acuity, but they generally suffer from headaches and visual obscurations. These are opposite to the symptoms that had been reported for astronauts.[10] It was clear that a new phenomenon had been encountered and, as a result of the Summit, NASA formally established papilledema and related abnormalities that could lead to vision loss as a new risk for long-duration spaceflight.[11]

NEAL PELLIS
USRA DSLS DIRECTOR

CHRISTIAN OTTO
USRA LEAD SCIENTIST,
NASA VIIP RISK PROGRAM

As the focus of research in space-related human physiology continued to shift, in 2010, USRA appointed its fifth director of the DSLS, Dr. Neal Pellis, a microbiologist who had worked for NASA for sixteen years.[12] In that year, the DSLS hosted a meeting to further examine vision issues related to spaceflight, and a large panel of experts identified elevated intracranial pressure as the probable cause of disc edema and other eye-related abnormalities that were being experienced by astronauts. This assessment was reinforced in 2011 by a case study led by Dr. Thomas H. Mader of the Alaska Native Medical Center in Anchorage. The Mader team studied data from seven astronauts after long-duration exposure to weightlessness, and they documented vision changes in approximately 300 additional astronauts. Based on their findings, the Mader team reported:

> *After 6 months of space flight, 7 astronauts had ophthalmic findings, consisting of disc edema in 5, globe flattening in 5, chorodial folds in 5, cotton wool spots … in 3, nerve fiber layer thickening … in 6, and decreased near vision in 6 astronauts. … The 300 postflight questionnaires documented that approximately 29% and 60% of astronauts on short and long-duration missions, respectively, experienced a degradation in distant and near visual acuity. Some of these vision changes remain unresolved years after flight.*[13]

THE VIIP SYNDROME

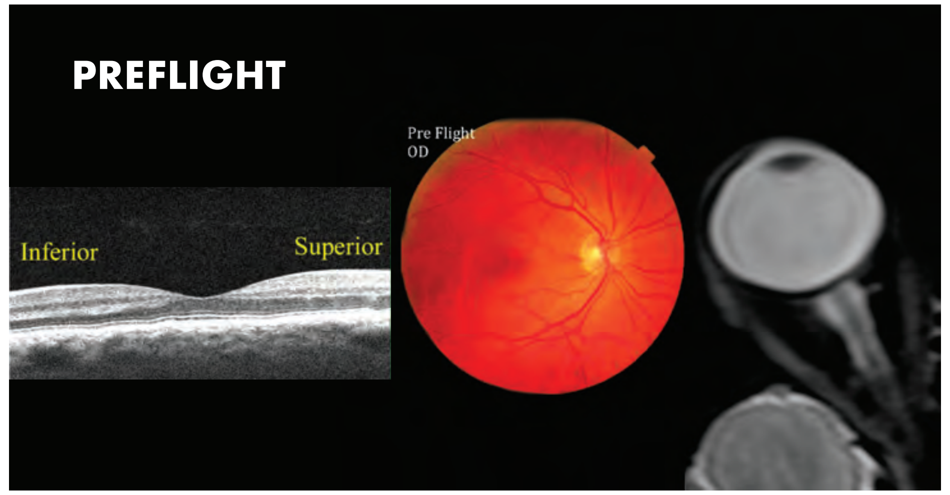
Also in 2011, NASA held a Visual Impairment Intracranial Pressure (VIIP) Summit, and the panel of experts at this meeting advised that the rise in intracranial pressure might not be the sole cause of the various observed changes in the eyes of the astronauts. The panel members were perplexed that none of the astronauts with disc edema and other symptoms complained of headaches or visual obscurations. They noted that in a terrestrial setting, more than 90% of patients with elevated intracranial pressure experienced headaches.[15]

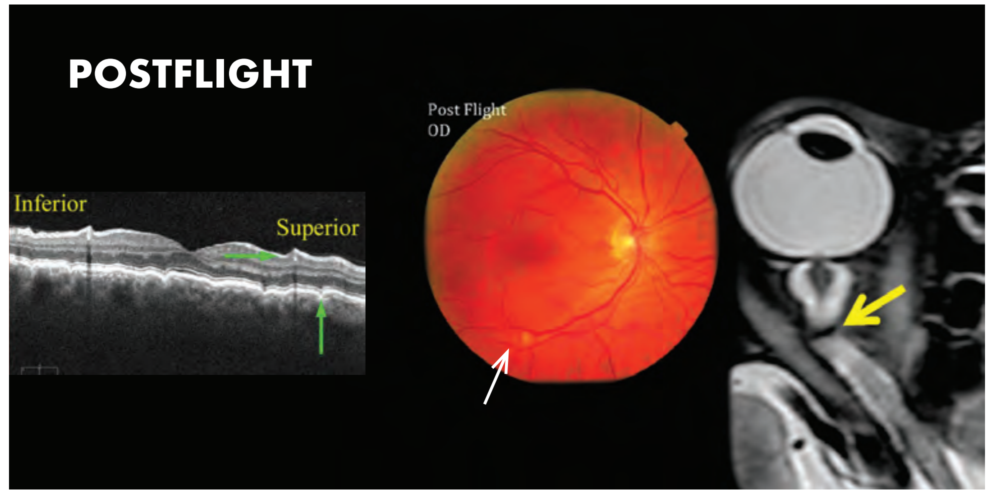
As a result of the research conducted, NASA's Human Research Program (HRP) Evidence Report, Risk of Spaceflight-Induced Intracranial Hypertension and Vision Alterations summarizes the threat as follows:

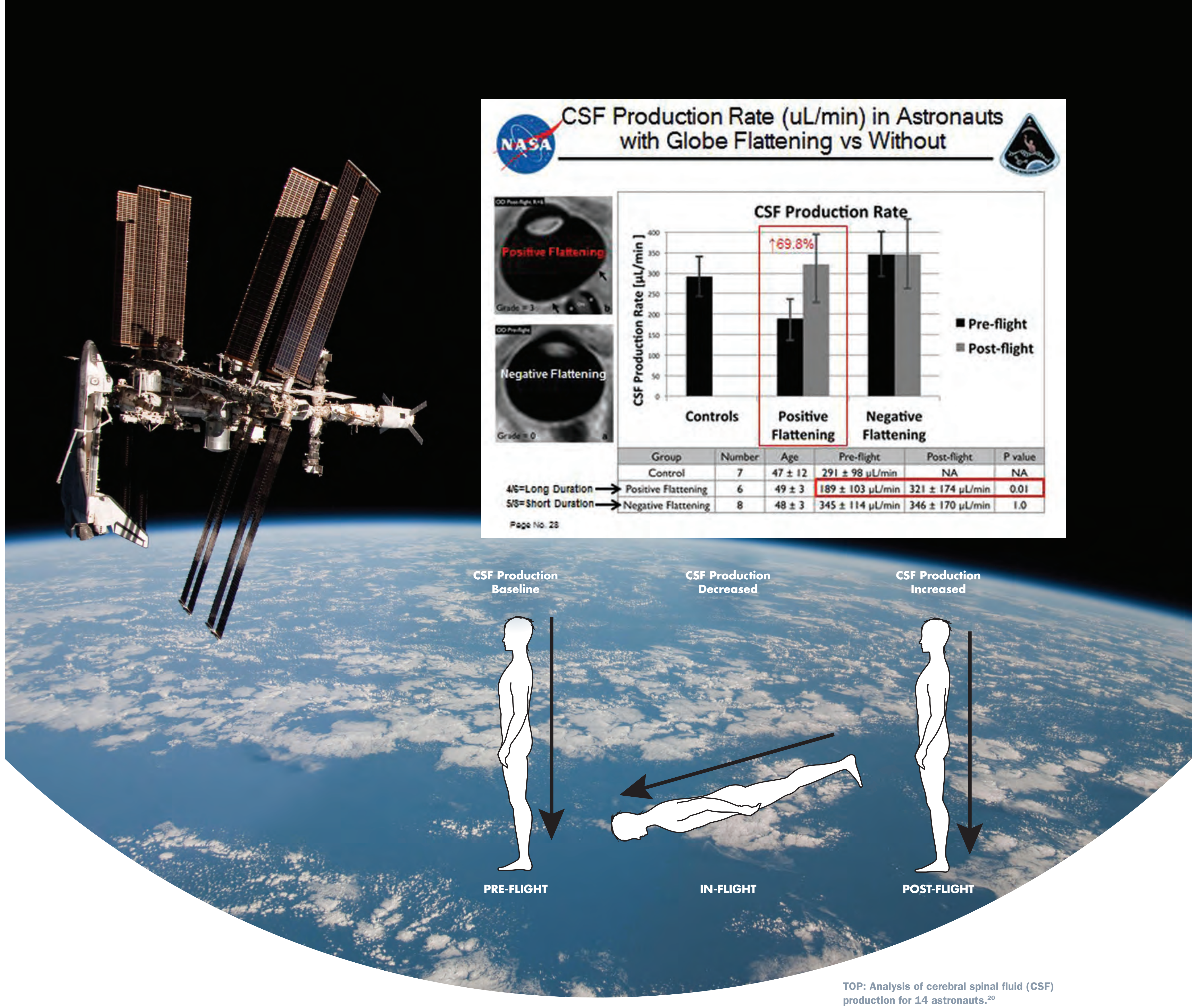
> *Over the last 40 years there have been reports of visual acuity impairments associated with spaceflight through testing and anecdotal reports. Until recently, these changes were thought to be transient, but a comparison of pre and postflight ocular measures have identified a potential risk of permanent visual changes as a result of microgravity exposure. There are limited pre and postflight measures to define the risk and even less in-flight data is available. These data show that there is a subset of crewmembers that experience visual performance decrements, cotton-wool spot formation, choroidal fold development, optic-disc edema, optic nerve sheath distention, and/or posterior globe flattening with varying degrees of severity and permanence. These changes define the visual impairment/intracranial pressure (VIIP) syndrome.*[16]

The report also cited four cases of disc edema for astronauts studied by the Mader team, where the pressure of the cerebral spinal fluid measured after the flights was borderline high or above normal, indicating increased intracranial pressure.[17]

Beyond the health risk to the astronauts, instances of visual impairment in orbit can risk operations. There has been one case of a visual field defect on orbit such







TOP: Analysis of cerebral spinal fluid (CSF) production for 14 astronauts.[20]

BOTTOM: Conceptual model of CSF production rate at different phases of space flight. The arrows indicate the direction of fluid shifts.[20]

BACKGROUND: The International Space Station and Docked Space Shuttle Endeavor, 2011. *(NASA/ESA)*

SARA ZWART
USRA SENIOR SCIENTIST, DSLS

VIIP IS NOW ONE OF THE RISKS LISTED IN NASA'S HUMAN RESEARCH ROADMAP THAT MUST BE RESOLVED BEFORE LONG-DURATION HUMAN MISSIONS CAN BE UNDERTAKEN.

that the astronaut had to tilt his head 15 degrees to view instruments and procedures.[18]

As with other human and performance risks of spaceflight, USRA scientists and engineers worked with NASA and other colleagues to find solutions to the VIIP syndrome. Dr. Christian Otto of USRA was the lead scientist for the NASA VIIP Risk program. Otto is experienced in remote medicine, high altitude medicine, and polar medicine, having worked in the Canadian High Arctic, and as a medical researcher on Mounts Everest, McKinley, and Logan.

The working hypothesis for the cause of VIIP is that the headward fluid shift that occurs when astronauts begin weightlessness results in increased intracranial pressure that is transmitted to the optic nerve. Among other things, this increased pressure causes globe flattening and optic disc edema. In addition, the elevated intracranial pressure constricts the central vein that allows blood to drain from the back of the eye, and since arterial blood continues to flow into the eye, the result is an increase in intraocular pressure.[19]

A study of 14 astronauts in 2015 by Otto and his colleagues demonstrated that 5 of the 6 astronauts who showed flattening of their eye globes prior to flight had a significant increase in the production of cerebral spinal fluid (CSF) as measured post flight. The authors of the report of the study concluded:

> *Increased CSF production rate in postflight astronauts with positive posterior globe flattening is compatible with the hypothesis of microgravity-induced intracranial hypertension. We propose that CSF production rate is significantly downregulated during space flight in this subgroup due to greater susceptibility to microgravity-induced cephalad fluid shifts. A new steady state of intracranial pressure and CSF production rate is then established, but remains above the preflight baseline, resulting in pathologic modification of the orbital structures. Upon return to normal gravity the cephalad fluid shift reverses, causing an abrupt decrease in ICP [Intracranial Pressure] stimulus with respect to the in-flight level. This sudden drop in ICP triggers a compensatory CSF upregulation to reestablish homeostasis.*[20]

A POSSIBLE GENETIC FACTOR

The VIIP problem is complex, and there are a number of unanswered questions. Why, for example, are some astronauts affected and others are not? Dr. Sara Zwart, who was a Senior Scientist in USRA's DSLS, examined the possibility that the ophthalmic changes observed in some of the astronauts could be related to individual differences in a particular metabolic pathway. This possibility was described in a paper published in 2012, for which Zwart was the lead author:

> *Factors that could contribute to the ophthalmic changes observed in some crewmembers after long-duration spaceflight include microgravity-induced fluid shifts…, increased intracranial pressure, optic nerve sheath changes, and/or changes in intraocular pressure…. At this point, the unifying pathologic mechanism is hypothesized to be prolonged exposure to the effects of cephalad fluid shifts that occur during microgravity exposure. The question remains, however: why are only ~ 20% of crewmembers affected when all crewmembers presumably experience fluid shifts on exposure to microgravity? Furthermore, why would one crewmember be affected during a particular mission when a fellow crewmember on the same mission (and exposed to the same environment) did not have ophthalmic changes? The evidence provided here suggests that this phenomenon could be explained by crewmembers who have ophthalmic changes have an altered metabolic pathway involving Hcy, cystathionine, 2MCA, and MMA. Our data show that an association exists between ophthalmic changes and higher concentrations of intermediates of the [metabolic] pathway involving these enzymes.*[21]

Hcy (homocysteine), cystathionine, 2MCA (2-methylcitric acid), and MMA (methylmalonic acid) are metabolites that are involved in folate- and vitamin B-12-dependent 1-carbon transfer metabolism. Zwart and her colleagues found that concentrations of these metabolites were 25% – 45% higher in astronauts with ophthalmic changes than in those without them.[22] Further, this correlation was found to exist in data taken preflight as well as during flight and post flight, suggesting the possibility that genetic differences among the astronauts might be responsible for who is, and who is not, predisposed to develop changes in vision during exposure to microgravity.

Zwart and her colleagues suggested possible ways that an altered 1-carbon transfer metabolic pathway could be linked to ophthalmic changes, based on clinical data. They then summarized their findings, as follows.

> *In summary, preexisting chemical differences, which have little or no demonstrable effect under Earth-gravity conditions, may set the stage for pathologic changes in affected astronauts during prolonged microgravity exposure. The existing data suggest that vision issues during spaceflight are associated with a difference in the folate- and vitamin B-12-dependent 1-carbon transfer pathway. Given the magnitude of the issue, follow-up with genetic analyses to examine the potential for polymorphisms in the pathway is required to provide a definitive answer. This association has important implications for future space travelers. Beyond that, these findings, taken together with the documented relationship between polymorphisms in the folate- and vitamin B-12-dependent 1-carbon pathway and predisposition to risk of clinical outcomes related to vascular events found in clinical practice, could have profound implications for a sizeable population of individuals on Earth.*[23]

As of this writing, the cause of visual impairment and elevated intracranial pressure among some astronauts during exposure to microgravity is not fully understood. It is now one of the risks listed in NASA's Human Research Roadmap that must be resolved before long-duration human missions can be undertaken.

IN SUMMARY

In his 1961 speech, President Kennedy said that a human mission to the Moon would be "important for the long-range exploration of space." It certainly was important for the human spirit of exploration, and it was important for lunar and planetary science, as well. It eventually led to a USRA research program that well demonstrated the vision of James Webb, the NASA Administrator who pushed to create an association of universities that could assist NASA in solving critical problems, such as finding a path that will one day make it possible for humans to explore Mars.

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HUMANS AND SPACE RADIATION

How USRA scientists helped assess the risks for humans who travel in space.

The supernova remnant Cassiopeia A is a source of cosmic rays within our Milky Way Galaxy

DURING NASA'S APOLLO PROGRAM, crew members of Apollo 11 reported seeing flashes of light while on their way to the Moon. Neil Armstrong and Edwin Aldrin Jr. reported seeing the flashes with their eyes either open or shut.[1]

Scientists soon realized that the flashes of light were the result of cosmic rays that had penetrated the cabin of the spacecraft and crossed through the retinas of the astronauts' eyes. Cosmic rays are charged particles, mostly protons, that travel near the speed of light and thus have very high energies. For human space travelers, the deadliest cosmic rays are those that come from sources in the Milky Way galaxy. Some of these "galactic cosmic rays" have high mass, high charge and so much energy that they easily penetrate the skin of a spacecraft. They are called HZE cosmic rays (the acronym derives from high (H) atomic number (Z) and energy (E)), with prominent examples including the nuclei of helium, carbon, oxygen or iron atoms.

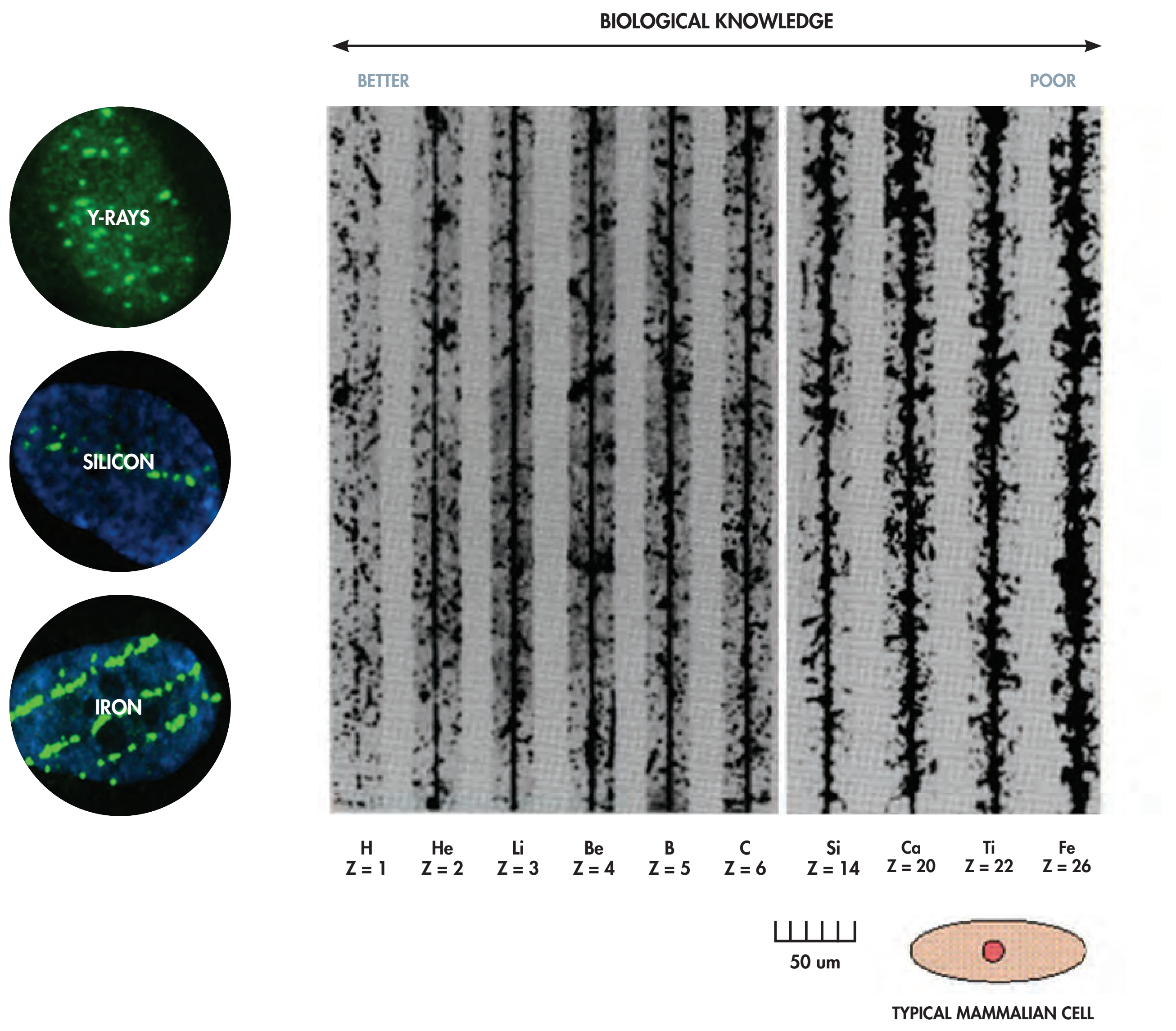
When massive stars explode, shock waves caused by the fast-moving gas produced during the explosion continue to generate X-rays and, more importantly for the subject of humans in space, galactic cosmic rays. There are many supernova remnants in the Milky Way Galaxy, such as Cassiopeia A. The galactic cosmic rays produced by Cassiopeia A and similar explosions pervade our solar system.

If a high-energy, charged particle passes through the nucleus of a living cell in an astronaut, it can disrupt individual molecules, including deoxyribonucleic acid (DNA) molecules that are essential for life. The biological effect of HZE ions is qualitatively different from the cell damage caused by terrestrial sources of radiation such as X-rays and γ-rays. For example, the left panel of the figure on page 88 shows three nuclei of human fibroblasts that have been exposed to γ-rays, high-energy silicon ions, or high-energy iron ions. Each green dot corresponds to a DNA double-

COSMIC RAYS FROM THE MILKY WAY ARE THE DEADLIEST TO HUMAN SPACE TRAVELERS.

TOP: CASSIOPEIA A: DEATH BECOMES HER.
(NASA/JPL-Caltech/STScI/CXC/SAO)

A comparison of particle tracks in nuclear emulsions and human cells. *From figure 1.2 of Cucinotta and Durante., 2006.*



EARTH'S MAGNETOSPHERE AND ATMOSPHERE SHIELD LIFE ON THE PLANET FROM GALACTIC COSMIC RAYS.

strand break. Cells that are exposed to HZE particles show DNA damage along tracks (one Si- and three Fe-particles, respectively), and the spacing between DNA double-strand breaks is reduced for more massive HZE ions. The graph on the right shows how increasing the charge Z increases the ionization density along the particle track.[2]

Earth's magnetosphere and atmosphere shield life on the planet from galactic cosmic rays. In near-Earth space, such as the environment of the International Space Station, the Earth's magnetic field provides some protection from galactic cosmic rays, as the field deflects the incoming charged particles. Away from Earth, in interplanetary space or on the surface of planetary bodies with little or no atmospheric or magnetic shielding, galactic cosmic rays pose a substantial hazard for astronauts.

During the 1970's, NASA was focused on human space flights of short duration and had not yet studied in detail the medical implications of long-duration space flights. In a 1975 report on the biomedical results of the Apollo program, J. Vernon Bailey of NASA's Johnson Space Center noted, "the effect of high-energy cosmic rays on humans is unknown but is considered by most authorities not to be of serious concern for exposures of less than a few years."[3]

USRA SUPPORTS NASA WITH FORMATION OF A NEW DIVISION

USRA's Division of Space Life Sciences (DSLS) was created in 1983 (originally as the Division of Space Biomedicine, or DSB) to work with NASA and other research organizations to find and develop countermeasures for the various hazards to which astronauts are exposed during space missions. Throughout the remainder of the 1980s, NASA conducted flights of the Space Shuttle that were of short duration, and exposure to galactic cosmic rays was minimal because of the shielding provided by the Earth and its magnetic field. Aside from occasional workshops on the topic of the effects of space radiation on astronauts, the DSB concentrated on countermeasures for other hazards of space missions.

WALTER SCHIMMERLING

AMONG THE FINDINGS OF THE PANEL WAS THE CONCLUSION THAT LONG-DURATION MISSIONS TO THE MOON OR TO MARS SHOULD BE DELAYED UNTIL UNCERTAINTIES IN RISK PREDICTION HAVE BEEN REDUCED.

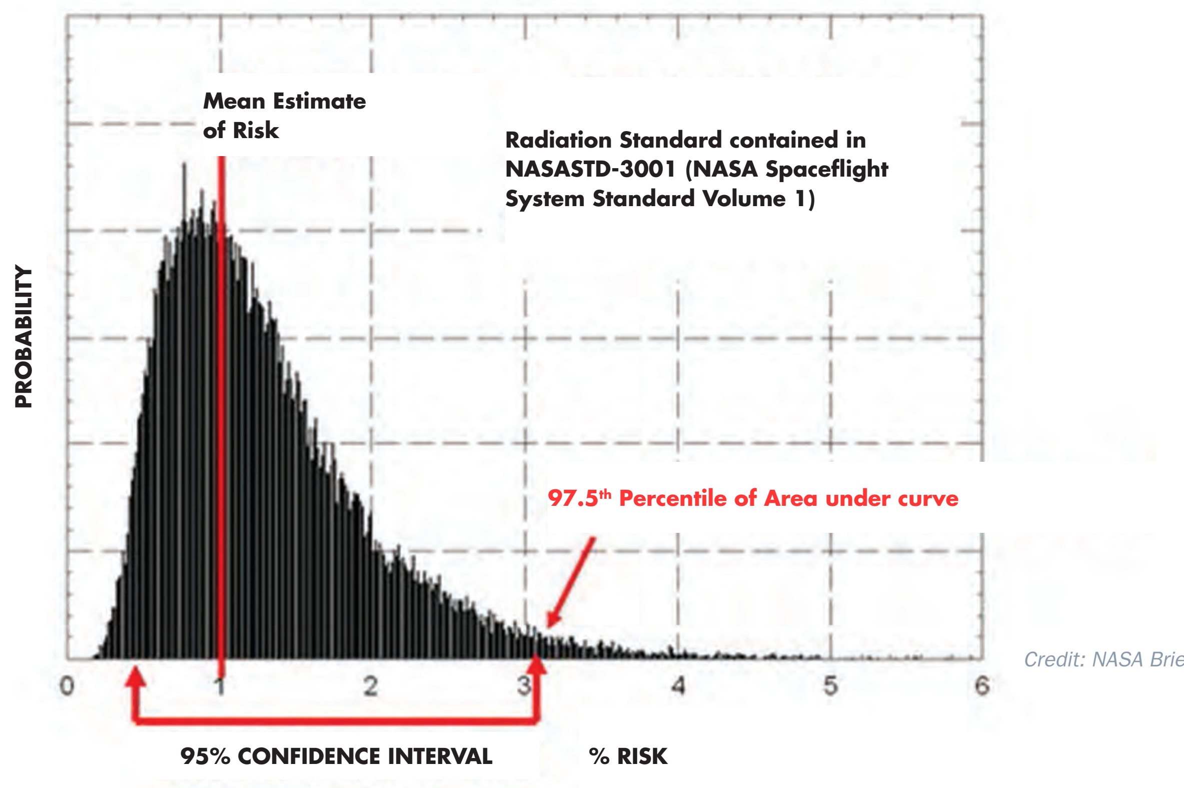
SCHIMMERLING'S FOCUS ON SPACE RADIATION

In 1992, Dr. Walter Schimmerling joined USRA and was assigned to NASA Headquarters. Schimmerling is a nuclear physicist who had worked at Princeton University and the Lawrence Berkeley National Laboratory at the University of California, Berkeley, in high-energy, heavy-ion physics and its application to cancer therapy and space. Later in his tenure with USRA, Schimmerling was detailed to NASA through an Intergovernmental Personnel Act agreement between USRA and NASA so that he could serve as Director and Program Scientist for NASA's Space Radiation Program. For his work there, Schimmerling received the Astronaut's Silver Snoopy Personal Achievement Award and the Administrator's Flag Award for outstanding direction in research. He also received a NASA award for, "championing the need for an expanded knowledge of space radiation effects that support human exploration of space and for unwavering efforts to create the NASA Space Radiation Laboratory."[4]

Schimmerling, among others at NASA and elsewhere, recognized the challenge of reducing the great uncertainties in establishing the health risks for astronauts who would be exposed to galactic cosmic rays on interplanetary missions. A particular problem was the development of risk statistics for galactic cosmic rays based on an extrapolation of data obtained from the exposure of humans to gamma rays and X-rays, primarily from data obtained from survivors of the atomic bombs dropped on Hiroshima and Nagasaki. Schimmerling advocated for the establishment of the NASA Space Radiation Laboratory (NSRL) at the Brookhaven National Laboratory (BNL) because the particle accelerators at BNL can produce beams of protons and other atomic nuclei to simulate galactic cosmic rays. The NSRL was commissioned in 2003, and scientists began to use the particle accelerators at BNL to determine the biological effects of exposure to HZE ions and the effectiveness of shielding materials, among other things.

SPACE RADIATION SUMMER SCHOOL FORMED

The following year, USRA's DSLS began to manage a NASA Space Radiation Summer School at BNL in collaboration with NASA, BNL, the US Department of Energy, Loma Linda University, and Lawrence Berkeley National Laboratory. At this writing, the Summer School continues as a three-week course for young researchers from the fields of molecular biology and genetics. The course is taught by leading university and national laboratory biologists and physicists who are actively engaged in NASA's space radiation research, and by BNL experts in heavy ion experimentation and methods. Following successful completion of the course, participants are qualified to submit experimental proposals and perform research at the NSRL.



Credit: NASA Briefing, 2015

FRANCIS A. CUCINOTTA

EXAMINING SPACE RADIATION RISKS

In 2008, the National Research Council of the National Academy of Sciences formed a panel of experts, including Schimmerling, to examine space radiation risks. Among the findings of the panel was the conclusion that long-duration missions to the Moon or to Mars should be delayed until uncertainties in risk prediction have been reduced.[5]

The reason for the finding was elaborated upon in an article by Drs. Marco Durante of Germany's Helmholtz Center for Heavy-Ion Research and Francis A. Cucinotta, who at the time was NASA's Program Scientist for space radiation research at NASA's Johnson Space Center. Durante and Cucinotta explained:

> *Among the various health risks, carcinogenesis caused by exposure to space radiation is now generally considered the main hindrance to interplanetary travel for the following reasons: large uncertainties are associated with the projected cancer risk estimates, no simple and effective countermeasures are available, and the large uncertainties prevent determining the effectiveness of countermeasures. Optimizing operational parameters such as the length of space missions and crew selection for age and gender, or applying mitigation measures, such as radiation shielding or use of biological countermeasures, can reduce risk, but these approaches are clouded by uncertainties.*[6]

Cucinotta and Durante provided a stark illustration of the risks associated with interplanetary travel, arguing in NASA's Evidence Book that, "in travelling to Mars, every cell nucleus within an astronaut would be traversed by a proton or secondary electron every few days, and by an HZE ion every few months."[7]

The challenge posed by galactic cosmic rays for interplanetary space is daunting, but Schimmerling insisted that the way forward for space biomedical researchers is to continue efforts to better understand and characterize the risk.

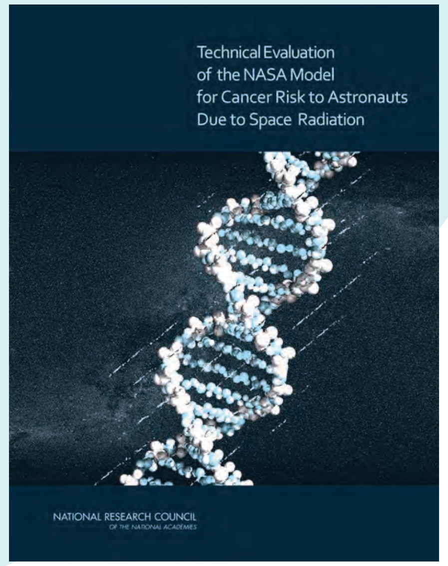
To this end, NASA seeks to characterize the risk to astronauts from exposure to space radiation by developing a model that contains the various conditions and processes associated with the Risk of Exposure Induced Death (REID) to astronauts. The model is interdisciplinary and comprehensive. It includes basic cancer risk data from a given population; models of exposure obtained from astrophysics and space physics, including the interaction of penetrating radiation with spacecraft shielding, spacecraft internal structure (or the surface of a planetary body), and the astronauts' bodies; the biological effect of a given dose rate; and the biological effect related to the nature of the radiation. All these factors have uncertainties and ranges of uncertainties. The risk probability distribution function is developed using a so-called Monte-Carlo simulation. The cancer risk is calculated for a large number of "runs," randomly varying the individual risk factors within their uncertainty ranges for each run and then binning the results to form an overall probability distribution function for REID.

Using this process, NASA has developed a policy to manage career exposures for astronauts by setting a limit that shall not exceed 3% REID for cancer mortality, adjusted for age and sex. The risk limit must be met at a 95% confidence level. The figure on page 90 illustrates a risk distribution in which the risk at the upper 95% confidence level is approximately 3%.

In 2012, NASA's lifetime risk assessment for a 940-day mission to Mars was 6.52% at the upper 95% confidence limit for a 45-year-old male astronaut who had never smoked. The risk for a 45-year-old female astronaut who had never smoked was calculated as 8.87% at the upper 95% confidence level.[8]

NASA's Space Cancer Risk (NSCR) model has been developed and revised through the collaborative efforts of DSLS and NASA scientists. In 2012, members of the DSLS team included Drs. Myung-Hee Y. Kim, Lori J. Chappell, Hatem Nounu, Shaowen Hu, Zarana Patel, Janapriya Saha, Minli Wang, Artem Ponomarev, Ianik Plante, Megumi Hada, and Janice Huff. Drs. Kim and Chappell were co-authors with the NASA Program Scientist for space radiation, Dr. Francis A. Cucinotta, on the 2010 and 2012 versions of the NSCR.

THE CHALLENGE POSED BY GALACTIC COSMIC RAYS FOR INTER-PLANETARY SPACE IS DAUNTING, BUT EFFORTS TO UNDERSTAND THE RISKS HAVE CONTINUED.



DSLS/NASA TEAM REPORT IN 2013

In their 2013 report, the DSLS/NASA team explained how the NSCR model is subject to continual refinements.[9] Improved knowledge of the space radiation environment has yielded better measurements and models that in turn produce advances in transport models used to describe how radiation at the location of a spacecraft makes its way to the tissue and various organs of an astronaut. For example, we now understand that the fluences of galactic cosmic rays and high-energy particles from the Sun vary as a function of distance from the Sun and are affected by the solar cycle. At a minimum in the solar cycle, galactic cosmic rays more easily penetrate the solar system to a given distance from the Sun, while, on average, there are fewer energetic particles coming from the Sun at the same distance. At solar maximum, the reverse is true.

Likewise, better understanding of cancer and human exposure to γ- and X radiations has led to improvements in (1) cancer risk projections (taking into account that 90% of astronauts are "never-smokers" and have a significantly reduced risk for lung cancer than the average US population), (2) the uncertainty factors of the cancer risk model (e.g., whether transfer models of Japanese nuclear survivor data apply to a US population), and (3) estimates that involve the factor of "radiation quality" (i.e., the relative biological effectiveness of the actual radiation striking an astronaut compared to γ- and X radiation).

DSLS team members helped NASA make a significant change in the way it determines radiation quality factors. Prior to their work, NASA had been determining radiation quality factors based on Linear Energy Transfer (LET), which is the amount of energy lost by a given charged particle per unit of length as it goes through a given material. In a 2008 paper, Ianik Plante of the DSLS and Francis Cucinotta of NASA demonstrated that for a given LET, ions of different charge and energy give rise to significantly different ionization track structures as they go through matter. Cucinotta and the DSLS team determined that a parameter defined as the square of the effective charge of the ion, divided by the square of its velocity in units of the speed of light (Z^{*2}/β^2), could be

THE 2012 DSLS TEAM

NASA's Space Cancer Risk (NSCR) model has been developed and revised through collaborative efforts of DSLS and NASA scientists.

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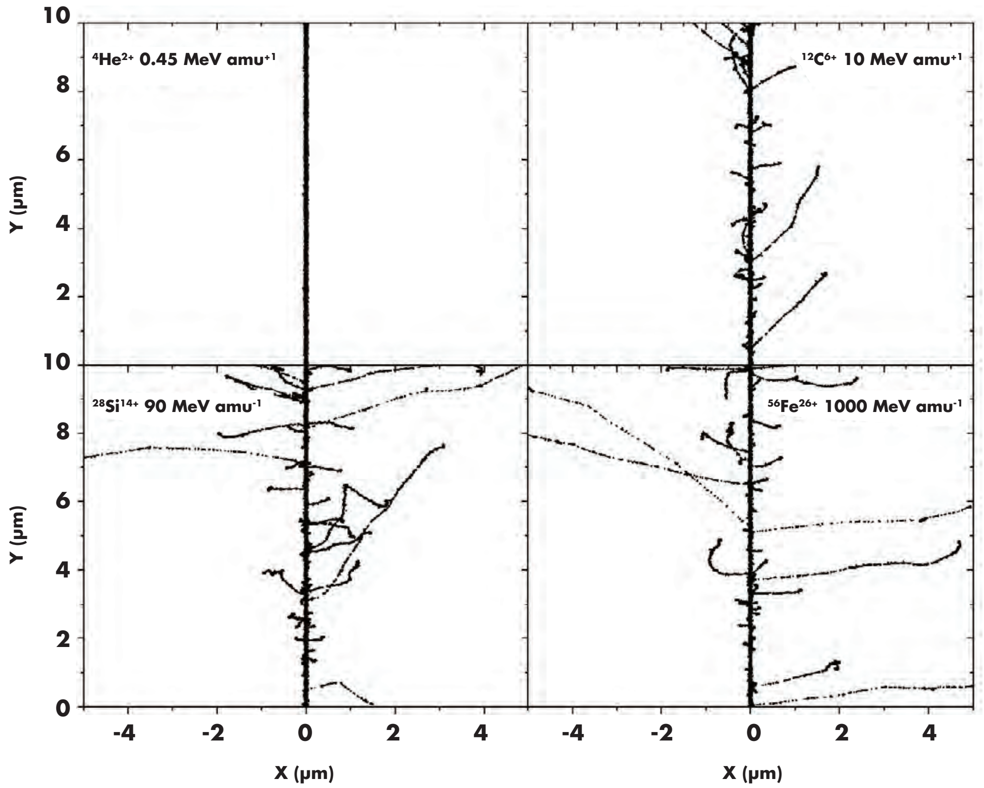

Projections over the XY -plane of simulated tracks segments (calculated at ~10^{-12} s) for the following impact ions: $4He^{2+}$ (0.45 MeV amu^{-1}), $^{12}C^{6+}$ (10 MeV amu^{-1}), $^{28}Si^{14+}$ (90 MeV amu^{-1}) and $^{56}Fe^{26+}$ (1 GeV amu^{-1}). Ions are generated at the origin along the Y -axis in liquid water at 25 °C under identical LET conditions (~150 keV μm^{-1}). Each dot represents a radiolytic species.
(From figure 6 in Plante and Cucinotta, 2008. p. 11)

used to better model the track-structure of ions and thus better model cancer-related biological endpoints, e.g., mutations and chromosomal aberrations, than models based on LET.

As a result, in their 2012 report on space radiation cancer risks, NASA proposed changing to a "track-structure-based" model of radiation quality factors. The National Academy of Sciences reviewed NASA's 2012 report and concluded that:

> *NASA's proposal to use Z^{*2}/β^2, rather than LET, and risk cross sections based on Z^{*2}/β^2 is reasonable and, hence, the committee judges that this change to the model is appropriate.*[10]

IN CONCLUSION

Improving the NASA cancer risk model might not result in lowering the estimated risk for astronauts on space missions that involve interplanetary travel. Further, the cancer risk model does not treat the risk for other potentially damaging effects of space radiation, e.g., the effect of radiation on the central nervous system. Nevertheless, the advice of Walter Schimmerling remains cogent, namely that the first step toward interplanetary travel for humans must be to thoroughly understand the risks. In this effort USRA researchers have made substantial contributions.

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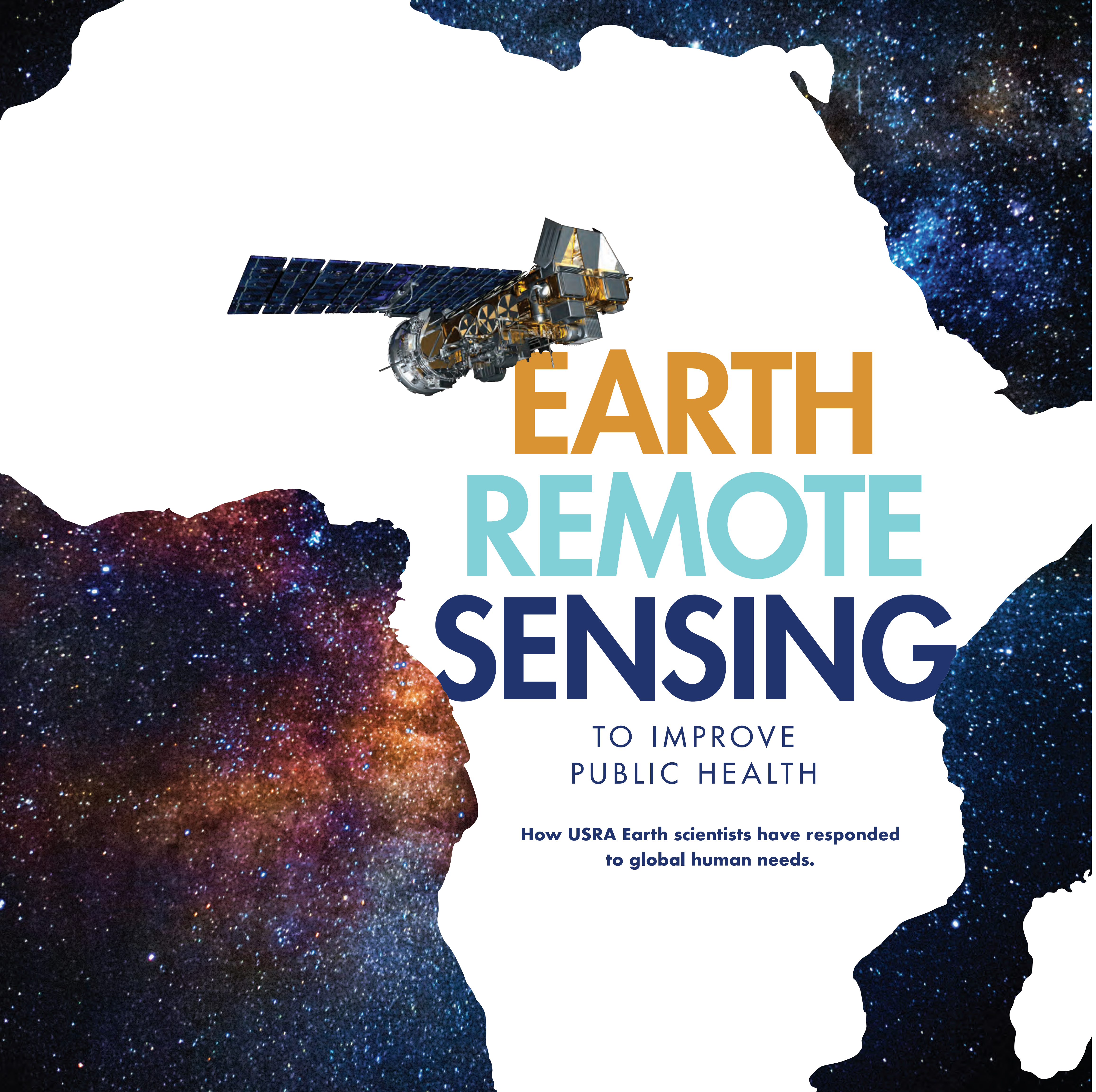


EARTH REMOTE SENSING

TO IMPROVE PUBLIC HEALTH

How USRA Earth scientists have responded to global human needs.

A part of the Great Rift Valley in eastern Africa, where the viral disease of Rift Valley fever was first identified. This disease affects domestic animals and humans throughout sub-Saharan Africa and results in widespread livestock losses and frequent human mortality.

USRA BEGAN ITS INVOLVEMENT IN THE EARTH SCIENCES IN 1976 when officials at NASA's Marshall Space Flight Center (MSFC) asked the Association to assist in defining the experimental program for the Low-Gravity Atmospheric Cloud Physics Laboratory (ACPL). USRA's second president, Professor Alexander J. Dessler, turned to Dr. Milford H. "Bill" Davis (1925–2010) to manage the work. Davis was a highly-regarded cloud physicist who had recently retired from the National Center for Atmospheric Research.

The ACPL was designed to investigate the physics of cloud formation, as Davis explained to the USRA Council of Institutions in the spring of 1976:

> *The Low-Gravity Atmospheric Cloud Physics Laboratory, if it is approved, will be flown on the first Spacelab missions in 1980. Spacelab is a part of the Space Shuttle Program which will provide a "shirt-sleeve" environment in which scientist-astronauts can perform experiments while in orbit, then return to earth after a few days or weeks.*
>
> *An orbiting platform provides many unique opportunities for observing the earth and other bodies from outside the atmosphere, and for performing experiments concerning the space environment itself. The idea behind the ACPL, however, is to make use of the very low gravity that is experienced in orbit (of the order of 10^{-6} surface gravity) to perform critical laboratory experiments on the behavior of the tiny water droplets and ice particles that are the subject matter of cloud microphysics and that govern much of what we call "weather."*[1]

M.H. "BILL" DAVIS

MUCH OF USRA'S WORK IN THE EARTH SCIENCES AT MSFC HAS BEEN FOCUSED ON ENABLING TECHNOLOGIES FOR ACQUIRING AND ANALYZING REMOTELY-SENSED DATA, PARTICULARLY AS IT RELATES TO THE EARTH'S HYDROLOGICAL CYCLE.

URBAN HEAT ISLANDS (UHI)

The UHI results from the replacement of "natural" land covers (e.g., trees and grass) with urban land surface types, such as pavement and buildings. Heat stored in these surfaces is released into the air and results in a "dome" of elevated air temperature that presides over cities. The effect of this dome of elevated air temperature is known as the UHI, which is most prevalent about 2–3 hours after sunset on days with intense solar radiation and calm winds.[6]

Davis explained that USRA's task was to assist MSFC in specifying the functional requirements of the ACPL and to provide science-based advice to the two companies, General Electric (GE) and TRW, bidding to build the laboratory:

> *More broadly, I see our function as making sure that good scientific research is done in the orbiting laboratory, and that the program is broadly based in the scientific community. We have come into the program quite late in its development, but I have a strong sense of the need for the sort of focus that we are providing.*[2]

After three years of further study and analysis, and the selection of GE as the contractor to build the orbital laboratory, the ACPL was approved for three flights on the Space Shuttle. However, the project was canceled when it became apparent that the thermal design requirements were so stringent that the laboratory couldn't be built within budget.

At the time, it seemed an inauspicious beginning for a USRA program in the Earth sciences. But it led to an ongoing collaboration with NASA in the Earth sciences, perhaps for the reason noted in Dessler's report to the USRA Board of Trustees following the cancellation of the ACPL:

> *Davis held a conference in Boulder that examined NASA's future role in the general field of cloud microphysics. Davis's report was characteristically candid, and he was congratulated for this by John Carruthers and others at NASA Headquarters.*[3]

Davis continued to manage USRA's support of MSFC in the Earth sciences, building a USRA visiting scientist program there in atmospheric science. It marked the beginning of a very successful area of research for USRA, with support from MSFC, NASA Headquarters, and NASA's Goddard Space Flight Center (GSFC).

USRA'S WORK IN EARTH SCIENCES AT MSFC

Much of USRA's work in the Earth sciences at MSFC has been focused on enabling technologies for acquiring and analyzing remotely-sensed data, particularly as it relates to the Earth's hydrological cycle. The work of Drs. William L. Crosson and Charles A. "Chip" Laymon, for example, advanced the ability to use remote sensing to measure soil moisture in the top ten centimeters of the Earth's surface. Their work indirectly affected public health, because it contributed to a better understanding of Earth-atmosphere interactions and improved weather forecasting.

Some of USRA's work at MSFC has been focused more directly on the use of remote sensing to examine issues related to public health. For example, the work of Maurice Estes Jr. and his colleagues, Drs. Crosson, Laymon and Mohammad Al-Hamdan, focused on the urban heat island phenomena, its relation to air and water quality and other threats to public health, such as the impact of air pollution on hypertension and cognitive health.[4, 5]

UNIVERSITIES EARTH SCIENCE PROGRAM

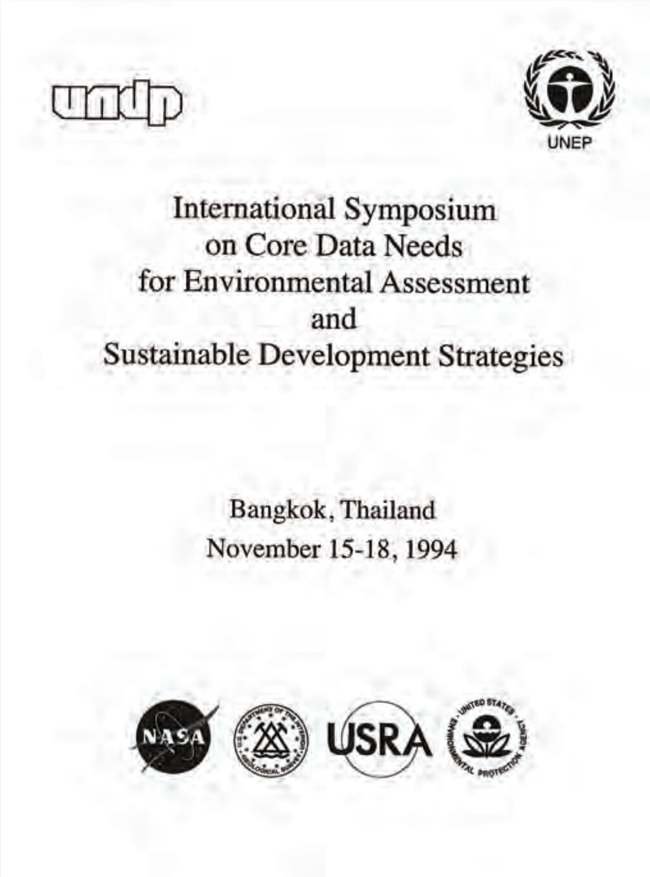
Maurice Estes was trained as an urban planner, and his work on the applications of Earth remote sensing to questions of public health was funded in part by the US Environmental Protection Agency and was confined to US cities such as Atlanta and Salt Lake City. USRA's work in Earth science applications related to public health on a more global scale began in earnest in 1992 with the establishment of a USRA Universities Earth Sciences Program (UESP), which was directed by another Estes, Professor John E. "Jack" Estes (1939–2001) of the University of California, Santa Barbara (UCSB), and funded by NASA Headquarters. Professor Estes worked on a part-time consulting basis to direct the UESP, so USRA assigned a senior administrator, Elizabeth Pentecost, to be the Deputy Program Manager for him.

Jack Estes had recently spent a year at NASA Headquarters on leave from UCSB, and he saw the need for a program that would provide an opportunity for junior and senior scientists from disciplines related to the Earth sciences to work for one- to two-year periods with managers at NASA Headquarters. Their assignment would be to bring outside technical expertise covering a broad spectrum of disciplines to help NASA managers better understand the state of Earth science, including the programmatic issues and requirements related to scientific uncertainties and information needs. These experts would assist in the definition of new NASA missions and formulate recommendations and alternatives as a basis for national and international policy.

Among the scientists whom Estes brought to NASA Headquarters was D. Wayne Mooneyhan, who had served as the director of NASA's Earth Resources Laboratory in Mississippi from 1970 to 1985. He also served as director of the United Nations Environmental Programme Global Resources Information Database before joining USRA through the UESP.[7]

Mooneyhan remained with USRA as a Visiting Senior Scientist following his two-year appointment with the UESP, and with funding from the United Nations, Mooneyhan and Pentecost assisted the United Nations Development Programme and the United Nations Environment Programme in organizing an *International Symposium on Core Data Needs for Environmental Assessment and Sustainable Development Strategies*, which was held in Bangkok, Thailand, on 15–18 November 1994.

The symposium had 65 participants from nations across the globe, including Argentina, Australia, Bangladesh, Brazil, China, Costa Rica, Denmark, Djibouti, Ghana, India, Italy, Japan, Jordan, Kenya, Lesotho, Malaysia, Mexico, the Netherlands, the Philippines, Russia, Senegal, South Africa, Thailand, the United Kingdom, Uganda, the United States, and Zimbabwe. The motivation for the symposium was to investigate the possible use of satellite remote sensing to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UNEP

International Symposium
on Core Data Needs
for Environmental Assessment
and
Sustainable Development Strategies

Bangkok, Thailand
November 15-18, 1994

NASA USRA

ASSAF ANYAMBA

aid countries, particularly in environmental management and development. The first step, and the main goal of the symposium, was to seek consensus on the priority issues for environmental assessment and sustainable development and the core data sets needed to respond to these issues.

One of the panels at the symposium dealt with human health data needs, and particularly the problem of diseases propagated by mosquitoes as "vectors." Dr. Mario Rodriguez of the Ministry of Health in Mexico, made the point that:

> *The prevention of vector-borne infectious diseases requires fresh and freshly-processed data. Environmental conditions determine the co-existence of the disease agent, animal reservoirs and humans and therefore, the presence of disease. Remote sensing can help detect these vectors and their interactions. Since health is connected to the environment, it is possible to use remote sensing … to study health.*[8]

THE RESEARCH OF DR. ASSAF ANYAMBA

The nexus of remote sensing, the environment, and public health would be the focus of the research of Dr. Assaf Anyamba, a USRA Earth scientist who grew up in the Nandi Hills area of western Kenya and received his undergraduate degree in Geography and Economics from Kenyatta University in Nairobi in 1989. He then obtained a Master's degree in Geography from Ohio University in 1992. Anyamba had to finish his thesis work early so that he could accept a summer internship in USRA's Graduate Student Summer Program in Earth System Science at GSFC. The program was open to students who had been accepted at an accredited graduate school, and Anyamba had been accepted into the PhD program at Clark University for the fall of 1992. Only ten students per year were invited to participate in the ten-week USRA Summer Program.

Anyamba had been interested initially in the application of satellite remote sensing to mapping. During his summer internship, he was introduced to the connections between changes in vegetation as observed by satellite remote sensing and the El Niño Southern Oscillation (ENSO).[9] Anyamba now knew what he wanted to study for his PhD at Clark University. Following his summer internship with USRA, he worked under Professor J. Ronald Eastman at Clark, and in 1997 he received his PhD in Geography with a focus on remote sensing of land surface patterns of the ENSO. Anyamba returned to USRA in 1999, when he joined the Visiting Scientist Program at GSFC.[11] That year, he and his colleagues published a paper in *Science* magazine that explained how satellite remote sensing might be used to predict the outbreak of Rift Valley fever in Kenya:

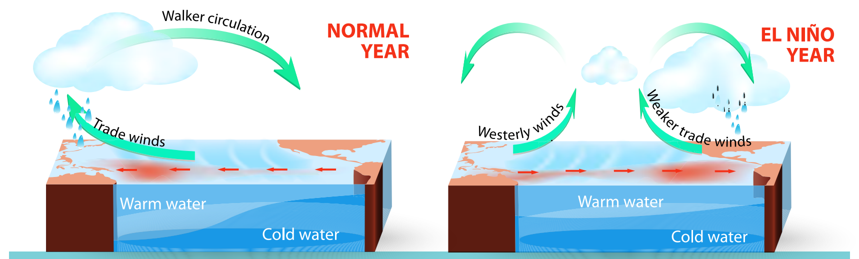
> *Rift Valley fever (RVF), a viral disease first described in Kenya in 1931, affects domestic animals and humans throughout sub-Saharan Africa and results in widespread livestock losses and frequent human mortality. Its occurrence is known to follow periods of widespread and heavy rainfall associated with the development of a strong intertropical convergence zone, the region in the equatorial tropics where air currents from the north and south converge and produce precipitation. Such heavy rainfall floods mosquito breeding habitats in East Africa, known as "dambos," which contain transovarially infected Aedes mosquito eggs and subsequently serve as good habitats for other Culex species mosquito vectors. …*
>
> *Vegetation responds to increased rainfall and can be easily measured by satellite. Normalized difference vegetation index (NDVI) data from the advanced very high resolution radiometer (AVHRR) on National Oceanic and Atmospheric Administration (NOAA) satellites have been used to detect conditions suitable for the earliest stages of an RVF epizootic.*[12]*… Here we show that several climatic indices can be used to predict outbreaks up to 5 months in advance.*[13]

NDVI

The Normalized Difference Vegetation Index (NDVI) is a measure derived by dividing the difference in infrared and red reflectance measurements by their sum

NDVI = $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$

where ρ_1 *and* ρ_2 *are the upwelling land surface reflectance in the red and infrared portions of the electromagnetic spectrum. A green vegetation canopy strongly absorbs incident solar radiation in the visible red band (0.55-0.70 μm)*[14] *due to high chlorophyll density and the presence of carotene pigments, and high scattering and thus reflectance in the infrared band (0.73-1.1 μm) resulting from leaf structural characteristics and phenological canopy effects. This index has been found to provide a strong vegetation signal and good spectral contrast from most background materials.*[15]



ENSO

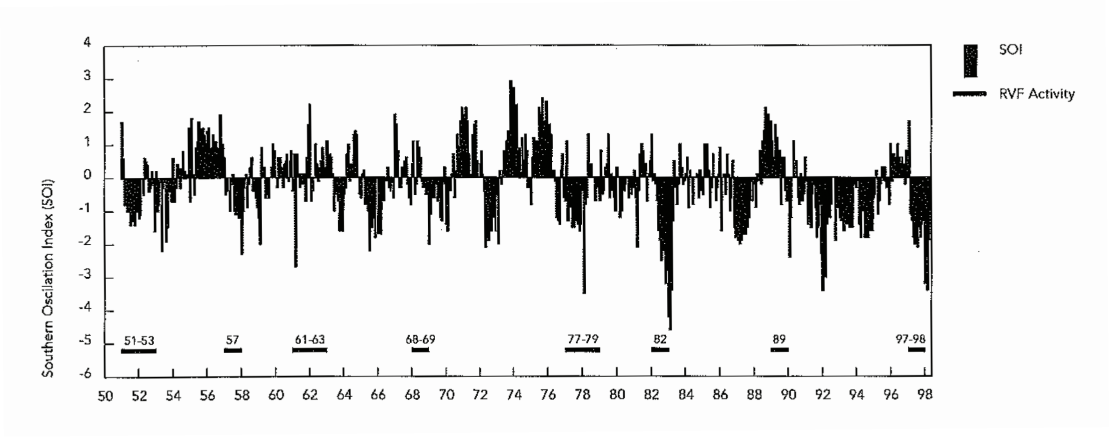
Over much of the middle to lower latitudes of the globe, El Niño-Southern Oscillation events are a most important source of year to year variability in climate. These episodes involve large-scale ocean-atmosphere interactions. The Southern Oscillation component represents a tendency for atmospheric surface pressure to stay below normal throughout the central and south Pacific while it stays above normal across Australia, South-East Asia and the Indian Ocean, and vice versa. During the phase where the pressure is low in the Pacific, warm water replaces the usually cool surface waters of the central and eastern equatorial Pacific–an event known as 'El Niño' (although originally 'El Niño' referred to only the warming off Peru). Together, the anomalies in the atmosphere and ocean are known as El Niño-Southern Oscillation (ENSO) events. During the opposite phase, an 'anti-ENSO event', surface waters in the eastern Pacific are colder than normal. ENSO events are aperiodic, but occur with a frequency of between 2 and 10 years. A commonly used ENSO indicator is the Southern Oscillation Index (SOI) which is based on the atmospheric pressure difference between Tahiti and Darwin.[10]

THE ABILITY TO FORECAST THESE ENSO EVENTS ALMOST A YEAR IN ADVANCE MEANS THAT WE CAN IN PRINCIPLE ANTICIPATE WITH SOME LEVEL OF CONFIDENCE THE AREAS THAT ARE LIKELY TO BE IMPACTED.

The authors further explained the link between ENSO and NDVI:

> *The El Niño-Southern Oscillation (ENSO) phenomenon is a principal cause of global interannual climate variability. Warm ENSO events are known to increase precipitation in some regions of East Africa. The Southern Oscillation Index (SOI) is the most commonly used index for the ENSO phenomena and extends back to the late 19th century. This index compares atmospheric pressure in Tahiti with that of Darwin, Australia, and is expressed as a standard deviation from the norm. Strong negative anomalies are associated with an El Niño event. Anomalous climatic conditions caused by ENSO are now recognized to be linked with outbreaks of various human and livestock diseases in various countries. Above normal East African rainfall is associated with negative SOI anomalies resulting in more green vegetation, which then is detected by the satellite-derived NDVI.*[16]

FIGURE: EL NIÑO *(Shutterstock).*



Time series of SOI anomalies from 1950 to May 1998. Periods of RVF activity in Kenya are depicted as thick black bars. Note that in most cases, outbreaks occurred during periods of the negative phase of the SOI. *(From figure 3 of Anyamba et al., 2001, p. S137.)*

Having grown up in Kenya, Anyamba knew firsthand the societal impacts of Rift Valley fever. In an article on climate-disease connections in Kenya, Anyamba and his colleagues wrote:

> *Rift Valley fever is a good example of a disease that is well coupled with climatic anomalies. The ability to forecast these ENSO events almost a year in advance means that we can in principle anticipate with some level of confidence the areas that are likely to be impacted. This provides a valuable lead-time to take measures to reduce negative societal impacts of ENSO on health and economic well-being. Livestock is the main source and in some cases the only source of livelihood and cash economy in the semi-arid and arid parts of Kenya. The death of large herds of livestock from RVF and other livestock-related diseases and flooding destroys the local economy. During the 1997–1998 ENSO event, the Gulf Arab countries banned the importation of livestock products from East Africa due to the fear of spreading RVF to humans in these countries. This ban, enforced for almost a year, resulted in a loss of foreign exchange earnings to Kenya, Somalia, and Ethiopia, and in effect jeopardized the domestic economy and the livelihoods of pastoral farmers. In addition, it takes many years to restock and build productive livestock herds to generate market value. The occurrence of RVF may and does perpetuate poverty conditions for several years in these areas. Pastoral farmers are forced to take loans from the respective governments to buy livestock. It often takes a long time to pay back these loans.*[17]

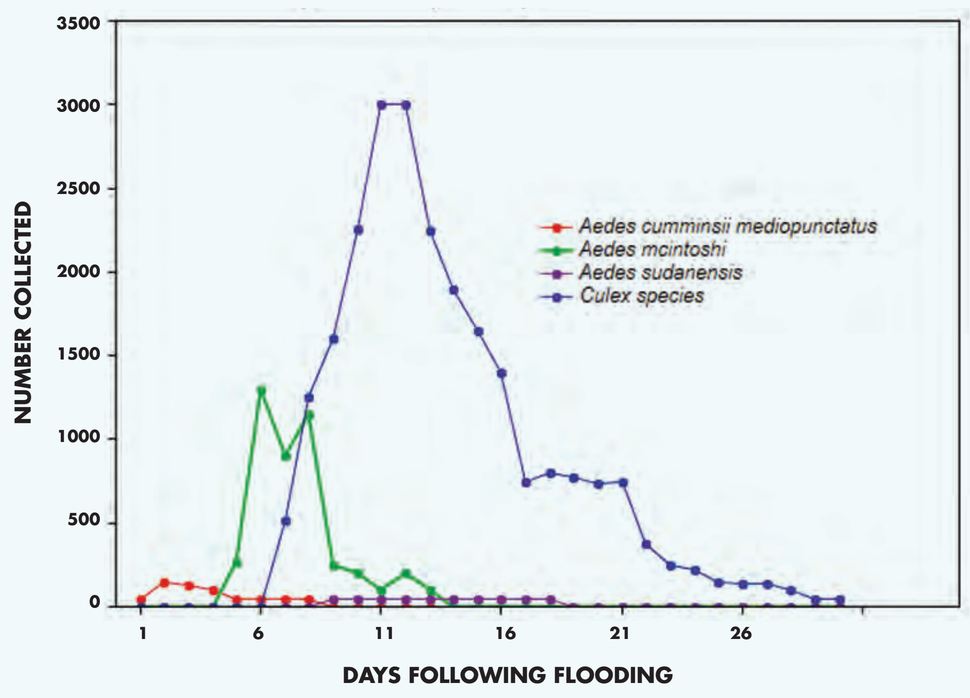
With this as background, Anyamba and a colleague from the US Department of Defense (DoD), Dr. Kenneth J. Linthicum,[18] designed an operational system by which lives and livelihoods might be saved, as opposed to analyzing data to show what might have been done to prevent the loss of lives and livelihoods. This operational system began to form in 1999, when NASA and the DoD initiated the development of a program to systematically monitor and map areas at potential risk for outbreaks of diseases such as RVF. As the joint program evolved, it increasingly used the NDVI data generated by the Global Inventory Mapping and Monitoring System that Anyamba and his colleagues had been developing at GSFC.

As Anyamba and others have noted, the challenge of implementing an effective operational program that uses remotely sensed data to provide advanced warnings of disease outbreaks is extremely complicated:

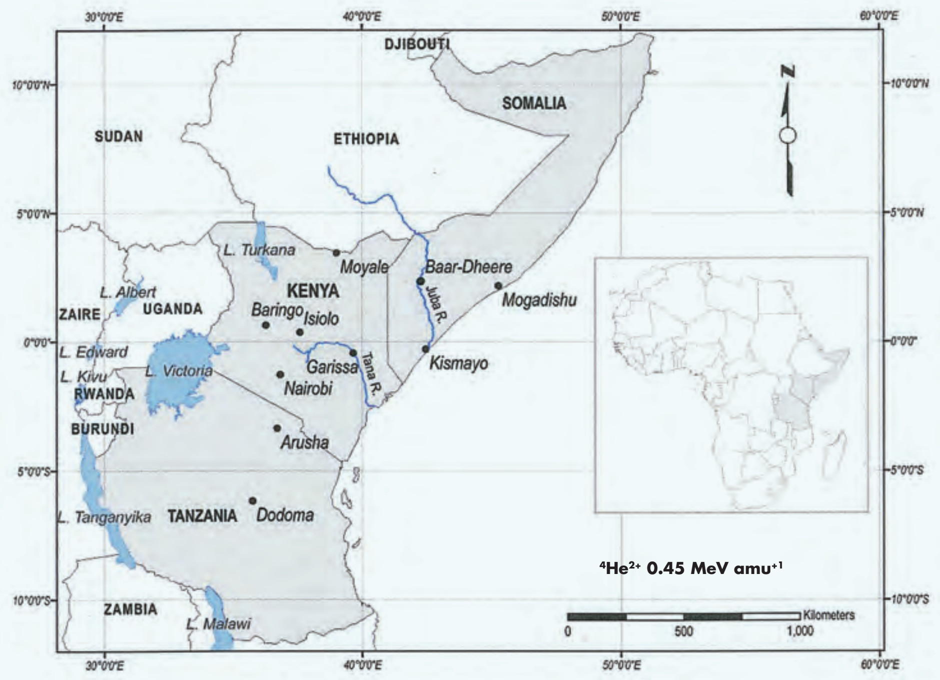
> *[T]he resolution of satellite-borne remotely sensed imagery is such that picture elements (pixels) commonly represent multiple land covers. In addition, remote sensing instruments sense electromagnetic energy that has travelled through the atmosphere. Thus, the seasonal character of vegetation index measurements over time may exhibit trends that represent changes in land cover and viewing conditions (such as changes in the presence of water vapor and aerosols) as well as true phenological responses.*[19]

Scientists taking samples from a flooded dambo in Kenya before the 2006 outbreak of Rift Valley fever. *Image courtesy: Assaf Anyamba*

Map of East Africa, showing the Great Rift Valley. Rift Valley fever takes its name from the region in Kenya where it was first discovered, namely the Great Rift Valley, which is part of the Rift Valley geological structure of East Africa. The structure is caused by a developing rupture of the African tectonic plate, forming two plates that are slowly moving apart. *Credit: good pix galleries (pixgood.com)*



Mosquito population dynamics after a flood event.
(From figure 2 in Anyamba et al., Remote sensing contributions to prediction … . 2012)



RVF outbreak region (shaded) in the Horn of Africa.
From figure S1 in Anyamba et al., 2009.

A single indicator, such as anomalies in the SOI, isn't sufficient to accurately predict elevated rainfall in at-risk regions. Concurrent anomalies in sea-surface temperatures in the eastern-central Pacific Ocean and the western equatorial Indian Ocean are much better leading indicators for elevated rainfall in the RVF endemic region of the Horn of Africa than anomalies in the SOI.[20]

The mosquito vectoring is also complex, involving different species of mosquitoes:

> *The flooding of dambos induces the hatching of transovarially infected Aedes mcintoshi mosquito eggs that are dormant in the soil, producing infected adult females in 7–10 days that can transmit RVF virus to domestic animals.… After a blood meal, the Aedes mosquitoes will lay infected eggs on moist soil at the edge of mosquito habitats, but appear to not be an efficient secondary vector of the virus between infected and noninfected domestic animals and humans.… However, Culex species mosquito vectors subsequently colonize these flooded dambos and, with a delay of several weeks, large populations of these mosquitoes emerge and efficiently transmit the virus from domestic animals, which amplify the virus, to noninfected domestic animals and humans …*[21]

And, while increased rainfall results in an increase in mosquito vector populations, decreased rainfall can be a problem as well:

> *Decreased rain can severely reduce or eliminate food resources forcing vectors and vertebrate hosts into human settlements, increasing vector-human contact …*[22]

Anyamba and his colleagues persevered despite these challenges, and by the early 2000s, the risk monitoring and mapping system they were developing used the analysis and interpretation of observations from several satellites, including data on sea surface temperatures, cloudiness, rainfall, and vegetation dynamics.

By the fall of 2006, their models were refined to the point of being able to predict outbreaks of RVF in various parts of the Horn of Africa. In an article for the *Proceedings of the National Academy of Sciences,* Anyamba and his team of colleagues–from the DoD's Division of Preventive Medicine, the World Health Organization's (WHO) Department of Epidemic and Pandemic Alert and Response, the US Army Medical Research Unit-Kenya, and the US Department of Agriculture's Research Service Center for Medical, Agricultural, and Veterinary Entomology–reported on the first prospective prediction of an RVF outbreak.[23]

The team used information from previous RVF outbreaks and the analysis of satellite data to map areas in Africa at elevated risk of RVF. They began to issue monthly early-warning advisories for the Horn of Africa in September 2006. Based on NDVI data that showed anomalously high levels of green vegetation during the month of October, the team could see that most of the central Rift Valley, eastern and north-eastern regions of Kenya, southern Ethiopia, most of central Somalia, and northern Tanzania were at an elevated risk for RVF outbreaks, and they issued an early-warning advisory for these regions in early November 2006. The US DoD–Global Emerging Infections Surveillance and Response System and the Department of Entomology and Vector-borne Disease, US Army Medical Research Unit-Kenya initiated entomological surveillance in Garissa, Kenya, in late November 2006. The first human cases of RVF in Kenya were reported from Garissa in mid-December 2006.[24]

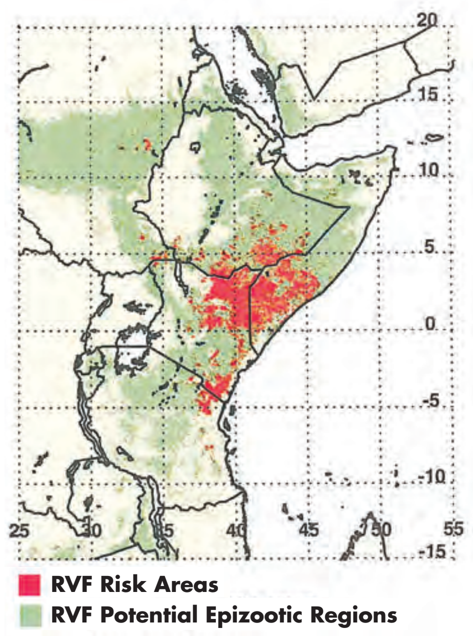
The impact of the outbreak of RVF was mitigated because the early warning enabled the government of Kenya, in collaboration with the WHO, the US Centers for Disease Control and Prevention, and the Food and Agricultural Organization of the United Nations to mobilize resources to implement disease mitigation and control activities in the affected areas, and prevent its spread to unaffected areas.[25]

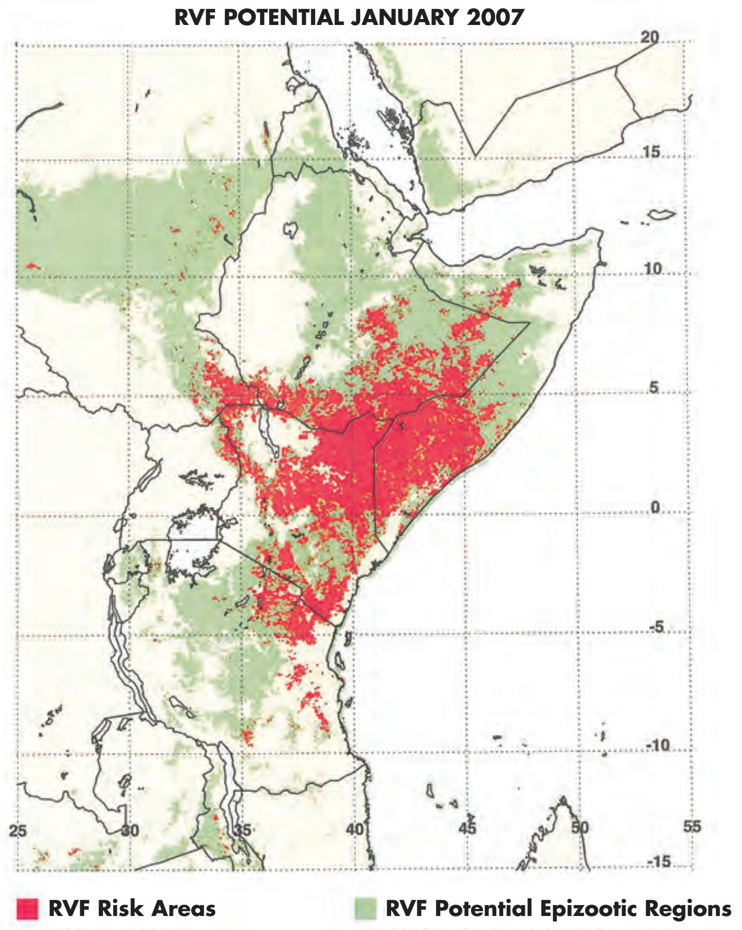
The locus of rainfall in East Africa began to shift southward during December 2006. By using their risk mapping models, the team then issued another alert on the potential of RVF in northern Tanzania, and from mid-January 2007 RVF cases began to be reported there.[26]

Continued monitoring in 2007 resulted in a warning alert for Sudan in early June, and the first human case of RVF was identified there in early October.[27]

The team reported its results in a journal article in 2010:

> *In contrast to the 1997–1998 outbreak …, the early warning described here for late 2006 and early 2007 enabled vector and disease surveillance activities to be initiated in Kenya and Tanzania 2 to 6 weeks before the human disease cases were identified. After the early identification of RVF transmission between the end of November and early December 2006 in Kenya, enabled by the early warning, subsequent enhanced surveillance activities and additional mitigation activities were implemented, including animal movement restrictions/ quarantines, distribution of mosquito nets, social mobilization and dissemination of public information related to reducing human contact with infected animal products and mosquito vectors, and specific domestic animal vaccination and mosquito control programs in at-risk areas…*
>
> *This analysis demonstrates that satellite monitoring and mapping of key climate conditions and land surface ecological dynamics … are an important and integral part of public health surveillance and can help reduce the impact of outbreaks of vector-borne diseases such as RVF. This is one of many societal benefits that result from a robust earth observing system that monitors key climate variables in a systematic and sustained fashion.*[28]





TOP: RVF calculated risk map for December 2006 for the Horn of Africa.

RIGHT: RVF calculated risk map for January 2007 for the Horn of Africa. Top from figure 6 of Anyamba et al., 2009, p. 957. Right from figure S6 of Anyamba et al., 2009, Supporting Information, p. 9.

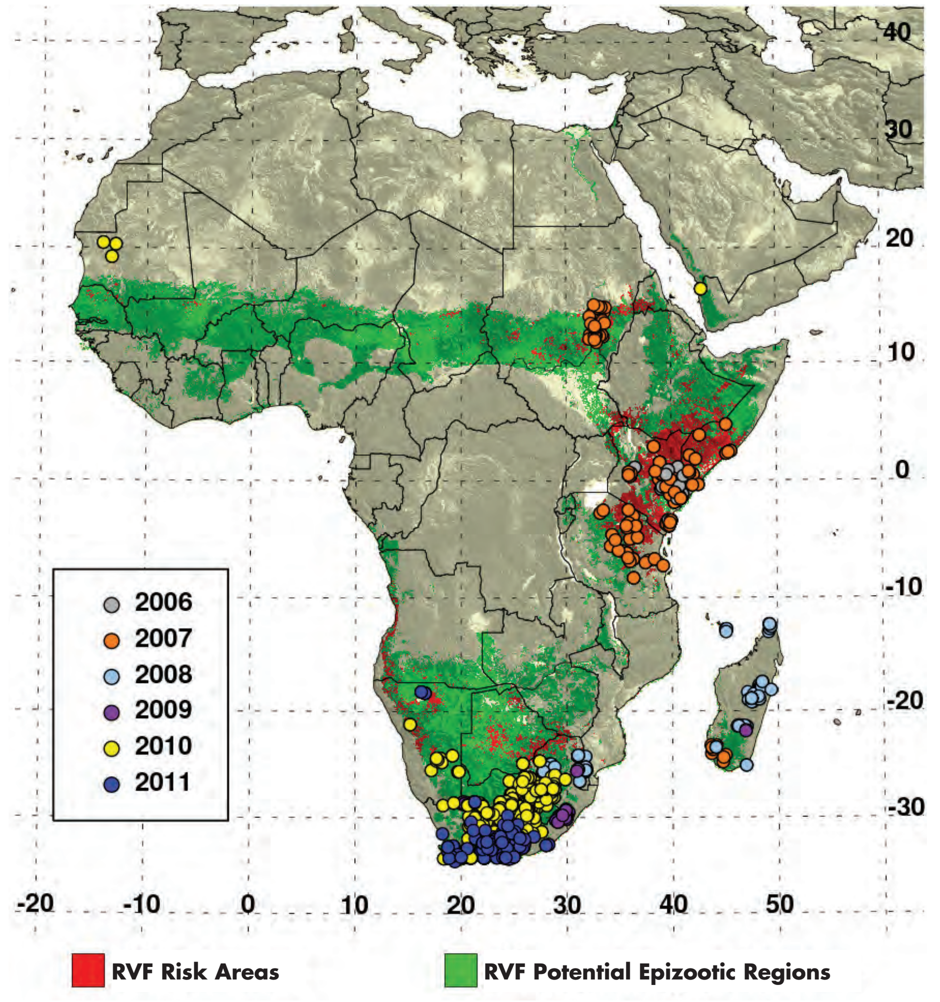
The human death toll from RVF in Kenya during the 2006–2007 outbreak was much less than it was during the 1997–1998 outbreak. Still, 158 Kenyans lost their lives to the disease. There were 51 deaths reported in Somalia, 109 in Tanzania, and 214 in Sudan.[29] The loss of livestock and forced closure of livestock markets, with the attendant negative societal effects, were substantial in these countries.

While others worked on additional approaches, such as the development of vaccines for use against the RVF virus in animals and humans, Anyamba and members of his multi-agency team continued to refine their risk model. During subsequent outbreaks of RVF, they have been able to lengthen the time gap between the early warning alert in each country and the first reported human case. Because of their advanced warning and the response of the government of Kenya, for example, where the vaccination of animals in areas where the outbreak was anticipated, there were no reported cases of RVF in Kenya during the strong ENSO event of 2015–2016.[30]

At this writing, the US Department of Agriculture hosts a Rift Valley Fever Monitor on the web that is updated on a monthly basis.[31] This system has been used to predict RVF outbreaks in other parts of Africa and in the Arabian peninsula as shown in the accompanying figure (page 104).

The Rift Valley Fever Project is now considered by the US DoD to be the initial

THE RIFT VALLEY FEVER PROJECT IS NOW CONSIDERED BY THE US DOD TO BE THE INITIAL EFFORT THAT SPURRED THE EXTENSION OF PREDICTIVE SURVEILLANCE CAPABILITIES TO OTHER PRIORITY VECTOR- AND WATER-BORNE DISEASES.



LEFT: Composite RVF risk map based upon extended heavy rainfall, ecological habitats associated with epizootics, and population density map of cattle, sheep, and goats, and outbreak locations based upon human case data. The composite RVF Risk Map shows data for (1) East Africa (September 2006–May 2007), (2) Sudan (June–November 2007), and (3) southern Africa including Madagascar (October–May composite aggregated for each year 2007–2011). RVF human case data are mapped for (1) East Africa (Kenya, Somalia, Tanzania) 2006–2007, (2) Sudan 2007, (3) Southern Africa (Madagascar, South Africa, Botswana, Namibia, South Africa) 2008–2001, and (4) West Africa/Middle East (Yemen/Saudi Arabia) 2010.
(From figure 2 of Linthicum et al., 2016, p. 407)

effort that spurred the extension of predictive surveillance capabilities to other priority vector- and water-borne diseases:

> *These include leishmaniasis, malaria, and Crimea-Congo and other viral hemorrhagic fevers in Central Asia and Africa, dengue fever in Asia and the Americas, Japanese encephalitis (JE) and chikungunya fever in Asia, and rickettsial and other tick-borne infections in the US, Africa and Asia.*[32]

USRA's Assaf Anyamba has been a key leader in the interagency team that has brought about these important predictive services that depend on satellite remote sensing. Organizations and agencies around the world now depend upon and use these services, since all are aware of the potential for the globalization of viruses such as happened with the West Nile virus.[33] The US DoD continues to support the surveillance work not only because of the protection it affords for US military forces stationed abroad, but also for the needed ability to discriminate between naturally occurring outbreaks and those that might have been deliberately introduced as a tactic of bioterrorism.[34]

It has taken determination fueled by passion on the part of Anyamba to overcome not only technical difficulties but programmatic and bureaucratic obstacles as well. An example of the latter was the withdrawal of funding from one of the key supporting agencies for about half a decade following the successful prediction of the outbreak of RVF in East Africa in 2006. This support has now been restored, but the lapse resulted in not only the loss of experienced staff but also the loss of years of archived data, which were vital to the risk model that the team had developed.

IN CONCLUSION

When USRA was formed in 1969, it was focused on a partnership with NASA for the exploration of the Moon. As the Nation's interest in space research expanded to include the Earth sciences, USRA's partnership with NASA continued, perhaps in part because NASA valued the integrity of USRA managers like Bill Davis. This continued partnership allowed USRA's scientists to bring to bear their passion and ingenuity on challenging problems that require collaborations with many different agencies, as illustrated by the career of Assaf Anyamba. At this writing, his work within USRA's Goddard Earth Sciences Technology and Research program directly supports research and program services for several agencies, including

- The Production Estimates and Crop Assessment Division of the US Department of Agriculture's Foreign Agriculture Service
- The US Agency for International Development's Famine Early Warning Systems Network
- The US DoD's Global Emerging Infections Surveillance System
- The US Department of Agriculture's Center for Medical, Agricultural and Veterinary Entomology
- The US Food and Drug Administration.

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24. Ibid., 956–957.
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4

COMPUTER SCIENCE AND INFORMATION TECHNOLOGY

FROM NUMERICAL ANALYSIS TO QUANTUM COMPUTING

How NASA-USRA collaborations have advanced knowledge in and with the use of new computing technologies.

WHEN USRA WAS CREATED IN 1969, ITS FIRST TASK WAS THE MANAGEMENT OF THE LUNAR SCIENCE INSTITUTE NEAR NASA'S MANNED SPACECRAFT CENTER (NOW THE JOHNSON SPACE CENTER). A little more than three years later, USRA began to manage the Institute for Computer Applications in Science and Engineering (ICASE) at NASA's Langley Research Center (LaRC). The rationale for creating ICASE was developed by Dr. John E. Duberg (1917–2002), who was the Associate Director at LaRC and later the Chief Scientist at the Center. In February of 1972, Duberg wrote a memorandum to the senior management of LaRC, expressing his view that:

> *The field of computers and their application in the scientific community has had a profound effect on the progress of aerospace research as well as technology in general for the past 15 years. With the advent of "super computers," based on parallel and pipeline techniques, the potentials for research and problem solving in the future seem even more promising and challenging. The only question is how long will it take to identify the potentials, harness the power, and develop the disciplines necessary to employ such tools effectively.*[1]

Twenty years later, Duberg reflected on the creation of ICASE:

> *By the 1970s, Langley's computing capabilities had kept pace with the rapidly developing technology in the hardware. ... [Center staff] recognized that if the Center was to realize to the fullest the world-class computing capability that it had assembled, a more aggressive and basic effort in the science of computing was needed.*[2]

LaRC had already formed one collaborative institute, the Joint Institute for the Advancement of Flight Sciences with George Washington University. Because that experience had been positive, it was decided that a new institute should now be formed, and two weeks after Duberg's internal memo, the Director of LaRC, Edgar Cortright (1923–2014), sent a memo to NASA Headquarters suggesting the establishment of another institute that would:

> *Bring together experts in applied mathematics and computer science from universities and industrial establishments for the exploitation of the capabilities at Langley Research Center and to influence through their competence the quality of activity now carried on throughout the Center.*[3]

ICASE HAS BEEN AT THE HEART OF ADVANCES IN NUMERICAL ANALYSIS AND ITS APPLICATIONS.
- ORSZAG, 1992

John E. Duberg, Chief Scientist, LaRC; George M. Low, former head of the Office of Manned Spaceflight at NASA Headquarters; and Edgar M. Cortright, Director of LaRC when ICASE was formed.

JAMES M. ORTEGA
THE FOUNDING DIRECTOR OF ICASE

ICASE THRIVED AT LARC BY BRINGING UNIVERSITY RESEARCHERS ON A VISITING BASIS TO WORK IN THE AREAS OF NUMERICAL MATHEMATICS, FLUID MECHANICS, AND APPLIED COMPUTER SCIENCE.

Cortright had been hired by the second NASA Administrator, James Webb, and he had been sent to LaRC by Webb to give the Center "a shot in the arm."[4] As Duberg later reflected, the new institute was to:

> *Involve a broad spectrum of universities to maximize the diversity of research interests. It would also increase the number of universities that could avail themselves of superior computing capabilities. Fortunately, it was not necessary to invent any new external mechanism to sponsor this venture. NASA had already encouraged the formation of the Universities Space Research Association (USRA) to manage its program for the analysis of rock samples from the Moon by the broad base of interested researchers that were to be found in the university community.*[5]

THE CREATION OF ICASE

NASA quickly negotiated a cooperative agreement with USRA for the operation of ICASE, which was formed in July of 1972. The search for a director resulted in the appointment of Dr. James M. Ortega (1932–2008) of the University of Maryland. Ortega had just completed two books on numerical methods: one was titled *Numerical Analysis: A Second Course*; and the other, co-authored with Werner Rheinboldt, was titled *Iterative Solutions of Nonlinear Equations in Several Variables*. Ortega's expertise and his interest in the marriage of computer science and applied mathematics made him an obvious choice to be the founding director of ICASE.

Part of the impetus for the creation of ICASE was the advent of computers that used parallel processing. LaRC was soon to receive delivery of Control Data Corporation's STAR 100 vector processor. The initial program plan for ICASE reflected a merger of LaRC's interest in developing the Center's capabilities using the new supercomputers with Ortega's interests in applied mathematics. Thus, the program plan's four categories:

1. Efficient use of vector and parallel computers, with particular emphasis on the CDC STAR-100.
2. Numerical analysis, with particular emphasis on the development and analysis of basic numerical algorithms.
3. Analysis and planning of large-scale software systems.
4. Computational research in engineering and the natural sciences, with particular emphasis on fluid dynamics.[6]

The STAR-100 did not prove to be very successful, but ICASE thrived at LaRC by bringing university researchers on a visiting basis to work in the areas of numerical mathematics, fluid mechanics, and applied computer science. ICASE had a small permanent staff and a cadre of 40 to 50 consultants from universities around the world who would visit the institute for varying periods of time. The staff and visitors could infuse the results of their research into the research programs at LaRC, often by conducting joint research with Langley staff. The challenging, real-world problems at NASA's oldest aeronautical research center were of great interest to academic researchers.

Ortega served as Director of ICASE from 1972 to 1977. His successors were Dr. Milton E. Rose (1925–1993), who served from 1977 to 1986; Dr. Robert G. Voigt, who served from 1986 to 1991; Dr. M. Yousuff Hussaini, who served from 1991 to 1996; and Mr. Manuel D. Salas, who served from 1996 to 2002.

ICASE'S ACCOMPLISHMENTS

For the 20th anniversary of ICASE in 1992, Director Yousuff Hussaini identified several of the institute's accomplishments, including:

- Performing the first application of multigrid methods to fluid flow problems
- Developing the first general theory of multigrid methods, using finite elements and the variational formulation
- Pioneering the development of spectral methods in fluid dynamics
- Developing a modern theory of boundary conditions for hyperbolic partial differential equations
- Developing unstructured multigrid strategies for improving efficiency of unstructured flow solvers in both two and three dimensions
- Developing highly effective and computationally tractable techniques for parameter estimation and feedback control
- Developing first nonparallel theories of linear and nonlinear growth of Görtler vortices in incompressible and compressible boundary layer flows [Görtler vortices can occur with flow over curved surfaces, e.g., the wing of an aircraft, and can lead to turbulent flow.]
- Performing the first direct numerical simulation of transition in supersonic boundary layers
- Developing the first compressible subgrid scale model for compressible turbulence, and performing the first large-eddy simulation of compressible homogeneous turbulence
- Developing new instability modes for high speed reacting mixing layers relevant to scramjets
- Developing the first high-order schemes for acoustics
- Performing seminal work on absorbing boundary conditions, allowing acoustics problems to be treated by standard algorithms
- Conducting pioneering work on parallel algorithms and architectures a decade before commercial parallel machines became available
- Designing and implementing the Finite Element Machine, one of the first Multiple Instruction, Multiple Data architectures and the first to incorporate fast summation hardware[7]

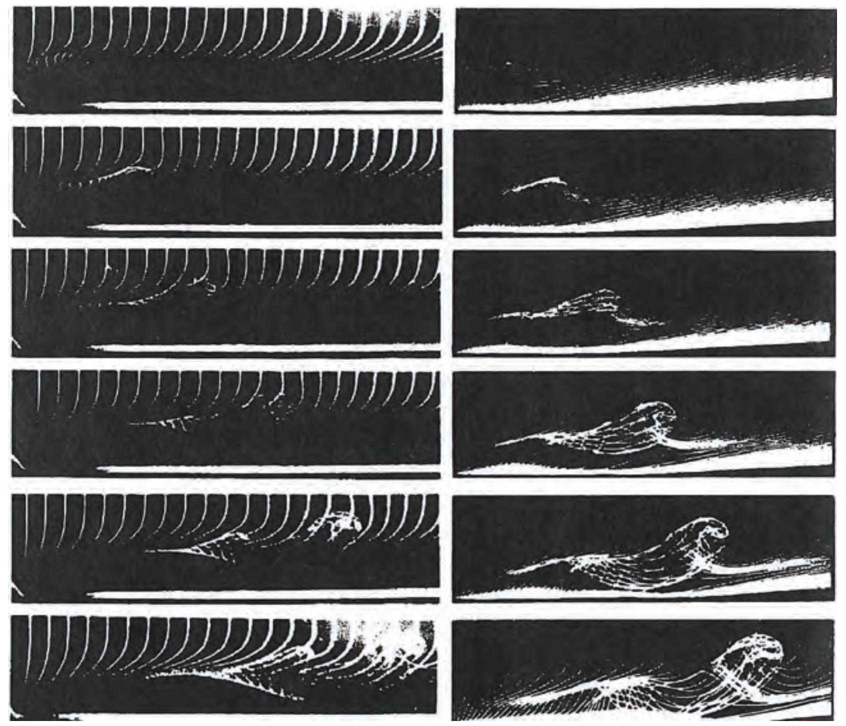
MILTON ROSE

YOUSUFF HUSSAINI

ROBERT VOIGT

MANUEL SALAS

ICASE staff and visiting scientists during the summer of 1986



Comparison of experiment (left) and ICASE numerical simulation (right) of an evolving boundary layer instability at six successive snapshots. [8]

Distinguished members of the applied mathematics research community recognized the success of ICASE in advancing knowledge in numerical methods and in fostering interactions between NASA and the university research community. Dr. Peter Lax of the Courant Institute of New York University wrote:

> *Through its far-flung visitor program, just about every important player in CFD [Computational Fluid Dynamics] spent some time at ICASE; through their interaction the importance of the ideas in this field were clarified.*[8]

Twenty years after the establishment of ICASE, Professor Steven Orszag (1943–2011) commented:

> *ICASE has been at the heart of advances in numerical analysis and its applications. Many of the great leaps in computational methods have marched to the beat of developments whose genesis was discussed in corridors and focused thinking in the offices of ICASE."*[9]

WILLIAM BALLHAUS

PETER DENNING

CREATION OF THE RESEARCH INSTITUTE FOR ADVANCED COMPUTER SCIENCE (RIACS)

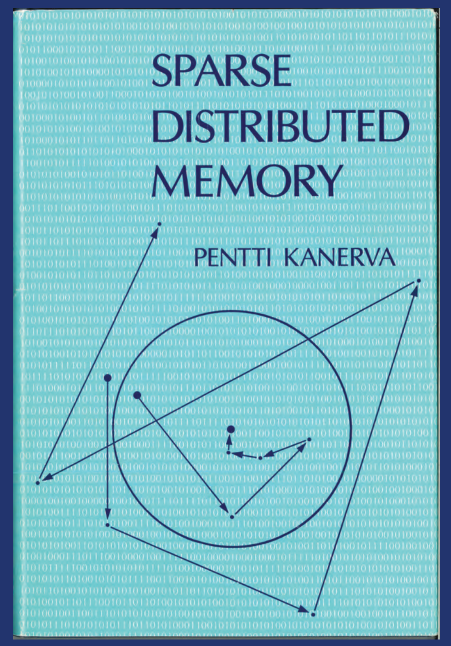
The success of ICASE led to a request from NASA in 1983 that USRA establish a second computer-oriented institute, this time at NASA's Ames Research Center. NASA Ames was soon to acquire an Intel iPSC Hypercube and Sequent Computing supercomputers. In response to NASA's request, USRA created the Research Institute for Advanced Computer Science (RIACS).

The founding director of RIACS was Dr. Peter J. Denning, who was a graduate of MIT's Electrical Engineering Department. By the time of his selection as Director of RIACS, Denning had written *Operating Systems Theory* with Edward G. Coffman and *Machines, Languages, and Computation* with Jack B. Dennis and Joseph E. Qualitz. Denning had taught at Princeton and Purdue Universities. He was the Head of the Department of Computer Sciences at Purdue just prior to joining RIACS.

With the support of the Center Director at NASA Ames, Dr. William F. Ballhaus Jr., Denning began to build interdisciplinary teams of computer scientists and NASA scientists and engineers that would tackle some of the hardest problems faced by NASA. The initial research areas at RIACS were computing, networking, and artificial intelligence. In 2014, Denning reflected on the accomplishments of RIACS during his tenure:

> *In the computing area our people helped NASA find new algorithms for efficiently computing fluid flows on parallel machines. An example that caught a lot of attention at the end was a pre-processor for programs targeted for the Connection Machine. The pre-processor mapped grid points on to neighboring CPUs and achieved a speedup over the Cray machines using a Connection Machine that cost 1/10 as much as the Cray.*
>
> *The AI group contributed similarly, and a couple of things stood out for me. One was the research of Dr. Pentti Kanerva and others in the group working on Sparse Distributed Memory (SDM), a memory architecture modeled after the human memory; it was producing results at learned responses better than neural networks at the time. The other was the Bayesian Learning group, which pioneered with the brand-new techniques of Bayesian learning, produced novel results in allied fields especially astronomy, and eventually became the hottest research area in AI.*
>
> *The Networking group got NASA-Ames into the full Internet age and into local networks that could keep up with supercomputers. They also pioneered in telescience, the conduct of scientific operations remotely, which turned into a major networking area in the years following.*
>
> *We were doing what NASA originally chartered us to do, which was to engage in grand challenge areas with them and make progress through computing. We were quite successful.*[10]

AS AN INDEPENDENT INSTITUTE OF A UNIVERSITY-BASED CONSORTIUM, RIACS ACCESSED A LEVEL OF RESEARCH ABILITY IN ITS UNIVERSITY MEMBERS THAT IS UNMATCHED ANYWHERE ELSE.
– HUBBARD, 2008



Book authored by RIACS researcher Pentti Kanerva

WE WERE DOING WHAT NASA ORIGINALLY CHARTERED US TO DO... ENGAGE IN GRAND CHALLENGE AREAS AND MAKE PROGRESS THROUGH COMPUTING. WE WERE QUITE SUCCESSFUL.
– DENNING, 2014

Distinguished members of the NASA and outside research communities agreed with Denning's assessment of RIACS. A former Director of NASA Ames, G. Scott Hubbard, wrote:

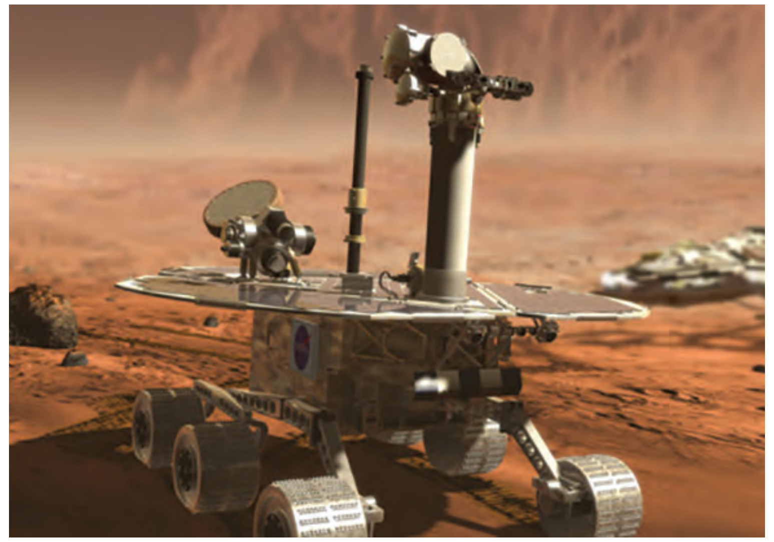
> *As an independent institute of a university-based consortium, RIACS accessed a level of research ability in its university members that is unmatched anywhere else. ... The tremendous talent of RIACS was regularly tapped by NASA to lead some of our most important efforts. Dr. Walter Brooks, a RIACS staff member, was asked to lead the Columbia Supercomputing effort. He led a team... to acquire the 10,240 processor Columbia Supercomputing System, at the time the fastest computer in the world.*[11]

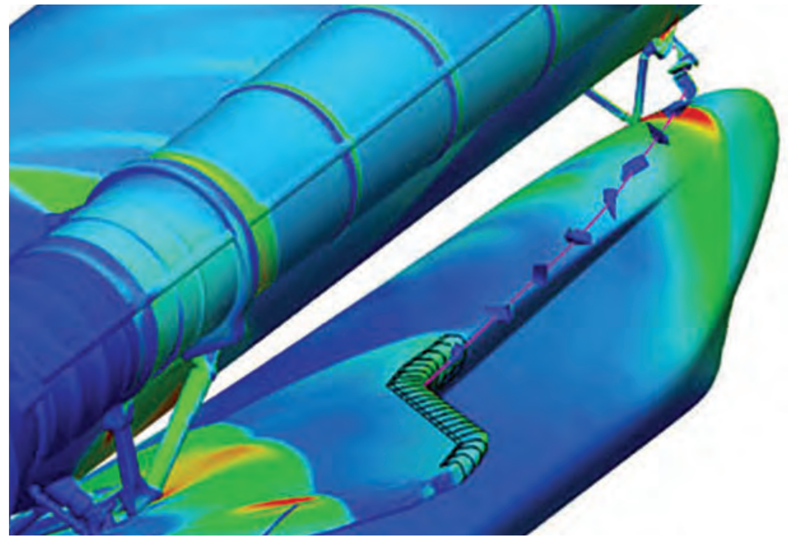
Douglas R Hofstadter, author of *Gödel, Escher, Bach: An Eternal Golden Braid*, wrote of Kanerva:

> *Sparse distributed memory is among the most inspiring ideas that I have ever encountered in all of cognitive science. ... Pentti Kanerva's work on sparse distributed memory points the way to new computing technologies that can deal with the ubiquitous approximations and blurry categories that characterize the real world and that are intractable to most types of computing technology. More specifically, sparse distributed memory is, in my view, exactly the right kind of software that could underlie the development of highly autonomous robots of the sort that could be sent to explore planets and their moons – a most exciting prospect in many dimensions.*[12]

Nils J. Nilsson, a renowned researcher and author in the field of artificial intelligence, wrote of RIACS scientist Dr. Peter Cheeseman's work on Bayesian Classification:

> *The Bayesian Classification research done by RIACS was quite controversial when it began, but time has definitely proven its soundness and importance through the penetration of Bayesian classification technologies in numerous industries.*[13]





RIACS researchers played leading roles in the development of artificial intelligence software to plan the work of the Mars rovers.
The Mars Exploration Rover Credit: NASA

Cart3D simulation of the trajectory of tumbling debris from foam and other sources during the ascent of the Space Shuttle Columbia

BARRY LEINER

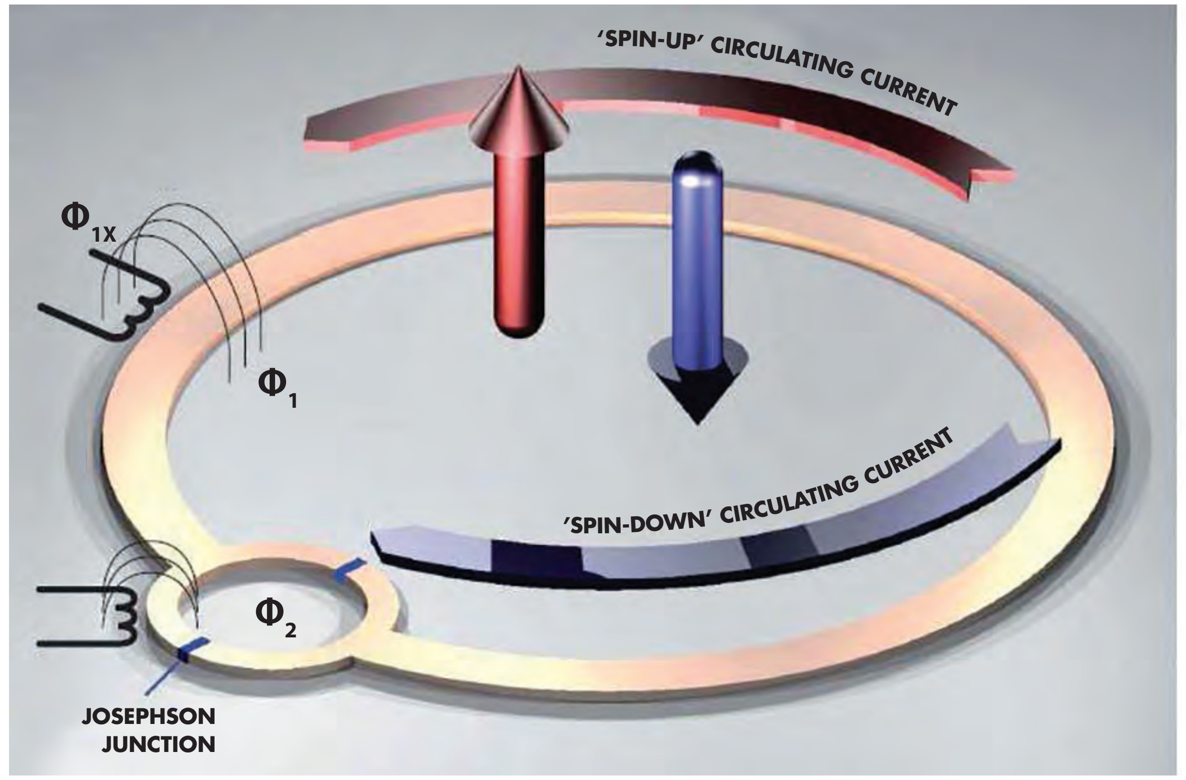
DAVID BELL

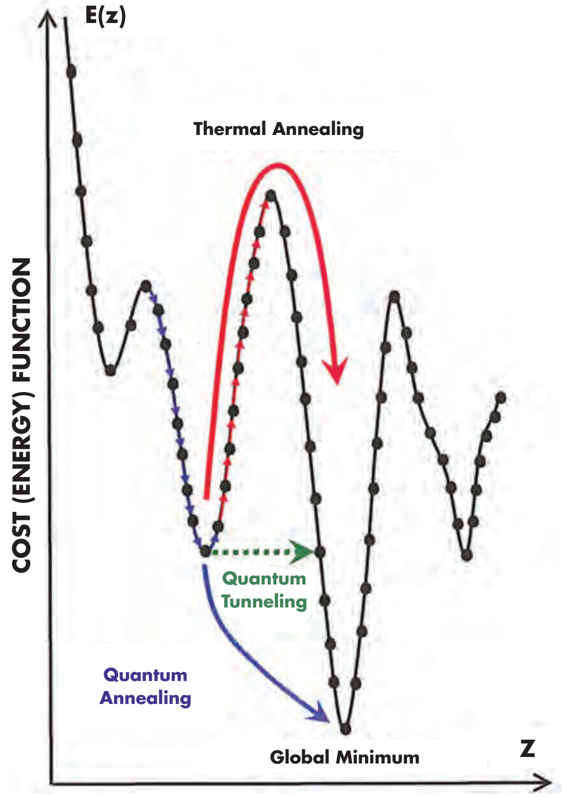
Denning served as Director of RIACS from 1983 to 1990. Among his notable successors was Dr. Barry M. Leiner (1945–2003), who served as Director of RIACS from 1999 to 2003. As a manager at the Defense Advanced Research Projects Agency (DARPA) in the early 1980s, Leiner was deeply involved in the evolution of the Internet, particularly in the establishment of a process to determine standards for its organizational structure.

OTHER ACCOMPLISHMENTS OF RIACS

After 25 years of innovation at RIACS, its Director, Dr. David Bell, noted a number of successes:

- In 1987 Peter Cheeseman was the principal developer of AutoClass, which was the first AI software to make a published astronomical discovery. Given real valued or discrete data, AutoClass determines the most probable number of classes present in the data, the most probable descriptions of those classes, and each object's probability of membership in each class.[14]
- Remote Agent was the first AI software to control a spacecraft in deep space and was the 1999 NASA Software of the Year co-winner.
- In 2002, Cart3D was named the NASA Software of the Year co-winner. RIACS visiting scientist Professor Marsha Berger of the Courant Institute, New York University, was co-inventor of Cart3D, which played a critical role in resolving the main physical cause of the Space Shuttle Columbia disaster–foam debris that struck the orbiter on ascent–by generating simulations that predicted the trajectory of tumbling debris from foam and other sources.[15]
- In collaboration with NASA scientists and engineers, RIACS scientists led the development of MAPGEN, a ground-based mixed-initiative, human-in-the-loop control system used to generate activity plans for the Mars rovers. In 2004, MAPGEN became the first artificial intelligence software to plan the work of robots on another planet. RIACS scientist, Dr. Ari Jónsson, was the lead inventor of EUROPA, a constraint-based planning and scheduling engine that lies at the heart of the MAPGEN application.[16]





The work of RIACS scientists Peter Cheeseman on AutoClass and Ari Jónsson on Remote Agent and EUROPA/MAPGEN are examples of optimization problems that are of great interest to NASA. The space agency often needs to find solutions to similar optimization problems, not only for planning and scheduling, but also for software verification and validation, spacecraft power allocation, image analysis, machine learning and many other artificial intelligence problems.

QUANTUM COMPUTING

In 2012, USRA entered into a joint Space Act Agreement with Google and NASA to conduct collaborative research on the benefits of quantum computing for a range of applications, but particularly for optimization problems. For the collaboration, USRA obtained from D-Wave Systems, Inc., a D-Wave quantum computer, which was installed in the NASA Advanced Supercomputing facility at NASA Ames. USRA manages the science operations for the collaboration, which includes an allocation of 20% of the computing time for the research community through a competitive selection process.

One way that the D-Wave quantum computer can be used to solve optimization problems is as a superconducting quantum annealing machine. In the ordinary annealing of a piece of metal, one heats the metal until it glows and then allows it to slowly cool. The heating frees the metal of discontinuities in its lattice structure, and the cooling allows the atoms in the metal to reform in a more perfect lattice structure that corresponds to the lowest energy state of the metal.

In superconducting quantum annealing, getting the solution to an optimization problem corresponds to finding the lowest energy state of an array of interacting quantum mechanical spin vectors. In the D-Wave computer, the spins are produced by loops of niobium metal maintained near absolute zero temperature so that they can carry quantized superconducting currents. The quantized currents produce quantum bits, called qubits. The current loops are arranged in arrays that are coupled so that the qubits can exchange information. Small external currents produce magnetic fluxes that allow the array of coupled qubits to be programmed, so that a particular optimization problem can be encoded.

The metallic loops contain Josephson junctions, which have insulating separations that force the electronic current to "tunnel" from one side of the junction to the other. The presence of this quantum effect enables the system of interacting spins to be prepared initially into a superposition of states that facilitates exploration of the energy landscape. In regular annealing, this corresponds to the initial heating of the metal. Several controllable, local magnetic fields are then gradually changed to decrease tunneling probabilities (corresponding to cooling of a metal sample during annealing), and the system of interacting spins is "frozen" into its minimum energy configuration, which gives the solution to the optimization problem with high probability.

TOP: A simplified schematic of a superconducting flux qubit acting as a quantum mechanical spin. Circulating current in the qubit loop gives rise to a flux inside, encoding two distinct spin states that can exist in a superposition.[18]

RIGHT: Energy landscape for a binary optimization problem. Black points correspond to different configurations of binary variables. In quantum annealing, the landscape can be explored through quantum tunneling, as well as thermally.[19]

The D-Wave 2XTM Quantum Computer in the NASA Advanced Supercomputing Facility at NASA's Ames Research Center.

THE INITIAL EFFORTS OF THE USRA TEAM HAVE BEEN TO CHARACTERIZE THE PERFORMANCE OF THE D-WAVE COMPUTER, E.G., TO EXPLORE THE EFFECT OF NOISE ON QUANTUM ANNEALING, TO DEMONSTRATE QUANTUM ENHANCEMENT OVER CLASSICAL METHODS, AND TO EXAMINE SMALL BUT VERY DIFFICULT OPTIMIZATION PROBLEMS.

USRA collaborates with Google and NASA in the operation of the Quantum Artificial Intelligence Laboratory at NASA Ames. As is always the case with research programs, progress is made through the excellence of individual researchers. In this instance, RIACS researchers Drs. Davide Venturelli, Kostya Kechedzhi and Zhihui Wang have helped to provide the needed expertise for USRA's part of the collaboration.

The initial efforts of the USRA team have been to characterize the performance of the D-Wave computer, e.g., to explore the effect of noise on quantum annealing, to demonstrate quantum enhancement over classical methods, and to examine small but very difficult optimization problems.

The first eight proposals that were accepted by USRA for use on the D-Wave quantum computer were from principal investigators at Mississippi State University, the University of Southern California, and the University of California, San Diego, and from universities in Canada, Italy, Mexico, and Switzerland. Research topics from the university research community ranged from condensed matter and quantum annealing device physics to machine learning and network optimization.

The experience of one of the researchers, Dr. Immanuel Trummer of the Swiss Federal Institute of Technology Losanne, illustrates the value of USRA's role in the Quantum Artificial Intelligence Laboratory to individuals and, ultimately, to US leadership in high-technology endeavors. In the spring of 2016, Trummer wrote the note on the facing page to Bell and Venturelli.

At this writing, Trummer is an Assistant Professor at Cornell University, and he is continuing his collaboration with quantum computer scientists at RIACS.

IN SUMMARY

Far-sighted NASA leaders such as James Webb, Edgar Cortright, and William Ballhaus recognized the value of collaborating with USRA on challenging problems. Their foresight has paid off time and time again, and there are hardly better examples than the advances made in the computational sciences from numerical analysis at ICASE to quantum computing at RIACS.

DAVIDE VENTURELLI
USRA QUANTUM SCIENTIST
EXPERT IN QUANTUM COHERENCE ANALYSIS

KOSTYA KECHEDZHI
USRA QUANTUM SCIENTIST
EXPERT IN SUPERCONDUCTING QUBIT NOISE

ZHIHUI WANG
VISITING SCIENTIST, UNIVERSITY OF SOUTHERN CALIFORNIA
EXPERT IN D-WAVE SIMULATION/ BENCHMARKING

From: Immanuel Trummer
Sent: Thursday, April 07, 2016 6:17 PM
To: Bell, David; Davide Venturelli
Subject: Update: Paper & Job Search - Thanks!

Dear David, dear Davide,
I hope you are doing well
Good news: our paper on quantum annealing has finally been accepted at VLDB2015, one of the two main database conferences. Thanks so much for all the comments and hints! I'm currently interviewing for tenure track professor positions in computer science in the US and Europe. It's going very well (first offers from Cornell and Maryland and I expect more in the next weeks) and one of the research projects in my portfolio that is attracting significant attention is the work on D-Wave.

Thanks so much for giving me the opportunity to make that happen!
...
Thanks a lot and best wishes,
Immanuel

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CESDIS & Beowulf

How USRA's creative research environment delivered unexpected computing technologies for science-based applications.

At the request of NASA in 1972, USRA established the Institute for Computer Applications in Science and Engineering (ICASE) at NASA's Langley Research Center. The subsequent success of ICASE prompted NASA to request USRA to create the Research Institute for Advanced Computer Science (RIACS) at NASA's Ames Research Center in 1983. In turn, the accomplishments of ICASE and RIACS led NASA to request a third computer-oriented institute from USRA in 1987, this time at NASA's Goddard Space Flight Center (GSFC). The new institute was called the Center of Excellence in Space Data and Information Sciences (CESDIS).

The original cooperative agreement between NASA and USRA for the establishment of ICASE stated that its first purpose would be to:

> *(P)rovide a focal point with a university atmosphere to serve as a center of the academic community for activities related to applied mathematics, computer science, and the application of the computer to the solution of scientific and engineering problems.*[1]

As an association of universities, USRA has sought to keep the spirit of this language in the management of all its programs, because "a university atmosphere" connotes freedom for creativity in research and often results in surprising benefits. CESDIS represents a case study of this principle.

At the urging of Dr. Milton Halem of GSFC, CESDIS was formed to carry out advanced computer science research in areas of potential, long-term interest to NASA programs, placing special focus on the processing and managing of data from space-borne, Earth-observing systems.

USRA asked Professor John Hopcroft of Cornell University to serve as the Interim Director of CESDIS while a search was conducted for the first permanent director. That search resulted in the appointment of Dr. Raymond E. Miller. The University of Maryland had collaborated with USRA in the formation of CESDIS by agreeing to provide a joint appointment for the CESDIS Director in its Computer Science Department at the College Park campus. Miller had been at Georgia Tech, but accepted a joint appointment with USRA and the University of Maryland to become the director.

RAYMOND MILLER
USRA DIRECTOR OF CESDIS

THE MOTIVATION FOR THESE RESEARCH AREAS AROSE OUT OF THE USE OF SATELLITES FOR EARTH SCIENCE STUDIES. CESDIS ISSUED CALLS FOR PROPOSALS TO THE COMPUTER SCIENCE COMMUNITY AND FUNDED THE TOP PROPOSALS.

Research areas of primary interest at CESDIS included:

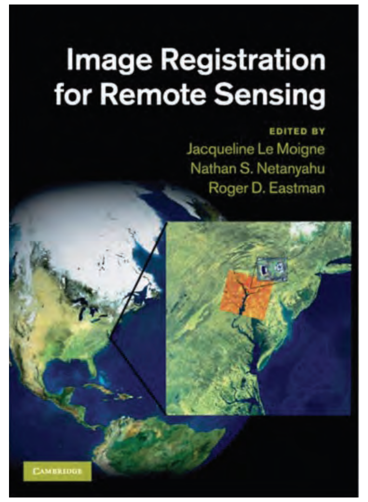
- High performance computing, especially software design and performance evaluation for massively parallel machines
- Parallel input/output and data storage systems for high performance parallel computers
- Database and intelligent data management systems for parallel computers
- Image processing
- Digital libraries
- Data compression

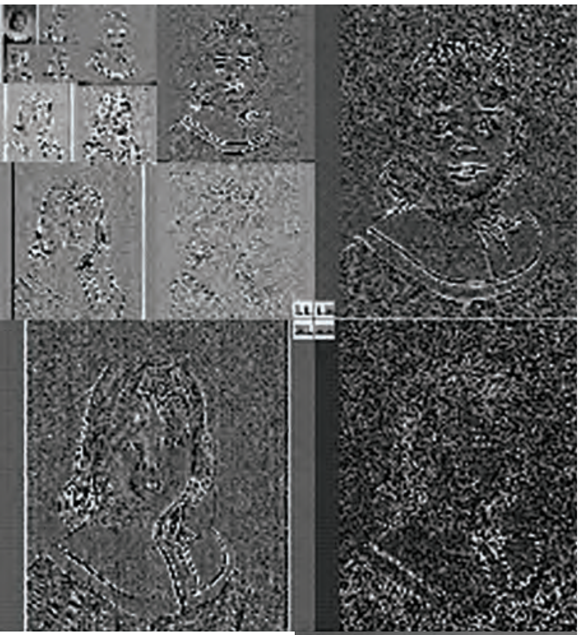
The motivation for these research areas arose out of the use of satellites for Earth science studies, e.g., climate change, crop yields, Earth resources, pollution studies and, in general, understanding the impact of human activities on major Earth ecosystems.[2]

As CESDIS had a small permanent staff, the Center issued calls for proposals to the computer science community and funded the top proposals on a competitive basis. Thus, a major part of the CESDIS research effort was carried out by associated scientists at universities who won the bids for multi-year funding.

In response to the first call for proposals issued in December 1987, CESDIS received 86 proposals. The first four awards from CESDIS were for:

- Parallel Compression of Space and Earth Data – Duke University
- A Knowledge-based Advisory System for General Scientific Data Visualization – George Washington University and Georgia Institute of Technology
- Computer Assisted Analysis of Auroral Images Obtained from High Altitude Polar Satellites – Stanford University and the University of Michigan
- Image Pattern Recognition Supporting Interactive Analysis and Graphical Visualization – The University of North Carolina at Chapel Hill





THE CORE STAFF OF CESDIS

The small core staff of CESDIS generally worked on enabling technologies, such as the task of finding efficient methods of registration of remotely sensed satellite imagery. Registration, which is the process of determining the best match of one scene with another, is a fundamental first step in the processing of satellite images of the Earth. For the large data flows produced by instruments on the Landsat and Earth Observing System satellites, image registration by hand is not feasible. The process must be automated, but automatic registration of satellite images is a difficult challenge for Earth science applications. The data often come from different instruments, on different satellites, with different resolutions, taken at different times of day and seasons.

Dr. Jacqueline Le Moigne, who joined CESDIS in 1992, became a world leader in automated image registration techniques that use wavelet transforms. Le Moigne received her PhD in Computer Vision from the Pierre and Marie Curie University in Paris before coming to the US.

Le Moigne's work was critical in the analysis of a stream of data from satellite imagery because one often wants to know when a sudden change occurred in the data stream, e.g., when an edge in the scene was encountered. Fourier transforms, which are based on sine and cosine functions, can give the overall frequency components of a signal, but are less useful in space localization. Transforms that use sets of wave functions of limited duration ("wavelets") are better at space localization and have found widespread application in image processing, including image registration.[3]

In a 1994 paper, Le Moigne used an image of her daughter to illustrate how:

> *Wavelet analysis can be implemented in a separable fashion by filtering the original image by a high-pass and a low-pass filter, iteratively in a multiresolution fashion, and separately in rows (vertical filter) and in columns (horizontal filter). At each level of decomposition, four new images are computed. Each of these images has one quarter of the number of pixels of the original image at the previous level, and it represents the low-frequency or high-frequency information of the image in the horizontal or/and the vertical directions; images LL (Low/Low), LH (Low/High), HL (High/Low), and HH (High/High).... The Low/Low image appears to be the same as the original image, except that it has a lower resolution. The other three images contain edge information, which when added to the Low/Low image can recreate the original image at full resolution.*[4]

CESDIS undertook many other tasks beyond the problem of image registration. In June 1991, USRA was asked by NASA to initiate a search for a Senior Technical Consultant within CESDIS to provide technical advice for NASA's High Performance Computing and Communications program. A USRA search committee, consisting of the directors of its three computer-oriented institutes, selected Dr. Thomas L. Sterling for the position. Sterling received his PhD from MIT's Electrical Engineering and Computer Science Department in 1984. Prior to joining USRA, he was a member of the research staff at the Supercomputing Research Center (SRC) of the Institute for Defense Analysis.

Raymond Miller retired as the Director of CESDIS in the fall of 1993. A search for his successor resulted in the appointment of Dr. Yelena Yesha as CESDIS Director in 1994. Born in the Ukraine, Yesha received her PhD in Computer and Information Science from the Ohio State University. Following her appointment, Yesha organized CESDIS into three branches:

- Applied Information Technology, headed by Yesha
- Computational Sciences, headed by Le Moigne
- Scalable Systems, headed by Sterling

THE BEOWULF PROJECT

In April 1994, Donald J. Becker joined CESDIS to explore the potential of a high performance parallel workstation built from inexpensive hardware and software. Becker was a graduate of MIT, and, like Sterling, had worked at the SRC before coming to CESDIS. While at the SRC, Becker wrote a substantial portion of the low-level Linux[5] networking code, including over a dozen device drivers for network adapters.[6] His experience on these drivers would be essential for the next phase of Becker's work. With the support of James R. Fischer, a NASA project manager at GSFC, Becker and Sterling teamed to work on the "Beowulf Project." As described by Sterling, et al:

> *Beowulf was the legendary sixth-century hero from a distant realm who freed the Danes of Heorot by destroying the oppressive monster Grendel. As a metaphor, 'Beowulf' has been applied to a new strategy in high performance computing that exploits mass-market technologies to overcome the oppressive costs in time and money of supercomputing.*[7]

The history of the project was recounted nicely in the citation of the Dr. Dobb's Excellence in Programming Award, which Becker was awarded in 1999 for his efforts in the development of the Beowulf.

AS A METAPHOR FOR A LEGENDARY HERO, 'BEOWULF' HAS BEEN APPLIED TO A NEW STRATEGY IN HIGH PERFORMANCE COMPUTING THAT EXPLOITS MASS-MARKET TECHNOLOGIES TO OVERCOME THE OPPRESSIVE COSTS IN TIME AND MONEY OF SUPERCOMPUTING.

JACQUELINE LE MOIGNE
USRA CESDIS,
COMPUTATIONAL SCIENCES

THOMAS STERLING
USRA CESDIS, SCALABLE SYSTEMS AND
BEOWULF PROJECT

YELENA YESHA
USRA DIRECTOR OF CESDIS AND
APPLIED INFORMATION TECHNOLOGY

DONALD BECKER
USRA CESDIS,
BEOWULF PROJECT

BEOWULF CLUSTERS TURNED OUT TO HAVE A SURPRISINGLY WIDE APPLICATION. THE USE OF BEOWULFS IS SO WIDESPREAD THAT "BEOWULF CLUSTER" NOW REFERS TO A CLASS OF SUPERCOMPUTERS.

One of the challenges in the realm of scientific computing is to efficiently and affordably handle large data sets. This is precisely the problem faced by researchers participating in the Earth and Space Sciences Project at the Goddard Space Flight Center. To tackle the problem, Donald Becker and Thomas Sterling launched the Beowulf Project, a cluster computer consisting of high-performance PCs built from off-the-shelf components, connected via Ethernet, and running under Linux. Ultimately, the goal of the Beowulf approach was to achieve supercomputer (gigaflop) performance at PC prices.

To implement such a system, however, Becker, who is a staff scientist with the Center of Excellence in Space Data and Information Sciences (or CESDIS, part of the Universities Space Research Association, a nonprofit consortium of universities that sponsors space-related research), had to come to grips with Linux's unstable networking capabilities, and the lack of Linux support for off-the-shelf network cards. Consequently, Becker ended up writing enhancements to the kernel network subsystem to support faster I/O on high-speed networks, device drivers for countless Ethernet cards, and a distributed shared memory package. ...

Although much of his initial work [at CESDIS] was in support of Beowulf, the entire computing community ultimately benefited from Becker's efforts. Linux would not have achieved the level of success and acceptance it has today had it not been for Becker's work, which resulted in a Linux with robust, stable networking and support for "every shipping Fast Ethernet chipset." As for Beowulf, dozens of university and research groups have now built their own Beowulf clusters, ranging from the original 16-node cluster running on Intel DX4 processors connected by channel-bonded 10-Mbits/sec Ethernet, to Avalon, a 19-gigaflop cluster of 140 Alpha processors that was built by the Los Alamos National Laboratory and that cost only $150,000.

Along with other members of his team at the Center of Excellence in Space Data and Information Sciences, Becker was the recipient of the ...1997 Gordon Bell Prize for Price/Performance "in recognition of their superior effort in practical parallel-processing research."[8]

The motivation for the development of the first Beowulf cluster computer at CESDIS was the desire to attack the problems faced by Earth and space science research communities, which are usually associated with large data sets. Beowulf clusters turned out to have a surprisingly wider application, so widespread that "Beowulf Cluster" now refers to a class of supercomputers. Dr. Phillip Merkey, a former CESDIS researcher, described the wider application:

> *Beowulf class cluster computers range from several node clusters to several hundred node clusters. Some systems have been built by computational scientists and are used in an operational setting, others have been built as test-beds for system research and others serve as inexpensive platforms to learn about parallel programming.*[9]

HOW TO BUILD A BEOWULF

In 1999, Sterling and Becker were co-authors (along with John Salmon and Daniel Savarese) of a popular book titled *How to Build a Beowulf: A Guide to the Implementation and Application of PC Clusters.* This book helped to make possible the construction of Beowulf clusters around the world, including at USRA institutes. As an example, at the request of NASA, Brian Fessler and others in the computer staff at USRA's Lunar and Planetary Institute constructed a 96-processor Beowulf cluster so that USRA's Division of Space Life Sciences (DSLS) could use it in NASA's Space Radiation Program. The DSLS Beowulf cluster was used to perform research on the health risks to astronauts from space radiation. Systems biology models of cancer, central nervous system effects, heart disease, and acute radiation sickness were developed by DSLS and NASA staff using the Beowulf cluster with models of particle track structure and the space environment. In addition, USRA's ICASE built a 64-processor Beowulf cluster to serve as a test bed for the institute's research activities in parallel and distributed computing, and CESDIS used the original 16-processor Beowulf cluster for its own research projects.

IN CONCLUSION

As noted above, USRA has interpreted "provide a focal point with a university atmosphere" to mean that USRA's institutes and programs should give researchers like Jacqueline Le Moigne, Thomas Sterling and Donald Becker as much freedom as possible to develop their innovative ideas. The results are often surprising and far reaching.

The Borg, a 52-node Beowulf cluster used by the McGill University pulsar group to search for pulsations from binary pulsars.

The Beowulf cluster at Michigan Technical University

ENDNOTES

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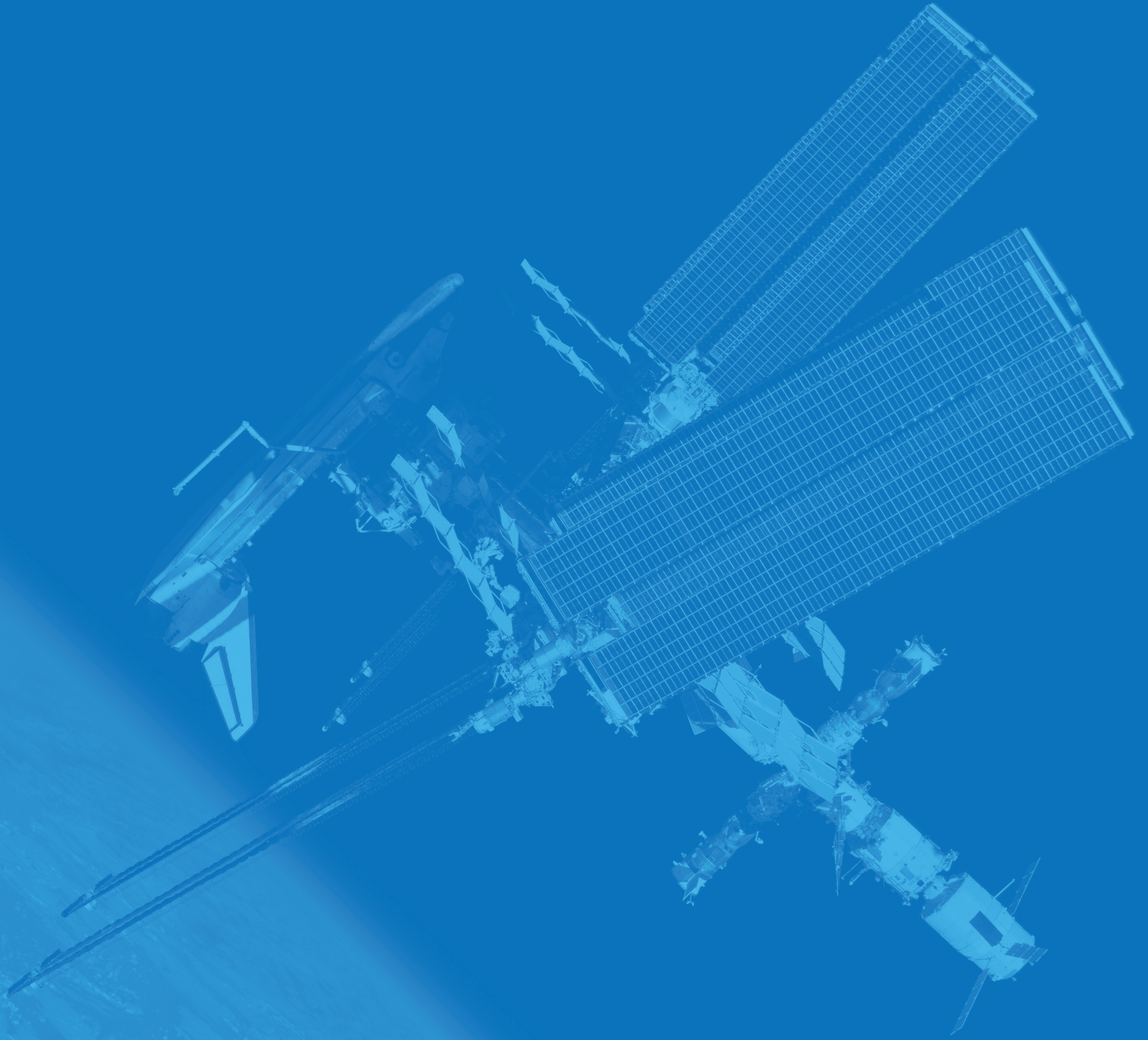
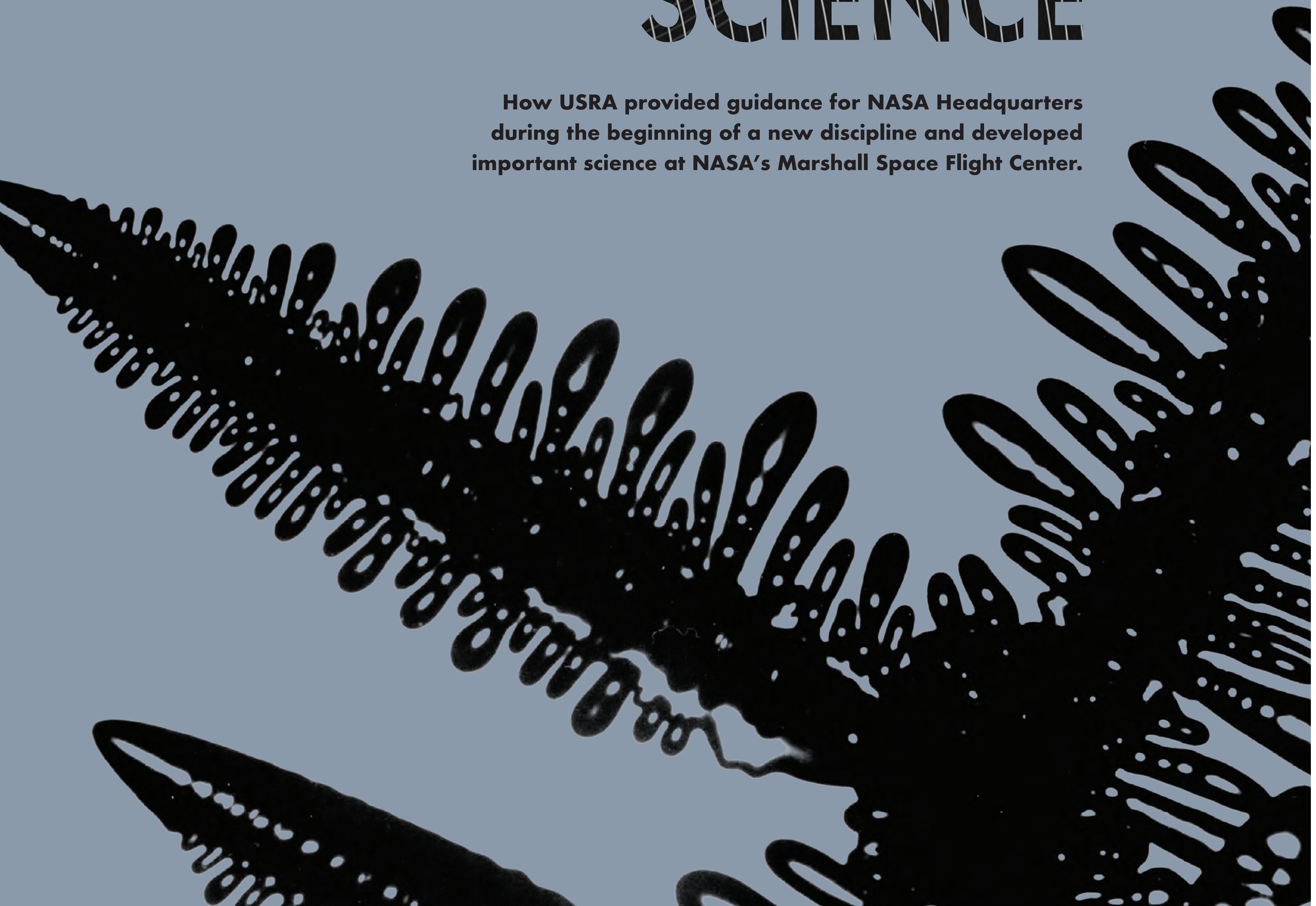
5

MICROGRAVITY SCIENCE



STARTING MICROGRAVITY SCIENCE

How USRA provided guidance for NASA Headquarters during the beginning of a new discipline and developed important science at NASA's Marshall Space Flight Center.



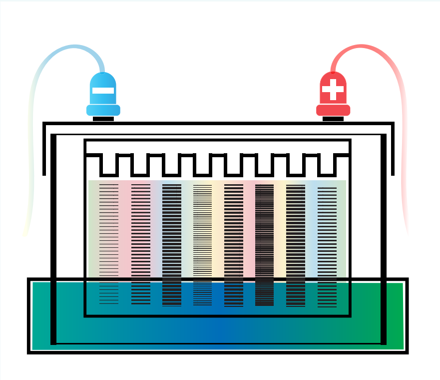
FROM NASA'S INCEPTION IN 1958, THE PROSPECTS OF OPERATING SPACE VEHICLES AND CONSTRUCTING STRUCTURES IN SPACE LED THE AGENCY TO STUDY THE BEHAVIOR OF FLUIDS IN SPACE.

> *The behavior of fluids in spacecraft was the object of a number of research efforts to design propellant management systems and other fluid systems required by emerging space technology. The development of spacecraft thermal control systems that utilize change of phase of materials for heat storage prompted questions concerning solidification phenomena in zero gravity. The possibility of the erection and repair of large structures in space by brazing and welding raised issues concerning the flow of liquid metals dominated by capillary forces.*[1]

As NASA prepared for laboratory facilities in space, the agency planned to more carefully study the behavior of fluids and materials as they relate to space operations. Some of the agency's managers who were involved in what came to be called "materials processing in space" also hoped for the development of another space-related industry, comparable in its impact to the highly visible and successful space communications industry. Dr. Robert J. Naumann of NASA's Marshall Space Flight Center (MSFC) expressed the hope of NASA managers who held this view:

> *The ultimate goal is to develop a viable commercial interest in using space (1) to perform research for improving industrial technology or developing new products; (2) to prepare research quantities of materials to serve as paradigms for comparing current earth-based technologies; (3) to manufacture limited quantities of a unique product to test market potential, or to fulfill a limited but compelling need; and (4) to produce materials in space of adequate quantity and value to be economically self-sufficient.*[2]

THE MOTIVATING IDEA WAS THAT A SPACE LABORATORY PROVIDED A FUNDAMENTALLY DIFFERENT ENVIRONMENT FOR FLUIDS THAN A LABORATORY ON THE EARTH'S SURFACE.



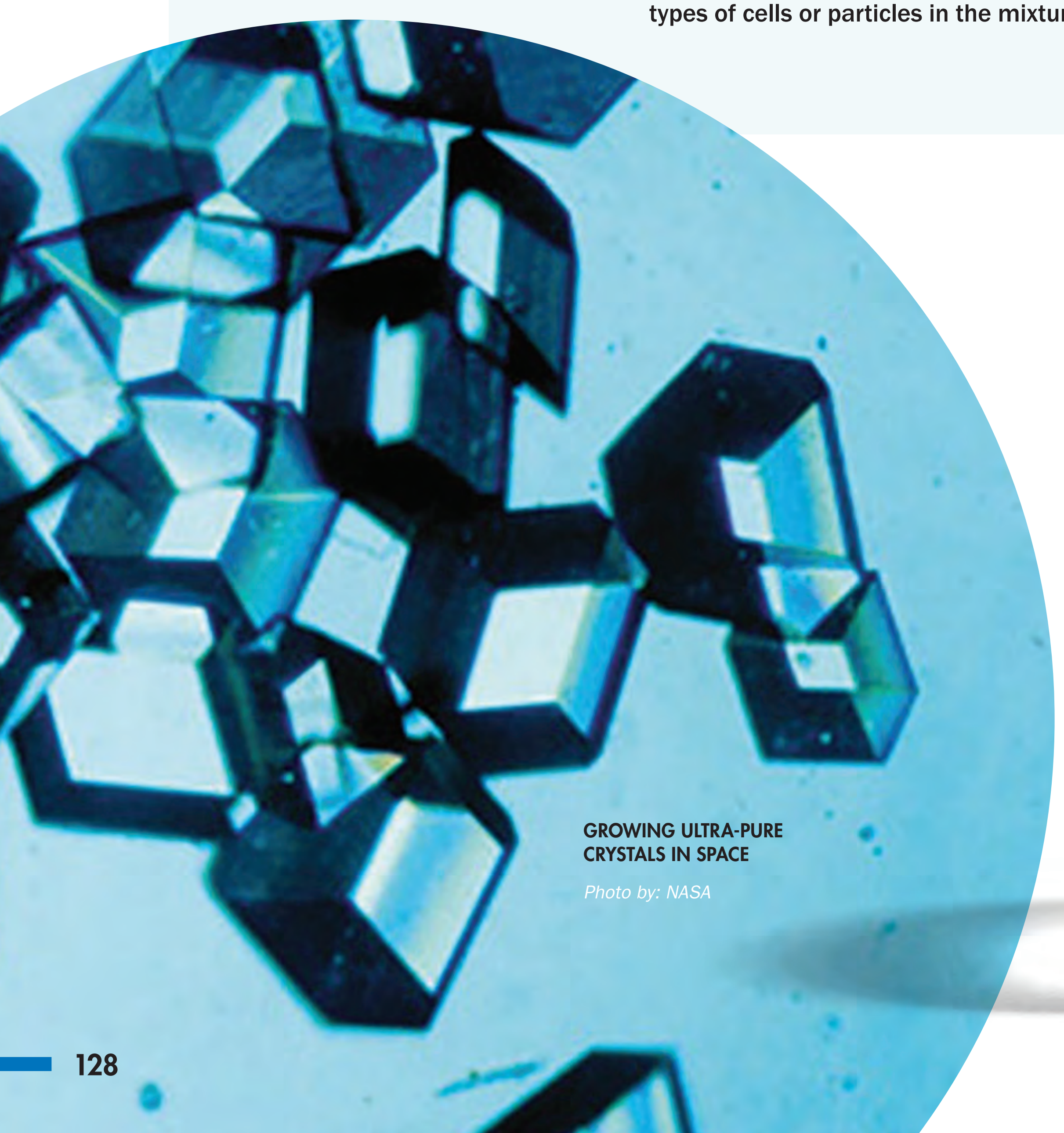
ELECTROPHORESIS

In electrophoresis, a mixture of particles to be separated, particularly different kinds of biological cells, is suspended in a buffer solution. Different cell types carry different charged species and charge densities on their surfaces due to the presence of characteristic membrane molecular structures. When an electric field is applied across the suspension, the cells or particles move in response to the field, but at different speeds, owing to different charge densities and configurations on the different cell types. The result is a separation of the different types of cells or particles in the mixture.

The motivating idea was that a space laboratory provided a fundamentally different environment for fluids than a laboratory on the Earth's surface. Fluids standing in Earth's gravity have a hydrostatic pressure caused by the weight of overlying layers of the fluid. The hydrostatic pressure thus decreases with height in the fluid. Bubbles and particles or fluid elements with less density than the surrounding fluid are pushed upward in response to this hydrostatic pressure gradient, whereas heavier elements sink. In Earth-based laboratories, this leads to phenomena such as buoyancy, sedimentation and convection currents, where heated elements rise and colder elements sink in a gravity field with a gradient.

Fluids in a space laboratory are in "free fall" around the Earth and have no hydrostatic pressure and no hydrostatic pressure gradient. The force of gravity in the best space laboratories is typically of the order of 10^{-6} of the force of gravity at Earth's surface, and for this reason the space laboratory environment came to be called a "microgravity environment." Naumann and others believed experimentation in this new environment might lead to discoveries that would have commercial value.

Many researchers thought of the use of a space laboratory primarily in terms of Materials Processing in Space, which was, in fact, the first name NASA used for its program in the microgravity materials sciences. Some examples of their research projects included: (1) growing ultra-pure crystals in space, since the absence of gravity-driven convection would eliminate unwanted fluctuations in composition, temperature, and flow at the surface of the growing crystal;[3] (2) processing material without a container, which could avoid contamination of material by the container, as well as the unwanted nucleation of crystals on the container's inner surface, while also permitting the processing of materials at temperatures beyond the melting point of the container;[4] (3) processing hollow glass spheres with a high degree of concentricity that could be used as fuel containers for inertially confined fusion experiments on Earth;[5] and (4) separating biological cells by the method known as electrophoresis, which could produce results superior to the results of the process on Earth, where convection and sedimentation are a hindrance.[6]



GROWING ULTRA-PURE CRYSTALS IN SPACE

Photo by: NASA

PROCESSING HOLLOW GLASS SPHERES

TO BE EFFECTIVE, THERE MUST BE MUCH MORE THAN EMPIRICAL TRIALS OF TERRESTRIAL TECHNIQUES: ATTENTION MUST BE PAID TO THE FUNDAMENTALS OF CONVECTION AND OTHER PHENOMENA.

USRA'S INVOLVEMENT IN MICROGRAVITY RESEARCH

USRA began its involvement in microgravity research soon after it was incorporated, and over the years the Association has been involved in a wide variety of efforts.

In June 1971, the first president of USRA, Professor A. Robert Kuhlthau (University of Virginia), responded to a request from NASA Headquarters for USRA to review, study, and evaluate possible flight experiments relating to materials processing in space. Kuhlthau appointed Professor Henry Leidheiser Jr. (1920–2011) to direct USRA's program on a consulting basis. For small, emerging, programs, USRA usually sought leadership from distinguished university professors on a consulting basis. Leidheiser was the Director of the Center for Surface and Coating Research at Lehigh University. As Kuhlthau reported to the USRA Council of Institutions in 1972:

> *The work involves providing technical guidance in the design and operation of experiments for Skylab[7] as well as preliminary demonstrations which are being conducted on board during the Apollo missions. At the moment we are concerned primarily with three areas: electrophoresis; convective heat transfer; and crystal growth. The program has involved participation by a number of scientists from ten universities, eight of which are members of USRA. Through this effort USRA has a significant role in one area of the Skylab program, and indications are that the effort will double during the coming year.[8]*

Very early microgravity experiments were carried out in the Apollo 14, 16, and 17 spacecraft when they were in unpowered flight between the Earth and the Moon. The results of the experiments began to show that the behavior of fluids in a microgravity environment would not be as simple as first supposed.[9] In particular, it was a mistake to assume that convection in fluids in space laboratories would not exist. Gradients in the surface tension of a fluid cause convective flows, for example, and since surface tension of a liquid depends on temperature, variations in the temperature of the surface of a fluid will result in convective flow.

ROBERT KUHLTHAU

HENRY LEIDHEISER

WILLIAM M. KAULA

Leidheiser managed discipline-based study groups, which became known as the "USRA Committees." By 1974, there were five USRA Committees, including: (1) Electrophoretic, Chemical and Biochemical Separation Processes; (2) Preparation of Glasses; (3) Solidification of Metals and Semiconductors; (4) Convection and Heat Flow; and (5) Containerless Processing Systems for Space.

Each committee would meet three or more times during the year with NASA representatives. Advice was given on program plans, details of specific experiments, and the feasibility of rocket experiments that could be accomplished prior to those planned for Skylab. In 1975, the five committees each prepared a chapter for a 119-page report that served as background material for a summer study panel on space processing convened by the National Academy of Engineering (NAE).[10]

Through the NAE study, NASA managers were trying to plot the future of microgravity materials research for the agency. At about the same time, in 1975, the USRA Board of Trustees established an Advisory Panel on the Orientation and Role of USRA. The panel was chaired by Professor William M. Kaula (1926–2000) (UCLA) and had as members Drs. George B. Field (Harvard), Herbert Friedman (1916–2000) (US Naval Research Laboratory), A. O. C. Nier (1911–1994) (University of Minnesota), Simon Ostrach (1923–2017) (Case Western Reserve University), and Robert M. Walker (1929–2004) (Washington University). The panel assessed national needs and the state of space experimentation in various disciplines in which USRA might become involved. On the topic of microgravity science, the panel noted:

> *To be effective, there must be much more than empirical trials of terrestrial techniques: attention must be paid to the fundamentals of convection and other phenomena.[11]*

IN 1977, USRA RECOMMENDED THAT NASA'S MICROGRAVITY PROGRAM DURING THE COMING YEARS SHOULD FOCUS ON "UNDERSTANDING PHENOMENA RATHER THAN THE DEVELOPMENT OF NEW PRODUCTS."

USRA'S TASK FORCE ON MICROGRAVITY MATERIALS RESEARCH

USRA's second president, Professor Alexander J. Dessler (Rice University), took office in 1975 and one of his first acts was to appoint a task force on microgravity materials research, with Simon Ostrach as its chair. Other members of the task force included Drs. John Carruthers (Bell Labs), Elias Snitzer (1925–2012) (American Optical), Donald Uhlmann (MIT), and Jay Zemel (University of Pennsylvania). Their report, shared with NASA, contained the recommendation that:

> *… principal attention of [NASA's microgravity materials] program during the coming years should be given to understanding phenomena rather than the development of new products.*[12]

ALEXANDER DESSLER
Photo by: Rice University

SIMON OSTRACH

The task force provided implications of its recommendations in the report as well, which included:

1. Establish an extensive scientifically and technologically significant ground-based research program directed toward the elucidation of phenomena which are important in space processing, and increase significantly the funding in this program.

2. Direct increased attention in space experiments to defining phenomena and materials characteristics which are important to space processing. … Such improved definition seems essential to achieve substantial industrial participation in the program.

3. Increased attention should be given to the use of space to obtain information which can contribute importantly to improving materials processing on Earth. Contact should be made with progressive industrial firms in various areas of technology, both to acquaint them with the characteristics and potential of space and to solicit their inputs to the program. The USRA Committees can play a significant role in establishing the desired dialog.

4. More detailed characterization of materials processed in space and comparison with Earth-processed materials should be carried out.

5. Develop through workshops and other programs the means by which potentially interested workers will be made aware of the field, its potential and its inherent interdisciplinary character.[13]

The USRA report was, in part, an attempt to focus NASA's efforts on the underlying science related to the behavior of materials and fluids in space. NASA began to implement the task force's recommendations, perhaps because one of the members of the task force, John Carruthers, soon became the Program Director for the Materials Processing in Space Division of NASA Headquarters.

Carruthers asked USRA to form Discipline Working Groups (DWGs) to assist his efforts at NASA Headquarters. Those in the disciplines of solidification processes, fluid and transport phenomena, bioprocessing, and containerless processing were to be the top level of a managerially nested series of working groups that also included Science Working Groups, Experiment Working Groups, and Investigator Working Groups. USRA's President Dessler appointed Dr. Guy E. Rindone (1922–2015), Professor Emeritus of Ceramic Science and Engineering at Pennsylvania State University, to head the new USRA program in the microgravity sciences in support of NASA Headquarters.

After a few years, Carruthers became frustrated with budget cuts at NASA that reduced research funding in the microgravity materials sciences, and he resigned. His deputy, Dr. Louis R. Testardi, who had been a solid-state researcher at Bell Labs, took over as manager of NASA's Materials Processing in Space Program.[14]

PHASE PARTITIONING

USRA persevered during the changes at NASA. Rindone's program established a liaison between USRA and European Space Agency (ESA) working groups and became involved in coordinating efforts to share experimental facilities between ESA and NASA principal investigators. In 1981, Rindone organized a review of the status of the microgravity program in the form of a conference that was jointly sponsored by the Materials Research Society (MRS) and held at their annual meeting in Boston. Rindone edited the book that was published for the symposium proceedings.

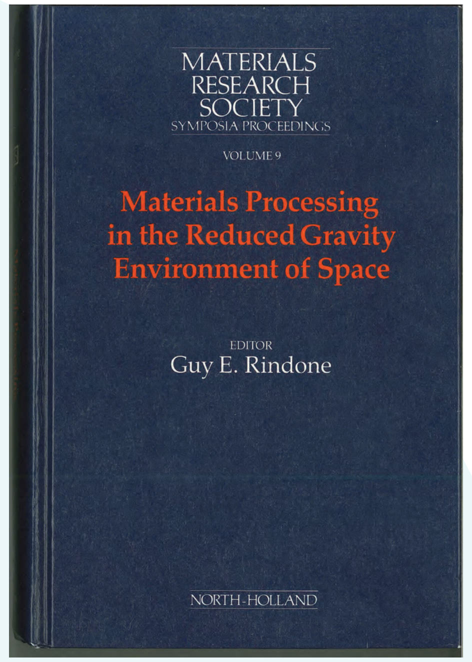
One of the papers at the MRS meeting in Boston in 1981 was by Professor Donald E. Brooks and Dr. Stephan Bamberger (University of British Columbia and University of Oregon Health Sciences Center) titled "Studies on Aqueous Two-Phase Polymer Systems Useful for Partitioning of Biological Materials." The work described was performed under the support of NASA contracts to Brooks beginning in the mid-1970s from MSFC, managed by Dr. Robert S. Snyder.[15] In their paper, the authors discussed the utility of two-phase systems for separating biological cells:

> *The two-phase systems which form when dextran … and poly(ethylene glycol) (PEG) are mixed to form aqueous solutions which are greater than a few percent in each, when appropriately buffered, have proven to be valuable as partition media for macromolecules, sub-cellular organelles and whole biological cells …When cells or microscopic particles are introduced to such systems, the systems shaken to emulsify the phases, and allowed to resettle, it is frequently found that the cells are distributed between the top, PEG-rich phase and the interface between the bulk phases, the dextran-rich phase being empty of cells. The interface therefore acts as a third phase with respect to the distribution of particulates in the system.*[16]

The authors noted the limitation of the separation process as carried out in ground-based laboratories and suggested that performing the separation experiment in low gravity could overcome the limitation:

> *Partitioning works well for relatively small cells. An inherent limitation appears for cells which sediment significantly during the time required for the phases to settle, however, since such cells will sediment into the interface, or to the bottom of the tube, before phase separation is complete. By working in a low gravity environment cell sedimentation would be eliminated …*[17]

The opportunity to perform the separation experiment in a low-gravity environment came a few years later. In the meantime, Testardi left NASA to become the Chief of the Metallurgy Division of the National Bureau of Standards in 1982. His successor at NASA Headquarters was Richard Halpern (1930–2009), who continued to rely on USRA. For example, Halpern followed up on Carruthers's efforts by asking USRA to reorganize the DWGs to assist him at NASA Headquarters. Halpern, who had successfully managed NASA's High Energy Astronomy Observatory project, used these committees to help him develop a strategic plan for NASA's microgravity program.



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GUY RINDONE

JAMES VAN ALSTINE

Photo Credit: NASA

PHASE PARTITION EXPERIMENT ON STS-51D

The astronaut who performed the Phase Partition Experiment on STS-51D was Senator Jake Garn (R-Utah), who was aboard the Shuttle as a Payload Specialist. At the time, Garn (top-right in this portrait of the STS-51D crew) was Chair of the subcommittee of the Senate Appropriations Committee that reviewed NASA's budget. As it happened, Dr. Rhea Seddon (bottom row, second from right) was a Mission Specialist for the flight. After leaving NASA in 1996, Seddon was the Assistant Chief Medical Officer of the Vanderbilt Medical Group. She was elected to serve on the USRA Board of Trustees in 2000 and served two terms on the board.

PHASE-PARTITION EXPERIMENT IN MICROGRAVITY

The scope of work for management of the USRA Committees expanded to include the hiring of USRA scientists to conduct research at MSFC. Brooks was a member and later Chair of USRA's Science Council for Materials Science and Applications, and he encouraged one of his PhD students, James Van Alstine, to apply for a position in USRA's materials science program at MSFC. Upon completion of his PhD in 1984, Dr. Van Alstine joined USRA's research group at MSFC.

While continuing to work with Brooks and others at the University of British Columbia, Van Alstine began a collaboration with colleagues at MSFC and the University of Alabama in Huntsville (UAH) to further study the phase separation process. Members of this team included Dr. Robert S. Snyder, senior NASA scientist and the manager of the Microgravity Fluid and Transport Processes Branch within MSFC; Dr. Blair J. Herren of MSFC; Dr. Laurel J. Karr, who had been a USRA Visiting Scientist and later moved to UAH; Dr. J. Milton Harris, a Professor of Chemistry at UAH; and Dr. Steven G. Shafer, also at UAH.[18]

The initial question Van Alstine's research group wanted to examine was why a simple model based on thermal energy considerations couldn't explain the results of phase-separation "distribution" experiments in laboratories on the Earth's surface.

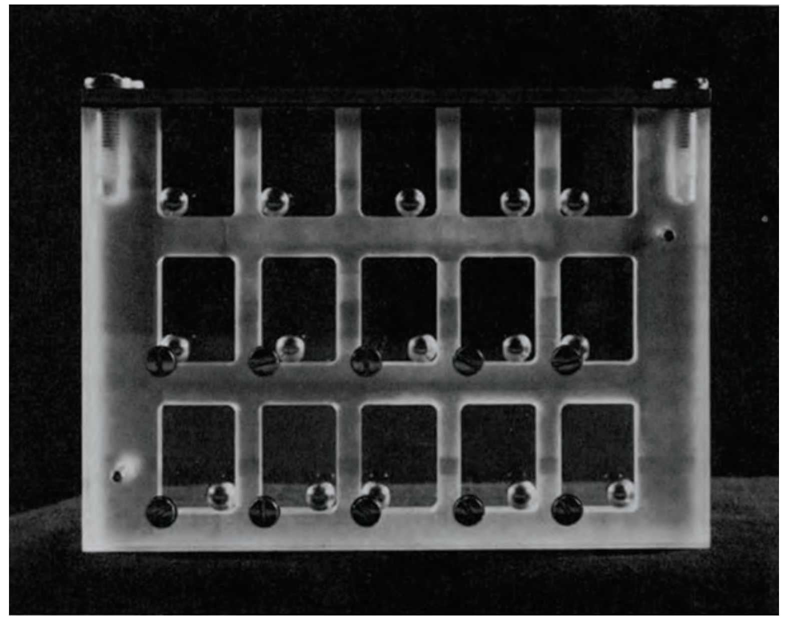
> *Cells which, on the basis of their adsorption free energy would be expected to be found at the interface [of the two phases] following a distribution experiment, have been removed from that location and released into the bulk phase by forces which are not thermal in nature.*[19]

Van Alstine and his colleagues felt that if these non-thermal forces could be identified:

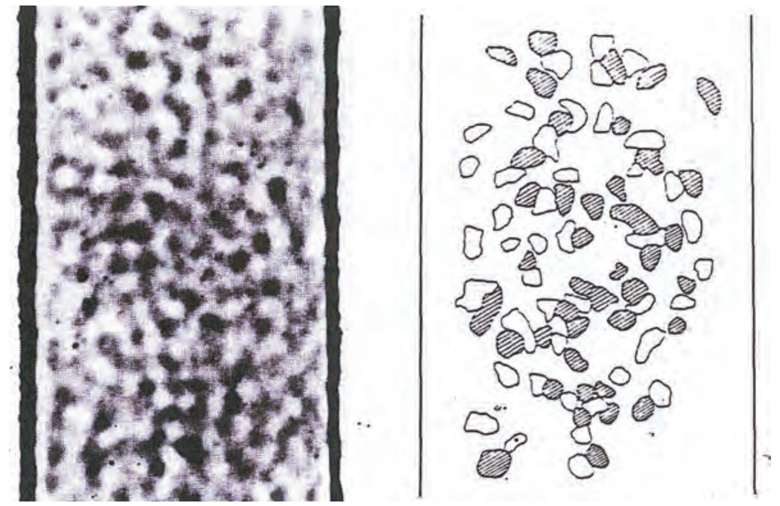
> *It should be possible to design a separation process that minimizes this influence. Much higher resolution separations would result, with attendant benefits to biomedical investigations and biotechnology.*[20]

Van Alstine, Brooks and their teammates suspected that the "other forces" were shear forces in the fluid that resulted from convection in the ground-based laboratory, and they proposed to test this hypothesis by flying a separation experiment in space. At this early stage of microgravity fluid experimentation, Van Alstine and his research group were not even sure that the phases, once mixed, would separate in a reasonable amount of time. In a Skylab experiment, oil and water emulsions were stable over a period of 10 hours, whereas the fluids separated completely on earth in 10 seconds.[21]

Van Alstine led the development of a simple hand-held phase-partition experiment (PPE) for the fourth flight of the Space Shuttle Discoverer in April 1985 (STS 51D). The device had fifteen chambers, each containing variations of the two-polymer phase system that Brooks and Bamberger had used – dextran and PEG. On Earth, these polymers rapidly separate into a less dense phase floating on top of the heavier phase. In the space experiment, the handheld device was shaken and the chambers were then photographed at intervals of time. The phases were observed to rapidly separate or demix, though slower than on the ground. The dextran-rich phase suspended, like an egg yolk, in the PEG-rich phase, which preferentially wetted the glass and plexiglass walls of the chambers. In related ground-based research, the team used wall coatings developed at UAH to control which phase would preferentially wet the walls of a container.[22]



Hand-held device for mixing two-phase systems on the Phase Partition Experiment of STS-51D. Five millimeter-diameter mixing balls are in the corners of each cell.[10]



Photograph of a stage in demixing process (left) and traced image for analysis (right).[25]

AS WILL BE SHOWN AT THE END OF THIS ESSAY, THE RESULTS OF THE PHASE PARTITION EXPERIMENT WERE PERHAPS LESS IMPORTANT THAN THE PROCESSES RELATED TO THE EXPERIMENT.

UNDERSTANDING THE RESEARCH RESULTS

The key to understanding the demixing process was to find the analytical form of the rate of demixing. The team had derived some approximate relations that described different scenarios for drop coalescence. If diffusion of small drops into larger ones was the dominant process, then the characteristic size of the drops was expected to increase as $t^{1/3}$, where 't' is the time from the onset of the mixing. If coalescence was produced by externally applied shear, such as might be present as a residual from the mixing process, the size of the drops was expected to increase exponentially with time. If coalescence was caused by shear produced by the local fluid disturbance generated by coalescence of two other drops, the size of the drops was expected to increase linearly with time.[23]

A measure of the rate of demixing was obtained by projecting the time-tagged photographs of the chambers, tracing the outlines of the connected domains, and then estimating the surface area and characteristic lengths of the domains of each phase as a function of time.

The initial space experiment on phase separations wasn't free of problems. It was found, for example, that the light source necessary to make the photographic record probably heated the fluids in the chambers by a few degrees, so data for only the first ten minutes of demixing was used in the analysis. Nevertheless, some conclusions could be drawn from the experiment. The team's analysis indicated:

> *… the slow mechanism of Ostwald ripening which involves the growth of large phase droplet regions by diffusive transport of material from smaller droplets culminating in a single large region of radius, r, growing asymptotically with time ($t^{1/3}$), is not responsible for demixing of these systems in low-g.*[24]

The most likely cause of the growth of droplets was coalescence, perhaps from externally applied shear, or slightly more likely from coalescence-induced shear.[25] As will be shown at the end of this essay, the results of the phase partition experiment were perhaps less important than the processes related to the experiment.

There were shuttle reflights of the PPE,[26] one on the Space Shuttle Challenger that was destroyed in flight on 28 January 1986. Space Shuttles were grounded after the tragedy while NASA sought to fully understand the reason for the catastrophic failure. During the down time, USRA continued to support NASA as the agency prepared for a resumption of shuttle flights and the construction and operation of what would become the International Space Station. In December 1986, USRA President Paul J. Coleman Jr. appointed Professor Martin E. Glicksman (Rensselaer Polytechnic Institute) to succeed Henry Leidheiser as director of USRA's Microgravity Science and Applications program. Van Alstine became Glicksman's deputy and manager of USRA's materials science program at MSFC.

MARTIN GLICKSMAN

Glicksman had served two terms on the USRA Board of Trustees and as chair in 1983–84. He came to the microgravity program as an internationally renowned materials scientist who would later act as Principal Investigator for three successful experiments, the Isothermal Dendritic Growth Experiments (IDGE), flown by NASA in 1994, 1996, and 1997 on Space Shuttle Columbia. IDGE experiments were to measure fundamental tests of the theories of kinetics and morphology of dendritic growth without complications induced by gravity-driven convection.[27]

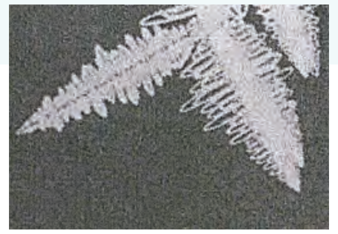
Glicksman shared the views of many of his university colleagues about first understanding the underlying science before attempting to develop space applications of material science:

> *Our experience on the IDGE gives support of our view that the best benefit of microgravity research in materials science is not to make something in space, but to try to gain scientific understanding.*[28]

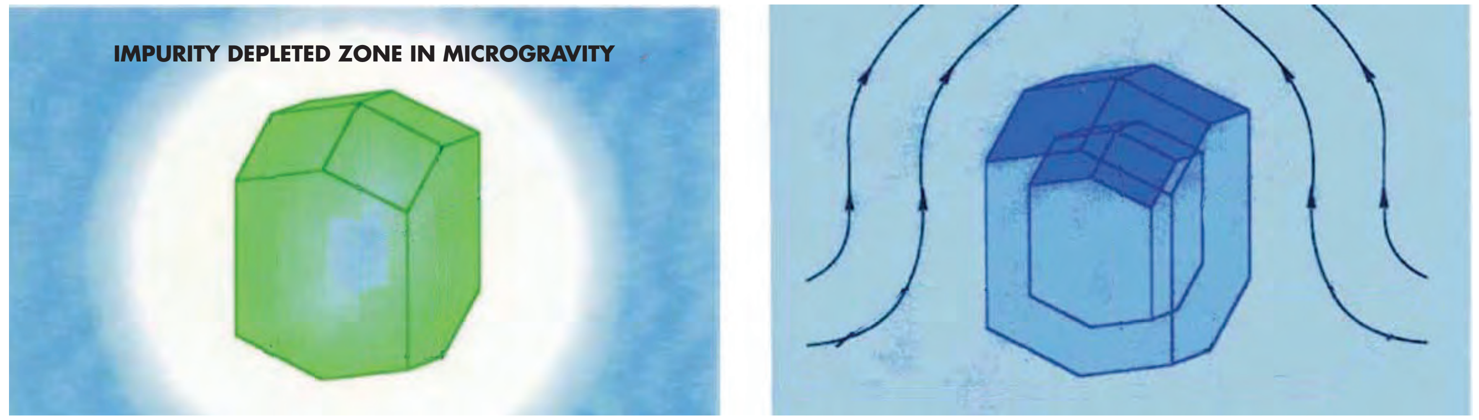
As IDGE was being developed, NASA suggested to Glicksman that the experiments could be used to test recently developed telescience technology, which would allow members of the IDGE team to remotely control the experiment. Glicksman accepted the suggestion and telescience (or tele-operations) was incorporated into the IDGE missions. At RIACS, USRA computer scientists had been heavily involved in the development of telescience[29] and thus USRA had an indirect, but important, impact on the IDGE mission. In his report of the first IDGE mission, Glicksman and his colleagues at Rensselaer wrote:

> *Tele-operational controls enabled optimization of finite resources, such as film capacity and orbital time, to accomplish specific goals despite several unpredicted events. We did not anticipate, for example, several eventualities encountered in the operation of the experiment. Without tele-operational control, the IDGE team would not even have known about some surprises until several months after the flight. Certainly we could not have altered the preset operational parameters to either avoid, or take advantage of those surprises and, in the process, improve the quality and quantity of the scientific data return.*[30]

Glicksman was elected to the US National Academy of Engineering in 1996. He authored two major materials science textbooks, *Diffusion in Solids*, and *Principles of Solidification*. He has been the recipient of several awards, including the Frank Prize of the International Organization of Crystal Growth (IOCG) in 2010.



Dendritic growth is a fundamental process observed in the casting of metals. This image is of dendrites of succinontrile grown in space during the first IDGE flight.[27]



Impurity concentration is designated by the blue color intensity. The crystallizing protein is symbolized by green. In a solution where diffusion is the dominant transport mode, the growing crystal preferentially traps impurities and purifies the solution around itself (left). If convection is present (right), liquid flow continuously brings new impurities to the crystal. [38]

PROTEIN CRYSTAL GROWTH

In 1996, an international search identified Dr. Alexander A. Chernov as the leading candidate to direct the Alliance for Microgravity Materials Science and Applications, which was a new collaborative effort between USRA, MSFC, the University of Alabama in Huntsville, and the Alabama Space Grant Consortium. Glicksman helped to persuade Chernov to take the job. Chernov, a distinguished Russian physicist, was an expert in crystal growth. He had been elected to the USSR Academy of Sciences in 1987 and was the recipient of several prizes for his contributions to science, including the first Frank Prize of the IOCG in 1989.

ALEXANDER CHERNOV

When Chernov arrived at USRA, one of the topics of intense interest at MSFC and worldwide was protein crystal growth. The first "let's see" experiments showed that crystallization of proteins or other biological macromolecules in the microgravity environment sometimes resulted in crystals of improved quality, probably owing to the elimination of convection near growing crystal surfaces. It was thought that these more perfect crystals might allow higher resolution diffraction that could better reveal the structure of the biomolecule that forms the crystal.[31]

The data showed that about 20% of the protein crystals grown in space were of better quality and larger than their terrestrial counterparts. A clear-cut explanation of this improvement and the conditions to consistently grow better crystals had not yet emerged.[32] Chernov and his colleagues assumed that, similar to inorganic materials, the lack of quality in the protein crystal was owing to the presence of impurities in it. For example, an impurity can distort the crystal lattice if the linear size of the impurity molecule exceeds that of the cavity that the lattice is able to provide.[33] Incorporation of the impurity into the crystal lattice causes lattice distortion and thus stress in the crystal. That stress is relieved by shifting the orientation of planes within the crystal structure, a phenomenon called mosaicity. Chernov and his colleagues argued that:

> *Understanding the principles controlling impurity distribution and establishing correlation between impurity content and the crystal perfection may suggest rational improvements in crystallization conditions.*[34]

And further:

> *Since molecular interactions are not affected by gravity, the only rational explanation of … improvement, if any, should be associated with convective versus diffusion transport difference and related changes in [protein crystal growth] surface processes.*[35]

To explain why some crystals are grown with more perfect structures in space, whereas more often they are not, Chernov developed the idea that the outcome depends on whether the growing crystals preferentially trap stress-inducing impurities.[36] Chernov explained:

> *Crystals growing in microgravity from solution should be more perfect if they preferentially trap stress-inducing impurities, thus creating an impurity-depleted zone around themselves. Evidently, such a zone is developed only around crystals growing in the absence of convection. Under terrestrial conditions, the self-purified depletion zone is destroyed by convection, the crystal traps more impurity and grows stressed. The stress relief causes mosaicity.*[37]

Chernov's hypothesis of diffusional self-purification of crystallization in microgravity has been accepted by research groups around the world. More generally, Chernov's work on understanding fundamental processes in biomacromolecular crystals has had a large impact on a growing and diverse science:

> *Crystallization of large biomacromolecules, acknowledged to be the rate-limiting step for structural proteomics and genomics, is also of fundamental interest as a new domain of phase transformation physics in general. Biomacromolecular crystals are also relatively new objects from the perspective of solid-state physics. Crystallization is based on molecular recognition and, as such, is of general biological interest, e.g., for enzymatic reactions and other similar problems of molecular biology and self-assembly.*[38]

Following seven years of service with USRA, Chernov joined the scientific staff of the Lawrence Livermore National Laboratory.

AN UNEXPECTED RESULT OF MICROGRAVITY RESEARCH

NASA's microgravity program had a difficult birth - between 1978 and 1989 there were seven different leaders of the microgravity program at NASA Headquarters. One of these managers, Dr. Frank Lemkey, was a Senior Research Fellow at United Technologies on loan to NASA through a senior executive exchange program. In the fall of 1989, Lemke wrote an article for a USRA newsletter in which he discussed the status of NASA's microgravity program:

> *We still suffer from the predictions and hyperbole of zealots who prophesied early commercial exploitation of novel semiconductors and space medicines* [39]

WHILE PURSUING FUNDAMENTAL RESEARCH ON PHASE PARTITIONING IN MICROGRAVITY, KNOWLEDGE GAINED ON THE PROCESSES USED IN THE EXPERIMENTS LED TO THE DEVELOPMENT OF SOME VERY IMPORTANT MEDICINES.

No novel space medicines, perhaps, but through a somewhat strange path, microgravity research eventually influenced the development of some very important medicines that are now produced in ground-based laboratories. The work of Van Alstine, Harris, Brooks and their teammates on surface coatings that were required for the Phase Partition Experiment (PPE) for Shuttle flights led to a USRA patent (US4690749A) on the use of polymer-coated surfaces to control the electric potential on these surfaces.[40] Among Van Alstine's co-inventers were Robert Snyder and Blair Herren of NASA, and Milton Harris and Steven Shafer of UAH. This was the first filed patent on what is now an industry-standard approach for controlling electroosmosis, or the movement of the whole fluid (not just its ions as in electrophoresis) under the influence of the electric field in electrophoresis devices. This control has been particularly important for capillary electrophoresis (CE), which, at this writing, is one of the most efficient separation techniques for the analysis of both large and small molecules. CE in coated capillaries is now a common bioanalytical method, as is the affinity electrophoresis method that also grew out of this work, and which is based on another of Van Alstine's patents (US5108568).

The research group with members at the University of Alabama in Huntsville, the University of British Columbia, and MSFC also began to work on PEG-related topics in biomedical research, noting:

> *The same chemistry used to covalently couple PEG to amino groups on glass surfaces can be employed to covalently link PEG molecules to protein gamma amino groups…* [41]

Members of the group began to further examine the covalent bonding of PEG to proteins, a process that came to be called "PEGylation." They and others found that PEGylated proteins could be of value by, among other things, increasing a medicine's half-life in a patient's bloodstream.

Following his research and research leadership at USRA, Van Alstine was appointed Professor of Chemistry at UAH, where he continued to work with Milton Harris and others. Van Alstine subsequently was appointed Professor of Surface Biotechnology at the Royal Institute of Technology in Stockholm, Sweden, before joining General Electric Healthcare in 1999.

Milton Harris remained at UAH and, in 1992, founded Shearwater Polymers, Inc., to advance PEG-related technologies. Harris's company helped develop several important drugs, among them Pegfilgrastim (sold under the brand name Neulasta®) and a PEGylated Interferon, Peginterferon alfa-2a (sold under the brand name Pegasys®). Pegfilgrastim is used to stimulate bone marrow to produce more white blood cells to fight infection in patients undergoing chemotherapy. Peginterferon alfa-2a has a longer life than Interferon and is thus better able to fight viral infections in the body.

IN SUMMARY

During the 1970s and 1980s, USRA provided a steadying influence on the emerging discipline of microgravity science by staying true to the vision of the second NASA Administrator, James Webb. Webb saw that an association of major research universities could bring needed expertise and insight as NASA encountered new scientific and technical challenges. In the case of microgravity science, the needed guidance came initially from Simon Ostrach's task force, which stressed the priority of understanding phenomena over making things in space. Coming from an association of research universities, such a view was perhaps predictable, but it has been amply validated as the proper course, because, as often happens, fundamental research has led to unexpected, but extremely important, applications.

ENDNOTES

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2. Naumann, R.J., 1979. Materials Processing in Space-An Overview of Studies in the USA. In *COSPAR: Space Research XIX; Proceedings of the Open Meeting of the Working Groups on Physical Sciences, Innsbruck, Austria, May 29–June 10, 1978.* Oxford, Pergamon Press, Ltd., pp. 489–502, p. 501.
3. Naumann and Herring, Materials processing in space, 16.
4. Ibid., 18.
5. Ibid., 23.
6. Ibid., 29.
7. Skylab was a US space station that orbited the Earth from 1973 to 1979. It was manned intermittently, with three work sessions between May 1973 and February 1974. Skylab contained a materials processing facility and a multipurpose furnace system.
8. Annual Report of the USRA President. 1972. Appendix V of the minutes of the annual meeting of the USRA Council of Institutions. USRA Archives.
9. Sharpe, R.J. and Wright, M.D., 2009. Analysis of Microgravity Experiments Conducted on the Apollo Spacecraft. NASA/TM – 2009-215905. National Aeronautics and Space Administration.
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11. Kaula, W.M., 1975. Report of the advisory panel on the orientation and role of USRA. Appendix C of the minutes of the annual meeting of the USRA Council of Institutions. USRA Archives.
12. Ostrach, S., 1977. Draft report of the USRA micro-gravity materials research task force. Appendix K of the minutes of the ninth annual meeting of USRA's Council of Institutions. USRA Archives.
13. Ibid., 8–9.
14. New Scientist. 1981. Cuts threaten US's efforts in space manufacturing. p.33.
15. In reviewing the history of USRA's involvement with NASA, one finds NASA managers who not only had a very good understanding of their science and/or technology but also an appreciation for the role of university researchers and USRA. Robert Snyder was one of those individuals, whose support for science and for USRA from within NASA was often crucial in allowing the collaboration between NASA and the university research community that was envisaged by the second NASA Administrator, James Webb.
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17. Ibid., 234.
18. Van Alstine, Brooks and Harris had collaborated on research related to polyethylene-glycol (PEG) while Van Alstine was pursuing his PhD in Chemical Pathology at the University of British Columbia.
19. Brooks, D.E., Bamberger, S.B., Harris, J.M., Vanalstine, J. and Snyder, R.S., 1988. Demixing kinetics of phase separated polymer solutions in microgravity. NASA Technical Report retrieved from the NASA Technical Report Server. Document ID 19890010910. (pp. 119–131).
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21. Lacy, L. and Otto, G., 1974, October. The stability of liquid dispersions in low gravity. In *Scientific investigations on the Skylab Satellite; Conference* (p. 1242).
22. Van Alstine et al., Phase partitioning in space and on Earth, 319.
23. Brooks et al., Demixing kinetics of phase separated polymer solutions, 129–130.
24. Van Alstine et al., Phase partitioning in space and on Earth, 311.
25. Brooks et al., Demixing kinetics of phase separated polymer solutions, 130.
26. In one of the reflights (Shuttle Transportation System (STS) 51G in June 1985) Van Alstine assisted Saudi Arabian engineers in the preparation of their experiment with the device. The person who conducted the phase partition experiment in that flight was Sultan bin Salman bin Abdulaziz Al Saud, who was a Lieutenant Colonel in the Royal Saudi Air Force. At the time Salman Al Saud was the youngest person to fly on the Space Shuttle (at the age of 28) and the first Arab to fly in space.
27. In 1988, a PPE was included on the STS 26, which was the first Shuttle flight after the Space Shuttle Challenger disaster of 28 January 1986. The experiment was flown on several other missions, the last being the First International Microgravity Laboratory (STS 42) in 1992. Many of these results were summarized as a chapter in a book providing an overview of low gravity fluid dynamics and transport phenomena. See Bamberger, S., Van Alstine, J.M., Brooks, D.E., Boyce, J., and Harris, J.M., 1990. Phase partitioning in reduced gravity. In *Low-gravity fluid dynamics and transport phenomena*., v. 130, (pp. 603–630).
28. Glicksman, M.E., Koss, M.B. and Winsa, E.A., 1995. The chronology of a microgravity spaceflight experiment: IDGE. *JOM, 47*(8), pp.49–54, p.49.
29. Ibid., 54.
30. USRA's Research Institute for Advanced Computer Science (RIACS) did the pioneering research and development on telescience at NASA, beginning in 1986. Specifically, the RIACS Networking Group, led by Dr. Barry Leiner (1945–2003), did the research and development, part of which involved the coordination of a Telescience Testbed Project for NASA that involved 15 research universities.
31. Glicksman et al., The chronology of a microgravity spaceflight experiment, pp. 53–54.
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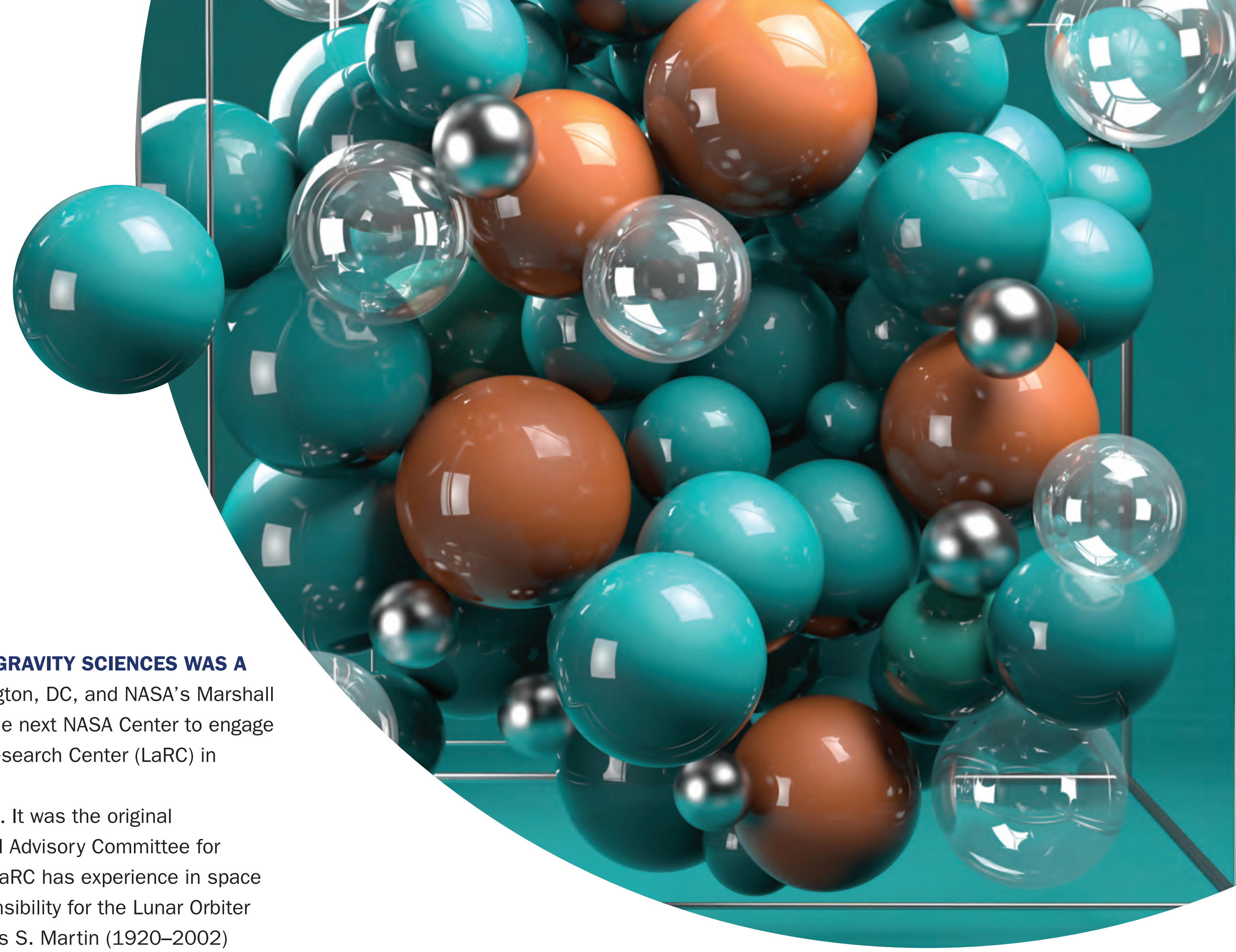
35. Ibid.
36. Ibid.
37. Some of the impurities in a crystal-growing solution, like dimers of the same protein (e.g., ferritin), may be spontaneously generated in the mother solution. (Chernov, A. A., personal communication)
38. Chernov, A.A., 1998. Crystal growth and crystallography. *Acta Crystallographica Section A: Foundations of Crystallography, 54*(6-1), pp.859–872, p.859.
39. Chernov, A.A., 2003. Protein crystals and their growth. *Journal of structural biology, 142*(1), pp.3–21, p.4.
40. Lemkey, F., 1989. Reflections of the Microgravity Director after 6 months on the Job. In *Microgravity* (A USRA newsletter edited by M.H. (Bill) Davis and John Masterson), Fall 1989 issue, p. 5., USRA Archives.
41. Patent US4690749 - Polymer-coated surfaces to control surface zeta potential. The patent is described as providing a method for eliminating or controlling electroosmosis and other zeta-potential-related phenomena in electrophoresis by using ectrophoretic surfaces coated with covalently-bound hydrophilic, neutral polymers. When a charged particle is in a fluid or on the surface of a container holding a fluid that contains ions, the electric field of the charged particle is partially shielded by surrounding ions that have charge opposite to its charge. The "zeta potential" refers to the residual electric potential difference between the partially shielded charge and the fluid.
42. Van Alstine et al., Phase partitioning in space and on Earth, 320.

DEVELOPING microgravity science

How USRA's technologists and technical managers, coupled with USRA's university structure, have assisted NASA in the development and implementation of important microgravity programs.



THE INITIAL INVOLVEMENT OF USRA IN MICROGRAVITY SCIENCES WAS A COLLABORATION with NASA Headquarters in Washington, DC, and NASA's Marshall Space Flight Center (MSFC) in Huntsville, Alabama. The next NASA Center to engage USRA in the microgravity sciences was the Langley Research Center (LaRC) in Hampton, Virginia.

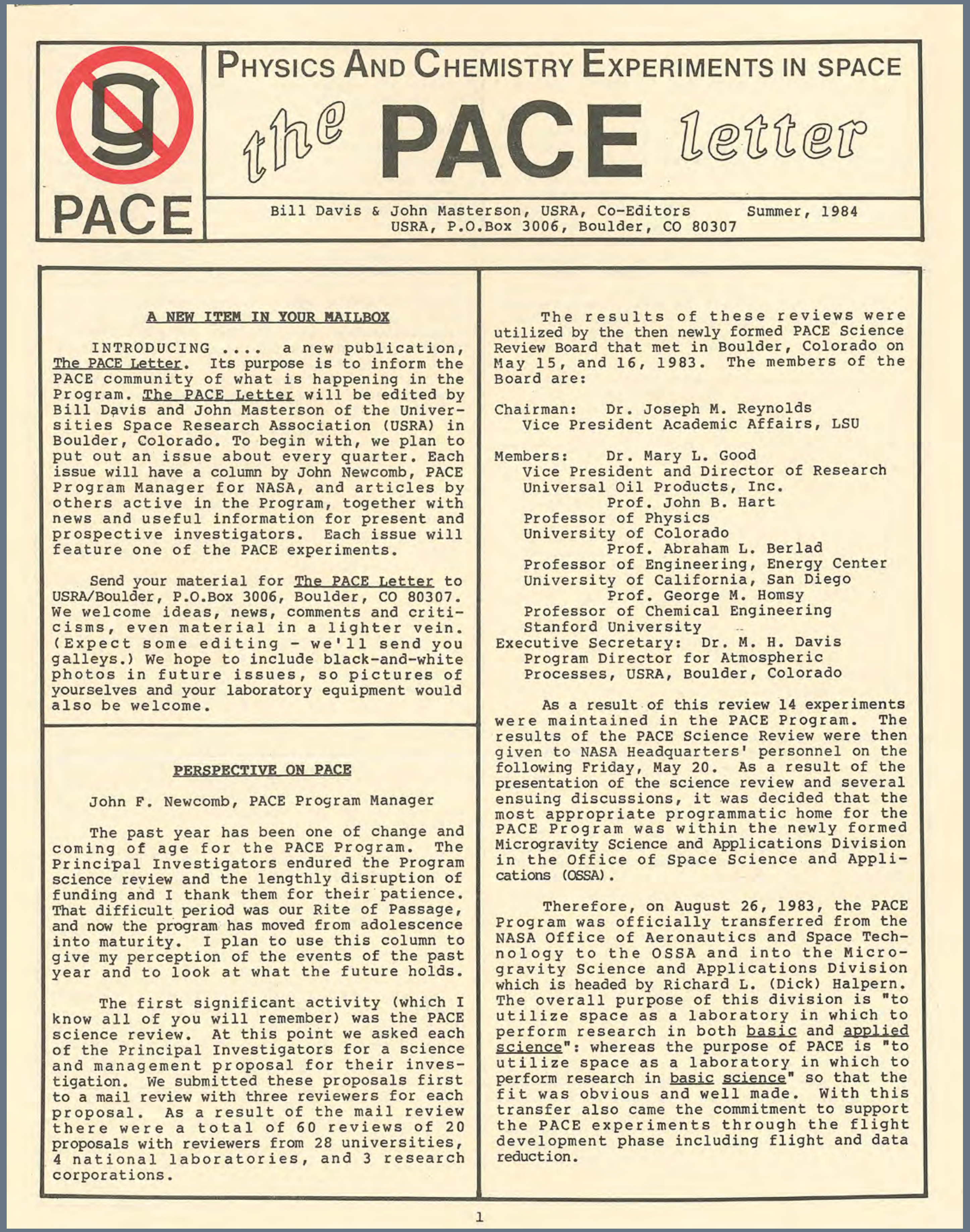
LaRC is best known for its research in aeronautics. It was the original aeronautical research center overseen by the National Advisory Committee for Aeronautics, which was the forerunner of NASA. But LaRC has experience in space research as well. The Center had management responsibility for the Lunar Orbiter project in the 1960s, and the LaRC team led by James S. Martin (1920–2002) managed the Viking missions to Mars. On 20 July 1976, the Viking 1 lander was the first US spacecraft to land on Mars.

By 1982, USRA's Institute for Computer Applications in Science and Engineering (ICASE) had been operating at LaRC for ten years. John Newcomb (1939–2016), a LaRC engineer who had important roles in both the Lunar Orbiter and the Viking missions,[1] knew about ICASE and its reputation for excellence, and he approached USRA for assistance with a program that he was managing called Physics and Chemistry Experiments (PACE) in space.

PHYSICS AND CHEMISTRY EXPERIMENTS (PACE) PROGRAM

Newcomb wanted USRA to put together a panel to review the PACE program experiments as they were being developed for possible flights on the Space Shuttle. USRA agreed to Newcomb's request, and a senior USRA manager, Dr. Milford H. "Bill" Davis (1925–2010), was assigned to develop and execute the project. As was typical for USRA, Davis turned to a distinguished individual in the university research community for assistance. He asked Professor Joseph M. Reynolds (1924–1997) to chair the PACE Science Review Board. Reynolds was the Vice President for Academic Affairs at Louisiana State University and a highly-regarded low-temperature physicist. He had served two consecutive terms on the National Science Board (NSB), which is essentially the board of directors for the National Science Foundation. Reynolds had also served a total of eight years on the USRA Board of Trustees. In the late 1980s, he would serve on the Space Science Board of the National Research Council and would have a large impact on the microgravity program being developed for the International Space Station (ISS).

JOSEPH REYNOLDS



PHYSICS AND CHEMISTRY EXPERIMENTS IN SPACE

the PACE letter

PACE

Bill Davis & John Masterson, USRA, Co-Editors   Summer, 1984
USRA, P.O.Box 3006, Boulder, CO 80307

A NEW ITEM IN YOUR MAILBOX

INTRODUCING .... a new publication, The PACE Letter. Its purpose is to inform the PACE community of what is happening in the Program. The PACE Letter will be edited by Bill Davis and John Masterson of the Universities Space Research Association (USRA) in Boulder, Colorado. To begin with, we plan to put out an issue about every quarter. Each issue will have a column by John Newcomb, PACE Program Manager for NASA, and articles by others active in the Program, together with news and useful information for present and prospective investigators. Each issue will feature one of the PACE experiments.

Send your material for The PACE Letter to USRA/Boulder, P.O.Box 3006, Boulder, CO 80307. We welcome ideas, news, comments and criticisms, even material in a lighter vein. (Expect some editing - we'll send you galleys.) We hope to include black-and-white photos in future issues, so pictures of yourselves and your laboratory equipment would also be welcome.

PERSPECTIVE ON PACE

John F. Newcomb, PACE Program Manager

The past year has been one of change and coming of age for the PACE Program. The Principal Investigators endured the Program science review and the lengthly disruption of funding and I thank them for their patience. That difficult period was our Rite of Passage, and now the program has moved from adolescence into maturity. I plan to use this column to give my perception of the events of the past year and to look at what the future holds.

The first significant activity (which I know all of you will remember) was the PACE science review. At this point we asked each of the Principal Investigators for a science and management proposal for their investigation. We submitted these proposals first to a mail review with three reviewers for each proposal. As a result of the mail review there were a total of 60 reviews of 20 proposals with reviewers from 28 universities, 4 national laboratories, and 3 research corporations.

The results of these reviews were utilized by the then newly formed PACE Science Review Board that met in Boulder, Colorado on May 15, and 16, 1983. The members of the Board are:

Chairman: Dr. Joseph M. Reynolds
Vice President Academic Affairs, LSU

Members: Dr. Mary L. Good
Vice President and Director of Research
Universal Oil Products, Inc.
Prof. John B. Hart
Professor of Physics
University of Colorado
Prof. Abraham L. Berlad
Professor of Engineering, Energy Center
University of California, San Diego
Prof. George M. Homsy
Professor of Chemical Engineering
Stanford University
Executive Secretary: Dr. M. H. Davis
Program Director for Atmospheric
Processes, USRA, Boulder, Colorado

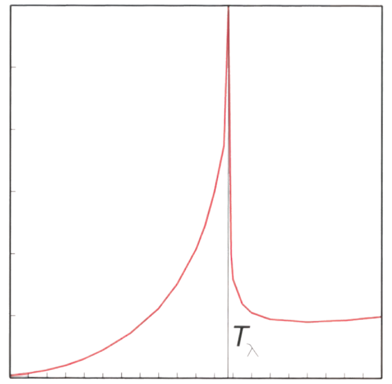
As a result of this review 14 experiments were maintained in the PACE Program. The results of the PACE Science Review were then given to NASA Headquarters' personnel on the following Friday, May 20. As a result of the presentation of the science review and several ensuing discussions, it was decided that the most appropriate programmatic home for the PACE Program was within the newly formed Microgravity Science and Applications Division in the Office of Space Science and Applications (OSSA).

Therefore, on August 26, 1983, the PACE Program was officially transferred from the NASA Office of Aeronautics and Space Technology to the OSSA and into the Microgravity Science and Applications Division which is headed by Richard L. (Dick) Halpern. The overall purpose of this division is "to utilize space as a laboratory in which to perform research in both basic and applied science": whereas the purpose of PACE is "to utilize space as a laboratory in which to perform research in basic science" so that the fit was obvious and well made. With this transfer also came the commitment to support the PACE experiments through the flight development phase including flight and data reduction.

1

Reynolds and Davis recruited other highly-qualified people to serve on the PACE Science Review Board, including Dr. Mary L. Good, who would later chair the NSB and become the Under Secretary for Technology in the Department of Commerce. As noted by Joseph C. Moorman, who succeeded Newcomb as NASA's manager for the PACE program:

> *The PACE Science Review Board, under the chairmanship of Dr. Joseph M. Reynolds, continues to be most supportive of the program. Its role in reviewing the science requirements and science definition at the appropriate time for each experiment provides an invaluable critique.*[2]



A plot of the heat capacity at constant pressure (Cp) versus absolute temperature for liquid helium at the point of transition from ordinary liquid helium to superfluid helium resembles the Greek letter lambda (λ) and is called the lambda-point transition.
Credit: Wikipedia

Bill Davis and his assistant, John Masterson, produced a periodical, the PACE Letter, to inform the PACE research community of what was happening in the program, which at that point included 14 experiments in various stages of development, aiming at eventual space flight opportunities. In addition to messages from NASA managers, the PACE Letter included short technical articles by some of the PACE researchers.

The main criteria for selecting PACE experiments for flight were the importance of the science and the necessity to use the space environment to conduct the experiment. One experiment by Professors Simon Ostrach and Yasuhiro Kamotani of Case Western Reserve University on surface-tension-driven convection under low-gravity conditions had implications for NASA's Materials Processing in Space program. Another experiment led by Professor Francis Everitt (Stanford University), which was ultimately carried out on the Gravity Probe B satellite, tested aspects of the theory of general relativity. Another experiment by Stanford University Professors William Fairbank (1917–1989) and John Lipa sought to characterize the transition of ordinary liquid helium to superfluid helium, the so-called lambda point transition, and provided a rigorous test of Dr. Kenneth G. Wilson's (1936–2013) Nobel prize-winning work on the application of renormalization group theory to phase transitions and critical point phenomena.

PACE "CRITICAL POINT" EXPERIMENTS

The PACE experiment of the group led by Professor Robert Gammon (University of Maryland) used light scattering techniques to measure density fluctuation decay times near the liquid-vapor transition of xenon. The experiment of Gammon and his colleagues was typical of so-called "critical-point" experiments, which shared certain features and difficulties in execution, as Gammon and his colleagues explained:

> *In a pure fluid near its liquid-vapor critical point, the otherwise small, statistical fluctuations in its density become as large as the wavelength of light when the system is still only 10 mK [mK = millikelvin = 10^{-3} kelvins of temperature] from the critical temperature, T_c. These large fluctuations scatter light very strongly, and the previously clear fluid turns milky white, a phenomenon known as critical opalescence.*
>
> *Indeed, many different systems have critical points, and large fluctuations of some thermodynamic parameter are a universal feature. Because critical fluctuations become macroscopic and involve enormous numbers of molecules, many features of critical-point behavior are controlled by the statistical behavior of the fluctuations, so that many types of systems exhibit the same behavior near the critical point.*
>
> *Light-scattering from critical fluctuations in a fluid is a simple and accurate technique to measure the decay rates of the fluctuations (the inverse of their lifetimes). However, near the critical point, the fluid becomes highly compressible, so the weight of the fluid alone causes severe density gradients in the sample, and distorts these measurements in a terrestrial laboratory.*[3]

The Gammon team used a very weak laser beam (17 μW away from the critical temperature and 1.7 μW near the critical temperature, where a μW is 10^{-6} watts of power) to measure the turbidity of xenon as its temperature approached the temperature of the phase transition:

> *Turbidity is the natural logarithm of the sample transmission per unit length, and is a measure of the overall cloudiness of the sample. We measured the intensity of the light leaving the sample and ratioed that with the intensity of the light entering the sample. Special electronics then calculated the logarithm of this ratio, giving us a measurement proportional to the turbidity of the xenon sample.*
>
> *The turbidity of a fluid increases as the fluid is taken nearer to its critical point and measuring the turbidity gives information about the average size (correlation length) of critical fluctuations.*[4]

The critical point experiments were difficult to carry out. After more than a decade of preparation, the PACE experiment of Gammon and his colleagues was finally flown on Space Shuttle flight (STS-62) in March of 1994.

MICROGRAVITY RESEARCH AT NASA'S LEWIS RESEARCH CENTER

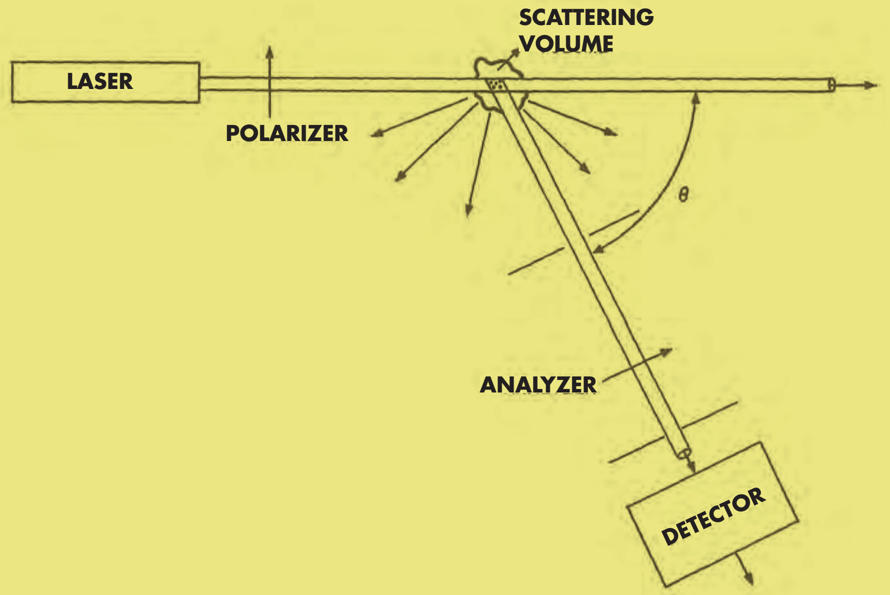
PACE experiments were on the "research" side of a continuing tension within NASA between those pushing for "materials processing in space" and those pushing for research on the phenomena related to the microgravity environment. In 1992, the Committee on Microgravity Research (CMGR) of the Space Studies Board of the National Research Council had issued a report titled *Toward a Microgravity Strategy*. The report contains the following admonition, (with emphases appearing as they did in the original):

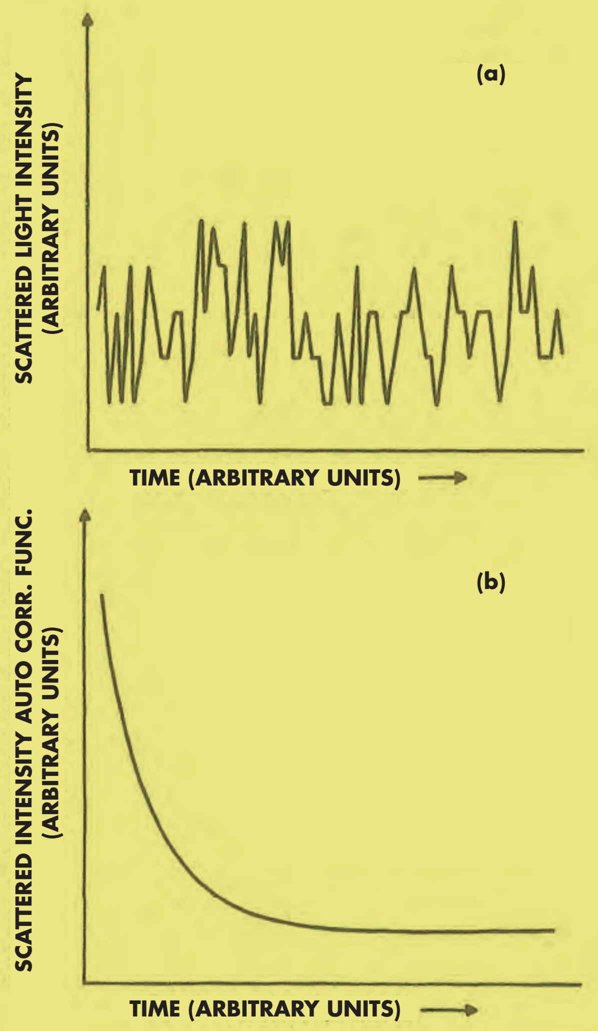
> *It should be recognized that, to date,* ***no*** *examples have been found of materials that are worthy of manufacture in space.* ***Unless and until such examples are found, space manufacturing of products to be used on earth should be deemphasized as a reason for undertaking microgravity research.*** *The descriptor "materials processing" is misleading and should be eliminated.* ***The CMGR recommends that "microgravity research"*** *be used instead. The main rationale for the microgravity research program should be to improve our fundamental scientific and technological knowledge base, particularly in areas that are likely to lead to improvements in processing and manufacturing on Earth. A secondary rationale should be to develop the technologies for handling materials in space and possibly for processing materials to be used in space.*[5]

The push for materials processing in space had been coming primarily from NASA's Marshall Space Flight Center. NASA's Lewis Research Center (LeRC), which was renamed the NASA John H. Glenn Research Center at Lewis Field (GRC) in 1999, was also interested in commercial payoffs for NASA's investment in microgravity research. But LeRC, located in Cleveland, Ohio, was designated a NASA Research Center, and its scientists (and their university colleagues) had been pursuing fundamental research on the behavior of fluids in low gravity for several years, using, among other things, two on-site drop towers that could provide 2.2 and 5.2 seconds of free fall for experiment packages. LeRC researchers also made frequent use of NASA's KC-135 Zero Gravity Trainer aircraft that could provide a low gravity environment for about 20 second intervals by flying successive parabolic flight paths.

In the mid-1980s, LeRC managers looked forward to the opportunity to take advantage of much longer periods of weightlessness in space laboratories, and they began to think about enabling technologies that would be required for future investigations in space. One such enabling technology was instrumentation for laser light-scattering experiments. These could be used to probe, relatively noninvasively, the characteristics of liquids, emulsions, and colloids in space laboratories, in much the same way that Gammon's team eventually had done with xenon in his PACE experiment. At the time, researchers and managers at LeRC knew very little about laser light-scattering technology, but they found a willing graduate student, who was completing work for a Master's degree at the University of Missouri-Rolla, and they asked him to quickly learn all he could about it. The student was William V. Meyer, and he would not only master laser light-scattering technology for use in the space environment, but also help to develop several other technologies for use on the Space Shuttle and the International Space Station (ISS).

Meyer was initially employed by Case Western Reserve University when he began to participate in the work of the Advanced Technology Development group at LeRC in the fall of 1987. He spent the next several months studying laser light-scattering and conferring with experts from all over the world. In September of 1988, he brought many of these experts together for a workshop in Cleveland to explore the capabilities





AUTOCORRELATION FUNCTIONS

Scattered light from moving suspended particles combine to appear at the detector as dancing speckles of light that are moving and individually changing in intensity. The rate at which this pattern changes at a particular scattering angle is collected to produce an autocorrelation curve. To compute the autocorrelation function for some quantity, e.g., light intensity E(t):

1. Partition some time interval T into small intervals that begin at t_0, t_1, t_2, etc., where in a simple analysis the intervals are all of equal length Δ.
2. Compute the average of $E(t_0)*E(t_0) + E(t_1)*E(t_1) + E(t_2)*E(t_2)$ + etc. over the interval T/2. This is just the approximate average of E(t)*E(t) over the time interval T/2, and it's the initial point on the autocorrelation curve, i.e., at the "delay" time $\tau = n*\Delta$, where n = 0.
3. Compute the average of $E(t_0)*E(t_1) + E(t_1)*E(t_2) + E(t_2)*E(t_3)$ + etc. over the interval $T/2 + 1*\Delta$, which gives the value of the autocorrelation curve at the time $\tau = 1*\Delta$.
4. Compute the average of $E(t_0)*E(t_2) + E(t_1)*E(t_3) + E(t_2)*E(t_4)$ + etc. over the interval $T/2 + 2*\Delta$. This gives the value of the autocorrelation curve at $\tau = 2*\Delta$.

By continuing in this manner, one can build the autocorrelation curve over the time interval T. At $\tau = 0$, the value of the autocorrelation function is a maximum, as it is just the average of the square of E(t) over some time interval T/2. As $\tau = n*\Delta$ increases, the sum of the product of E at time t and at time t + τ decreases until, as it turns out, it becomes the square of the average of the E(t). The shape of the autocorrelation curve is related to the rate of diffusion of the suspended particles. For example, smaller particles tend to diffuse more rapidly than larger ones. The faster the diffusivity, the more rapid the fluctuations in the intensity of the scattered light, and the steeper the decline of the autocorrelation curve.[9, 10]

TOP FIGURE: A schematic representation of a light-scattering experiment. Adapted from figure 1.2.1 of Berne and Pecora, 1976, p.6.

BOTTOM (a) Intensity of scattered light from 1.01 μm polystyrene spheres in water as a function of time.

BOTTOM (b) The autocorrelation function of the scattered intensity shown in (a) as a function of the "delay" time τ. See the above explanation of autocorrelation functions.

of existing laser light-scattering hardware and software and to assess user requirements for use of this technology with microgravity experiments.

In 1988, commercially available equipment for laser light-scattering experiments was bulky, heavy, fragile, and expensive. Fortunately, technological advancements were being made at some university and defense laboratories around the world. One such laboratory was the Royal Signals and Radar Establishment in Malvern, Worchestershire, United Kingdom. At the 1988 Cleveland workshop, Dr. Robert G. W. Brown of that laboratory described his lab's development of miniature instrumentation for laser light-scattering experiments, including solid-state lasers and detectors, electrical circuits that would fit on small boards, and optical fibers to transmit the laser light.[6]

In a typical laser light-scattering experiment, a polarized laser beam illuminates part of a fluid sample that contains a small fraction of suspended particles. According to classical electrodynamics, the oscillating electric field of the coherent laser light causes electrons in the molecules of the suspended particles to oscillate so that these particles radiate, and this radiation is the "scattered" light. A detector placed at a given angle with respect to the direction of the incident beam collects the light scattered from individual suspended particles in the scattering volume. The suspended particles are perpetually moving because of the bombardment of molecules in the surrounding host fluid, the so-called Brownian motion. Because of this motion, the positions of the charges in the molecules of the suspended particles are constantly changing so that the scattered wave electric field, which is the net "interference" electric field from several particles, will fluctuate erratically, resembling a noise signal. It turns out, however, that this "noise" signal can be analyzed using autocorrelation techniques to obtain information about the scattering particles, such as particle size and structure, molecular weight, and particle-particle interactions.[7, 8]

After the workshop, Meyer and his colleagues at LeRC and elsewhere began to work on a laser light-scattering device that could be used to study a range of fluid phenomena that are better examined in a low-gravity environment. Motivated by the discussions during the 1988 workshop, Meyer wanted a device with miniature, modular components that could be easily reconfigured. The device could be optimized for a wide range of experiments that would be proposed by Principal Investigators responding to NASA Announcements of Opportunity. Meyer envisioned a laser-light scattering device that would be tested first as a Space Shuttle experiment and later used on the ISS.[11]

HARD-SPHERE CRYSTALS

As early as the 1930s, university chemists had been developing models of liquids based on statistical mechanics, and in 1939 John G. Kirkwood (1907–1959), then of Cornell University, came to the following conclusion:

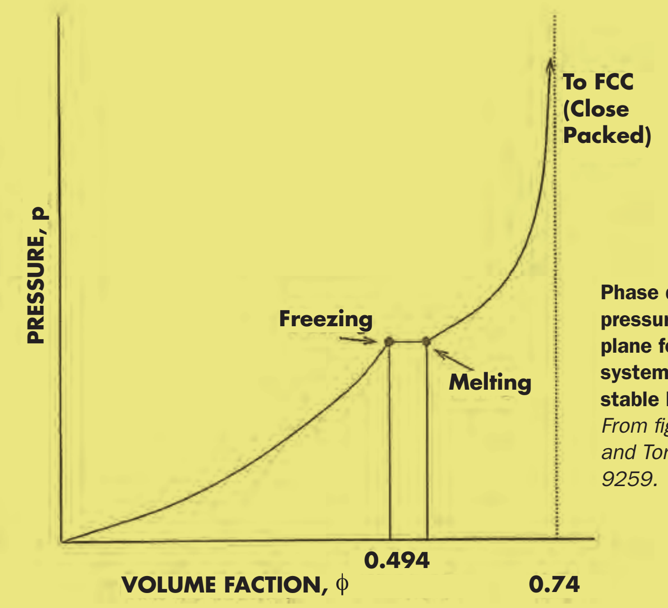
> *A limiting density exists above which a liquid type of distribution and a liquid structure cannot exist. Above this density, only structures with crystalline long range order would be possible.*[12]

Kirkwood and others kept working on his model for the behavior of liquids, but exact analytical solutions of their equations seemed to be unattainable. The advent of high-speed computers at US nuclear energy research laboratories in the 1950s enabled numerical approaches to the problem. These "computer experiments" revealed that at certain densities, a collection of hard spheres can exist in either of two states: in one where the particles are all confined to a narrow region of space determined by their neighbors; or in another where the particles have acquired enough freedom to exchange positions with the surrounding particles.[13, 14]

Further computer experiments indicated that hard-spheres systems can exist in (1) a disordered (liquid) state; (2) a state in which ordered and disordered parts coexist; and (3) a crystal-like ordered state. Early computer simulations also indicated the existence of a frozen, disordered, glassy state for hard-sphere systems, but more precise simulations with much faster computers showed that the glassy state does not exist. All hard-spheres systems, when all the spheres are of the same size, eventually reach a crystalline state.[15] Phase transitions between the three states depend on the volume fraction ϕ = (volume occupied by the particles/ total volume of the sample). When ϕ is below 0.494, the hard spheres exist in a "liquid" (disordered) phase. When ϕ is between 0.494 and 0.545, hard spheres in the liquid or "melted" phase coexist with collections of hard spheres that have "frozen" into an ordered, crystal-like state. When ϕ is between 0.545 and the volume fraction for close packing (0.74), all the hard spheres are in the crystal state.

The crystallization transition for hard spheres is said to be driven by entropy alone. Since the entropy of a closed system must increase during the crystallization transition, entropy loss associated with a more ordered arrangement of the hard spheres is more than compensated by the freeing up of space, providing more freedom for the individual particles (a higher state of entropy) in the collection of hard spheres when a lattice is formed.[16] This kind of entropy has been called "geometrical entropy" or "configurational entropy."

Computer experiments on hard sphere systems continued at US nuclear energy research laboratories into the 1960s. Meanwhile, the direct study of ordered colloidal systems was made easier by the ability to make tiny spherical polymer



Phase diagram in the pressure-volume fraction plane for the hard-sphere system, showing only the stable branches. *From figure 1 of Rintoul and Torquato, 1996, p. 9259.*

particles of almost exactly the same size. These systems are called monodisperse colloidal suspensions, and ones in which the polymer particles have diameters of the order of a micrometer (μm), a thousandth of a millimeter, have been used extensively. An advantage of the physical study of these colloidal suspensions over computer experiments is that one can use optical techniques to better understand the transition from disordered to ordered phases and, by studying diffraction patterns, one can examine the nature of the crystalline structures, e.g., whether they were face-centered cubic crystals or some other type. Another advantage is that the crystallization process for colloids typically has durations of hours to days, which is many orders of magnitude slower, and hence more convenient for study purposes, than the time scale for formation of crystals by atoms.[17]

Scientists in laboratories around the world have continued to perform experiments on monodisperse colloidal suspensions since the 1960s. By adjusting the surface coatings on the suspended particles, it has been possible to very closely approach the hard-sphere model, in which there were no electrical forces between the particles. As predicted by the computer experiments, transitions from disordered systems to ordered crystal-like arrays were observed even without any attractive or repulsive forces between the particles (other than at contact).

The left part of the figure is a photograph of a pre-flight, ground-based, CDOT sample of a solution of polymer spheres at a volume fraction ϕ = 0.504 (in the coexistence phase). The right part of the figure is a photograph taken in space of the same sample. The insert, under higher magnification, shows the dendritic growth of the crystals. (From figure 3 in Zhu et al., 1997.) White light incident upon the crystallites show them in different colors because of the wavelength dependence of the scattering. {Rogers et al., 1997, p. 7495.}

COLLOIDAL DISORDER-ORDER TRANSITION (CDOT) EXPERIMENTS

The first experiment slated to use components being developed by Meyer and his colleagues at Princeton University, Professors Paul Chaikin and William Russel, was the Colloidal Disorder-Order Transition (CDOT) experiment, which would examine the behavior of so-called hard-sphere systems in a colloidal dispersion. These are systems in which the dispersed particles are idealized as spheres that don't interact until they collide as perfectly hard bodies. The systems exhibit phase transitions best observed in the microgravity environment of space.

The first CDOT experiment was flown on Space Shuttle Columbia (STS-73), which was launched on 20 October 1995. The compact experimental equipment, approximately the size of a shoebox, examined fifteen different concentrations of spheres in the volume fraction range $0.482 \le \phi \le 0.634$.[18] As noted in a paper coauthored by Meyer, the first CDOT experiment made discoveries about the formation of colloidal crystals:

> *We … see dendritic growth instabilities that are not evident in normal gravity, presumably because they are disrupted by shear-induced stresses as the crystals settle under gravity. [And disordered, i.e.] glassy samples at high volume fraction which fail to crystallize after more than a year on Earth crystallize fully in less than two weeks in microgravity. Clearly gravity masks or alters some of the intrinsic aspects of colloidal crystallization.*[19]

The equipment for the CDOT-1 experiment worked as planned, but the colloidal crystallites grown in microgravity were much larger (up to 3.5 mm) than those grown in ground-based laboratories (up to 0.1 mm). This unanticipated difference caused problems in the laser-light scattering part of the experiment because the width of the incident laser beam was too small to properly analyze the larger crystallites.

Meyer continued to work with the laser-light scattering research community to improve designs for space use. He organized and co-chaired a conference on photon correlation spectroscopy in Capri, Italy, in August 1996, and he continued his own advanced technology development work at LeRC.

SIMON OSTRACH

ESTABLISHING THE NATIONAL CENTER FOR MICROGRAVITY RESEARCH (NCMR) ON FLUIDS AND COMBUSTION

In the meantime, on 12 March 1997, USRA partnered with Case Western Reserve University (CWRU) and NASA's Lewis Research Center to establish the National Center for Microgravity Research (NCMR) on Fluids and Combustion. The Founding Director of NCMR was Dr. Simon Ostrach, who was a Distinguished Professor of Engineering at CWRU and a member of the National Academy of Engineering since 1978. Ostrach had been elected to chair USRA's Council of Institutions in 1976, and he had served two terms on USRA's Board of Trustees (1987–1992).

Ostrach had chaired the USRA Microgravity Task Force, which had produced its report in 1977. Twenty years later, he now had the opportunity to put into practice some of the ideas of this report. For example, the report recommended:

> *Increased attention should be given to the use of space to obtain information which can contribute importantly to improving materials processing on Earth. Contact should be made with progressive industrial firms in various areas of technology, both to acquaint them with the characteristics and potential of space and to solicit their inputs to the program.*[20]

With this point in mind, Ostrach put in place an Industrial Outreach program as part of the NCMR. He began to recruit a ten-member Industrial Liaison Board (ILB) whose members were all vice presidents of research and technology, or equivalent, across a broad spectrum of major companies in the US. Dr. William Ballhaus, Jr., who was then the Vice President for Science and Engineering at the Lockheed-Martin Corporation, chaired the board. The members of the ILB included individuals from companies that used colloidal materials in their products, for example, the paints produced by the Sherman Williams Company, which was represented on the Board.

WILLIAM MEYER

NCMR AND THE ISS

A primary task of the NCMR was to help develop concepts that would lead to important experiments on the ISS. Bill Meyer had been the Project Scientist for CDOT-1, and he played the same role for two flights of the Physics of Hard Sphere Experiment (PHaSE), which flew on Space Shuttle missions STS-83 and STS-94 in 1997. The fit between the goals and aspirations of Bill Meyer and the NCMR were excellent, and he joined USRA and the NCMR on 16 February 1998.

Later that year, Space Shuttle Discovery (STS-95) carried CDOT-2 to low-earth orbit. The results from CDOT-2 confirmed those from CDOT-1 and the PHaSE experiments, namely that, in microgravity, crystallites of hard spheres form as millimeter-size dendrites in the coexistence part of the phase diagram and that face-centered cubic crystals form in what had previously been considered the "glass" part of the phase diagram. These experiments, as well as similar US experiments on board the Russian Mir Space Station in 1996 and 1997, made it abundantly clear that gravity in Earth-based laboratories masks important processes in colloids. This realization assured that colloids would be further studied on flights of the Space Shuttle and the ISS, the construction of which began in the fall of 1998.

Prior to the completion of the ISS, the Mir space station was available for microgravity research, and the next advance in microgravity research on colloids was conducted on the Mir in 1996, using equipment called the Binary Colloidal Alloy Test (BCAT). This equipment had been developed at NASA's Glenn Research Center in collaboration with Professor David Weitz and later with his PhD graduate student, Peter Lu, at Harvard University. Bill Meyer was the Project Scientist for the follow-on versions of BCAT (BCAT 3/4/5/6) that began to be a part of the microgravity laboratory on board the ISS in 2003. The first ISS BCAT experiment (BCAT3) examined phase separation in a mixture of weakly attractive colloidal particles and polymers near their critical point. The rationale for the experiment was described in a paper by Peter Lu, David Weitz, Bill Meyer, and others as follows:

> *BCAT3 is the first experiment to use the size advantage of colloids (which can be used to model atoms) to systematically and precisely locate the critical point and characterize the behavior around it. These particles are not only large enough to scatter light (and thus be visible to the camera, as well as the naked eye), but also large enough to slow down the dynamics to speeds that allow us to photograph the phase separation of samples over a period of weeks to months, using apparatus already onboard the ISS.…*

European Space Agency astronaut Paolo Nespoli operating the Light Microscopy Module microscope aboard the International Space Station. *(Credit NASA)*

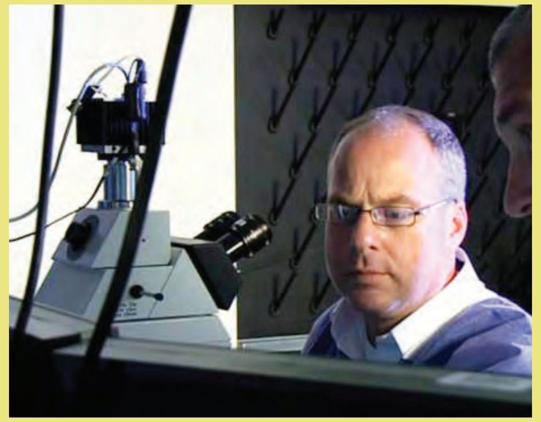
BCAT3 also has a number of direct applications with a potentially large impact on the everyday life of the general public. The specific dynamics of colloid-polymer mixtures are of great economic importance to product stability, as the colloid-polymer mixtures we study in BCAT3 have very close analogs in a number of household products. For instance, fabric softener is composed of vesicles (which behave like colloids) and polymer, added to increase viscosity and improve product performance. The general phase behavior is of great interest to manufacturers, who want to add more polymer without inducing the phase separation that we are observing in the BCAT3 samples, for if phase separation occurs during the shelf-life of certain household products, then their value to the consumer markedly declines. …

Finally, BCAT3 may play a role in enabling long-term manned spaceflight, such as those proposed for missions to the Moon and to Mars. Almost all studies on phase separation, and phase behavior, have been done on Earth, with its concomitant gravitational field. The evolution of complex fluids in the zero-gravity environment, particularly over the long term, is not nearly so well understood, and not well studied. Understanding how gravity influences the fundamental thermodynamic and kinetic processes of phase separation and gelation would therefore be extremely useful, and would facilitate the development of personal care products (necessary for any long-term spaceflight or mission) that are known to behave properly for long periods of time in the absence of gravity.[21]

Meyer continued his role as NASA's Project Scientist as Principal Investigators used the equipment that he had helped to develop for the ISS. The original equipment evolved with increased capabilities, and additional equipment, such as the Light Microscopy Module (LMM), was added to the ISS. Meyer has served as the NASA Program Scientist for the Advanced Colloids Experiment (ACE) since 2014, and he has been NASA's Project Scientist for many individual flight experiments for both the LMM and ACE. As of this writing, the ACE investigations are being conducted by teams that include investigators from New York University, Harvard University, the University of Pennsylvania, the Colorado School of Mines, the University of California-Irvine, the New Jersey Institute of Technology, the University of Kentucky–Louisville, the University of Milan (Italy), the University of Montpellier (France), the University of Amsterdam (the Netherlands), the Chungnam National University (South Korea), and Procter & Gamble.

The more advanced equipment on the ISS has enabled experiments in "colloidal engineering," such as the self-assembly of microstructures in a controlled fashion, with future experiments planned that will add self-replication to self-assembly. The equipment has also allowed the study of the behavior of mixtures of colloids of different sized particles (polydisperse colloids) that are commonly found in commercial products. The study of these polydisperse colloids in ground-based laboratories suffers from their tendency to sediment because of gravity. In many commercial applications, the manufacturer strives for the formation of a colloidal gel, which is a connected network of colloidal particles that can stabilize the system against sedimentation. As a colloidal gel, the product is in an arrested state of transition between a fluid and a solid, and the aim of the manufacturer is to keep it in this state for as long as possible so that the product can have a long "shelf life."[22]

This was one of the motivations for the research of Dr. Matthew Lynch of Procter & Gamble. At this writing, Lynch is the Principal Investigator for one of the ACE experiments, for which Meyer is the Project Scientist. By using the LMM on the ISS, Lynch has discovered that two sizes of stabilizer particles (2.2 μm and 1.8 μm) behave quite differently in microgravity. The larger particles build scaffolding (product stabilizers) and the smaller particles swarm about.[23] The discovery of this behavior is a step toward understanding polydisperse colloidal systems and how polydispersity could affect the stability of colloidal gels, and it was one reason that Lynch was one of four recipients of the 2013 award for the "Most Compelling Results from the ISS."



MATTHEW LYNCH

PROCTER & GAMBLE IN SPACE

In 2009, the Space Exploration Technologies Corporation (SpaceX) agreed to donate experimental payload space aboard a flight of their Falcon-9 rocket with a Dragon space capsule to support the Heinlein Trust Microgravity Research Competition. Bill Meyer asked Matthew Lynch to participate with him as a Co-Principal Investigator on a proposal that USRA would submit for this competition. The proposal, which was titled Low-Gravity Colloidal Engineering, did not win the Heinlein prize and the free space in the Dragon space capsule, but Matthew Lynch and Procter & Gamble have since been very involved in microgravity research. The Low-Gravity Colloidal Engineering experiment was later conducted very successfully as an ACE experiment on the ISS by Lynch and his colleagues.

USRA'S SUCCESS IN MICROGRAVITY RESEARCH CAN BE TRACED TO THE WILLINGNESS OF DISTINGUISHED MEMBERS OF THE UNIVERSITY RESEARCH COMMUNITY TO ASSIST IN ITS EFFORTS AND TO THE PASSION, PERSISTENCE, AND INGENUITY OF ITS SCIENTISTS, TECHNOLOGISTS, AND MANAGERS.

The research of Matthew Lynch is a good example of the resolution of the previous tension within NASA and the research community over the importance of basic research versus applications. In a letter to Bill Meyer, Lynch wrote:

We are very excited to be a part of this project with NASA and the other investigators. The goal of the project is to gain unique insights into the coarsening behavior of weak gels. Clearly the Company [Procter & Gamble] sees exceptional value in understanding and exploiting this knowledge for commercial benefit. At the same time, this work represents a much broader scientific question of critical importance to the broader scientific community. The historical challenge has been related to the density mismatch between the fluid and the dispersed particles. Coarsening has been masked by gravity-induced separation and gravitational stresses. Doing this work in microgravity is an exciting alternative to obtain otherwise extremely difficult data to move this field forward. … Finally, we are thrilled to be working this project with other world-class PIs, including Dave Weitz (Harvard University), to ensure the optimal scientific exploitation of this work; in addition, we also look forward to working with Professor Maia (Case Western University) to model these data.[24]

IN CONCLUSION

The goal of using microgravity research to improve Earth-based processes and products was recommended in the 1992 report of the National Research Council (*Toward a Microgravity Strategy*) and fifteen years before that in the 1977 report of the USRA Task Force that was led by Simon Ostrach.

USRA's success in this field has come in large part from the willingness of distinguished members of the university research community to assist in its work. Joseph Reynolds, Simon Ostrach, and Martin Glicksman are exemplars. Such assistance is perhaps a necessary but not a sufficient condition for performance that helps USRA team members and collaborators drive advancements in space-related science and technology. Outstanding scientists, technologists, and managers within USRA are also needed. Bill Meyer is representative of this ingredient for success. His passion, persistence, technological ingenuity, and his ability to coordinate the work of others have earned him the appreciation of the many scientists and engineers with whom he has worked. It has also earned him recognition by NASA. Meyer has received the Silver Snoopy Award, given by NASA's Astronauts; three Special Achievement Awards, given by the Director of NASA's Glenn Research Center; NASA's 2005 Exceptional Technology Achievement Medal and NASA's 2014 Exceptional Public Service Medal. The latter two marks of distinction are NASA's highest awards.

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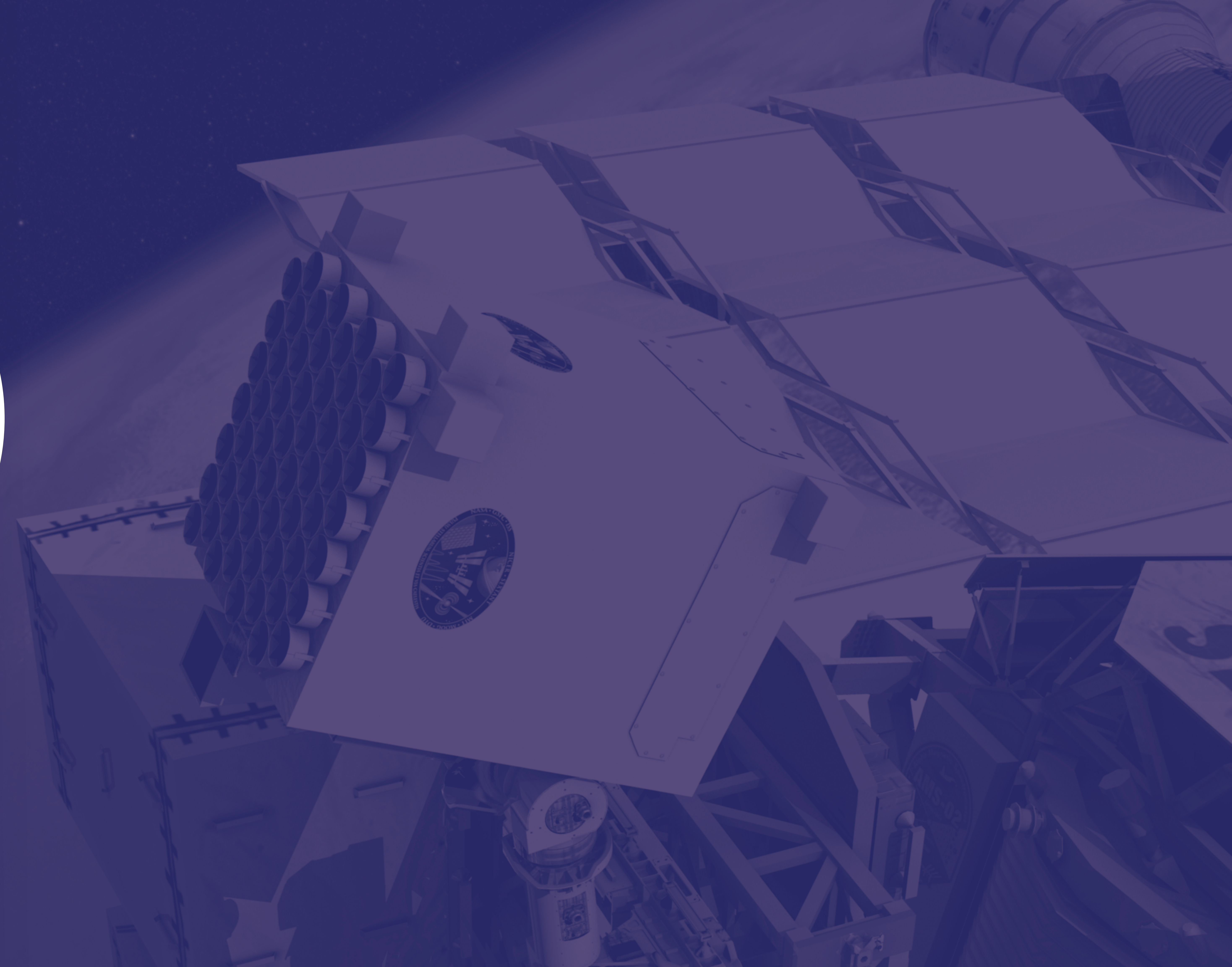


SPACE TECHNOLOGY

REVOLUTIONS IN SPACE

How USRA developed a means of supporting revolutionary advanced concepts for space exploration and applications on Earth.

Professor Dava Newman in her BioSuit.
Credit: Professor Dava Newman, MIT: Inventor, Science and Engineering; Guillermo Trotti, A.I.A., Trotti and Associates, Inc. (Cambridge, MA): Design; Dainese (Vincenca, Italy): Fabrication; Douglas Sonders

NIAC PROVIDED A PATHWAY FOR REVOLUTIONARY DISCOVERIES BY INNOVATORS WITH THE ABILITY FOR NON-LINEAR CREATIVITY TO EXPLORE NEW POSSIBILITIES FOR NEAR AND FAR TERM AEROSPACE ENDEAVORS.

ABOUT 500,000 CHILDREN IN THE UNITED STATES HAVE SOME FORM OF CEREBRAL PALSY. These children are unable to fully coordinate their arms and legs and other body parts. Cerebral palsy is not yet a curable condition, but a group of researchers at Children's Hospital in Boston, Harvard's Wyss Institute, Boston University, Draper Laboratory, and MIT are trying to change that. Their goal is to use "BioSuit" technology to guide the movement of infants with cerebral palsy and in the process, to reshape the motor programs in their brains.

The BioSuit technology was developed by Dr. Dava Newman of MIT to replace the bulky, gas-filled spacesuits that have been used by astronauts since before the Apollo program:

> *The BioSuit is based on the idea that there is another way to apply the necessary pressure to an astronaut's body. In theory at least, a form-fitting suit that presses directly on the skin can accomplish the job. What is needed is an elastic fabric and structure that can provide about one-third of sea-level atmospheric pressure, or 4.3 psi (approximately the pressure at the top of Mt. Everest). The skintight suit would allow for a degree of mobility impossible in a gas-filled suit.*
>
> *Thanks to some funding from the NASA Institute for Advanced Concepts, we were able to gather a team to begin the practical work that would test our hypothesis.*[1]

ROBERT CASSANOVA
USRA DIRECTOR OF NIAC

NASA INSTITUTE FOR ADVANCED CONCEPTS

The NASA Institute for Advanced Concepts (NIAC) that helped Dava Newman start work on the BioSuit was organized and developed by USRA in 1998 in response to a NASA request for proposals.

NIAC was a virtual institute. Its members were researchers, called NIAC Fellows, who had received funding from NIAC to develop aerospace and space science concepts for systems or architectures that might be realized 10 to 40 years in the future. NIAC funded revolutionary ideas and did not require that all the enabling technologies for the advanced concepts be currently available. In many cases the NIAC concepts spurred research on the required enabling technologies.

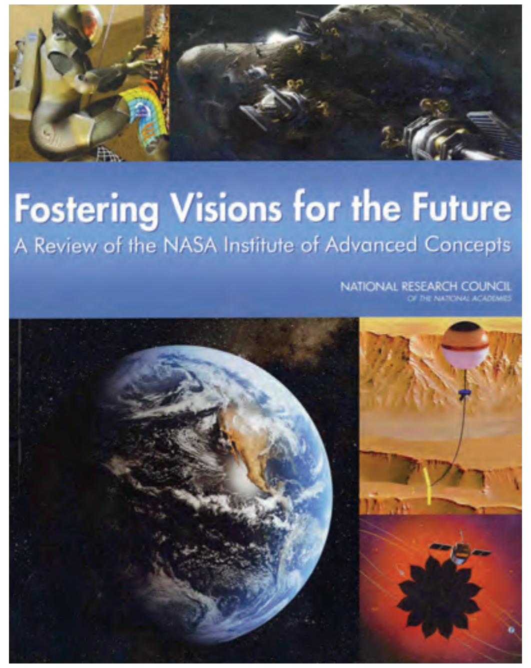
NIAC received a total of 1,309 proposals during the nine years of its existence as a USRA institute. From these proposals, NIAC made 126 Phase I grants (6 months, up to $75,000) and 42 Phase II contracts (2 years, up to $500,000) for studies based in a wide range of universities and businesses. NIAC was funded by NASA at a level of about $4 million per year, and more than 75% of the funding went to the projects of the NIAC Fellows.

The Director of NIAC was Dr. Robert Cassanova, who had been the Director of the Aerospace and Transportation Laboratory of the Georgia Tech Research Institute. Cassanova was also a member of the USRA Board of Trustees and served as its Chair from 1993 to 1997.

Several years after the conclusion of NIAC, Cassanova summarized his view of the effectiveness of the institute as follows.

> *Throughout its nine years of operation, the NIAC inspired and nurtured a number of revolutionary advanced concepts that someday may have a significant impact on future directions in aeronautics and space. NIAC provided a pathway for revolutionary discoveries by innovators with the ability for non-linear creativity to explore new possibilities for near and far term aerospace endeavors.*[2]

SEVERAL OF THE PROJECTS FUNDED BY THE ORIGINAL NIAC SUBSEQUENTLY RECEIVED ADDITIONAL FUNDING FROM A VARIETY OF AGENCIES AND COMPANIES.



The accomplishments of NIAC Fellows created a near-constant demand for information from outside the institute. Press releases captured the attention of mass media outlets around the world. NIAC staff were consistently available for public comment and served as resources for a broad array of publications, radio, and television programming, allowing the media to directly interface with NIAC Fellows. Beyond the popular press, NIAC and NIAC-sponsored advanced concepts received widespread recognition in technical journals. NIAC Fellows were highly visible in technical society meetings, with numerous presentations and publication of research papers in referred journals.

NIAC held annual meetings at which the NIAC Fellows gave progress reports. Following the October 2005 meeting, the NIAC leadership team organized a program to identify and nurture innovative undergraduates who had shown exceptional creativity and promise for success in building visions of the future. The NIAC Student Fellows Prize, sponsored by USRA and managed by NIAC, was initiated in 2005 to attract these students and to facilitate their studies. The prize, in the amount of $9,000, fostered mentoring, networking, and creativity, and provided undergraduate students a first opportunity to exercise responsibility in project management.

Through his work as the Director of NIAC, Cassanova received NASA's Public Service Medal for exceptional contributions to the Mission of NASA. For her guidance throughout the operation of NIAC, Sharon Garrison, the Coordinator for NIAC at NASA-GSFC, received the NASA Exceptional Achievement Medal. The NIAC team, including NASA and USRA's partner, the ANSER Corporation, received the NASA Group Achievement Award.

Despite these and other acknowledgements of success, NASA informed USRA in 2006 that it would not be able to continue funding NIAC, owing to budget cuts imposed on the Agency. The institute ceased operations on 31 August 2007.

In the report that accompanied NASA's appropriations bill for fiscal year 2008, the NASA administrator was directed to:

> *Enter into an arrangement with the National Research Council [NRC] to evaluate NIAC's effectiveness in meeting its mission, including a review of the grants made by the Institute, their results, and the likelihood that they will contribute to the Institute's stated goals; evaluate the method by which grantees are selected and recommend changes, if needed; and make recommendations as to whether the Institute should continue to be funded by the federal government and, if so, what changes, if any, should be made to its mission, goals, operations, or other matters.*[3]

In its report, "Fostering Visions for the Future: A Review of the NASA Institute of Advanced Concepts," the NRC Committee was very positive about the effectiveness of NIAC. The committee recommended that:

> *NASA should reestablish a NIAC-like entity, referred to in this report as NIAC2, to seek out visionary, far-reaching, advanced concepts with the potential of significant benefit to accomplishing NASA's charter and to begin the process of maturing these advanced concepts for infusion into NASA's missions.*[4]

NASA accepted the recommendation of the NRC committee and established the NASA Innovative Advanced Concepts (NIAC) program in 2011. The new NIAC program is very similar to the original NIAC but is operated within NASA. Robert Cassanova was chosen to be the first chair of the NIAC External Committee.

Several of the projects funded by the original NIAC subsequently received additional funding from a variety of agencies and companies. Three of these projects are briefly described on the following pages.

ROBERT P. HOYT
NIAC FELLOW

TETHER TRANSPORT SYSTEMS

Robert Hoyt of Tethers Unlimited, Inc., won a NIAC Phase I award in November 1998 for a study on Tether Transport Systems for LEO-MEO-GEO-Lunar Traffic. Based on the successful completion of that study, Hoyt was awarded a Phase II contract in August 1999 for the study of a Moon & Mars Orbiting Spinning Tether Transport system.

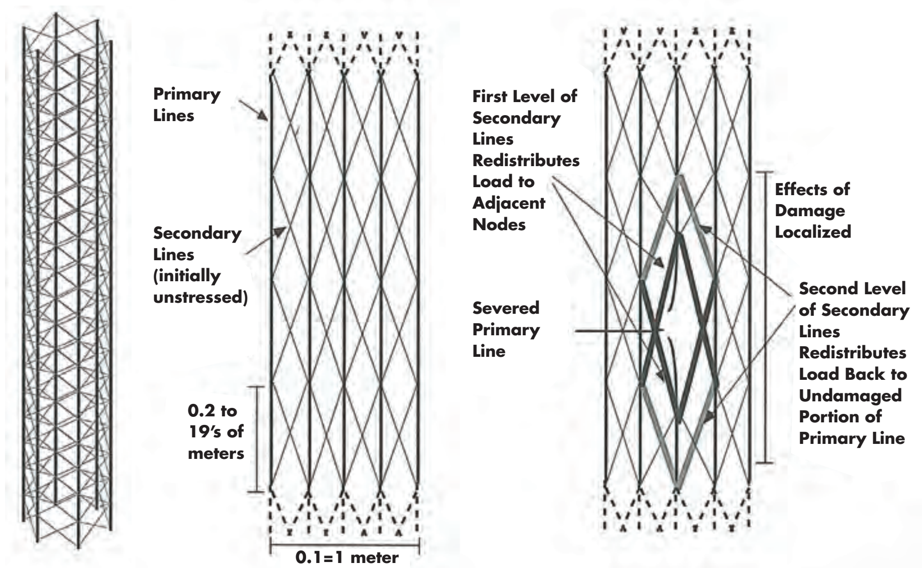
The basis for the space technology studied by Hoyt and his colleagues is a system of momentum exchange that makes use of a satellite with a tether that has the capability to catch payloads in one orbit and toss them into another orbit.

> *In a momentum-exchange tether system, a long, thin, high-strength cable is deployed in orbit and set into rotation around a central body. If the tether facility is placed in an elliptical orbit and its rotation is timed so that the tether is oriented vertically below the central body and swinging backwards when the facility reaches perigee, then a grapple assembly located at the tether tip can rendezvous with and capture a payload moving in a lower orbit, as illustrated in figure 1 [See page 157]. Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit. This concept is termed a momentum-exchange tether because when the tether picks up and tosses the payload, it transfers some of its orbital energy and momentum to the payload, resulting in a drop in the tether facility's apogee.*[5]

In his study, Hoyt examined the technological challenges of developing his Tether Transport System. These challenges included (1) a means to restore the tether facility to its original orbit after a transfer, (2) a reliable way to capture the payload, and (3) the design of a high-strength cable that could withstand the space environment.

To restore the tether facility to its original orbit after it has been used to toss a payload into a higher orbit, Hoyt proposed using thrust from a current that would run down the tether and interact with the Earth's magnetic field. Depending on the direction of the current in the tether, the force on the tether would either produce a drag on the system or give it thrust and raise it to a higher orbit. For this "electrodynamic reboost," no rocket propellant would be required to restore the tether facility to its original orbit.

Hoyt thought that the design of the capture process was the most difficult challenge for his Tether Transport System. He envisioned that the length of the tether would be on the order of 100 km and that the tip of the tether would be travelling at about 1 km/s as it passed close to the payload to be captured. By letting the payload capture mechanism at the tip of the tether release a tethered grapple, the encounter time for the capture could be extended to several tens of seconds.



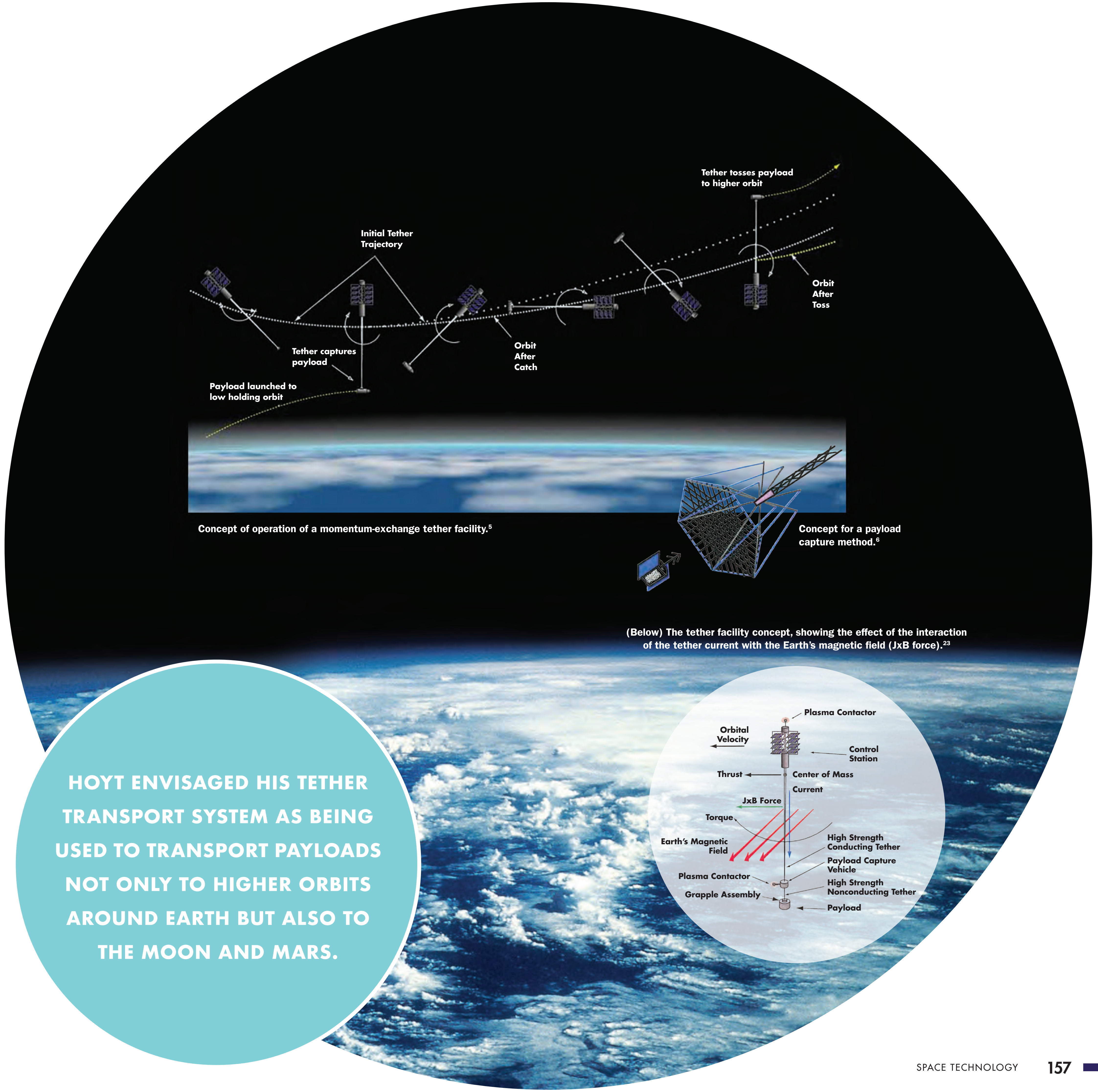
A possible grapple mechanism is a "net and harpoon" design. The payload maneuvers to the proximity of the net and then shoots a tethered harpoon into the net. One half a rotation later, the payload is released by retracting the barbs on the harpoon.[6]

The third major challenge for Hoyt's tether transport facility was the design of the tether. It had to have high strength and low weight, and it had to be durable in the environment of near-Earth space. Hoyt's solution was a trademarked product, the Hoytether, which is an open net structure that provided redundant linkages to allow for the possibility that the tether might be damaged by micrometeoroids or space debris.

Such a possibility was demonstrated in 1994 during an actual tether experiment in space (the Small Expendable-tether Deployment System–2) that used a cylindrical braided line with a diameter of 0.8 mm and a length of 20 km. This tether (not a Hoytether) was cut by a meteoroid or debris impactor about 4 days after deployment.[7]

Hoyt envisaged his tether transport system as being used to transport payloads not only to higher orbits around Earth but also to the Moon and Mars, and he thought about it in terms of a commercial venture.

> *If a tether-based transportation architecture is to be developed in part or in whole by a commercial venture, the deployment of the system must follow a path that is commensurate with a viable business plan. An Earth-Moon-Mars Tether Transportation System will require at least three tether facilities, one in Earth orbit, a second in lunar orbit, and a third in Martian orbit. Each of these will require a significant investment in technology development, system fabrication, and facility launch. To keep the capital investments small enough for a business plan to close, the system architecture must be designed in a manner in which the first components can immediately serve useful functions to generate revenue to fund the development of the rest of the system. This would be quite analogous to the development of the cross-continental railroads, where each extension of the rail line was used to generate revenue to help build the rest of the line.*[8]



Concept of operation of a momentum-exchange tether facility.[5]

Concept for a payload capture method.[6]

(Below) The tether facility concept, showing the effect of the interaction of the tether current with the Earth's magnetic field (JxB force).[23]

HOYT ENVISAGED HIS TETHER TRANSPORT SYSTEM AS BEING USED TO TRANSPORT PAYLOADS NOT ONLY TO HIGHER ORBITS AROUND EARTH BUT ALSO TO THE MOON AND MARS.

WEBSTER C. CASH
NIAC FELLOW

THE NEW WORLDS IMAGER

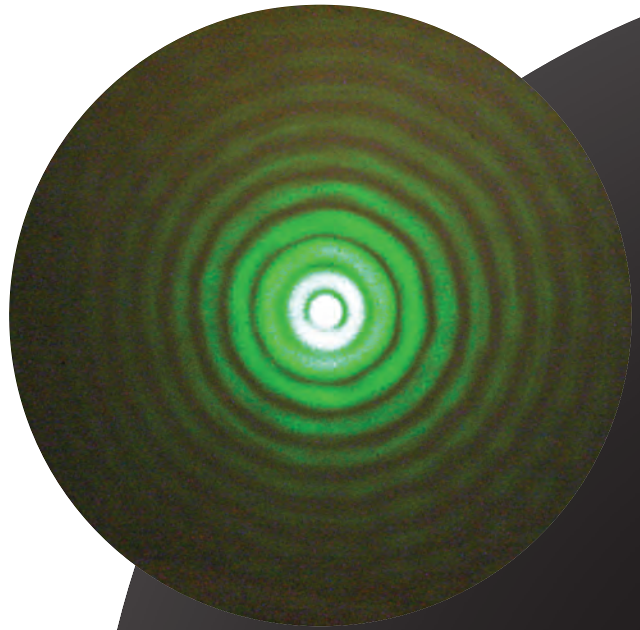
In 1962, Lyman Spitzer Jr., (1914–1997) delivered a lecture at the Third International Space Science Symposium (COSPAR) in Washington, DC with the title of "The Beginnings and Future of Space Astronomy."[9] In the lecture, Spitzer discussed the opportunity and challenge of detecting planets around other stars, which he viewed as:

> *(A) matter of very great philosophical and cultural as well as scientific interest. Our view of man and his place in the universe naturally depends very much on whether planetary systems like ours are exceptional or whether they occur very frequently throughout the Galaxy. In fact, in many ways, the question of how frequently stars are accompanied by planets capable of supporting life is fully as important as the over-all structure of the universe, i.e., whether space is flat or curved.*
>
> *The detection of other planets, however, is an extraordinary difficult problem. Not only are planets intrinsically very faint, they are necessarily very close to a star if they can be detected at all, and light from the central star, scattered or diffracted in the telescope system, inevitably tends to mask the very faint planetary light.*[10]

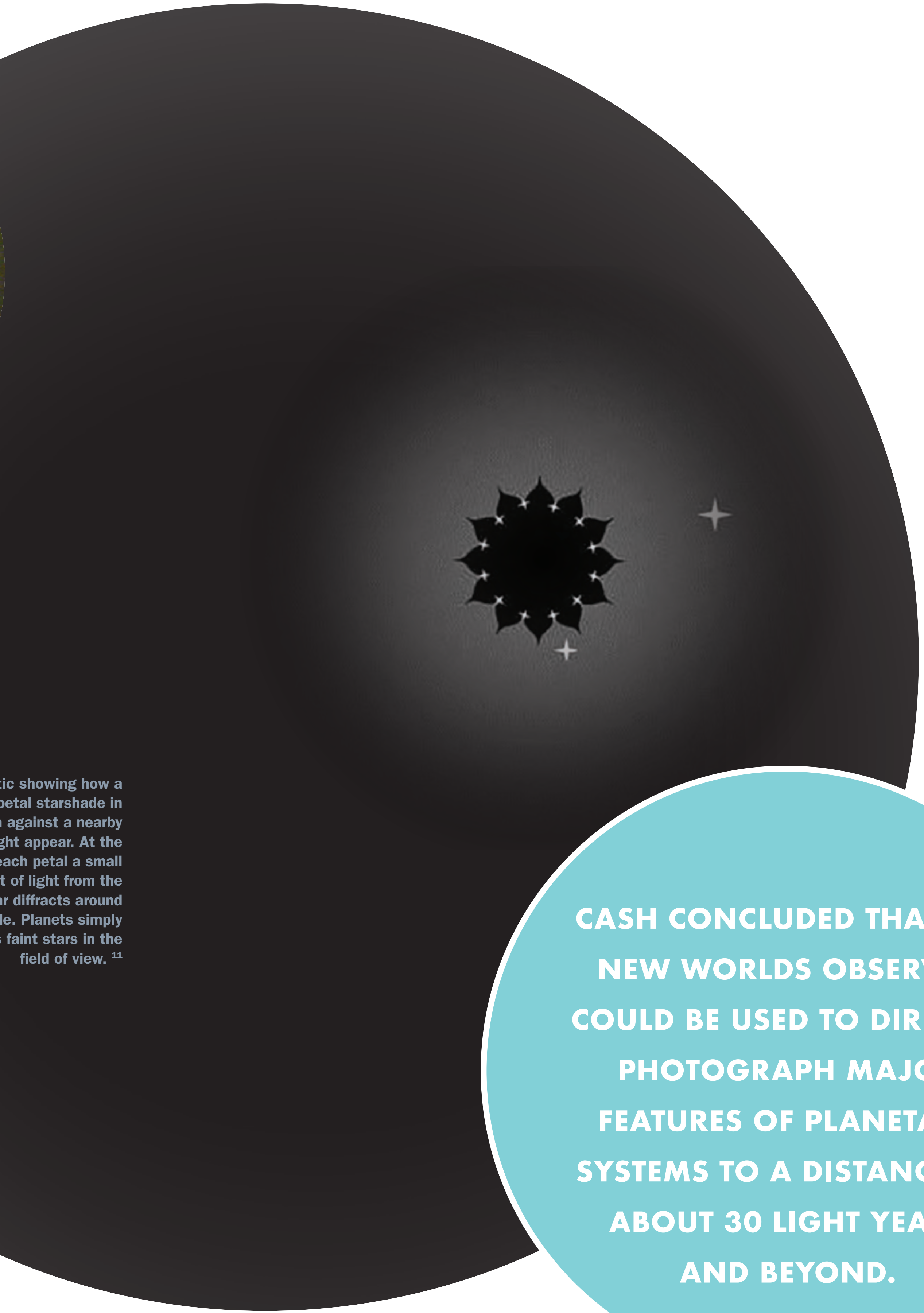
Spitzer discussed a possible approach to the problem of detecting planets around stars, namely the use of a large occulting disc far in front of a space telescope. He attributed this idea to his Princeton colleague, Robert Danielson (1931–1976). This was the idea behind the NIAC proposal submitted by Webster Cash of the University of Colorado in 2004, titled "New Worlds Imager." In his Phase I and Phase II studies, Cash examined the many challenges related to the use of an occulter to observe planets around other stars.

To understand how an occulter works, imagine if our solar system were viewed from a distance of 30 light years. The distance from the Sun to the Earth would subtend an arc of about 0.1 seconds (1/36,000th of a degree), and the Sun would be ten billion times brighter than the Earth. Cash viewed the primary challenge as that of finding a way to almost totally eliminate the light from the star in the shadow of the occulter, which he called a starshade.

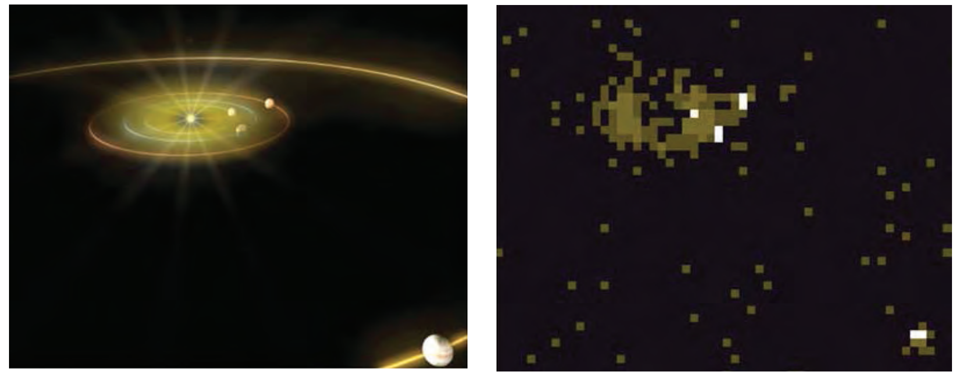
A starshade in the form of a disc would not work, because light waves diffracted all along the circular edge of such a disc would arrive at the center of the shadowed area with the same phase and thus constructively interfere. A bit off center in the shadowed area, diffracted light waves from one half of the disc rim would destructively interfere with the diffracted light waves from the other half, producing a dark ring. Still further out from the extension of the line defined by the star and the occulter, constructive interference would occur. The result would be a pattern of bright and dark circles, as demonstrated in an undergraduate student lab experiment using laser light, seen here at left (page 158).



Diffraction pattern using an occulting disc and laser light. (From a University of Michigan student lab experiment)



Schematic showing how a flower-petal starshade in position against a nearby star might appear. At the base of each petal a small amount of light from the parent star diffracts around the shade. Planets simply appear as faint stars in the field of view.[11]



Seeing Earth-like planets – a simulation. Artwork is courtesy of Ball Aerospace.[11]

Cash found a way to shape the starshade so that it would create a circular zone with the diffraction brightness in this zone reduced by a factor of ten billion across a broad range of frequencies in the visible range. The zone would be produced tens of kilometers behind the starshade, and it would be at least two meters wide. His starshade is flower-shaped, with an opaque circular central part and petals extending from this core.

> *The New Worlds Observer [is comprised of] two spacecraft, a flower-shaped starshade about 50m from tip to tip, and a conventional-quality telescope. The telescope optic must be diffraction-limited in the visible band and at least 1m in diameter. The mission operates by flying the starshade into the line of sight of a nearby star, a move that can take several days.*[11]

Cash examined other challenges for his New Worlds Observer, including ways to deploy the large starshade and keep it stationary, relative to the celestial sphere, through automated station-keeping with small thrusters.

Cash also performed computer simulations to show what might be possible with his system. He demonstrated that If the New Worlds Observer were turned onto our own solar system from a distance of about 20 light years, using an occulter and the James Webb Space Telescope, then Earth, Mars and Jupiter would be visible as bright white spots.[12]

Cash concluded that his New Worlds Observer could be used to directly photograph major features of planetary systems to a distance of about 30 light years and beyond.

> *It can detect all the major planets (from the habitable zone outward), the zodiacal light, debris disks and possibly even comets. Photometric variations might show the presence of surface features like oceans and continents. Follow-up spectroscopy of the detected planets would enable classification by type, and the presence of water would be clearly visible in atmospheric absorption lines. Atmospheric markers (like free oxygen absorption lines) could potentially provide the first evidence of life outside our Solar System.*[13]

CASH CONCLUDED THAT HIS NEW WORLDS OBSERVER COULD BE USED TO DIRECTLY PHOTOGRAPH MAJOR FEATURES OF PLANETARY SYSTEMS TO A DISTANCE OF ABOUT 30 LIGHT YEARS AND BEYOND.

DAVA J. NEWMAN
NIAC FELLOW
(NASA)

"WE'LL PROBABLY SEND A DOZEN OR SO PEOPLE TO MARS IN MY LIFETIME. I HOPE I SEE IT. BUT IMAGINE IF WE COULD HELP KIDS WITH CEREBRAL PALSY JUST MOVE AROUND A LITTLE BIT BETTER."

BioSuit illustration. Credit Trotti and Associates, Inc.

ASTRONAUT BIOSUIT SYSTEM FOR EXPLORATION-CLASS MISSIONS

The spacesuit worn by Apollo astronauts was gas-filled and able to keep a uniform pressure of 3.7 psi on the bodies of the astronauts. Advancing spacesuit technology was not among the critical issues identified by the National Commission on Space in 1986 in their report titled Pioneering the Space Frontier.[14]

Professor Dava Newman of MIT had a different perspective. In her Phase I and Phase II studies for NIAC, titled "Astronaut Bio-Suit for Exploration Class Missions," Newman examined a different kind of spacesuit that would allow astronauts to move freely and quickly on the Martian surface.

> *The suits that kept NASA astronauts alive on the moon and those worn by Space Shuttle and International Space Station crewmembers for extravehicular activities (EVAs), including the Hubble repair missions, are technological marvels; in effect, they are miniature spacecraft that provide the pressure, oxygen, and thermal control that humans need to survive in the vacuum of space. The greatest problem with these suits is their rigidity. The air that supplies the necessary pressure to the bodies of wearers turns them into stiff balloons that make movement difficult and tiring. These suits are officially known as EMUs— extravehicular mobility units—but they allow only limited mobility. Astronauts who perform repair work in space find the stiffness of spacesuit gloves especially challenging: imagine manipulating tools and small parts for hours wearing gas-filled gloves that fight against the flexing of your fingers.*[15]

Newman also pointed out that in addition to providing better mobility, her BioSuit would be safer than the traditional spacesuit.

> *While an abrasion or micrometeor puncture in a traditional suit would threaten sudden decompression— puncturing the balloon and causing a major emergency and immediate termination of the EVA—a small breach in the BioSuit could be readily repaired with a kind of high-tech Ace bandage to cover a small tear.*[16]

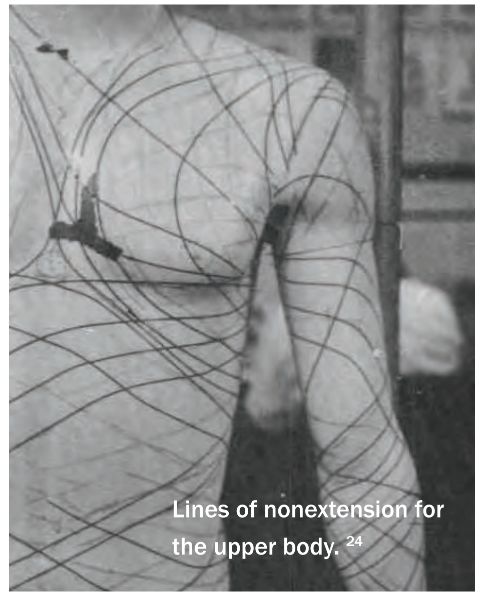
Newman and her team took advantage of earlier work on the design of spacesuits that used elastic fabric garments to supply the pressure needed by the wearer in the near vacuum of space. As early as 1968, Paul Webb (1923–2014) and others worked on the design of a Space Activity Suit that Webb called an "elastic leotard."[17] Newman also made use of the research by Arthur Iberall (1918–2002) on what Iberall called "lines of nonextension" of the human body. Iberall had found that while the human skin generally stretches during body motion, there are certain lines on the body where there is virtually no stretch. About Iberall's work, Newman wrote:

> *We have expanded his great idea of a pattern of three-dimensional lines on the body that do not extend by deriving the mathematical representation and visualization of what I call a soft exoskeleton and structure of the BioSuit. … Laminating our mathematically derived web of less-flexible lines, or the soft exoskeleton pattern, to our elastic compression suit has gotten us closer to the necessary pressure production goals, and we've exceeded our mobility and flexibility performance goals.*[18]

Newman and her team used 3D laser scanning of human subjects to measure the change in surface area and strain in the human skin for various leg motions. These measurements, together with Iberall's work on lines of nonextension, suggested the orientation, or "weave" direction, of the tensile fibers for the BioSuit design.

One of the challenges of the BioSuit is to find a way to quickly put it on and take it off. This challenge led Newman to investigate the use of "smart" materials, such as shape memory polymers that are pliable below a transition temperature but return to a more rigid "memory" state above the transition temperature. The team also investigated electroactive materials, as an alternative to shape memory polymers, to solve the "don/doff" problem. This led Newman's team to study the possibility that electroactive materials in the BioSuit might be used as a countermeasure for astronaut deconditioning.

> *If such materials were incorporated into the boots or legs of the BioSuit, an electrical forcing function could drive them to vibrate the legs and mechanically stimulate bone growth.*[19]



Lines of nonextension for the upper body.[24]

BioSuit illustration. Credit Trotti and Associates, Inc.

Newman's research on electroactive materials in her BioSuit led to an important collaboration on an effort that is not related to space exploration.

> *We have been working with colleagues at Children's Hospital in Boston, Harvard's Wyss Institute, Boston University, and Draper Laboratory to see if we can use our technology and engineering designs to help infants with brain damage that affects motor skills, children with cerebral palsy, and stroke victims, who typically lose motor skills on one side of their bodies. The idea is first to use BioSuit "sleeves" with built-in sensors on the legs to measure movements—to understand, for instance, how much motion and kicking by infants is typical and compare that with the limited kicking and motions of children with cerebral palsy. The next step—a big one—is to add actuators that can enhance and direct movement. In the case of cerebral palsy and stroke victims, that would be a way of giving back some of the lost motion. People with cerebral palsy expend a lot of energy moving and have stiffened muscles; our BioSuit technology and know-how could guide movement and enhance mobility to make it more efficient. And because the brains of newborns are still so plastic, enhancing the natural kicking of infants with potential motor problems from brain damage might actually reshape the motor programs and partly "heal" their brains.*[20]

In an interview with Mihai Andrei in 2013, Newman put a finer point on the broader application of BioSuit technology, *"We'll probably send a dozen or so people to Mars in my lifetime. I hope I see it. But imagine if we could help kids with cerebral palsy just move around a little bit better."* [21]

As the NRC review committee concluded

> *At the onset of soliciting advanced concept proposals, NIAC's criteria for selecting concepts for funding included the statement that the concept should have the potential for revolutionizing aerospace endeavors and that enabling technologies may not be available. Many of the funded concepts were notably successful in providing an expanded vision for the development of technologies that would have applications far beyond the original advanced concept.*[22]

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LOOSENING THE BONDS

How USRA computer scientists, engineers, and neutron-star astrophysicists helped pioneer new technologies for autonomous spacecraft control and navigation.

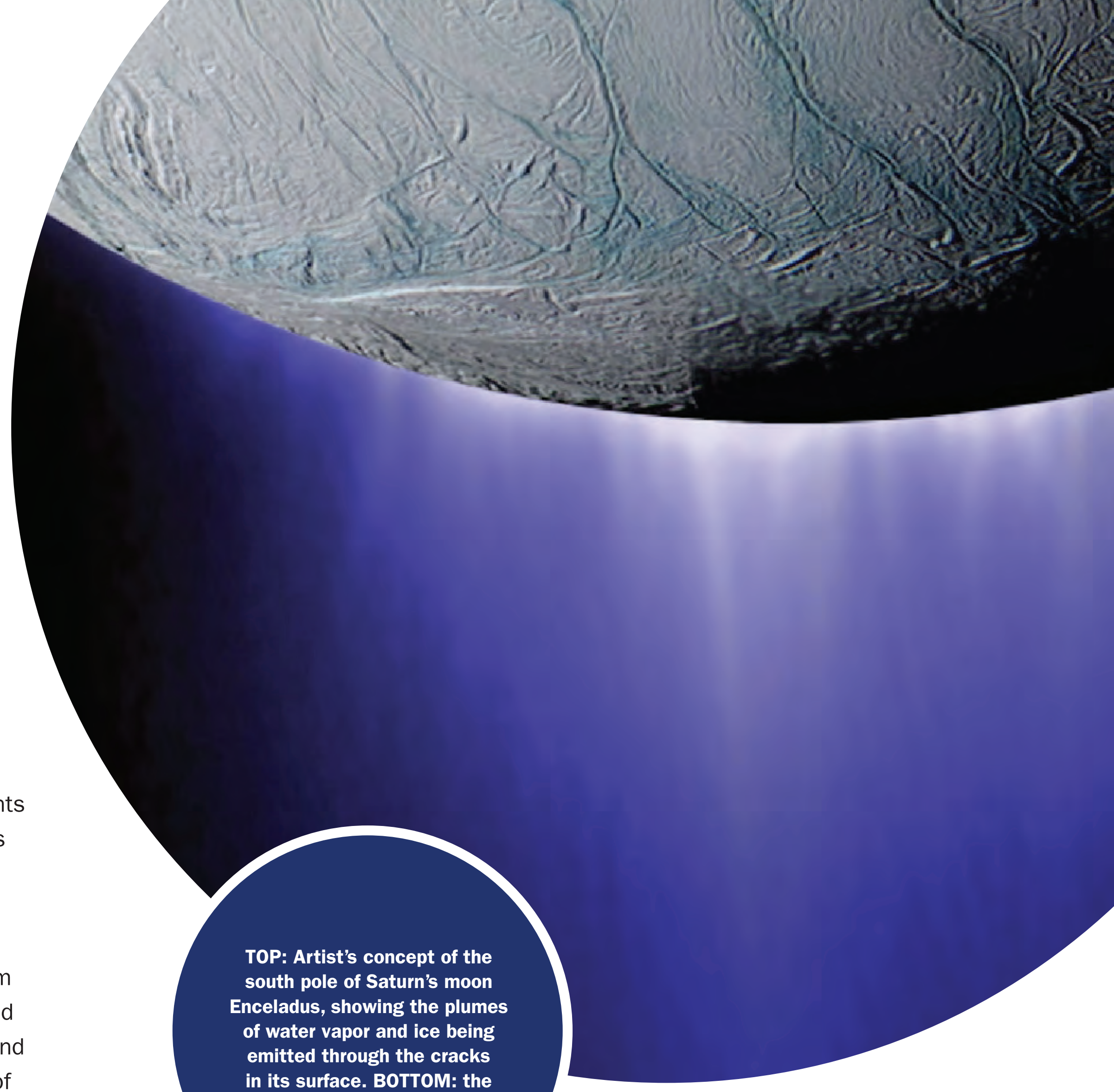
ON 28 OCTOBER 2015, THE CASSINI SPACECRAFT passed about 50 kilometers (30 miles) above the south pole of Enceladus, one of the moons of Saturn that's presumed to have an ice-covered ocean. During this pass, instruments aboard Cassini sampled water vapor and ice that had been emitted through cracks in the surface of the moon.

To maneuver Cassini for this close approach to a very small moon (500 km in diameter), flight controllers communicated with the spacecraft through NASA's Deep Space Network (DSN). The DSN sends and receives radio signals to and from spacecraft by means of large antennas in Goldstone, California; Madrid, Spain; and Canberra, Australia. In addition to receiving data from spacecraft in deep space, and transmitting instructions to them, flight controllers send "range codes" as a part of their instructions. When a distant spacecraft receives a range code, it immediately returns it to the DSN. The radio signals to and from the spacecraft travel at the constant speed of light ($c = 3 \times 10^5$ km/sec), allowing the flight controllers to use the time interval between the sending and receiving of the range codes to compute the distance to the spacecraft.

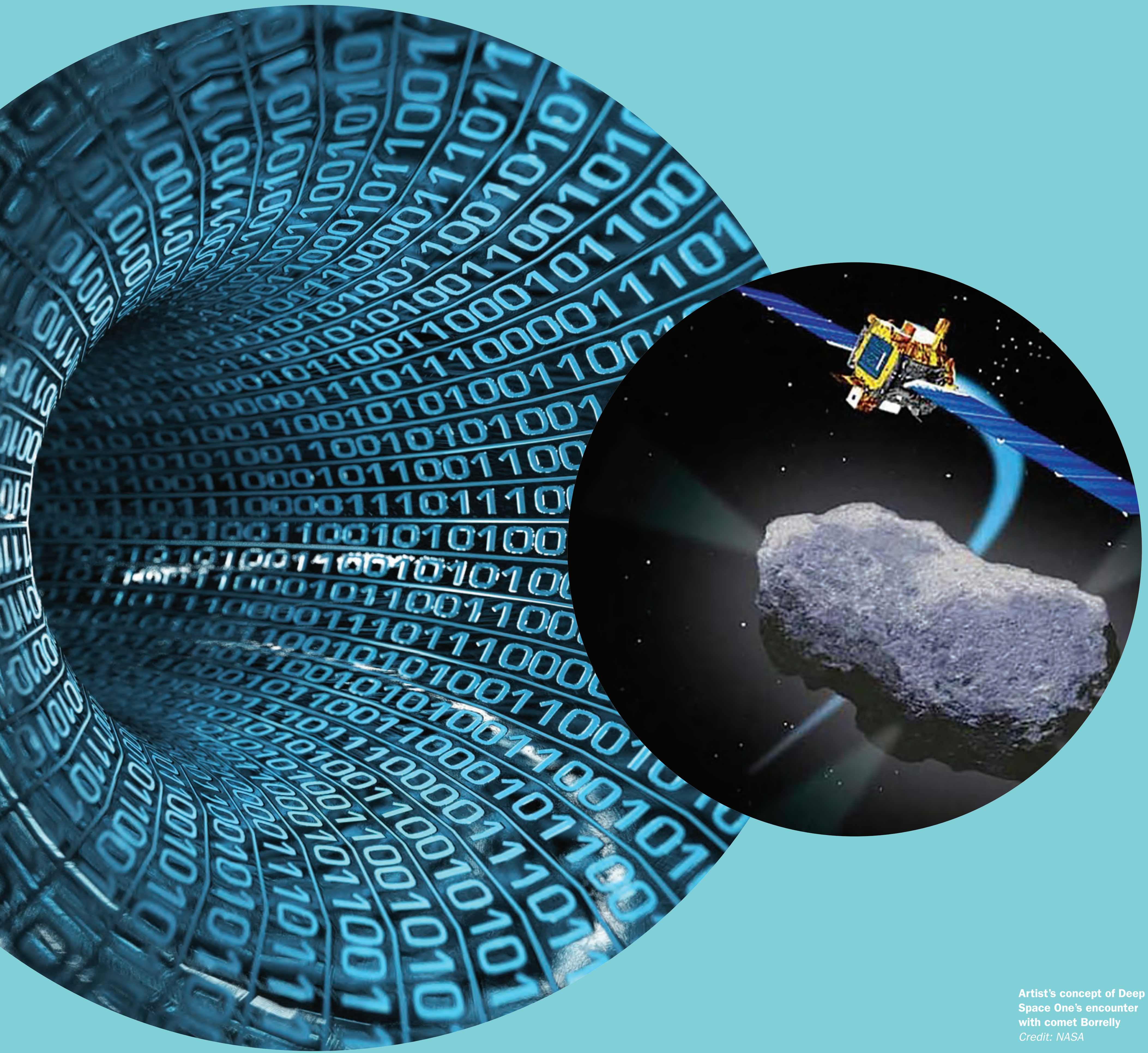
The range of the spacecraft was one of three data points needed to accurately calculate the Cassini's position. The other two data points were obtained by using cameras on board the spacecraft to locate other moons of Saturn against the background of stars with precisely known locations in the sky.

When Cassini made its close approach to Enceladus, the round-trip travel time of the range codes was about three hours. The time available for taking data during the close approach to Enceladus was a few tens of seconds. Thus, the DSN played a critical role assisting NASA's flight controllers with positioning Cassini in the right place at the right time to gather the data from the plumes of Enceladus.

At the time, Cassini's pass was the latest in a series of remarkable examples of spacecraft navigation performed by the DSN and NASA's flight controllers during the decades of space exploration. But as humankind reached farther into the solar system and beyond, the long travel times of radio signals to and from distant spacecraft posed increasing risks to mission success. If a subsystem failed, or showed signs of a possible failure, it could take many hours before a "work around" could be sent to the spacecraft from controllers on Earth. For example, when the New Horizons spacecraft flew past Pluto on 14 July 2015, the round-trip travel time for communication with the spacecraft was about nine hours. When Voyager 1 entered interstellar space on 25 August 2012, the round-trip travel time was about 34 hours.



TOP: Artist's concept of the south pole of Saturn's moon Enceladus, showing the plumes of water vapor and ice being emitted through the cracks in its surface. BOTTOM: the Goldstone antenna
(Credits: NASA)



Artist's concept of Deep Space One's encounter with comet Borrelly
Credit: NASA

IN THE NEW MODEL OF OPERATIONS, THE SCIENTISTS WILL COMMUNICATE HIGH-LEVEL SCIENCE GOALS DIRECTLY TO THE SPACECRAFT.

THE NEW MODEL OF OPERATIONS

In the mid to late 1990s, computer scientists working at NASA's Ames Research Center (ARC), the Jet Propulsion Laboratory (JPL), and USRA's Research Institute for Advanced Computer Science (RIACS) began to collaborate on a way to decrease the dependence of spacecraft operations on ground-based flight controllers and the DSN. They articulated their vision as follows:

> *In the new model of operations, the scientists will communicate high-level science goals directly to the spacecraft. The spacecraft will then perform its own science planning and scheduling, translate those schedules into sequences, verify that they will not damage the spacecraft, and ultimately execute them without routine human intervention.*[1]

The on-board computer software that would allow the spacecraft to perform certain functions autonomously was thought of as a "Remote Agent" (RA) of the ground-based human operators. Computer scientists collaborating on development of the software, including Drs. Barney Pell and Pandurang Nayak of RIACS, argued that an RA for future space missions was needed to reduce spacecraft operations costs, to ensure robust operations in the presence of uncertainty, and to take advantage of unplanned science opportunities.[2]

For example:

> *An ultraviolet spectrometer on a comet flyby mission might identify a region of particular interest for intense scrutiny. With current technology, scientists have to make do with whatever pre-planned sequence of observations has been stored on-board and cannot reprogram any of those to examine more closely the newly identified region of interest. With a future RA, plans may be revised based on this new information hours or minutes before flyby. With ground-based control, a turnaround time of hours is impractical and a turnaround time of minutes is physically impossible due to the speed of light.*[3]

A REMOTE AGENT OPERATES DEEP SPACE ONE

The RIACS computer scientists and their collaborators at ARC and JPL won an opportunity to test their ideas with the flight of NASA's Deep Space One spacecraft, which was launched on 24 October 1998, one year after the launch of Cassini. Deep Space One had some science objectives – passing close by an asteroid and a comet – but its primary mission was to validate a dozen new technologies, including an ion-propulsion engine, silicone lenses to concentrate sunlight onto solar cells, an autonomous navigation system, and the RA.

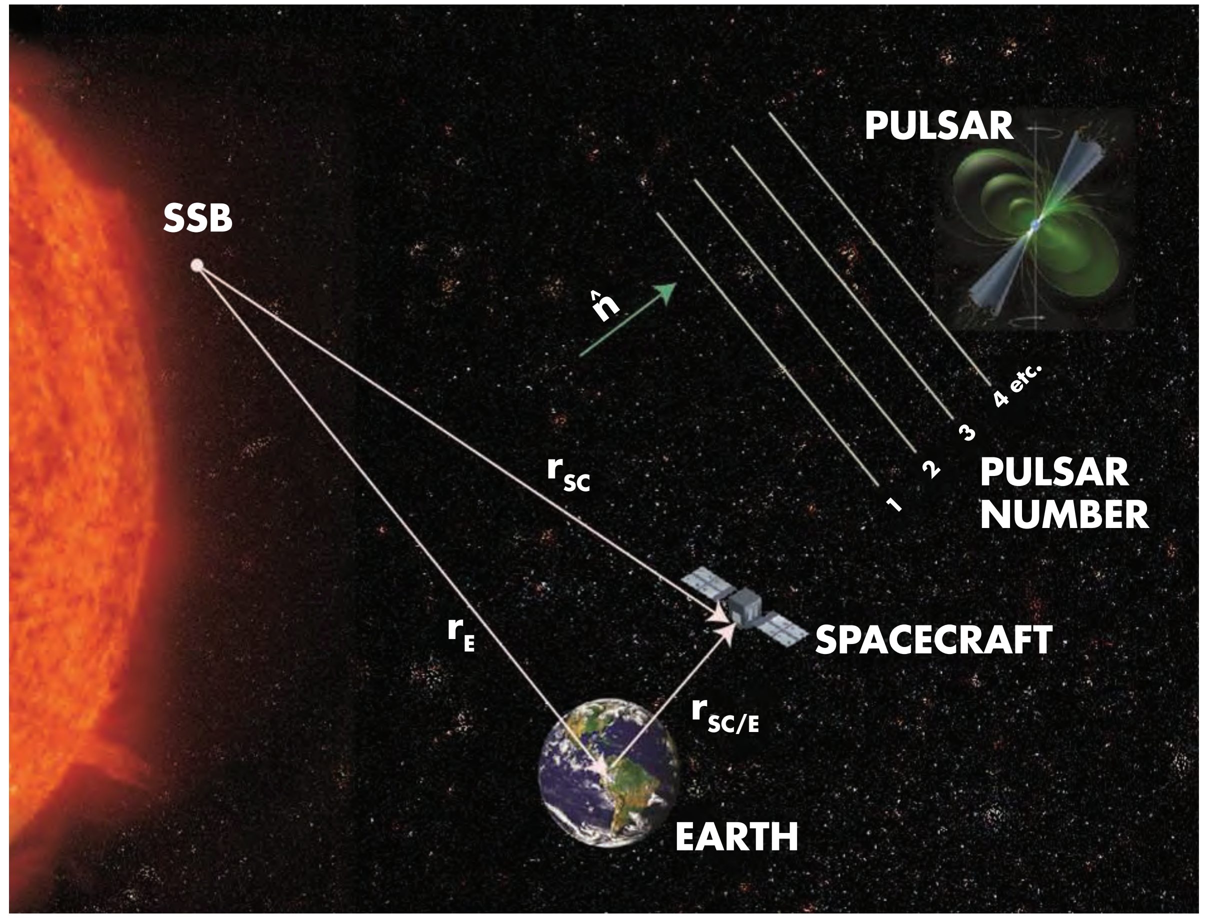
During a two-day experiment that began on 17 May 1999, the RA was given primary control of Deep Space One and thereby became the first artificial intelligence software to fly onboard a spacecraft and control its operation in deep space with no human intervention. In a second experiment four days later, the RA successfully responded to three simulated faults on the spacecraft. The first simulated fault was the failure of an electronics unit, and the RA successfully diagnosed the problem and reactivated the unit. The second was a sensor indicating that a device onboard the spacecraft had failed, and the RA determined that it was the sensor, rather than the device, that had failed. The third simulated fault was a small thruster that had stuck in a closed condition. The RA responded by switching to an alternate spacecraft control mode that didn't use the failed thruster. After the experiment, the Project Manager for Deep Space One, Dr. Marc Raymond, reported:

> *With the successful achievement of all the desired testing, the experiment completed amid many references to HAL 9000*[4] *and to Star Trek.*[5]

RIACS scientists, including Nayak, Pell, Dr. Ari Jonsson, and Mr. Kanna Rajan, were co-inventors of the RA architecture and the three main artificial intelligence technologies used in RA: a smart executive, a mode-identification and recovery fault-diagnosis system, and a mission planner/scheduler. The RA team won the NASA Software-of-the-Year Award for 1999. RIACS scientists continued to develop elements of the work they had done on Deep Space One for use in follow-on NASA missions. For example, the planning software called MAPGEN became the first artificial intelligence software to plan the work of robots (the Mars Explorer Rovers) on another planet.

The autonomous navigation system (AutoNav) on Deep Space One did not rely on range determinations via the DSN. AutoNav used onboard cameras to track the path of a few bright asteroids against the background field of stars. The known paths of the asteroids through the solar system were combined with the image data from the spacecraft's cameras to triangulate the spacecraft's position to within ± 250 km and its velocity to within ± 0.2 m/sec.[6] For a spacecraft in the main asteroid belt, these are relatively large errors compared to what can be achieved with standard ground-based navigation techniques, i.e., combining radio tracking from the DSN with optical data from onboard cameras.[7] But the disadvantages of dependency on ground-based control and maintenance, "the increasing position and velocity uncertainty with increasing distance from Earth, as well as the large propagation delay and weakening of the signals at large distances"[8] argued for the value of experimentation with autonomous navigation systems.

The basis for an X-Ray navigation system (XNAV)[15]. SSB stands for Solar System Barycenter13.



FRANK DRAKE

TOWARD A MORE EFFECTIVE AUTONOMOUS NAVIGATION SYSTEM

The journey toward a more effective autonomous navigation system for spacecraft began in the summer of 1967 at the Mullard Radio Astronomy Observatory of the University of Cambridge in the UK, when the graduate student Susan Jocelyn Bell discovered pulsars. Soon after this discovery, Dr. Frank Drake and his colleagues at Arecibo pointed out the utility of the pulsed signals for space navigation of extra-terrestrial civilizations, though the Arecibo group argued that it was very unlikely that the pulsar discovered by Jocelyn Bell was a signal from such a source. Drake and his colleagues noted, however, that for Earth-based civilizations, "The precise timing of the pulses provides a new time service which may be useful in some circumstances."[9]

It wasn't long before astronomers and graduate students began to flesh out this suggestion as it applied to the use of pulsars for space navigation. G. S. Downs of the JPL developed a navigational method for spacecraft based on the use of onboard antennas and software that would measure the pulse arrival times of three radio pulsars.[10] Downs noted several potential problems with his technique, including the requirement for a continuation of earth-based measurements of pulsar arrival times, the necessity for large antenna arrays on the spacecraft, long integration times to accumulate enough signal to make precise measurements, and the dispersion of the radio waves as they travel through interstellar space.

In a 1981 report for the JPL, T. J. Chester and S. A. Butman raised the idea of using X-ray pulsars, rather than radio pulsars for spacecraft navigation:

> *Approximately one-dozen X-ray pulsars are presently known which emit strong stable pulses with periods of 0.7 to ~ 1000 s. By comparing the arrival times of these pulses at a spacecraft and at the Earth (via an Earth-orbiting satellite), a three-dimensional position of the spacecraft can be determined. One day of data from a small (~0.1 m^2) on-board X-ray detector yields a three-dimensional position accurate to ~150 km. This accuracy is independent of spacecraft distance from the Earth. Present techniques for determining the two spacecraft coordinates other than range measure angles and thus degrade with increasing spacecraft range. Thus, navigation using X-ray pulsars will always be superior to present techniques in measuring these two coordinates for sufficiently distant spacecraft. At present, the break-even point occurs near the orbit of Jupiter.*[11]

The parenthetical reference to Earth-orbiting satellites was necessary because X-ray pulsars can't be measured from Earth's surface due to the absorption of X-rays by the Earth's atmosphere. Thus, Chester and Butman's method requires an Earth-orbiting satellite to detect them.

POSSIBILITIES OF USING X-RAY PULSARS FOR NAVIGATION CONTINUES

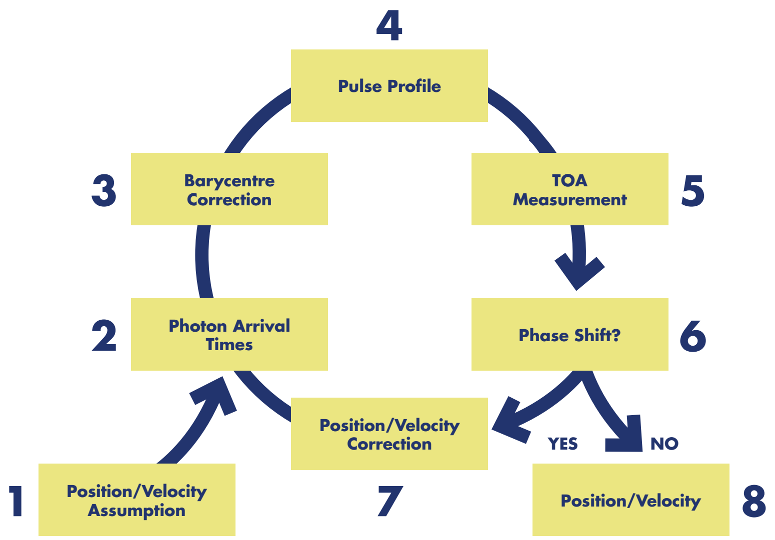
Through the 1980s and beyond, work continued on the possibility of using X-ray pulsars for spacecraft navigation, notably through the efforts of Dr. Kent Wood and others at the US Naval Research Laboratory (NRL). Wood proposed the Unconventional Stellar Aspect (USA) experiment to study the feasibility of X-ray navigation (XNAV) onboard the Advanced Research and Global Observation Satellite (ARGOS). ARGOS was a project of the Space Test Program of the Department of Defense (DoD), which was interested in developing an autonomous spacecraft-navigation system that didn't depend on the availability of its network of Global Positioning System (GPS) satellites. ARGOS was launched into a low-Earth orbit on 23 February 1999, and USA could explore methodologies for attitude, position, and time determination using a single sensor of simple design and low cost.[12]

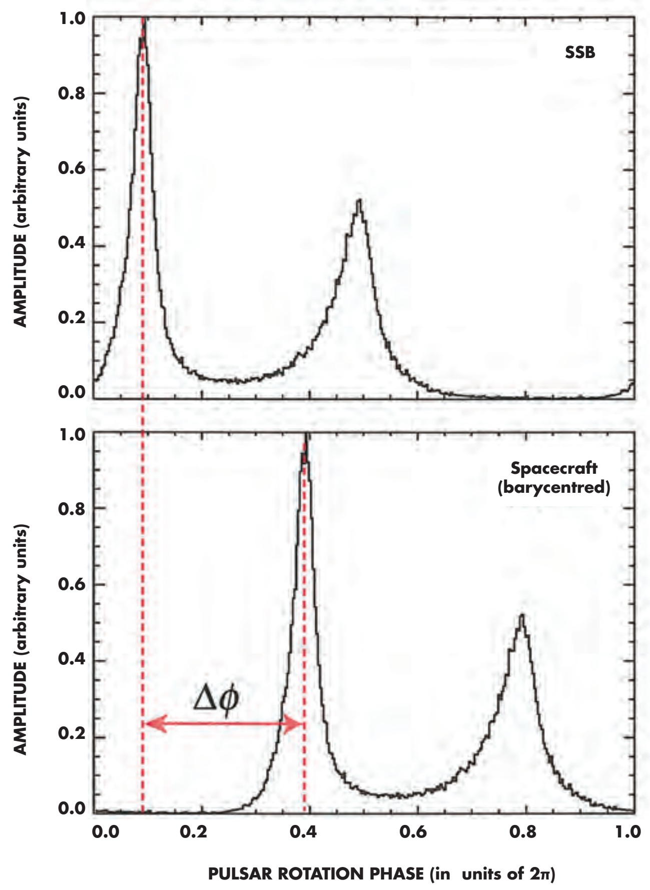
Several groups from around the world also worked on the development of a pulsar-based XNAV system. For example, a group led by Werner Becker of the Max-Planck-Institut für extraterrestrische Physik described an iterative approach:

> *An initial assumption of position and velocity is given by the planned orbit parameters of the spacecraft (1). The iteration starts with a pulsar observation, during which the arrival times of individual photons are recorded (2). The photon arrival times have to be corrected for the proper motion of the spacecraft by transforming the arrival times (3) to an inertial reference location; e.g., the solar system barycenter (SSB).*[13] *This correction requires knowledge of the (assumed or deduced) spacecraft position and velocity as input parameters. The barycenter corrected photon arrival times allow then the construction of a pulse profile or pulse phase histogram (4) representing the temporal emission characteristics and timing signature of the pulsar. This pulse profile, which is continuously improving in significance during an observation, is permanently correlated with a pulse profile template in order to increase the accuracy of the absolute pulse-phase measurement (5), or equivalently, pulse arrival time (TOA). From the pulsar ephemeris that includes the information of the absolute pulse phase for a given epoch, the phase difference Δφ between the measured and predicted pulse phase can be determined. … In this scheme, a phase shift (6) with respect to the absolute pulse phase corresponds to a range difference Δx = cP(Δφ + n) along the line of sight toward the observed pulsar. Here c is the speed of light, P the pulse period, Δφ the phase shift and n = 0, ±1, ±2, … an integer that takes into account the periodicity of the observed pulses. If the phase shift is non-zero, the position and velocity of the spacecraft needs to be corrected accordingly and the next iteration step is taken (7). If the phase shift is zero, or falls below a certain threshold, the position and velocity used during the barycenter correction was correct (8) and corresponds to the actual orbit of the spacecraft.*
>
> *A three-dimensional position fix can be derived from observations of at least three different pulsars … . If on-board clock calibration is necessary, the observation of a fourth pulsar is required.*[14]

THE NICER/SEXTANT MISSION - TESTING NAVIGATION WITH PULSARS

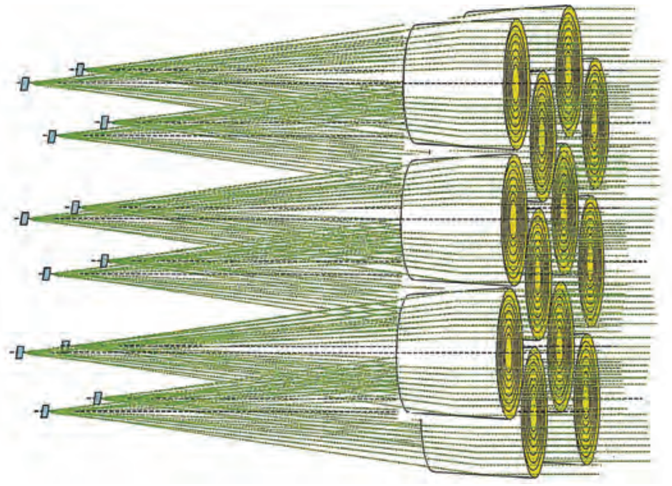
When Dr. Zaven Arzoumanian joined USRA in the fall of 2001, he began to work with his colleagues at USRA and NASA on various aspects of high-energy astrophysics.





TOP: Iterative determination of position and velocity by a pulsar-based navigation system. (figure 5[14])

BOTTOM: Measuring the phase difference between the expected and measured pulse peak at an inertial reference location; e.g., the solar system barycenter (SSB)[13]. The top profile shows the main peak location expected at the SSB. The bottom profile is the one which has been measured at the spacecraft and transformed to the SSB by assuming the spacecraft position and velocity during the observation. If the position and velocity assumption was wrong, a phase shift Δφ is observed. (figure 6[14])



ABOVE: Array of X-ray concentrators for the NICER/SEXTANT X-ray Timing Instrument [18]

TOP RIGHT: Zaven Arzoumanian and Keith Gendreau

BOTTOM RIGHT: X-ray concentrators (XRCs) for NICER/SEXTANT

AT SOME POINT IN THE FUTURE, AUTONOMOUS SPACECRAFT CONTROL AND NAVIGATION WILL LIKELY BE THE NORM, MADE POSSIBLE IN PART BY THE PIONEERING CONTRIBUTIONS OF USRA COMPUTER SCIENTISTS, ENGINEERS, AND ASTROPHYSICISTS.

About a decade later, Arzoumanian and Dr. Keith Gendreau of NASA GSFC won an opportunity to develop a space mission that, in addition to some important science objectives related to neutron stars (see the essay in this book titled "The Interior of Neutron Stars"), could provide a means for navigating in deep space using pulsars. Their mission is titled the Neutron Star Interior Composition Explorer/Station Explorer for X-ray Timing and Navigation Technology, or NICER/SEXTANT. Gendreau is the Principal Investigator (PI) and Arzoumanian is the Deputy PI for the mission team, which includes scientists and engineers from USRA, GSFC, and MIT, as well as other universities and NRL. The observing instrument for NICER/SEXTANT was mounted on the International Space Station (ISS) in June 2017.

The NICER/SEXTANT X-ray Timing Instrument is a co-aligned set of 56 X-ray Concentrators (XRCs) and associated X-ray detectors. Each XRC has 24 nested parabolic foils to guide X-ray photons onto small silicon detectors by means of grazing-incidence reflections. The energy of an individual X-ray photon is determined by measuring the amount of ionization it produces in the target silicon. X-rays in the range 0.2–12 keV will be collected, and for 1.5 keV X-rays, the total effective collection area is nearly 2000 cm^2.

The NICER/SEXTANT system offers the capability to demonstrate for the first time that XNAV can determine spacecraft positions with greater accuracy than other existing systems. During an experiment in November of 2017, the ISS orbit as determined by XNAV via NICER/SEXTANT was compared with the orbit as determined by the Earth's GPS system. The experiment used four millisecond pulsars and was successful in determining the position of the ISS to within a sphere with a radius of about 16 kilometers. The goal of determining the position of the ISS to within a few kilometers will require the measurement by NICER/SEXTANT of pulse times-of-arrival from five to six pulsars to accuracies of 10 microseconds, where the time needed for the measurements is less than about 4 hours for each pulsar.[15] The need for measurements from a few different pulsars arises because of the "ambiguity problem." If one knew how many pulses intervene between the satellite and the pulsar, one could calculate the distance to the pulsar from the spacecraft by measuring the time between pulses and multiplying by the speed of light and the number of pulses. The problem is that one doesn't know how many pulses intervene between a given pulsar and the spacecraft. The accompanying figure (page 169) indicates how the measurement of a few pulsars can solve the ambiguity problem.

As noted by Arzoumanian:

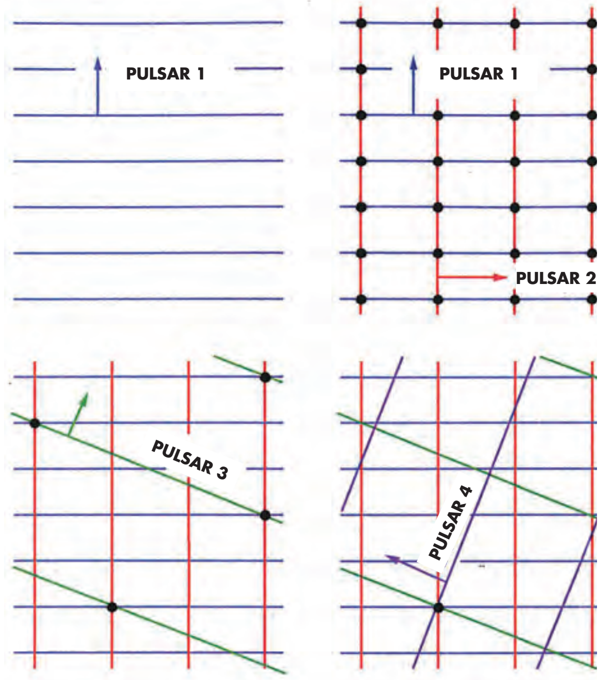
> *The best current capabilities for spacecraft position determination are Earth-centric, resource intensive, and pushed to their practical limits for critical maneuvers at Jupiter and beyond. XNAV offers the possibility to achieve the required accuracies, and to do it autonomously.*[16]

If we want to more thoroughly investigate distant planets and their satellites, XNAV will be a necessity. Earth-centric approaches are not only more expensive, but also provide less accuracy than is required. The current uncertainties of Earth-based position determinations for spacecraft around planets and their satellites beyond Jupiter is in the 10s to 100s of kilometers, whereas an orbital insertion around Enceladus, for example, requires an accuracy of 1–5 km.[17]

At some point in the future, autonomous spacecraft control and navigation will likely be the norm, made possible in part by the pioneering contributions of USRA computer scientists, engineers, and astrophysicists.

Arzoumanian demonstrates the NICER/SEXTANT technology using a 1/5 scale model.

The NICER payload, as mounted on the International Space Station. *Credit: NASA*



Solving the ambiguity problem by observing four pulsars (drawn in two dimensions). The arrows point along the pulsars' lines of sight. Straight lines represent planes of constant pulse phase; black dots indicate intersections of planes. (figure 7[14])

ENDNOTES

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2. Bernard, D.E., Dorais, G.A., Fry, C., Gamble, E.B., Kanefsky, B., Kurien, J., Millar, W., Muscettola, N., Nayak, P.P., Pell, B. and Rajan, K., 1998, March. Design of the remote agent experiment for spacecraft autonomy. In *Aerospace Conference, 1998 IEEE* (Vol. 2, pp. 259–281). IEEE.
3. Ibid., 260.
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9. Drake, F.D., Gundermann, E.J., Jauncey, D.L., Comella, J.M., Zeissig, G.A., and Craft Jr, H.D., 1968. The rapidly pulsating radio source in vulpecula. *Science, 160*(3827), pp. 503–507.
10. Downs, G.S., 1974. Interplanetary navigation using pulsating radio sources. Retrieved from the NASA Technical Report Server - https://ntrs.nasa.gov/search.jsp?R=19740026037.
11. Chester, T.J. and Butman, S.A., 1981. Navigation using X-ray pulsars. *Jet Propulsion Laboratory, Pasadena, CA, NASA Tech. Rep. 81N27129*, p.22.
12. Wood, K.S., 1993, September. Navigation studies utilizing the NRL-801 experiment and the ARGOS satellite. In *Small Satellite Technology and Applications III* (Vol. 1940, pp. 105–117). International Society for Optics and Photonics.
13. Solar System Barycenter (SSB) – the SSB is the center of mass of the solar system, the point about which all members of the solar system, including the Sun, revolve. Primarily because of the mass of the planet Jupiter, the SSB is outside the photosphere of the Sun.
14. Becker et al., Design of the remote agent experiment, 7–8.
15. Arzoumanian, Z., 2010. Spacecraft navigation via X-ray timing of pulsars: A technology demonstration proposal for International Space Station (ISS) utilization, Dr. Keith Gendreau, Principal Investigator. A presentation given to the Center for Research and Exploration in Space Science and Technology. USRA Archives.
16. Ibid.
17. Ibid.
18. Ray, P.S., Sheikh, S.I., Graven, P.H., Wolff, M.T., Wood, K.S. and Gendreau, K.C., 2008, January. Deep space navigation using celestial X-ray sources. In *Proc. ION 2008 National Technical Meeting* (pp. 101–109), figure 2.

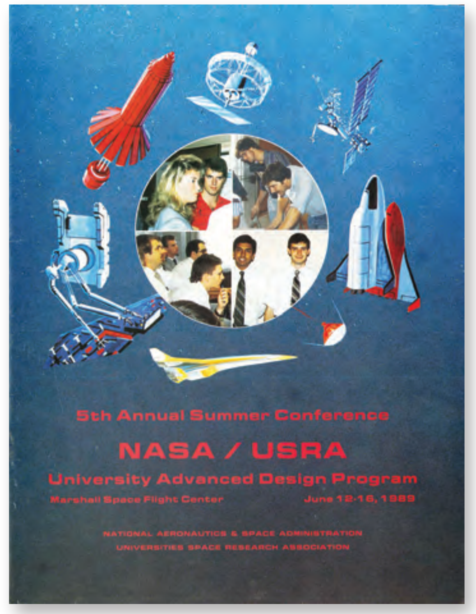
Credit for photo of Frank Drake. http://www.skyandtelescope.com/astronomy-news/the-chance-of-finding-aliens/.

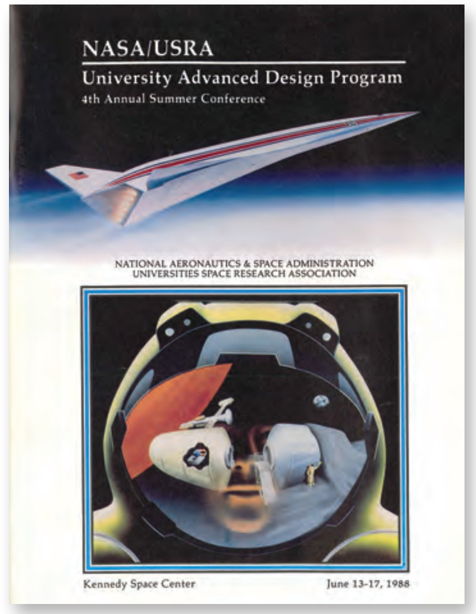
7

UNIVERSITY-BASED PROGRAMS

ENGINEERING UNDERGRADUATE EDUCATION

How USRA, in collaboration with NASA and universities, improved undergraduate education in aerospace engineering and Earth sciences.





FOR SEVERAL YEARS LEADING UP TO 1983, NASA's Office of Aeronautics and Space Technology (OAST) had tried to engage university faculty by conducting summer studies for the consideration of various advanced concepts, including subjects such as lunar bases, space station automation, orbital laboratories, and lighter-than-air airships. Because participating faculty members had not been familiar with the topic at the start of the study, considerable time was spent in educating them in comparison to the time spent doing useful work.

With this problem in mind, Stanley R. Sadin of NASA's OAST arranged to spend a year at USRA Headquarters.[1] During many conversations with USRA staff members and engineering faculty from USRA member universities, Sadin began to think about a parallel problem: the unsatisfactory way that undergraduate engineering design courses were being taught. All too often, the design courses failed to give the students vital experiences that they would need to be successful in their careers, e.g., working in teams to reach a common goal, as opposed to individual effort; knowing there isn't one right answer to a design problem; writing a technical report and having the ability to stand up in front of an audience to explain what you did and why; and approaching a problem from a systems point-of-view, having to make trade-offs between performance, weight, and costs to arrive at the "best" solution to a given problem.

Sadin began to develop an idea for an alternative way to conduct design education courses for engineering students at universities that, at the same time, would allow NASA to engage universities in new space and aeronautical design concepts. Sadin's idea became the NASA/USRA University Advanced Design Program, or ADP, for short. It began in 1984, under the leadership of USRA's John R. (Jack) Sevier (1929–1999), who had been a distinguished engineer at NASA before joining USRA.[2]

JACK SEVIER
USRA DIRECTOR,
DIVISION OF EDUCATION PROGRAMS

CLOSE COOPERATION BETWEEN THE NASA CENTERS AND THE UNIVERSITIES RESULTED IN A SUCCESSFUL FIRST YEAR OF THE ADP PILOT PROGRAM.

PARTICIPANTS IN THE INITIAL PILOT PROGRAM FOR ADP

UNIVERSITY	TOPIC	NASA CENTER
Colorado	Habitat at Geosynchronous Orbit	Ames Research Center
Georgia Tech	Lunar Construction Equipment	Marshall Space Flight Center
Michigan	Lunar Transfer Vehicle with Aero-assisted Return	Marshall Space Flight Center
MIT	Post Space Station Mission Analysis	Langley Research Center
Texas	Mars Mission Analysis	Johnson Space Center
Texas A&M	Mars Mission Analysis	Johnson Space Center
VPI & SU	Space Station-based Satellite Servicing Facility	Langley Research Center
Washington	Solar Space Power System	Lewis Research Center
Wisconsin	Mars Habitat	Lewis Research Center

VICKI JOHNSON
USRA PROGRAM MANAGER,
DIVISION OF EDUCATION PROGRAMS

THE ADVANCED DESIGN PROGRAM (ADP)

The ADP began with a grant from NASA to USRA for a pilot program that involved the capstone engineering design classes from nine universities, each linked with a NASA center.

The universities agreed to take a topic of interest to NASA as the focus for their senior engineering design classes. NASA engineers and scientists from the centers were available during the academic term to support the engineering design courses with background material, information on NASA design tools, literature references, lectures, etc.

Close cooperation between the NASA centers and the universities, the careful selection of design topics, and the unbridled enthusiasm of the students resulted in a successful first year of the pilot program, and NASA agreed to extend the experiment for a second year. Nineteen universities and eight NASA centers were involved in the second year's effort.

The pilot program, which lasted for four years, allowed university design faculty to provide their input on the desired structure of the ADP. Universities would be selected via a competitive process. NASA funding to the universities would be used to support a teaching assistant for the design class during the academic year and for a ten-week summer internship at the partnering NASA center prior to the beginning of the design course. Additionally, a NASA center would host a summer design conference at which the students would present their final design studies to their peers and receive critiques from industry, NASA, and USRA. Finally, each participating university would submit a formal written report to be included in the annual conference proceedings.

In practice, the success of the program was tied closely to contact between individuals at the NASA centers, who were termed "center mentors," and the faculty and students at the universities. Center mentors, and the interning teaching assistants, were able to provide background technical information for the design classes to sharpen the quality of the projects.

By the 5th annual ADP summer design conference, hosted by NASA's Marshall Space Flight Center in 1989, there were 400 participants, representing 37 universities, NASA Headquarters, eight NASA centers, USRA, Boeing, Battelle Memorial Institute, Eagle Engineering, Lockheed, McDonald Douglas, United Technologies, Martin Marietta, General Dynamics, Hercules Aerospace, Teledyne Brown, the National Academy of Sciences, the United States Air Force, the Soviet Union, the People's Republic of China, and France.

The ADP was well managed by Sevier, who served as Director of USRA's Division of Education Programs, and by Dr. Vicki S. Johnson, who served as Program Manager beginning in 1991. During the ADP's ten years of operation, 12,656 students, taught by 152 professors, from 69 university departments representing 55 different universities, had participated in the program. NASA distributed a total of $9,129,151 to the universities, but it is estimated that an additional $4,711,193 in resources was leveraged by the universities. In addition, McDonnell Douglas Corporation and the Boeing Airplane Group contributed funding and expertise to the program.

ENGINEERING PROGRAMS GET A MAKEOVER WITH THE HELP OF ADP

1992

ABET ENGINEERING CRITERIA 1992[3]

CERTIFICATION BASED ON:

- The size and competence of the faculty, the standards and quality of instruction in the engineering departments and in the scientific and other operating departments in which engineering students receive instruction, and evidence of concern about improving the effectiveness of pedagogical techniques
- The extent to which a program develops the ability to apply pertinent knowledge to the practice of engineering in an effective and professional manner
- [Curricular content] in the areas of mathematics, basic sciences, humanities and social sciences, and engineering topics
- The admission, retention, and scholastic work of students and the records of graduates both in further academic study and in professional practice
- The attitude and policy of the administration of the engineering division toward teaching, research, and scholarly production, and the quality of leadership at all levels of administration of the division
- Adequate physical facilities, including office and classroom space, laboratories, and shop facilities ..., [as well as] libraries and computer facilities

2000

ABET ENGINEERING CRITERIA 2000[4]

ENGINEERING PROGRAMS MUST DEMONSTRATE THEIR GRADUATES HAVE:

- An ability to apply knowledge of mathematics, science, and engineering
- An ability to design and conduct experiments, as well as to analyze and interpret data
- An ability to design a system, component, or process to meet desired needs
- An ability to function on multi-disciplinary teams
- An ability to identify, formulate, and solve engineering problems
- An understanding of professional and ethical responsibility
- An ability to communicate effectively
- The broad education necessary to understand the impact of engineering solutions in a global and societal context
- A recognition of the need for, and an ability to engage in life-long learning
- A knowledge of contemporary issues
- An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

CHANGES IN THE ACCREDITATION BOARD FOR ENGINEERING AND TECHNOLOGY (ABET) CRITERIA

While the ADP was operating during the 1980s and into the early 1990s the engineering education community in the US was engaged in a discussion about the need to change the accreditation criteria that had been established by the Accreditation Board for Engineering and Technology (ABET). Until this time, the ABET accreditation criteria were focused on the quality of the faculty, facilities, student body, administration of the engineering division and the institutional commitment of the university.

The 1992 (and earlier) ABET evaluation criteria were "input" oriented, i.e., they were "based on the premise that the desired outcomes [excellent engineering graduates] will be consistent with and derived from the appropriate inputs [quality of faculty and facilities, etc.]."

After lengthy discussion within the engineering community, in October 1995, the ABET Board of Directors approved the publication of new, outcome-driven, criteria for evaluating university engineering programs, known as Engineering Criteria 2000.

The change in the ABET Engineering Criteria was very significant for the course of engineering education in the United States, and there were many influences that gave rise to the change, most notably, the voices of engineers from industry such as John McMasters of the Boeing company. McMasters had been involved with the ADP, and in 1994 he and others at Boeing developed what became known as the Boeing list of "Desired Attributes of an Engineer,"[5] which was similar to the revised ABET engineering criteria.

Others who influenced the change in the ABET criteria were the engineering faculty and deans at US universities. The NASA/USRA University ADP was influential as well, in that it provided a model for engineering design courses during the height of the ABET discussion in the 1980s and 1990s. As one participating ADP professor recalled, "the ADP has done more for engineering design education than all the talk of the past twenty years."

IMPACT OF THE ADP

Mid-way through the ADP, the USRA/ADP managers asked the participating faculty and students to comment on the impact of the program. The faculty reported a wide variety of benefits, including the development of dedicated design facilities within their departments; greater communication among students and faculty across discipline boundaries at their universities; expanded interactions, not only with NASA but also other federal agencies, companies, and other universities as their students sought expertise while developing their designs; and, in general, a welcomed rebalance of engineering synthesis, as opposed to engineering analysis, in the education of their students.

Students involved with ADP also had positive comments about their design courses, as the following sample indicates.[6]

– *Of all the classes I've taken, the design classes have excited me most and have been the most beneficial in applying what I have learned. I wish there were more. (student from MIT)*

– *The design course is the best class I've taken because it involved using ALL my engineering and communications skills. I learned a lot about myself and the overall mechanics involved in design. (student from Purdue)*

– *The design class proved our capabilities and showed us how much we really knew. (student from Penn State)*

– *It's nice to finally see what all that theory was for. (student from UCLA)*

The NASA perspective on ADP was reflected in a report of the NASA Advisory Council's Task Force on University Relations in 1993:

> *Through the Universities Space Research Association, NASA funds Advanced Design Programs allowing undergraduates as well as graduate students to participate in a systems engineering approach to design providing an important mechanism for improving design curricula. This is a low-cost, high-impact approach to enriching the education of engineering students in aeronautical and space system design.*[7]

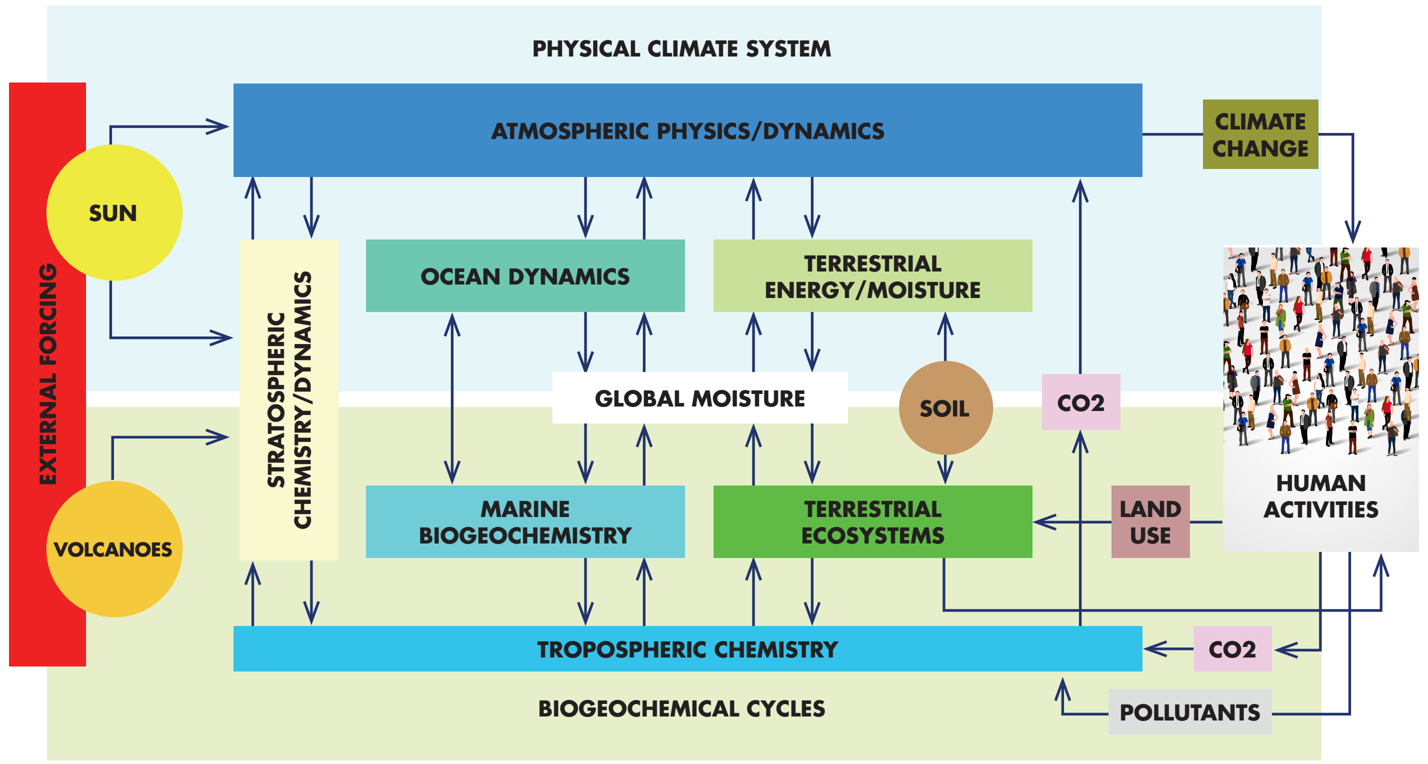
DON JOHNSON
USRA DIRECTOR,
EARTH SYSTEM SCIENCE
EDUCATION PROGRAM

EARTH SCIENCE DISCIPLINES AND THE WORK OF DONALD R. JOHNSON

The ADP affected the lives of many engineering students in the 1980s and 1990s, as well as many more students in years to come due to its influence on the change in accreditation criteria for ABET. But it also had an effect on students in the Earth-science disciplines, and this is primarily due to the work of Professor Donald R. Johnson (1930–2017) of the University of Wisconsin.

Since 1981, Johnson and his colleagues at the Space Science and Engineering Center of the University of Wisconsin had been funded by the National Science Foundation to develop teaching modules for atmospheric science using satellite imagery.[8] At this same time, Johnson was increasingly involved with USRA. He was the Institutional Representative from the University of Wisconsin on the USRA Council of Institutions (COI), served as Chair of the COI in 1982, was appointed as Chair of the USRA Science Council for Earth Sciences in 1984, and began a six-year term on the USRA Board of Trustees in 1989.

Because of these positions, Johnson saw the development of the ADP and the effect that it was having on engineering education in US universities. He also saw the need for a similar university-based program in the Earth sciences, and he worked with the USRA Science Council for Earth Sciences to develop a proposal that would be submitted to NASA.



BRETHERTON DIAGRAM

Johnson's initial idea was a pilot program that would involve a small number of universities, as had been the process with the establishment of the ADP. Instead of the planned five universities, however, NASA provided initial funds for the participation of twenty-two universities in a program that would be called the Cooperative University-based Program in Earth System Science Education (ESSE), which began in 1991.

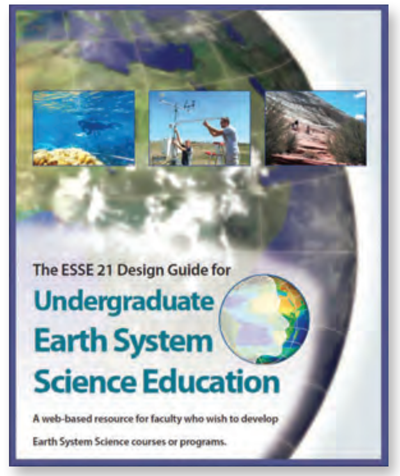
THE EARTH SYSTEM SCIENCE EDUCATION (ESSE) PROGRAM BEGINS

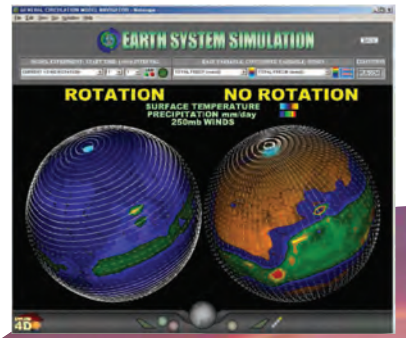
From the beginning, Johnson knew and stressed the value of making the program "university based," because his aim was to help establish a national academic underpinning for Earth system and global change science. Johnson also stressed the need for an interdisciplinary systems approach to Earth science, and he recognized the need for mechanisms to stimulate scientific collaboration among scientists and departments within universities, among universities, and between university and government science communities.

The initial five-year ESSE program began with Don Johnson as its USRA Director. Twenty-two universities were competitively selected to participate by developing and offering a survey course and a senior level course in which faculty presented Earth-systems issues as a socially relevant, challenging, and important class of scientific problems. The objective of the survey level course was to instill among the general student population an appreciation of the social, economic and political implications of global change, and a scientific understanding of inter-relationships between the Earth's physical climate system and ecological systems. The focus of the senior course was on the application of advanced concepts and analytical products in a problem-solving, project-oriented environment. The senior courses generally engaged advanced students from different academic departments working in teams to implement conceptual and computer models of physical, chemical, and biological processes that link the components of the Earth system, as often illustrated by the so-called Bretherton Diagram.

Johnson solidified the NASA-university connection by asking each participating university to work with a NASA-based scientist who contributed informally to the university's academic program through advising classes with projects relevant to NASA missions and facilitating access to NASA data, technical material, and other resources appropriate for use in the undergraduate courses.

MARTIN RUZEK
USRA PROGRAM MANAGER, ESSE 21





ESSE FOR THE 21ST CENTURY

In 2003, Martin Ruzek began to manage the follow-on program to ESSE, Earth System Science Education for the 21st Century (ESSE 21). ESSE and ESSE 21 ran for a total of 15 years. Among the legacies of ESSE, beyond the creation of Earth System Science courses and degree programs at many universities, were the development and hosting of the Earth Science Picture of the Day (EPOD), which continues to be maintained on the Web as a service of USRA; the creation of a Design Guide for Undergraduate ESS Education; and the development of the Journal of Earth System Science Education (JESSE), which was an early experiment in web-based science journalism.[9]

The cover of the Design Guide is shown here, along with a figure from a JESSE article by Owen Thompson (University of Maryland) and colleagues titled "Computationally Intensive Models in the Classroom: Earth System Science Education."

In May 2006, the ESSE 21 program organized a special issue of the Journal of Geoscience Education, published by the National Association of Geoscience Teachers, edited by Ruzek and Professor Gene Rankey (University of Miami). The special issue was entitled "The Symphony of the Spheres: Recent Advances in Earth System Science Education," and was intended to serve as a capstone publication that captured the experiences of progress in Earth system science education. The journal focused on exploring exemplary courses, curricula, degree programs, learning resources, and programs centered on using an Earth system science approach. The Special Issue had thirty papers describing lessons learned in developing and sharing content, utilizing Earth system science topics to engage students in science, technology, engineering, and mathematics (STEM) learning, and building working interdisciplinary partnerships.[10]

In 2014, the American Meteorological Society held a symposium to honor Donald Johnson for his many contributions to science and education. In a presentation by Martin Ruzek, Professor Owen Thompson of the University of Maryland was quoted, as follows:

> *His work in fostering "Earth system science" has led to new, fully integrated university curricula that place the most fantastic natural phenomena on the top of solid science and mathematics bases. This is a key outcome of the "Earth System Science Education" initiative, and has helped in remapping environmental science education from the ground up. … I was profoundly moved by Don's ability to persuade us all to think more broadly about the breadth, depth, and strategy of educating the next generation about this complex collection of subjects. … Don Johnson's scientific and educational contributions will influence teachers, students, and decision-makers for generations to come.*[11]

When ESSE 21 concluded in 2007, the program and its predecessor, ESSE, had supported 57 colleges and universities with small grants for the development and offering of over 130 courses in Earth system science that reached tens of thousands of students.

The ESSE program and the ADP proved to be remarkable examples of what could be achieved through the collaboration of NASA and the university community made possible by USRA.

EPOD.USRA.EDU
An Earth Science Picture of the Day from May 29, 2014 was photographed by Manolis Thravalos, depicting a high-arching double rainbow on Samos Island, Greece. Since 2000, photographers from all over the world use tools that range from camera phones to satellites in order to capture images for the EPOD website that serve as a resource for scientists, educators, students, and the general public.

Participants of the 2005 ESSE 21 Team Meeting, held in Anchorage, Alaska.

DON JOHNSON'S WORK IN FOSTERING "EARTH SYSTEM SCIENCE" HAS LED TO NEW, FULLY INTEGRATED UNIVERSITY CURRICULA THAT PLACE THE MOST FANTASTIC NATURAL PHENOMENA ON THE TOP OF SOLID SCIENCE AND MATHEMATICS BASES.

ENDNOTES

1. NASA and USRA used the mechanism provided by the Intergovernmental Personnel Act. As a nonprofit organization, USRA is eligible to participate in personnel transfers authorized by the act.
2. Sevier had chaired the Lunar Surface Traverse Planning Team for the Apollo program and had been the Deputy Program Scientist for the Skylab missions. Following 26 years at NASA and NACA (the National Advisory Committee for Aeronautics – the predecessor to NASA), Sevier had joined USRA in 1977.
3. Engineering Accreditation Commission, 1993. *Criteria for accrediting programs in Engineering in the United States (1993–1994).* Accreditation Board for Engineering and Technology, Inc., pp.61–65.
4. Seagrave, R.C., 2007. Reflecting back: Recollections of a past president. In *A Proud Legacy of Quality Assurance in the Preparation of Technical Professionals: ABET 75th Anniversary Retrospective* (pp. 254–255), p.255.
5. McMasters, J.H., 2004. Influencing Engineering Education: One (Acrospace) Industry Perspective. *International Journal of Engineering Education, 20*(3), pp.353–371, p.359.
6. Student quotes appeared in the 1990–91 Program Evaluation Report of the NASA/USRA University Advanced Design Program.
7. NASA Advisory Council, 1993. Report of the University Relations Task Force. (56 pp.) Washington, DC: National Aeronautics and Space Administration, p.22.
8. Phillips, J., 2013. An Early Vision for Earth System Science Education. Retrieved from News Archive of the Space Science and Engineering Center (29 May 2013), http://www.ssec.wisc.edu/news/articles/page/6, Space Science and Engineering Center, University of Wisconsin.
9. Thompson, O.E., Johnson, D., Kalnay, E., Zhang, D., Cai, M., Suarez, M., Yanuk, D. and Schaack, T., 2001. Computationally intensive models in the classroom. *Journal of Earth System Science Education, 1,* pp.1–13. Retrieved from http://jesse.usra.edu/public/default.cfm?content=456.
10. Rankey, E.C. and Ruzek, M. (Eds.)., 2006. Special Issue: The Symphony of the Spheres - Recent Advances in Earth System Science Education. *Journal of Geoscience Education, 54*(3). Retrieved from http://nagt.org/nagt/jge/abstracts/may06.html.
11. Ruzek, M., 2014. Earth System Science Education: Don Johnson's Leadership in Systemic Reform. Presentation at the Donald R. Johnson Symposium of the 94th Annual Meeting of the American Meteorological Society.

LAUNCHING CAREERS WITH SMALL-SATS

How a USRA small-satellite program demonstrated triple value – low cost, hands-on training of students, and excellent science.

Students interacting with the Student Nitric Oxide Explorer in the Spacecraft Monitoring and Operation Center at the Laboratory for Atmospheric and Space Physics of the University of Colorado.

DURING THE VERY EARLIEST DAYS OF THE SPACE PROGRAM, it was common for graduate students to be intimately involved with the design, development, and operation of science payloads for spacecraft. As an example, George Ludwig was a graduate student under Professor James Van Allen (1914–2006) of the University of Iowa when he designed and developed the cosmic ray experiment packages for Explorer 1 and Explorer 3, which were launched in 1958.[1] It was the data from Ludwig's instruments that led to the discovery of the Van Allen radiation belts.[2]

The first two successful Explorer spacecraft were relatively small and simple compared to later space vehicles. Spacecraft steadily became larger and more complicated. The time between launch opportunities grew, and the time between concept and launch of spacecraft often exceeded the normal time for the development of a PhD thesis at a university. For all of these reasons, by the 1980s, university principal investigators for spacecraft missions began to turn to aerospace companies to better ensure the success of their experiments, the design and development of which no longer afforded graduate students much opportunity for "hands-on" training.

In response to this problem, USRA began to search for low-cost access to space by small spacecraft for university-based research. In May of 1990, the third USRA president, Dr. Paul Coleman, contacted the US Arms Control and Disarmament Agency to urge that the Strategic Arms Reduction Treaty not require destruction of surplus sea-launched ballistic missiles and (non-mobile) intercontinental ballistic missiles, as these missiles could be converted into small expendable launch vehicles for university space experiments. For the next two years, in testimony before congress and meetings with NASA and DoD officials, Coleman continued to push this idea. Finally, on 30 April 1993, Coleman received a letter from the Office of the Under Secretary of Defense, stating that:

> *On April 21, 1993, the Deputy Secretary approved the policy that would permit use of excess strategic missiles for space launch purposes on a selected basis. In particular, this allows the conversion of such assets into small expendable launch vehicles (SELVs) for the purposes you suggest.*[3]

SPACECRAFT STEADILY BECAME LARGER AND MORE COMPLICATED. THE TIME BETWEEN LAUNCH OPPORTUNITIES GREW, AND THE TIME BETWEEN CONCEPT AND LAUNCH OF SPACECRAFT OFTEN EXCEEDED THE NORMAL TIME FOR THE DEVELOPMENT OF A PhD THESIS AT A UNIVERSITY.

STEDI SEMI-FINALIST TEAMS

Proposing Entity and PI	Satellite Name	Scientific/Technology Purpose
Maryland Space Grant Consortium, Richard Henry	Hydrogen Recombination Radiation Experiment (HRRE)	Detect and map the distribution of intergalactic ionized hydrogen.
University of New Hampshire, David Forrest	Cooperative Astrophysics and Technology Satellite (CATSAT)	Determine the distance of gamma-ray burst sources.
Colorado Space Grant, Elaine Hanson	Educational Ozone Researcher (EOR)	Simultaneously measure ozone and chemical species that destroy ozone in Earth's atmosphere.
Boston University, Daniel Cotton	Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS)	Use computer assisted tomography data analysis methods to construct two-dimensional "slices" of the ionosphere.
University of Colorado/ Laboratory for Atmospheric and Space Physics, Charles Barth	Student Nitric Oxide Explorer (SNOE)	Explore the mechanisms for producing nitric oxide in the Earth's atmosphere.
University of Michigan, Brian Gilchrist	Atmospheric/Ionospheric Research Satellite using Advanced Tether Technology (AIRSATT)	Directly measure atmospheric properties in the lower thermosphere as well as atmospheric interactions with the satellite and its 20-km tether.

In July 1992, Coleman had met with Mr. Dan Goldin, the NASA Administrator, to propose that NASA undertake a series of spaceflight missions using smaller, cheaper, but very capable spacecraft. Coleman argued that this would allow for a small-mission complement that could accomplish significant scientific, technological, and educational objectives at a fraction of the cost in comparison with traditional government-funded space flight research projects. After winning the DoD policy decision that he had pursued over a three-year period, Coleman met again with Goldin in May 1993. At this meeting, Goldin challenged USRA to demonstrate the program capabilities and economic feasibility of low-cost, university-based missions by conducting a three-year program, consisting of multiple polar-orbiting spacecraft. In November 1993, USRA submitted to NASA a formal proposal for the Student Explorer Demonstration Initiative (STEDI) Program. STEDI was designed as a flight program with an objective to prove the concept and feasibility of low-cost, efficient space investigations.

In May 1994, the STEDI Program was established as a NASA Cooperative Agreement with USRA. Shortly afterwards, USRA released the STEDI Announcement of Opportunity (AO) to universities, calling for complete missions that would be able to operate for up to one year in polar orbit. The cost for each mission (including spacecraft/instrument design, development, test, integration, and operation for one year in orbit) could not exceed $4.4 million, and the research projects had to be ready for launch within two years from project start. In addition, the proposals had to demonstrate that there would be significant and meaningful student involvement over the course of the entire project. The initial STEDI Program Manager was Mr. John R. Sevier, an experienced USRA engineer and manager.

As noted above, USRA and NASA had envisioned the use of surplus missiles that would be converted to expendable launch vehicles for STEDI missions. However, a change in the National Space Transportation Policy announced on 5 August 1994 made that impossible. The new policy stated, "these assets [surplus DoD missiles] may be used within the US Government in accordance with DoD procedures, for any purpose except to launch payloads into orbit."[4]

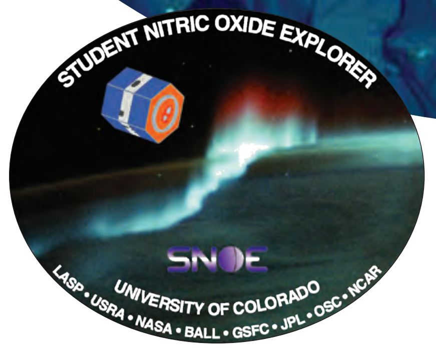
The policy change was presumably influenced by the argument that such use of government assets might harm the US commercial providers of small expendable launch vehicles. In any case, on 15 November 1995, NASA announced the selection of Orbital Sciences Corporation to negotiate a firm fixed price contract to provide launch services for ultralight-class payloads, which included the STEDI spacecraft.

From the 66 proposals that were received in response to the STEDI AO, six groups were given $160,000 each for a four-month study to prepare for a final selection. The semi-finalist teams are shown in the chart above.

THE SNOE SUCCESS PROVED THAT STEDI MISSIONS COULD SIGNIFICANTLY ENHANCE THE EDUCATION OF YOUNG ENGINEERS/ SCIENTISTS, AND COULD MAKE IMPORTANT CONTRIBUTIONS TO SPACE SCIENCE AND TECHNOLOGY.

Paul Coleman, USRA's third president, standing beside the Pegasus XL launch vehicle, which was mounted to the underside of a Lockheed L-1011 aircraft.

In February 1995, two university-based projects, SNOE of the University of Colorado and TERRIERS of Boston University, were initially selected for final development, launch, and mission operations, and a third, CATSAT of the University of New Hampshire, was added a year later.



STUDENT NITRIC OXIDE EXPLORER (SNOE)

The scientific objectives of the SNOE were to determine (a) how variations in the solar soft X-radiation produce changes in the density of nitric oxide in the lower thermosphere, and (b) how auroral activity produces increased nitric oxide in the polar regions.

Properties of the lower thermosphere are difficult to measure. This region of the atmosphere is too high for scientific balloons and too low for extended operations by orbiting satellites. Yet the lower thermosphere plays a critical role in the energetics, dynamics and coupling of the Earth's atmospheric system with solar activity.

SNOE carried three scientific instruments: an ultraviolet spectrometer to measure nitric oxide altitude profiles in Earth's atmosphere, a two-channel auroral photometer to measure auroral emissions beneath the spacecraft, and a five-channel solar soft X-ray photometer. Students were involved in all aspects of the project. Under the supervision of mentors from the Laboratory for Atmospheric and Space Physics (LASP) and industry (particularly Ball Aerospace), students at the University of Colorado designed and built the spacecraft and instruments, wrote the flight software, integrated the subsystems, and conducted the test program.[5]

SNOE was launched by an Orbital Sciences Corporation's Pegasus XL rocket system into a polar orbit on 26 February 1998. The satellite occupied the front half of the Pegasus payload stage.

Once SNOE achieved orbit, students operated the spacecraft. Students typically applied to be members of the SNOE operations team at the end of their sophomore year. The top applicants were selected to undergo an extensive summer-long training program that began with "basic training" lectures by LASP professionals on how spacecraft work, including: mechanical structures; thermal control; electrical power production, storage and distribution; computer and data handling systems; communications; propulsion; attitude determination and control; and scientific instrumentation. Students also received lectures on related topics, such as the nature of the space environment and orbital mechanics.

After basic training was complete, the students had to learn all the details of SNOE, including the workings of each of the two dozen or so major components of the spacecraft, the instructions making up the command uplink set, and how to interpret the hundreds of pieces of information returned by the satellite. They also received training on the ground systems used for SNOE operations.

During the second half of the summer, the students worked with existing members of the operations team to learn all of the tasks and procedures necessary to safely operate the SNOE spacecraft. Finally, after all the classroom and hands-on training had been completed, the students had to pass a comprehensive examination before being certified as full members of the operations team.[6]

TOP: The SNOE spacecraft mounted on the Pegasus launch vehicle.

BOTTOM: The University of Colorado students who worked on the SNOE spacecraft, standing behind the spacecraft.

The SNOE satellite orbited the Earth with its spin axis normal to its orbital plane. The satellite was placed in a sun-synchronous orbit so that its northward crossing of the equatorial plane always occurred at approximately 10:30 am local time. The student operations team at the University of Colorado interacted with the satellite daily to monitor the status of its systems, retrieve data, and send instructions to the SNOE experiments.

CHARLES BARTH
SNOE PRINCIPAL INVESTIGATOR

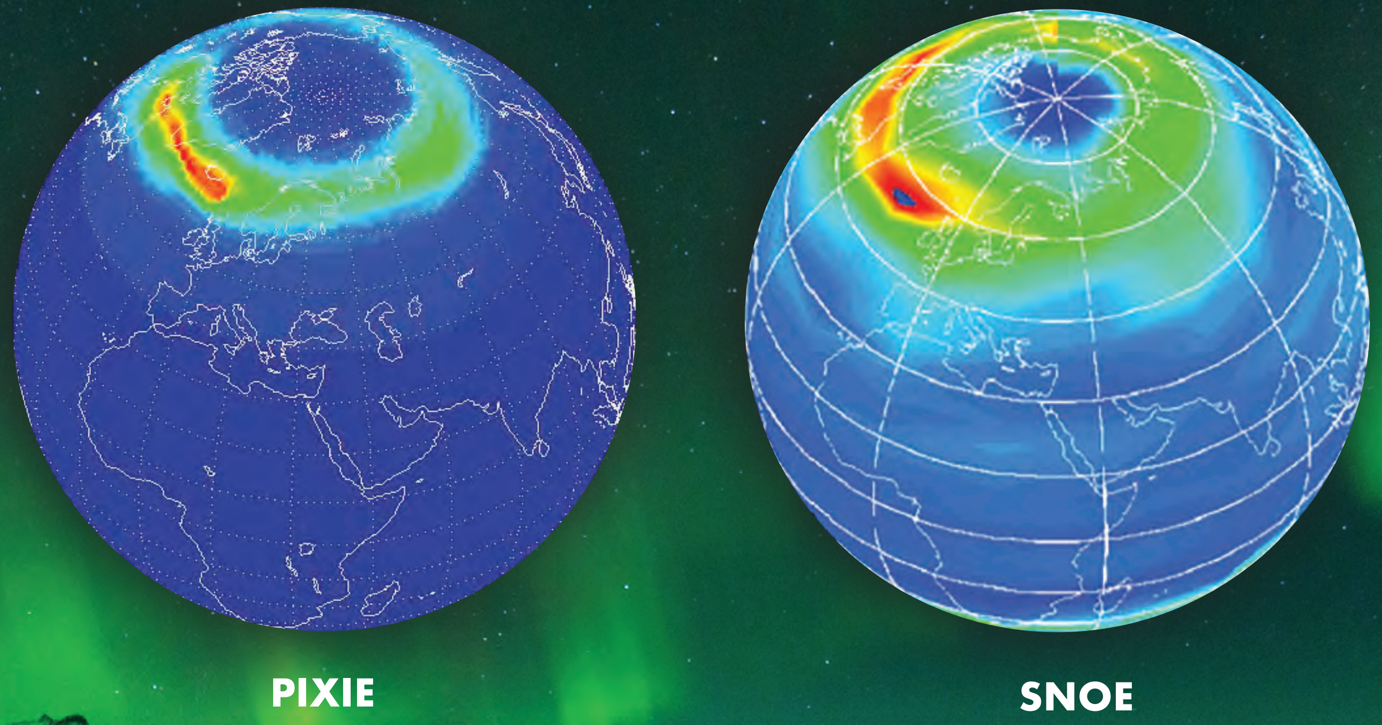
Professor Charles Barth (1930–2014) of the University of Colorado was the Principal Investigator for the SNOE mission. In 1988, Barth had proposed that the solar X-ray flux between 2 and 10 nanometers was responsible for the variation of the nitric oxide density in the Earth's atmosphere at low latitudes.[7] Barth's hypothesis could not be proven at the time because of the lack of simultaneous measurements of the solar soft X-ray flux and the nitric oxide density in the atmosphere at low latitudes.

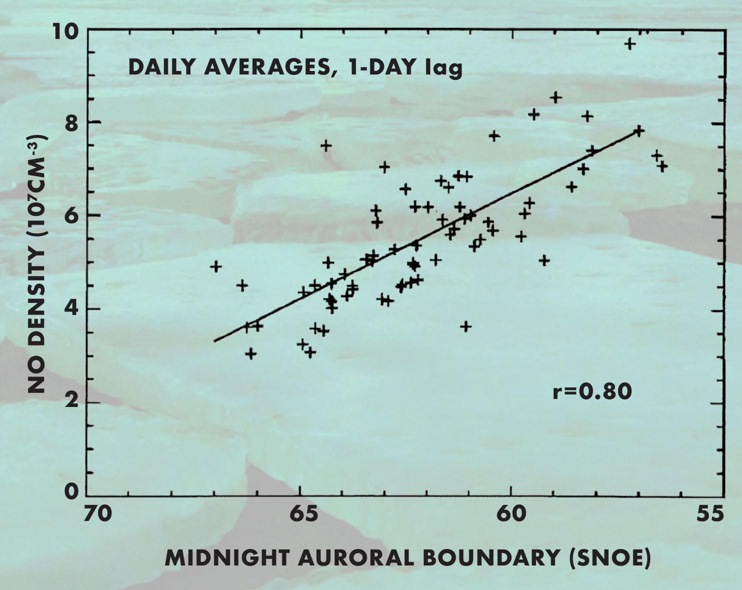
The SNOE mission was designed to verify Barth's hypothesis, and the SNOE data showed that the low-latitude thermospheric nitric oxide density and the solar soft X-ray flux are highly correlated.[8]

The second goal of the SNOE mission was to determine how the downward flow (precipitation) of electrons in the auroral zone affects the density of nitric oxide in the upper atmosphere. From the ground, near midnight and later, the aurorae often appear to be curtains of light in the sky at high latitudes. The light is known to be caused by the excitation of atoms in the thermosphere caused by the precipitation of electrons along magnetic field lines in the polar regions. Viewed from space the auroral zones are seen to be ovals around northern and southern magnetic poles. The auroral ovals are typically found between 60° and 70° geomagnetic latitude (aurora borealis) and -60° and -70° geomagnetic latitude (aurora australis).

The SNOE satellite measured the nitric oxide density in the lower thermosphere (97–150 km) as a function of altitude and latitude for a two-and-a-half-year period from 11 March 1998 until 30 September 2000. The measurements showed that the maximum density of nitric oxide occurs near 106–110 km, the density is highly variable, and the mean density in the auroral zones is much higher than in the equatorial region.[9]

To investigate the relationship between auroral activity and the production of nitric oxide in the auroral zone, Barth and his colleagues used the equatorward boundary of the auroral zone at midnight as an indicator of auroral activity.[10] Other researchers, such as Gussenhoven et al., had shown that the latitude of this boundary at midnight is a good indicator of auroral activity and total energy deposition into the atmosphere by precipitating electrons, with lower latitude





Nitric oxide auroral region daily averages plotted against the previous day midnight auroral boundary daily averages for 80 days in 1998.[5]

MEASURING AURORAL ZONES

LEFT GLOBE: Electrons that travel down magnetic field lines in the auroral zone cause the emission of X-rays as well as visible light when they impact atoms in the thermosphere. The PIXIE instrument on the Polar satellite measured these X-rays. *Credit: NASA*

RIGHT GLOBE: The SNOE satellite measured the density of nitric oxide in the northern auroral zone on the same day (4 May 1998) that the PIXIE instrument measured the emission of X-rays there. *Credit: NASA*

Background: Aurora image captured at midnight on April 10, 2015, in Delta Junction, Alaska.
(NASA and Sebastian Saarloos)

Mission Scenario for SNOE

boundaries corresponding to greater auroral activity on average.[11] The SNOE data demonstrated that the nitric oxide density in the auroral zone is well correlated with auroral activity, with a one-day lag.

The one-day lag occurs because in the night-side auroral zone nitrogen and oxygen molecules are dissociated by precipitating electrons, and nitric oxide is thereby formed. Once the available atomic nitrogen is consumed in this process, the density of night-side nitric oxide in the auroral regions remains constant. As the Earth rotates, the nitric oxide enters the sunlit side of the Earth and begins to be destroyed by solar ultraviolet light and X-rays. The technique used by the SNOE instrumentation to measure the nitric oxide density depends on observing the fluorescence of nitric oxide molecules as they are being impacted by ultraviolet light from the Sun. Hence, the nitric oxide density could be measured by SNOE only on the sunlit half of the Earth. The lifetime of nitric oxide in the sunlit atmosphere is about half a day. The combination of observational delay and lifetime effects explain the approximate one-day lag in the correlation between the nitric oxide density and location of the midnight auroral boundary.[12]

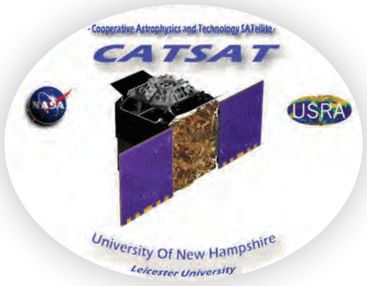
The SNOE satellite reentered the Earth's atmosphere on 13 December 2003. Its useful scientific lifetime far exceeded the one-year target, and SNOE data was frequently used in conjunction with other satellite data in the years following its launch in 1998. For example, a comparison of SNOE nitric oxide data with data from the Polar Ionosphere X-ray Imaging Experiment (PIXIE) instrument on the Polar satellite demonstrated the correlation between auroral activity and nitric oxide abundance for a single day, 4 May 1998.

The SNOE success proved USRA president Paul Coleman's contention that STEDI missions not only could significantly enhance the education of young engineers and scientists, but also could make important contributions to space science and technology. The other two STEDI missions were also very successful in providing students and other young space professionals hands-on experience in the design, development, testing, etc., of small satellites, even though the satellites were not able to collect any data.

TOMOGRAPHIC EXPERIMENT USING RADIATIVE RECOMBINATIVE IONOSPHERIC EUV AND RADIO SOURCES (TERRIERS)

TERRIERS was successfully launched on 18 May 1999 by a Pegasus XL launch vehicle, but the spacecraft lost power due to attitude control problems during the first day of operation. The satellite was not able to orient itself so that its solar panels fully faced the sun, and it soon ran out of battery power.

Launch delays posed a significant problem for the STEDI program. Failure of the first two flights of the Pegasus XL launch vehicle in the fall of 1995 caused a delay of almost a year for SNOE. The delay for TERRIERS was almost two years.



COOPERATIVE ASTROPHYSICS AND TECHNOLOGY SATELLITE (CATSAT)

The third project, CATSAT, was originally scheduled for launch on 15 July 1998 and was eventually manifested as a secondary payload on a Boeing Delta II rocket that was scheduled for launch on 15 December 2001. The primary payload for the Delta II rocket was ICESat, which was a major NASA spacecraft. Partially to avoid risk to the launch of ICESat, NASA decided to close out the CATSAT project, and the satellite was never launched.[13]

CATSAT was mothballed for several years and eventually put on display at the McAuliffe-Shepard Discovery Center in Concord, New Hampshire. When the spacecraft first went on display at the Center, Mark Granoff, who had worked on the satellite, gave an overview of the project and its impact on the University of New Hampshire, as reported by Jack Rooney in the Concord Monitor:

> *The CATSAT project "was a milestone for student involvement at UNH," Granoff said. "It was the coolest thing on campus during its day. If you were working on CATSAT, you were the best of the best in terms of students. Drive, initiative, focus – all the things that make good engineers – this is what they worked on. It was a milestone for New Hampshire."*
>
> *Granoff said the project drew students from mechanical, electrical and software engineering as well as physics to guide the satellite from its proposal stage … all the way to the UNH control room once it was in orbit. And while the satellite never launched, Granoff said it did launch a number of careers. Students who worked on the project have gone on to work for aerospace companies and agencies including Raytheon and NASA's Jet Propulsion Lab.*
>
> *"This was a long-term program," he said. "Students came in from sophomore year onward where they had a real driving interest in aerospace and science. There was turnover because the project was longer than one student's term, but they would leapfrog and they would hand off to the new students. Then they would end up graduating and this would go on their resume as a real first-class hardware experience.*[14]

In the final program report for STEDI, Mr. Jeffery Cardenas, who succeeded Sevier as USRA's STEDI Program Manager, summarized the program as follows:

> *The program dramatically demonstrated that STEDI-class missions are ideally suited for development in a university environment. The hardware development time of 2–3 years corresponds to the typical graduate student's (i.e., master's level) tenure. The magnitude and complexity of the tasks were at the right level for students to handle (when properly supervised and mentored by experienced professionals), and the university environment was and will continue to be uniquely adapted to the low-cost constraints imposed. More importantly, the successes, shortfalls, and unique challenges of the STEDI Program have been an invaluable hands-on educational experience for both undergraduates and graduates alike.*[15]

ENDNOTES

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12. Solomon et al., SNOE Spacecraft, 1261.
13. The launch of ICEsat was delayed until January 2003. The secondary payload for the launch was the CHIPSat (Cosmic Hot Interstellar Plasma Spectrometer satellite), which was the first and only small satellite to be flown as a part of NASA's follow on to the STEDI program, called University-class Explorers.
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ADVOCACY FOR THE UNIVERSITY
SPACE RESEARCH COMMUNITY

MORE OPPORTUNITIES FOR STUDENT HANDS-ON TRAINING

How USRA developed the capability to advocate for the university space research community.

THE THIRD PRESIDENT OF USRA, PROFESSOR PAUL J. COLEMAN JR., worked during the early 1990s to convince NASA and other federal agencies that universities could successfully manage small spaceflight missions of high scientific merit. His efforts culminated with the NASA-sponsored, USRA-managed, Student Explorer Demonstration Initiative (STEDI), consisting of low-cost, university-led spaceflight missions that involved undergraduate and graduate students in a hands-on way with all aspects of satellite design, development, and operations. USRA's STEDI program began in the spring of 1994, and soon thereafter, three university groups were selected through a proposal competition and were hard at work on their missions.

While STEDI was underway, Coleman thought more broadly about the future of university space research. In the spring of 1995, he wrote an internal USRA memo and predicted that:

1. *Most future space research will be done with total mission costs significantly lower than was the experience prior to 1994. Spacecraft will be smaller and more sophisticated.*
2. *For most flight missions that involve university researchers, the principal investigator (PI) will be responsible for all aspects of the mission, except, perhaps, the launch vehicle.*
3. *There will be a more thorough-going integration of instruments with the spacecraft ("science craft"), less of the "box in a box" mode that has allowed instruments to be developed on a campus and then integrated into the spacecraft.*
4. *The pressure to maintain cost and schedule on flight projects will be even greater in the future than it has been in the past.*[1]

From the above premises, Coleman concluded that:

- *University researchers in all aspects of space research need to prepare for missions in which the PI has total mission responsibility, as opposed to participation on facility-class missions.*
- *Students will need more hands-on training in the design and development of hardware and data systems. Among other reasons, a greater level of experience among young scientists and engineers will give the community a better chance to meet mission objectives within cost and schedule ceilings.*[2]

PAUL COLEMAN

USRA PUSHED FOR LOW-COST ACCESS TO SPACE TO SUPPORT STUDENT SPACEFLIGHT MISSIONS.

A NASA-managed University Explorer Program succeeded STEDI but was cancelled after one spaceflight mission.

USRA continued to push for low-cost access to space to support student spaceflight missions. Coleman pursued opportunities for universities to have access to retired Department of Defense rockets for research launches, and he approached commercial launch firms for opportunities as well. USRA even created a for-profit company, Space Operations International (SOI), to act as a "freight consolidator" for commercial launch providers. SOI would match university payloads with available space on commercial rockets. The challenges of payload integration and indemnification proved costly beyond USRA's financial resources, however, and SOI was dissolved in 2003.

DAVID BLACK

The need to train more space professionals was emphasized in the 2001 "Report of the Commission to Assess United States National Security Space Management and Organization," and in the 2002 "Report of the Commission on the Future of the United States Aerospace Industry:"

> *Our policymakers need to acknowledge that the nation's apathy toward developing a scientifically and technologically trained workforce is the equivalent of intellectual and industrial disarmament and is a direct threat to our nation's capability to continue as a world leader.*[3]

BLACK CONTINUES TO PRESS FOR MORE HANDS-ON TRAINING

Consequently, the fourth president of USRA, Dr. David C. Black, continued to seek ways to provide more hands-on training through low-cost spaceflight opportunities for university students. In June of 2003, Black sent to key members of the university space research community a survey that sought to identify issues related to the development and implementation of small-satellite missions. Using this input, USRA then organized the "Access-to-Space Workshop" in July, and Black issued a position paper in September titled, "A Response to the National Need to Train Future US Scientists and Engineers in the Use of Space Technology." In his paper, Black referred to the STEDI program and argued that:

> *Small university space missions, of a size not currently funded, have been demonstrated as means of producing science and engineering graduates who are exceptionally well-trained in space technology and sought after by both industry and government. Such small missions, costing between $3M and $10M (plus launch costs), are of a size and complexity that afford significant science to be accomplished by university researchers and, at the same time, allow undergraduate students to get hands-on training with an actual space mission, from design to launch to satellite control. A modest investment by our country in a small space flight program, with certain defined characteristics, will assure that the US will have the future space workforce that is now recognized as crucial to our security and economic strength.*[4]

In January of 2004, President George W. Bush announced a new vision for the US civil space program with the goal of advancing the nation's scientific, security, and economic interests through a robust space exploration program.[5] President Bush cited four objectives for his new vision:

- *Implement a sustained and affordable human and robotic program to explore the solar system and beyond*
- *Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations*
- *Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration*
- *Promote international and commercial participation in exploration to further US scientific, security, and economic interests.*[6]

The president appointed a commission (The President's Commission on Implementation of United States Space Exploration Policy) to make recommendations for the implementation of the vision, and the final report of the commission made the following observation:

> *At present, there are insufficient methods for students to acquire hands-on experience in the scientific and technical disciplines necessary for space commerce and exploration.*[7]

USRA's Council of Institutions (COI) meeting in 2005 focused on "The Future of University Space Research: Perspectives from NASA, DOD, and the Private Sector." Through the meeting's symposium and other means, Black promoted discussion of space-related workforce development. He was joined by other voices expressing concern about this and related issues. In 2005 George Abbey and Neal Lane (both of Rice University) published a paper identifying barriers to US progress in space science and its application. Two of these barriers were:

- *The strict regulation of satellite exports as munitions under the State Department rules, and*
- *A projected shortfall in the science and engineering workforce.*[8]

USRA eventually addressed both of these barriers.

Also in 2005, the "Augustine Committee" of the National Academy of Sciences chaired by Norman R. Augustine wrote a report titled, "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future," which advocated to:

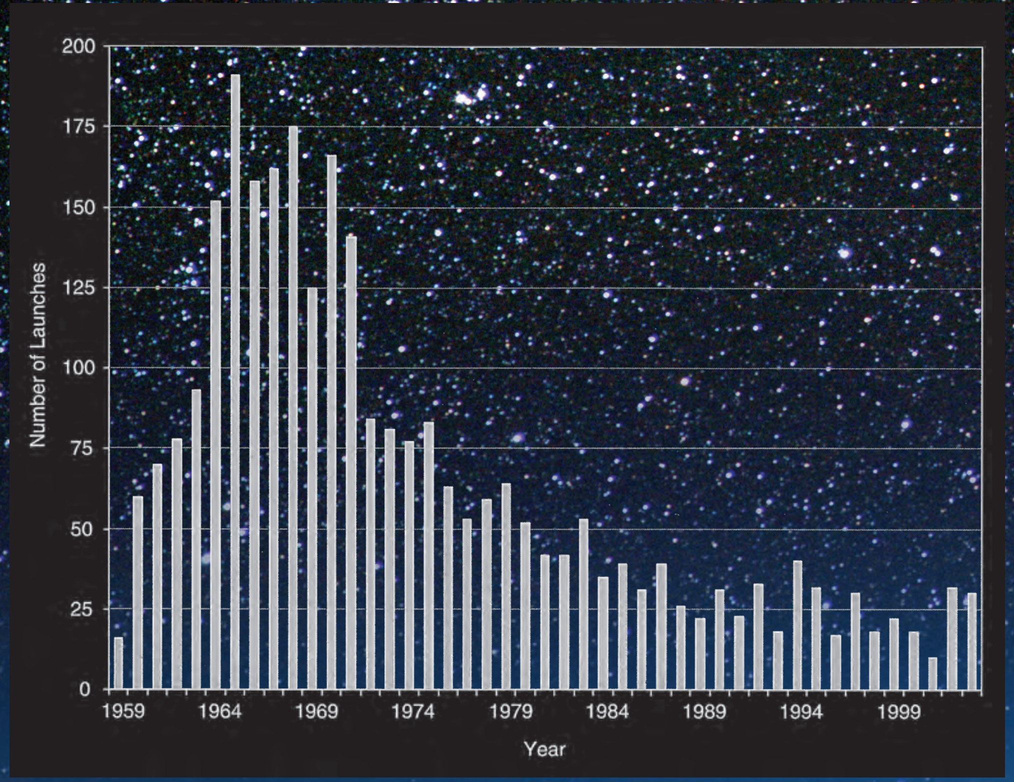
> *Make the United States the most attractive setting in which to study and perform research so that we can develop, recruit, and retain the best and brightest students, scientists, and engineers from within the United States and throughout the world.*[9]

Meanwhile, Black continued to focus attention on the implications of these concerns for the university space research community. In late 2005, he was appointed as co-chair of the National Research Council's Committee on Meeting the Workforce Needs for the National Vision for Space Exploration. NASA asked the committee to study the long-range science and technology workforce needs of NASA and the larger US aerospace science and engineering community to achieve President Bush's Vision for Space Exploration. Half of the recommendations of the committee were related to hands-on training:

- *Provide hands-on training opportunities for NASA workers.*
- *Support university programs and provide hands-on opportunities at the college level.*
- *Support involvement in suborbital programs and nontraditional approaches to developing skills.*[10]

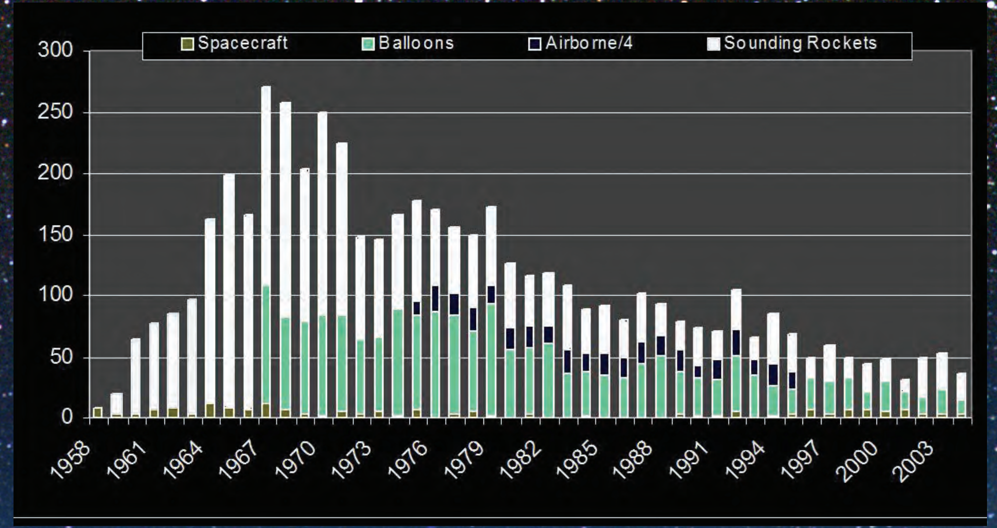
In the committee report, Black used a figure developed at USRA headquarters that showed NASA's sounding rocket launches by year from 1959 to 2005[11]. The figure dramatically illustrated the decline of opportunities for hands-on training that NASA's sounding rocket program had provided over the years.

Black led another USRA symposium on "The Future of University Space Research" at the COI annual meeting in 2006. For that meeting, interest and concern within the university space research community was heightened because NASA had announced that it proposed to spend $3.1 billion less than previously planned over the next five years for science missions and research. The agency was planning to shift money from science missions and research and other categories to fund the exploration systems needed to meet President Bush's Vision for Space Exploration. At the symposium, Black discussed the impact of NASA's proposed budget shifts on the university space research community.



NASA sounding rocket launches by year, from 1959 to 2005.
(From figure 4.4 in Building a Better NASA Workforce.)

THE ANNUAL NUMBER OF NASA'S SOUNDING ROCKET LAUNCHES DRAMATICALLY DECREASED FROM PEAK LEVELS IN THE 1960s.



Number of US orbital and suborbital opportunities for graduate students to gain hands-on experience in the earth and space sciences by year of launch.

USRA BEGAN TO ADVOCATE FOR HANDS-ON INVOLVEMENT OF GRADUATE STUDENTS IN SPACE EXPLORATIONS.

For his presentation at the COI symposium, Black broadened the USRA headquarters study to include not only sounding rockets, but also spacecraft, balloon flights, and experiments carried out on NASA's Kuiper Airborne Observatory. The idea was to examine whether other opportunities for hands-on training might have offset the decline in the rate of launches of sounding rockets. The answer was no; there had been a decline in all these opportunities.[12]

The charts Black used at the symposium were disturbing, and he closed his remarks as follows:

> *I believe that the university space research community must join the public debate very forcefully and do so on the basis of some agreed-upon guidelines. My initial thoughts on these guidelines are as follows, and I will welcome your reaction to them.*
>
> *– We must not pit mission against mission, discipline against discipline, or even the robotic against the human aspects of the overall space program.*
>
> *– We must rely upon for guidance and support the discipline-based roadmaps, decadal studies, etc., to develop prioritizations.*
>
> *– We must insist on the same level of hands-on involvement of graduate students in space explorations as the nation has enjoyed in the past, because these experiences will mold the future leaders of space research.*
>
> *– We must insist that the university space research community have a voice in decisions that affect the community's ability to deliver an aerospace workforce that will meet the needs of the nation.*[13]

THE FORMATION OF THE ISSUES AND PROGRAM COMMITTEE (IPC)

After the COI meeting, follow-on discussion between Black and some of the COI representatives caused Black to ask members of his headquarters staff to think of ways that USRA might become a voice for the university space research community to air issues of concern and to coordinate action around finding solutions. The author, Mr. Kevin Schmadel, and Dr. Hussein Jirdeh, who was the Director of University Relations for USRA, proposed the idea of a steering committee comprised of a COI representative from each of USRA's nine regional groups and reporting to the USRA Board of Trustees. The steering committee would identify a critical issue facing the university space research community and draft a position paper that would be submitted to the full COI for their approval. If approved by the COI, USRA would engage a lobbying firm to assist in finding a solution.[14]

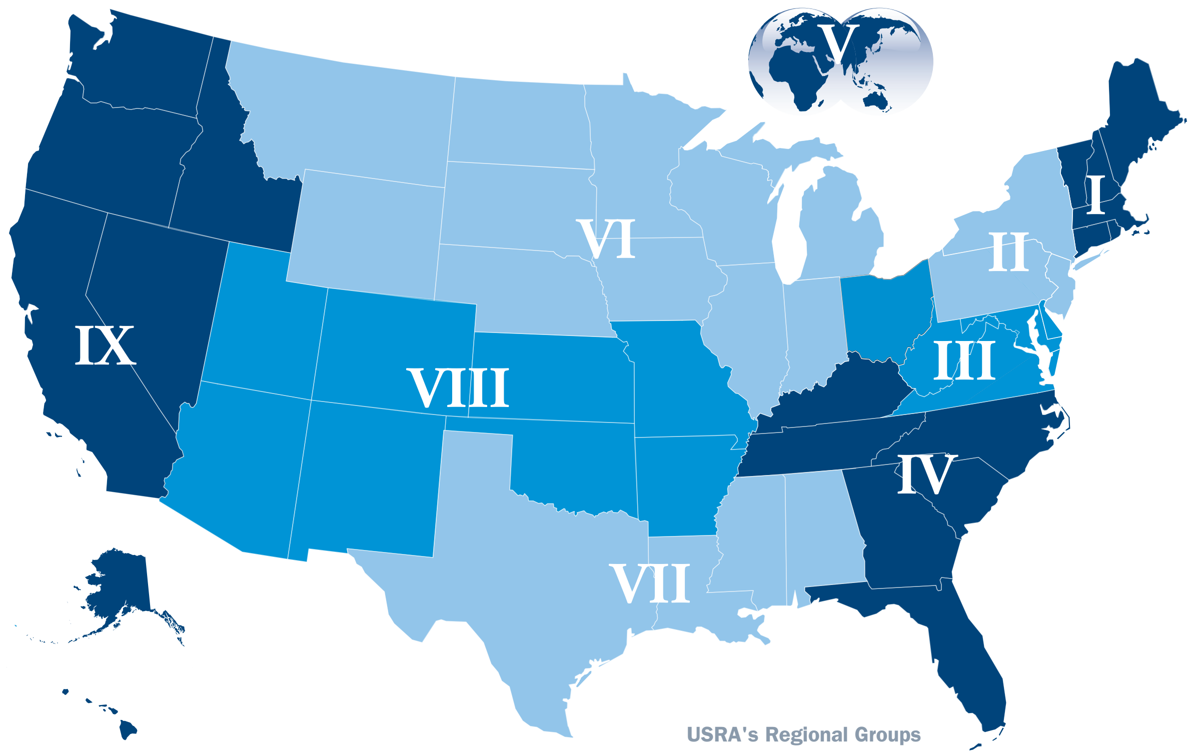
The USRA headquarters team next presented the idea to Professor W. Jeffrey Hughes (Boston University), chair of the COI, and then to Professor Edward J. Groth (Princeton University), the vice-chair.

At the next USRA Board of Trustees meeting at the end of June, 2006, Hughes led a discussion of the idea, which had evolved a bit. Instead of creating an additional board committee, it was proposed that the Program Committee of the board would be restructured and renamed as the Issues and Program Committee (IPC). The charter and membership structure of the IPC would be the same as specified in the original conception.

The USRA Board of Trustees accepted the idea on a two-year trial basis. The board soon reconsidered, however, and decided that the IPC should be a committee of the USRA Council of Institutions, rather than a committee of the Board of Trustees, and the wording of the charter for the IPC was changed accordingly. (In 2008, the USRA COI changed the bylaws of the Association to recognize the IPC as a committee of the COI.)[15]

HUGHES AND THE IPC START TO WORK

In the Fall of 2006, Hughes solicited recommendations from the COI representatives regarding the most pressing issues for the university space research community, and the response was that the first issue to be addressed by the IPC should be the continued diminishing number of hands-on flight research opportunities for graduate students in the Earth and space sciences.



USRA's Regional Groups

JEFFREY HUGHES

THE ORIGINAL MEMBERS OF THE USRA IPC WERE:

- Jeffrey Hughes (Boston University) (Chair)
- Edward Groth (Princeton University) (Vice-Chair)
- Roy Torbert (University of New Hampshire)
- Kenneth Gertz (University of Maryland)
- Paul Feldman (Johns Hopkins University)
- Peggy Evanich (University of Florida)
- Thomas Zurbuchen (University of Michigan)
- Chris Stevens (University of Sydney)
- Victoria Coverstone (University of Illinois at Urbana-Champaign)
- Truell Hyde (Baylor University)
- Daniel Baker (University of Colorado, Boulder)
- Robert Holzworth (University of Washington)

AS DETERMINED BY THE IPC, THE TITLE OF THE SYMPOSIUM FOR THE USRA COI MEETING IN THE SPRING OF 2007 WAS “HANDS-ON TRAINING FOR TOMORROW’S SPACE RESEARCHERS.”

Immediately following the first meeting of the IPC, Hughes drafted a position paper titled, “Educating the Next Generation of Space Scientists and Engineers” and a resolution on this topic that would be presented to the COI at their meeting in the spring of 2007. IPC members made visits to NASA, the US Congress, and other offices during the following months, relaying points made in Hughes’s paper, which read, in part, as follows:

> *There is a significant deficit of scientists and engineers in the United States with meaningful hands-on experience with space instrumentation and space systems, which is jeopardizing the ability of the nation to maintain a vigorous presence in space into the future, regardless of whether we are in space for reasons of commerce, exploration, national defense, or scientific research. This deficit leads not only to a loss of capability, but also to escalating costs of many of the space systems vital to the nation’s security and industrial competitiveness.*
>
> *Space scientists and engineers are trained at universities, particularly in the science and engineering graduate programs of those research universities active in space research. To attract good students into these fields requires sufficient funding for graduate stipends from either research projects or graduate fellowships, and projects or research opportunities that excite students so that they choose space research over other possible areas. These projects or research opportunities must also provide the students with the range of experiences they need to become fully trained scientists and engineers.*[16]

Referring to the chart Black had presented at the previous meeting of the COI, Hughes continued as follows:

> *The chart shows that the number of these opportunities peaked in 1968, at the height of the Apollo program. Since then the number of student opportunities provided by spacecraft missions, rocket and balloon flights and airborne observatory sorties has diminished from over 250 per year to consistently less than 50 per year. Most graduate students now never have an opportunity to do hands-on science. Instead the clear majority of science PhD students analyze data obtained from instruments they have never seen and thus have only a vague idea of how they work or how they might malfunction. They certainly don’t learn the important skills needed to conceive of, and to help design and construct, a space experiment.*
>
> *The chart hides another phenomenon. As space missions have, necessarily, become more complex, they also take longer to design and construct. The increasing complexity means that fewer universities have the resources and capabilities of managing the complexity, so increasingly missions are being run by non-academic laboratories and research centers. The mission time scale is now significantly longer than a typical graduate student remains in school. Both of these effects significantly decrease the likelihood of graduate student involvement, exacerbating the problem.*
>
> *This is a national problem. It affects not only space science, but also human space exploration, global climate prediction, commercial ventures in space, and national security uses of space. All these enterprises require space engineers able to design and construct reliable space hardware, and space scientists who understand the space environment and the rigors of conducting any activity, robotic or human, in space.*
>
> ***What needs to be done?***
>
> *These critical needs are addressed by a proposed hands-on, rapid cycle flight program of moderate risk that focuses on inexpensive system development for suborbital and orbital applications. This program should provide multiple flight opportunities involving graduate and undergraduate students from science and engineering disciplines, and should provide the excitement of discovery to attract those who will become leaders of the future US space enterprise. The program should permit a four-fold increase of hands-on experiences over present levels to return to the peak levels of the 60’s and 70’s. The proposed level of activity should allow an average of two launches per month or more.*[17]

As determined by the IPC, the title of the symposium for the USRA COI meeting in the Spring of 2007 was “Hands-on Training for Tomorrow’s Space Researchers.” At this meeting, Hughes raised, and the COI passed, his resolution that read in part:

> *Now therefore, be it resolved, that the council supports the plan outlined by the USRA Issues and Program Committee to provide multiple flight opportunities involving graduate and undergraduate students; and*
>
> *Resolved further, that we urge the United States Government and others to implement and facilitate a plan to provide space flight opportunities that enable the hands-on training for graduate and undergraduate students.*[18]

TARANTINO CONTINUES THE EFFORT

Dr. Frederick A. Tarantino (2006–2014) succeeded Black as USRA president in December of 2006, and he continued Black’s support of the activities of the IPC. Tarantino and Hughes met with senior officials of the White House Office of Science and Technology Policy and with several congressional staffers. Tarantino met with key staff from the Maryland congressional delegation, and he testified on behalf of USRA before a congressional committee in the fall of 2007. Earlier, during the summer of 2007, Professors Roy Torbert, Thomas Zurbuchen, and Daniel Baker were among the members of the IPC who gave testimony before subcommittees of Congress regarding the need for more hands-on training for students in space sciences and engineering.

Kevin C. Schmadel provided the primary support from USRA Headquarters to the IPC, often working as the intermediary between the IPC and the lobbying firm Patton Boggs that USRA had engaged.

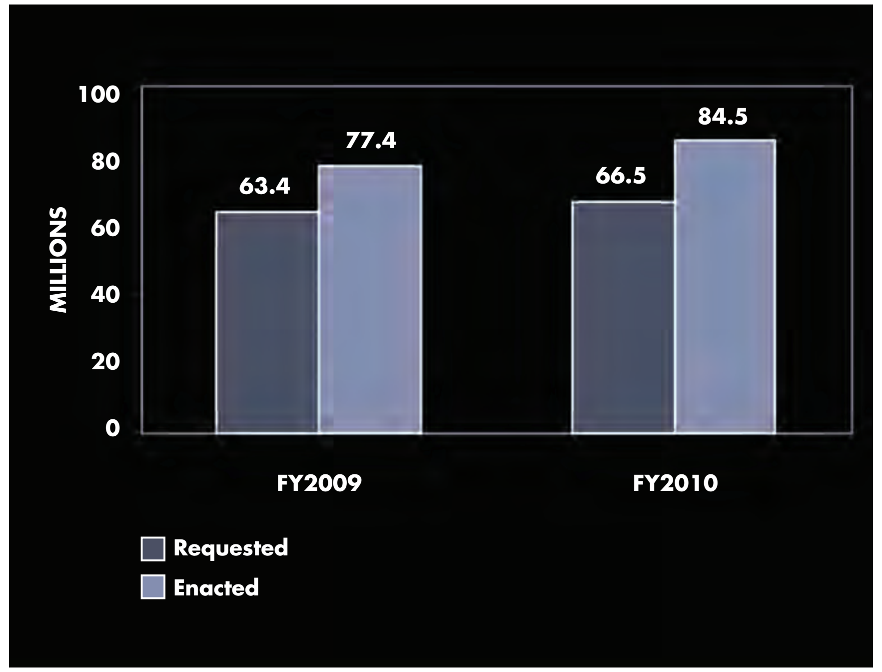
THE ISSUES THAT THE COUNCIL OF INSTITUTIONS HAS IDENTIFIED ARE VERY IMPORTANT, NOT ONLY FOR THE UNIVERSITY SPACE RESEARCH COMMUNITY BUT FOR THE NATION AS A WHOLE. INDIVIDUAL UNIVERSITIES OFTEN HAVE MORE LOCAL INTERESTS AT THE TOP OF THEIR PRIORITY LISTS, SO IT IS ESSENTIAL TO HAVE A NATIONAL ASSOCIATION LIKE USRA TO HELP US ARTICULATE AND PRESS FOR THE CHANGES THAT WE ALL NEED.

– Daniel Mote, President of the University of Maryland

FREDERICK TARANTINO

KEVIN SCHMADEL

SOUNDING ROCKET PROGRAM



ABOVE: USRA Board members Scott Pace (far right) and Thomas Zurbuchen (center right) testify before the Committee on Science, Space, and Technology of the US House of Representatives in 2012.

In his testimony before Congress on NASA's strategic directions, Professor Thomas Zurbuchen argued for the vital importance of involving students in small space missions.

The 2008 USRA annual symposium was titled "The Space Workforce: A Shared Dependency." In his keynote speech for the symposium, Dr. Daniel Mote, President of the University of Maryland, gave an assessment of the importance of USRA's new effort to influence public policy as it relates to university space research. Mote had been a member of the Augustine Committee, and he viewed USRA's efforts as consistent with the recommendations the committee had made relative to higher education. He urged the Institutional Representatives of the COI to, "continue to press the case to the Congress and agencies of the Federal Government for the need for a sustained program of small missions."[19]

Mote also charged the USRA COI to:

> *Continue to serve as a forum to identify issues of importance to the university space research community, and USRA's management should continue to help organize efforts to effect the changes we need.*[20]

In closing his speech, Mote noted that:

> *The issues that the Council of Institutions has identified are very important, not only for the university space research community but for the nation as a whole. Individual universities often have more local interests at the top of their priority lists, so it is essential to have a national association like USRA to help us articulate and press for the changes that we all need.*[21]

During the annual meeting in the Spring of 2008, the COI unanimously passed a resolution stating that:

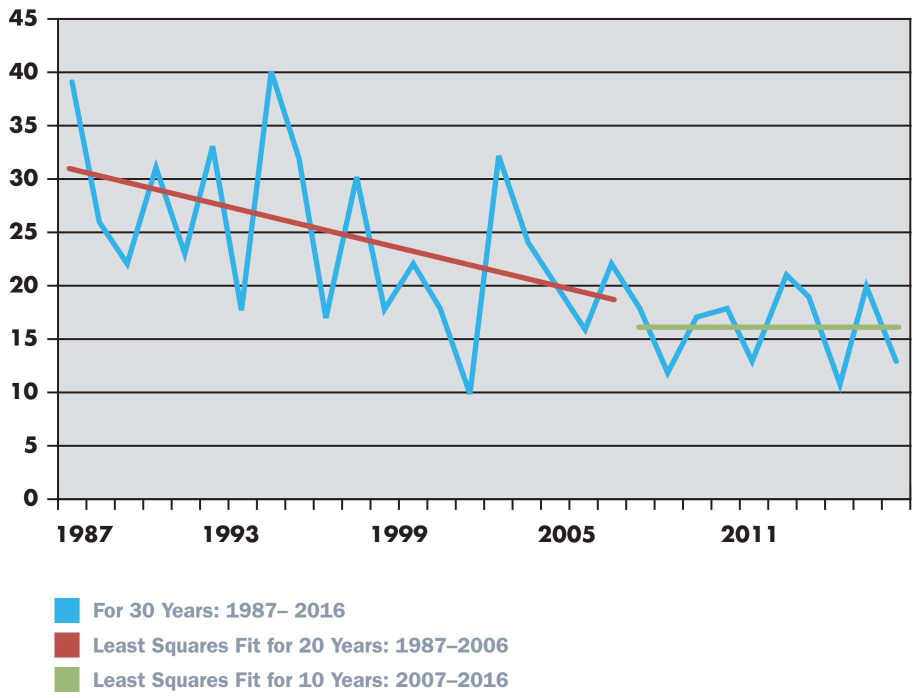
> *The NASA reauthorization should specifically acknowledge NASA's support of universities as partners who generate new knowledge, make new discoveries in disciplines related to space and aeronautics, and train the specialized workforce needed to accomplish NASA's missions; and that*
>
> *Future NASA budgets should specify that at least 1% of NASA's total budget will be devoted to funding competitive opportunities for university missions on sounding rockets, high altitude balloons, remotely piloted vehicles, emerging commercial space flights, and university class space flight missions...*[22]

In the late spring and summer of 2008, the IPC and USRA management continued to press for the changes desired by the COI. For example, Tarantino asked for more funding for hands-on training opportunities at a congressional hearing on "Reauthorizing the Vision for Space Exploration."

When the NASA Authorization Act of 2008 was passed, Tarantino congratulated the IPC because of:

> *The clear recognition in the NASA Authorization Act of the importance of hands-on training for graduate students. This was the first critical issue recognized by the IPC, and I think we have made some real progress in getting that message across to Congress.*[23]

SOUNDING ROCKET LAUNCHES BY YEAR



Tarantino was optimistic because of the wording of the NASA Authorization Act of 2008. The IPC offered language in support of suborbital research at universities, and subsection (a) of Section 505 of the Act, titled Suborbital Research Activities, contained their suggested language, which read:

> *(a) Sense of Congress- It is the sense of Congress that suborbital flight activities, including the use of sounding rockets, aircraft, and high-altitude balloons, and suborbital reusable launch vehicles, offer valuable opportunities to advance science, train the next generation of scientists and engineers, and provide opportunities for participants in the programs to acquire skills in systems engineering and systems integration that are critical to maintaining the Nation's leadership in space programs. The Congress believes that it is in the national interest to expand the size of NASA's suborbital research program. It is further the sense of Congress that funding for suborbital research activities should be considered part of the contribution of NASA to United States competitive and educational enhancement and should represent increased funding as contemplated in section 2001 of the America COMPETES Act (42 U.S.C. 16611(a)).*[24]

The NASA Authorization Act of 2008 authorized increased funding levels for NASA suborbital efforts in Earth Science, Astrophysics, and Heliophysics by about 11 percent. It also directed NASA to arrange for the US National Academies to "conduct a review of the suborbital mission capabilities of NASA."[25] The IPC advocated for this study, which was subsequently carried out by the National Research Council under the sponsorship of the Space Studies Board of the National Academies.[26]

At USRA's annual meeting in the spring of 2009, the COI passed a resolution asking for funding in suborbital experimental budget lines in accordance with the NASA authorization for these lines as "a first step on the way to allocate 1% of the NASA budget for suborbital (sounding rockets, balloons, aircraft) and small satellite programs."[27]

The Senate Appropriations bill for NASA in 2010 included report language as follows:

> *The Committee notes that suborbital science missions provide important hands-on experience for science, technology, engineering, and mathematics [STEM] undergraduates and graduate students, and directs NASA to increase their participation of these missions.*[28]

HARD-WON PROGRESS

As the work of the IPC continued, it became clear that any progress was going to be hard won. There was some increased funding for NASA's sounding rocket program from fiscal year 2009 to 2010, but it wasn't overwhelming.

In 2010, the NRC released a report advocated by the IPC titled, "Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing Workforce," and the final paragraphs read as follows:

> *Put succinctly, whether because of budget cuts, changing priorities, full-cost accounting, outsourcing, development of government-owned, contractor operated facilities, or other complexities and challenges facing NASA and its suborbital program, the committee could not escape the ineluctable conclusion that NASA has lost its bearings with respect to the essential importance of the suborbital program to the future of the agency. What was alarming to the committee is that these capabilities and therefore the engine of NASA's success are slipping away, viewed as merely facilities to meet demand, not as the heart of the agency.*
>
> *The committee decided in general not to include documentation of the evolution of the funding of the suborbital program because changes over time in NASA's complex accounting procedures make it extremely difficult to obtain meaningful trends. Nonetheless, the funding necessary for a robust and healthy suborbital program is modest both in*

absolute terms and certainly in terms of NASA's overall budget. The lack of sufficient funding is driven more by NASA priorities than it is by lack of funding. Under budget pressures, NASA appears to ignore the warning that the declining health of the suborbital program might presage the fate of the rest of NASA's capabilities as well…

The science yield of suborbital programs and the opportunities for training they provide are so central to NASA's mission and future that we recommend a marked change of course.[29]

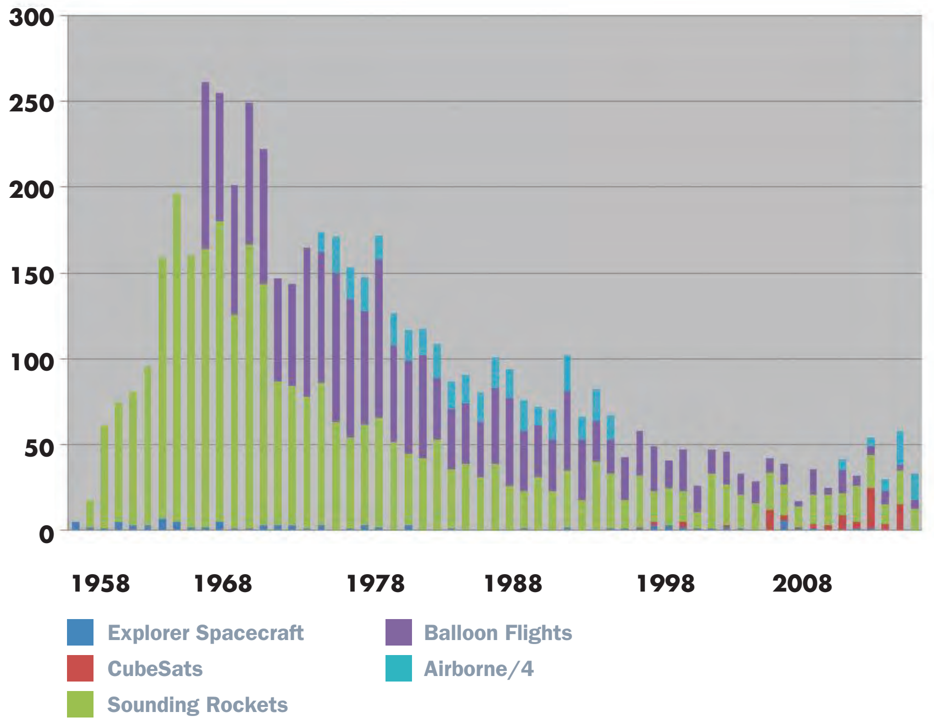
The NRC report made five recommendations:

RECOMMENDATION 1: *NASA should undertake the restoration of the suborbital program as a foundation of its mission responsibilities, workforce requirements, instrumentation development needs, and anticipated capability requirements. To do so, NASA should reorder its priorities to increase funding to suborbital programs.*

RECOMMENDATION 2: *NASA should assign a program lead to the staff of the associate administrator for the Science Mission Directorate to coordinate the suborbital program. This lead would be responsible for the development of short- and long-term strategic plans for maintaining, renewing and extending suborbital facilities and capabilities. Further, the lead would monitor progress toward strategic objectives and advocate for enhanced suborbital activities, workforce development, and integration of suborbital activities within NASA.*

RECOMMENDATION 3: *To increase the number of space scientists, engineers, and system engineers with hands-on training, NASA should use the suborbital elements as an integral part of on-the-job training and career development for engineers, experimental scientists, systems engineers, and project managers.*

RECOMMENDATION 4: *NASA should make essential investments in stabilizing and advancing the capabilities in each of the suborbital elements. These include the development of ultra-long-duration super-pressure balloons with the capability to carry 2 to 3 tons of payload to 130,000 feet, the execution of a thorough conceptual study of a short-duration orbital capability for sounding rockets, as well as the modernization of the core suborbital airborne fleet. (The committee notes that it was not asked to prioritize the different elements of the suborbital program, but such a prioritization should be an integral part of implementing this recommendation.)*



RECOMMENDATION 5: *NASA should continue to monitor commercial suborbital space developments. Whereas the developers stated to the committee that they do not need NASA funding to meet their business objectives, this entrepreneurial approach offers the potential for a range of opportunities for low-cost quick-access to space that may benefit NASA as well as other federal agencies.*[30]

Armed with the NRC's report, IPC members visited congressional staff to advocate for specific legislation implementing the report's recommendations. The IPC efforts led to the NASA Authorization Act of 2010 incorporating the recommendations of the NRC study, translated into legislative language suggested by the IPC. The Act was signed into law by President Obama on 11 October 2010.

In FY 2012, the IPC worked to ensure the implementation of the legislation by NASA. At its January 18 meeting at the USRA Washington Office, the IPC was reassured by David Pierce, Senior Program Executive for Suborbital Research, NASA Science Mission Directorate. This new position at NASA headquarters was created by the legislation, which directed NASA to designate an official, "responsible for the development of short- and long term strategic plans for maintaining, renewing and extending suborbital facilities and capabilities." Mr. Pierce reported to the IPC on NASA's implementation of each aspect of the legislation. He noted that the suborbital program was now stable and new investments were being made.

USRA'S EFFORTS HELPED SHAPE THE NATIONAL CONCERN ABOUT THE IMPORTANCE OF HANDS-ON TRAINING FOR UNIVERSITY STUDENTS INVOLVED IN SPACE RESEARCH.

On 22 March 2012, USRA and The George Washington University Space Policy Institute jointly organized a symposium on "Suborbital and Small Satellite Missions: Research for Today, Training for Tomorrow," in conjunction with the USRA Annual Meeting. The symposium was held across from NASA headquarters and was well-attended by over 150 attendees with standing room only.

The importance of hands-on training for graduate students in the space sciences was gaining traction. USRA's efforts were an important factor, and the actions taken by the IPC helped to stabilize NASA's sounding rocket program.

By 2016, the picture for hands-on training was looking a little better. CubeSats[31], first developed in 1999 by students and faculty at the California Polytechnic State University, San Luis Obispo and Stanford University, began to provide more and more opportunities for hands-on training, particularly after the National Science Foundation began a program using them in 2008, and NASA found launch opportunities for them in 2011. Then, airborne science resumed when the Stratospheric Observatory for Infrared Astronomy (SOFIA) began to fly science missions in 2010. The combination of these factors gave hope, if not confidence, that more and more opportunities for the hands-on training of university students in the space and Earth sciences might be forthcoming.

IN SUMMARY

USRA's efforts beginning with Paul Coleman and David Black and continuing through the formation of USRA's IPC and the efforts of Fred Tarantino helped shape the national concern about the importance of hands-on training for university students involved in space research. In addition, as the first chair of the IPC, Jeffrey Hughes, reported to the USRA Board of Trustees in 2008, by establishing the IPC, there was now more strength and clarity in the organization of USRA at the COI level, and USRA had established:

A new means of providing a stronger voice for the university space research community on issues of vital importance to the community.[32]

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1. Coleman, Jr, P.J., 1995. Issues of importance to the university space research community as it considers future space flight missions, p. 1. USRA Archives.
2. Ibid.
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4. Black, D.C., 2003. A response to the national need to train future U.S. scientists and engineers in the use of space technology: A position paper from the Universities Space Research Association, September 2003, abstract. USRA Archives.
5. Bush, G.W., 2004. *A Renewed Spirit of Discovery: The President's Vision for US Space Exploration,* p.1., White House.
6. Ibid.
7. Aldridge Jr, E., 2004. *Report of the President's Commission on Implementation of United States Space Exploration Policy: A Journey to Inspire, Innovate, and Discover*, p.43.
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9. Augustine, N.R., 2005. Rising above the gathering storm: Energizing and employing America for a brighter economic future, The National Academies of Sciences.
10. Board, S.S. and National Research Council, 2007. *Building a Better NASA Workforce: Meeting the Workforce Needs for the National Vision for Space Exploration* (Vol. 5), pp.7–8. National Academies Press.
11. The chair of the USRA COI, Professor Jeffrey Hughes of Boston University, had suggested that USRA Headquarters staff examine the decline in opportunities for graduate students to get hands-on experience using NASA-funded sounding rockets, and this was the impetus for developing the chart that Black had used in the NRC report titled *Building a Better NASA Workforce.*
12. The chart shows all launches, whether or not successful. Data from all spacecraft launches that involved US participants was used, except flights associated with NASA's human space program. The annual number of airborne flights was arbitrarily divided by four, since many flights on the Kuiper Airborne Observatory were re-flights that involved the same students.
13. Black, D.C., 2006. Opening and closing remarks at the USRA symposium – The Future of University Space Research, pp.10-11. USRA Archives.
14. USRA was permitted to do a limited amount of lobbying, having recently taken the 501(h) election.
15. USRA Bylaws - Article II, Section 9. Issues and Program Committee. The Chair of the Council shall appoint an advisory committee, the Issues and Program Committee. The Chair and Vice-Chair of the Council shall be Chair and Vice-Chair of the Committee. The Chair of the Committee shall appoint one member of the Council from each Regional Group to serve on the Committee. Members of the Committee will serve the same term as the Chair. The Committee will raise issues of interest to the member universities and bring them to the attention of USRA Board of Trustees so that, in cooperation with its members and other organizations as appropriate, USRA can advocate in favor of the interests of its member universities. The Committee will also develop the program for the annual symposium held in conjunction with the Annual Meeting of the Council.
16. Hughes, J., 2007. Educating the next generation of space scientists and engineers. USRA Archives.
17. Ibid.
18. USRA Council of Institutions Minutes, 2007. Attachment - Resolution of the Council of Institutions of the Universities Space Research Association. USRA Archives.
19. Mote, C.D., 2008. The Gathering Storm Report and Space. Keynote address at the USRA Annual Symposium. USRA Archives.
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22. USRA Council of Institutions Minutes, 2008. Attachment - Resolution of the Council of Institutions of the Universities Space Research Association. USRA Archives.
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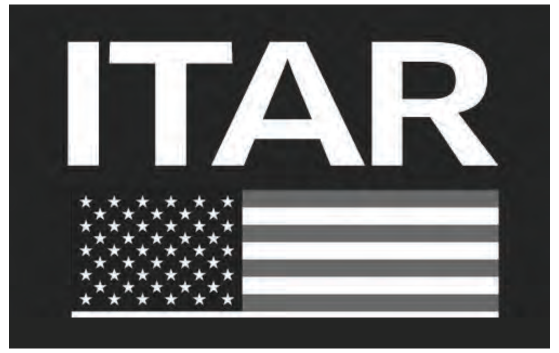
28. Commerce, Justice, Science and Related Agencies Appropriations Bill, 2010. (H.R. 2847), Accompanying report of the Senate Committee on Appropriations (Report 111–34).
29. *Revitalizing NASA's Suborbital Program,* 66–67.
30. Ibid., 67.
31. "Started in 1999, the CubeSat Project began as a collaborative effort between Professor Jordi Puig-Suari at California Polytechnic State University (Cal Poly), San Luis Obispo, and Professor Bob Twiggs at Stanford University's Space Systems Development Laboratory (SSDL). The purpose of the project is to provide a standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches. … A CubeSat is a 10 cm cube with a mass of up to 1.33 kg." Retrieved from http://www.cubesat.org/. The standardization for CubeSat dimensions and mass has allowed the development of inexpensive, commercially provided components for the satellites. CubeSat units can be combined to form larger payloads, e.g., 2U, 3U CubeSats.
32. Hughes, J. 2008. Actions taken in response to the COI resolution – Hands-on training. Presentation to the USRA Board of Trustees at their meeting of 14 February 2008. USRA Archives.

REFORM OF US EXPORT REGULATIONS

How USRA helped to bring about changes in the International Traffic in Arms Regulations for the benefit of the university space research community.



ONE WOULDN'T NORMALLY ASSOCIATE the space research community with international arms traffickers, but for over a decade, US legislation placed the same constraints on university space researchers that it had on companies that were selling satellites and space technologies that might be used against the United States. A series of otherwise unrelated events led to that situation, and it took the concentrated efforts of USRA and other space-related organizations to correct it.

The somewhat unpredictable course of events began on the Fourth of July in 1982, when President Ronald Reagan issued a National Security Decision Directive that included the following basic principle:

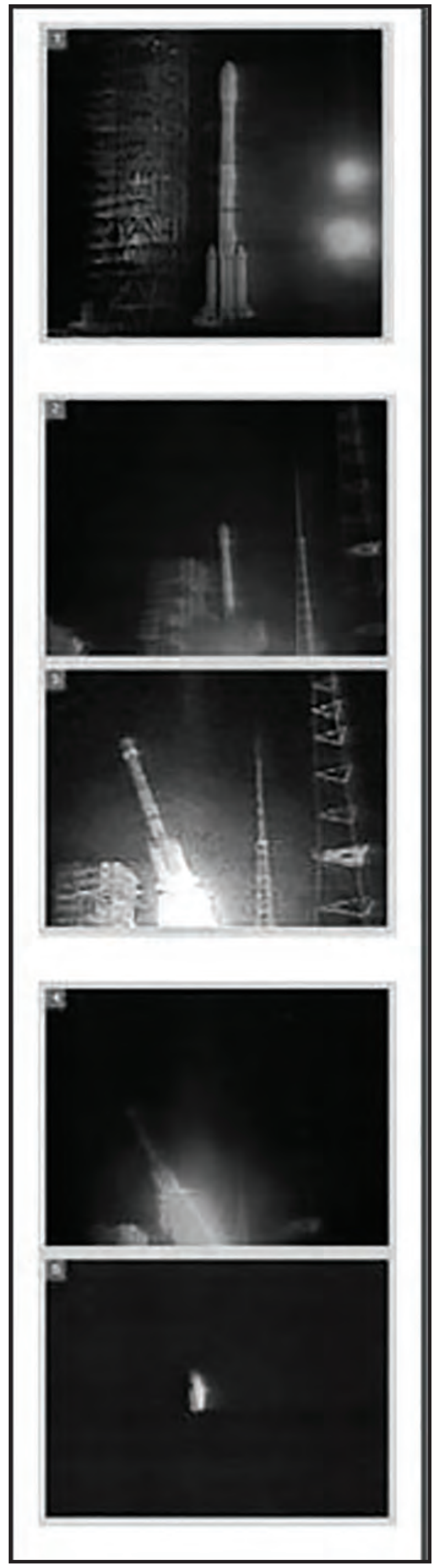
> *The United States Space Transportation System (STS) [i.e., the Space Shuttle] is the primary space launch system for both national security and civil government missions. STS capabilities and capacities shall be developed to meet appropriate national needs and shall be available to authorized users – domestic and foreign, commercial, and governmental.*[1]

Instead of "expendable launch vehicles," i.e., ground-launched rockets, the Space Shuttle would be used to get satellites into orbit. Once in the Space Shuttle's low Earth orbit, satellites would be moved to other orbits or sent on interplanetary journeys with attached rocket stages. Presumably, this policy was adopted in part to make the development and operation of the Space Shuttle economically feasible. However, an unanticipated result of the policy was that a growing global market for the launch of communications satellites began to look to launch providers outside the US.

> *As the US government stopped ordering rockets in anticipation of the shuttle replacing expendable launchers, US launch facilities were phased out and US launch complexes neither modernized nor expanded. As a result, the new additional commercial launcher demand greatly exceeded the US launch capacity, resulting in longer delays in launching satellites. Additionally, US launch costs rose to two to four times Russian and Chinese launch costs. International customers for the satellites, usually consortia of private and government investors, looked to invest the $250 million or so launch-plus-satellite cost and the $50 million or so insurance cost optimally.*[2]

NASA poster from the 1980s
Credit: NASA

THE LONG MARCH 3B ROCKET FAILURE OCCURRED AMIDST A LARGER DEBATE WITHIN THE US GOVERNMENT OVER THE WISDOM OF COLLABORATING WITH CHINA IN AREAS RELATED TO US NATIONAL SECURITY.



Long March 3B rocket failure
Credit: The Cox Report

One apparently optimal solution for the launch of communications satellites was a state-owned company, the Great Wall Industry Corporation, in the People's Republic of China (PRC). On 15 February 1996, a Long March 3B rocket owned by the China Great Wall Industry Corporation veered off course immediately after liftoff from the Xichang Satellite Launch Center in the PRC and crashed into the side of a nearby hill.[3] The rocket carried an Intelsat communications satellite made by a US company, Space Systems/Loral.

Loral and other companies became involved in a launch-failure review with the PRC-owned China Great Wall Industry Corporation. Loral had obtained an export license from the US Department of State for the launch of its communications satellite on the Long March 3B rocket, but it didn't obtain an export license for the discussion or release of technical data concerning a rocket failure analysis or investigation.[4] The fact that Loral had provided technical assistance to the PRC in the launch failure investigation of the Long March 3B rocket without an export license alarmed the US Department of State and the US Defense Technology Security Administration. The latter recommended that the matter be referred to the US Department of Justice for a possible criminal investigation, and Loral ultimately paid a civil fine of $14 million to the US Department of State.

The Long March 3B rocket failure occurred amidst a larger debate within the US government over the wisdom of collaborating with China in areas related to US national security. The struggle manifested, in part, in a disagreement over which agency, the Department of Commerce or the Department of State, should have jurisdiction over export control regulations for commercial communications satellites. In March 1996, President Clinton made the decision in favor of the Department of Commerce, directing that all commercial communications satellites be transferred from the State Department's US Munitions List (USML) to the Commerce Control List of the Department of Commerce. This decision was subsequently reversed by Congress in the Strom Thurmond National Defense Act for FY 1999.

THE MANDATE OF THE COX COMMITTEE

The involvement of a US company in analyzing the launch failure was investigated by the "Cox Committee," a Select Committee on US National Security and Military/Commercial Concerns with the People's Republic of China, chaired by US Representative Christopher Cox (R-CA). During its deliberations, the Cox committee learned that:

> *The White House and the Commerce Department, in coordination with the US aerospace industry, were developing an executive order that would give Commerce the right to appeal State licensing decisions on license applications regarding items on the USML.*[5]

The Cox Committee determined to close off the ability to circumvent the USML and the licensing authority of the State Department. The committee's report, unanimously approved by the five Republican and four Democratic members, contained 38 recommendations, including two that became known as the "mandate" of the Cox Committee:

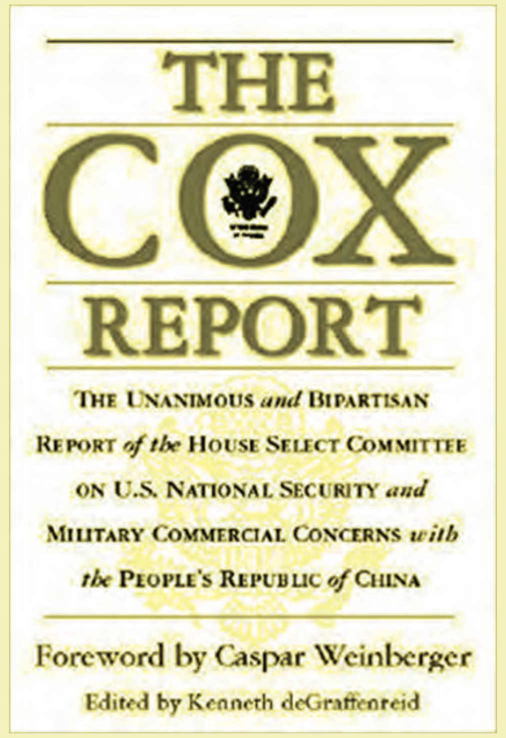
> ***15. Implementation of the Strom Thurmond National Defense Authorization Act for FY 1999.*** *The Select Committee expects that the Executive branch will aggressively implement the Satellite Export Control Provisions of the Strom Thurmond National Defense Authorization Act for FY 1999.*
>
> ***16. State Department should have sole satellite licensing authority.*** *To protect the national security, the congressional judgment that the Department of State is the appropriate agency for licensing both exports of satellites and any satellite launch failure investigations must be faithfully and fully implemented.*[6]

Passage of the Strom Thurmond National Defense Authorization Act for Fiscal Year 1999 and the Cox Committee mandate entangled the US space research community with the International Traffic in Arms Regulations (ITAR). The Act expressed the sense of Congress that:

> *Due to the military sensitivity of the technologies involved, it is in the national security interests of the United States that United States satellites and related items be subject to the same export controls that apply under United States law and practices to munitions.*[7]

Furthermore, the Act transferred "all satellites and related items" from the Commerce Control List to the State Department's USML. All satellites, including those that might be used by the university space research community, would now be subject to the ITAR as specified in the Arms Export Control Act. At the time, Category XV of the USML covered spacecraft systems and associated equipment, and it explicitly designated scientific satellites among other types of satellites as "defense articles." Ground control stations for satellite telemetry, radiation-hardened microelectronic circuits, and other components of spacecraft systems were also covered.[8]

Thus, US satellites carrying university research experiments began to be classified as munitions.



In addition to hardware and software, ITAR covers:

> *Technical data and defense services (for example, furnishing of technical data or training). Under ITAR, an "export" includes a defense article taken out of the United States as well as the act of "disclosing (including oral or visual disclosure) or transferring technical data to a foreign person, whether in the United States or abroad." It also includes a defense service performed "on behalf of, or for the benefit of, a foreign person, whether in the United States or abroad." Except in a few instances as defined in ITAR, all transfers of US defense articles or services to foreign persons require a case-by-case review and preauthorization by the Department of State.*[9]

CHRISTOPHER COX

DEEMED EXPORTS

The "deemed export rule" soon became an important concept related to ITAR, particularly as it applied in a university setting.

> *In its simplest terms, a "Deemed Export" can be defined as the release of technology or source code having both military and civilian applications to a foreign national within the United States. Thus, even though the release in question takes place within the confines of the United States, the transaction is "deemed" to be an export and*

From Deemed Exports Presentations for: Coalition for Academic Scientific Computation. *Credit: US Department of Commerce*

> *therefore subject to certain United States Government export control regulations… [For example] A university researcher conducting a project involving a foreign national student may be required to obtain an export license before sharing knowledge with that student relating to equipment used in a research project if that equipment might also have a military application.*[10]

The effects of the passage of the Strom Thurmond National Defense Authorization Act and the mandate of the Cox Committee were increasingly felt on university campuses following the terrorist attacks of 11 September 2001. Concern over national security greatly intensified and security tightened in many aspects across the US, including the enforcement of export regulations.

University space researchers and their university administrators began to complain that basic research had been entangled in regulations that were meant for commercial or defense entities. As a result, in 2002, the State department amended the language of ITAR so that accredited US institutions of higher learning were given a "fundamental research exclusion." These institutions didn't have to obtain ITAR licenses for interacting with persons in some other countries, and with some non-US persons in this country, for the purpose of conducting fundamental research, defined as "basic and applied research in science and engineering where the resulting information is ordinarily published and shared broadly within the scientific community."[11] The fundamental research exclusion turned out to be inadequate, as discussed below.

THE "DEEMED EXPORT RULE" SOON BECAME AN IMPORTANT CONCEPT RELATED TO ITAR, PARTICULARLY AS IT APPLIED IN A UNIVERSITY SETTING.

DEVELOPING TENSIONS

For the next few years, the university space research community operated with increasing awareness and caution under the revised ITAR regulations. The tension between university science and technology research and national security was widely discussed, notably through the work of the National Research Council (NRC) of the US National Academies. In 2006, the NRC established a Committee on a New Government-University Partnership for Science and Security, which held regional meetings to hear and discuss concerns from government officials about security threats confronting the US. Among the concerns that the Committee heard were the possibilities that:

- Terrorists might pose as (or in fact be) students in order to gain entry and find cover in a university community;
- Terrorists aspiring to apply advanced technology to the development of weapons might develop the technical capability to do so through a university education (in the US);
- Because the US military edge is built on the skillful application of advanced technology, … other countries might benefit militarily from access to scientific or technical information available in the university environment; and
- Since America's economic well-being is founded on the maintenance of its scientific and technological edge … foreign countries could seek to penetrate US universities … for the purpose of obtaining early access to technology in order to supplant US capabilities and reap the economic gains for themselves.[12]

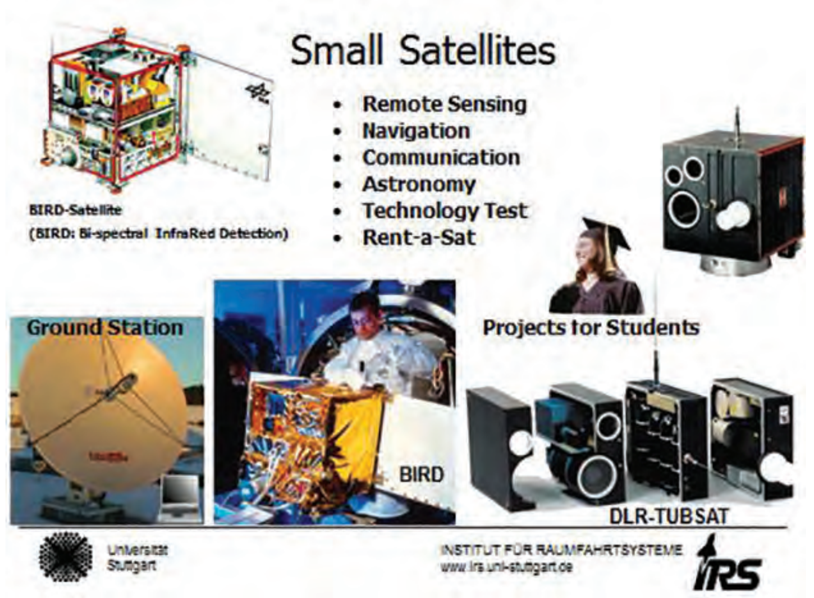
The committee report noted, however, that:

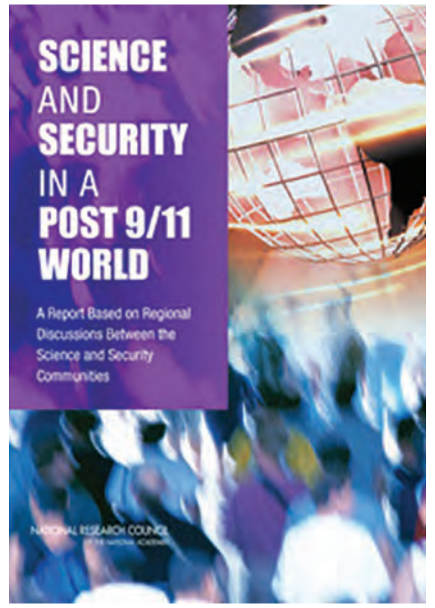
> *The success of US science and engineering has been built on a system of information sharing and open communication, not only among US institutions, but also with the international science and technology communities. The global scientific enterprise thrives on the movement of students and scholars across borders and among institutions. For more than 50 years, US research universities—the envy of the world—have welcomed and fostered the talents of both foreign-born and US students in the service of national and economic security. Foreign-born scientists and engineers come to the United States, stay in large numbers, and make significant contributions to America's ability to achieve and maintain technological and economic leadership. Given the current diminishing rates of new scientific and engineering talent in the United States—the subject of other reports and a topic of national concern—the size of the US research and development effort cannot be sustained without a significant and steady infusion of foreign nationals. We must continue to encourage US-born citizens to pursue science and engineering degrees and at the same time remain open to the benefits that foreign-born, but US-trained, scientists and engineers bring to our country in terms of technological and economic growth.*[13]

At one of the regional meetings of the NRC committee, Professor Richard K. Lester of MIT summarized the reasons for the tensions between the university research community and the US government over security issues:

> *The fact that universities and businesses need the free flow of ideas and knowledge while government needs to keep its citizens safe and to prevent weapons or knowledge of how to make weapons from falling into the hands of the wrong people, these differences and the tensions that are implicit in these differences are likely to grow more rather than less pronounced as time goes on. We must assume that the security imperatives of the government will become more challenging rather than less over the coming years and decades, and at the same time it seems likely that the importance of the university's role as a public space in an increasingly globalized innovation process will also grow.*[14]

By 2007, USRA was advocating vigorously for more hands-on training in space research and engineering at universities, and the resolution passed by the USRA Council of Institutions (COI) in the spring of that year had hands-on training as its single focus. However, the impact of ITAR on the university research





RIGHT: Report of the NRC Committee on a New Government-University Partnership for Science and Security. *Credit National Academies Press*

LEFT: Slide presented by Hans-Peter Roeser at a USRA COI meeting in 2007.

DANIEL BAKER

THE VALUE OF USRA'S VOICE IN THE DEBATE WAS THAT OFTEN INDIVIDUALS IN KEY ORGANIZATIONAL ROLES WERE RESEARCH SCIENTISTS WHO COULD SPEAK FROM PERSONAL EXPERIENCE ABOUT THE ISSUES AT HAND.

community surfaced as another issue of concern at a session of the COI in 2007. In a presentation on the small satellite program at the University of Stuttgart, Professor Hans-Peter Roeser (1949–2015) mentioned that he was able to get spaceflight rides for his student-built small satellites on European and Russian rockets, partly because there were no regulations such as ITAR to deal with. He further noted that some spaceflight services in Europe were being advertised as "ITAR-free." The impact of ITAR on US university space research programs would soon become the second major issue for the USRA Issues and Program Committee (IPC).[15]

In addition to the National Research Council and various committees of the US National Academies, several other organizations made important contributions to the debate. Among these organizations were the Association of American Universities, the Council on Governmental Relations, and the Center for Strategic and International Studies. An advisory committee established by the US Department of Commerce, the Deemed Export Advisory Committee, also issued an influential report at the end of 2007, pointing out that "The current Deemed Export regulations have become increasingly irrelevant to the prevailing global situation."[16]

The value of USRA's voice in the debate was that often individuals in key organizational roles, such as the Board of Trustees, the Council of Institutions, and the Issues and Program Committee, were research scientists who could speak from personal experience about the issues at hand. Further, in pursuing a solution for the university space research community, one of USRA's strengths was that Institutional Representatives of the member universities that make up the COI are often leaders in the scientific community and serve on key national committees for the community. A case in point is Professor Daniel Baker of the University of Colorado, who represented Region VIII of the COI on the IPC. Baker was Chair of the Committee on Solar and Space Physics of the National Research Council and a member of the Space Studies Board of The National Academies of Sciences, Engineering, and Medicine. Because of these positions, he was asked to serve on a workshop planning committee organized by the Space Studies Board titled, "Space Science and the International Traffic in Arms Regulations." The workshop was held on 12–13 September 2007 at the National Academy of Sciences Building in Washington, DC. Professor Roy Torbert of the University of New Hampshire participated in this workshop and served as a reviewer for the final report. Torbert was a member of the IPC, representing Region I of the COI. The summary of the report on the 2007 NRC workshop included the following:

> ***EFFECTS ON SCIENTIFIC RESEARCH*** *Science, perhaps more than most fields of endeavor, depends on a full and open discussion and exchange of ideas among researchers who are addressing a given problem. If researchers are constrained by security classification or proprietary interests, communication is necessarily limited. Because most of the results of space science research are placed in the public domain, most space research activity qualifies as "fundamental research," which is excluded from ITAR controls as long as the research is conducted by "accredited institutions of higher learning." However, the bulk of government-sponsored fundamental space research at universities is conducted by consortia, including government research laboratories and private companies, and ITAR requires licensing when persons from other countries are involved—and they usually are. Since the dawn of the space age, other nations have invested in developing their own capabilities and have thereby made themselves desirable partners of the United States. Furthermore, many space-based scientific efforts focus on the science of Earth, and so international collaboration is necessary if global perspectives are to be drawn. The costs and delays imposed by ITAR processing requirements, coupled with other nations' reluctance to be made subject to restrictions derived from US law and regulations, are making the United States less and less desirable as a partner to its foreign collaborators. The implications for continued international collaboration are grave.*
>
> ***EFFECTS ON ACADEMIC OPERATIONS*** *Ambiguities about what constitutes fundamental research that can thus be excluded from ITAR controls, about what information can be placed in the public domain, and about what specific kinds of involvement with non-US persons require licensing have led to great uncertainties in the university community about the participation of foreign students and researchers in projects involving potentially controlled hardware or technology. Universities must choose between either going through the burdensome licensing or technical-assistance agreement process to involve their students and researchers from other countries or consciously excluding any non-US nationals from space-related research. The latter approach is injurious to the quality of research and to the educational value inherent in diversity. It is especially damaging when the non-US participants could contribute critical and unique knowledge and skills to a project, as is often the case. According to workshop participants, the same uncertainties are leading some professors to "dumb down" course content rather than risk ITAR violations by discussing their research in the classroom setting. Although they believe that the vitality of education in the US university system depends on its links to state-of-the-art research, many cite fears of breaking the law inadvertently.*[17]

From the discussions at the 2007 NRC workshop, it was clear that obtaining relief from ITAR for the university space research community was going to be difficult. Dr. Robie Samanta-Roy represented the Office of Science and Technology Policy at the workshop, and he offered two observations about the prospects for changing the ITAR in the near term:

> *There is no appetite for fundamental reform of ITAR either in the administration or in Congress, and … because ITAR is prescribed by law, any changes will have to come from Congress.*[18]

Professor Tapio Schneider of Caltech
Credit: Caltech

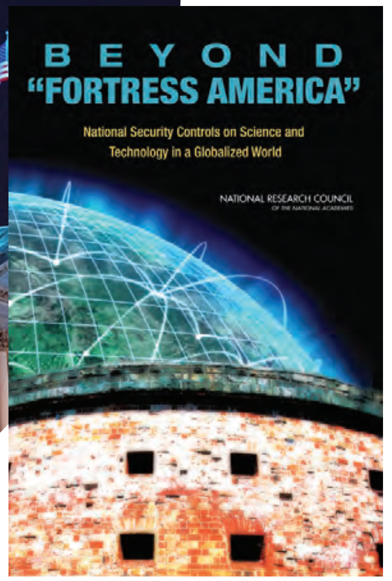
In a similar vein, David Fite, a senior member of the professional staff of the House Committee on Foreign Affairs, noted at the workshop that:

> *If proposed actions were seen as having any potential to jeopardize national security, national security would always prevail. … In the post-9/11 environment, anything that can be represented, or even misrepresented, as abetting terrorism is a tough vote for members.*[19]

USRA BEGINS TO GET INVOLVED

Following the USRA COI meeting in the spring of 2007, the IPC further examined the effects that ITAR and export control were having on university space research. The committee drafted a position paper and a resolution for presentation to the COI at its spring meeting in 2008. At that meeting, Professor Claude Canizares, the Vice President for Research and Associate Provost at MIT, gave a talk entitled "ITAR and Space Science," in which he outlined the difficulties posed by ITAR for university researchers in the space sciences as they tried to collaborate with international partners. The request for a modification

EDWARD GROTH



…"BEYOND 'FORTRESS AMERICA:' NATIONAL SECURITY CONTROLS ON SCIENCE AND TECHNOLOGY IN A GLOBALIZED WORLD"…FOUND THAT THE CURRENT SYSTEM OF EXPORT CONTROLS NOW HARMS OUR NATIONAL AND HOMELAND SECURITY, AS WELL AS OUR ABILITY TO COMPETE ECONOMICALLY.

of ITAR, along with continued requests for more support for hands-on training opportunities for university students, was incorporated in the resolution passed by the USRA COI at their business meeting in the spring of 2008.

Following the 2008 COI meeting, the IPC intensified its advocacy efforts for relief from the impact of ITAR on university researchers. Professor Edward Groth, who succeeded Jeffrey Hughes as the COI and IPC chair following the annual meeting, led the charge along with Professor Thomas Zurbuchen of the University of Michigan, who was elected vice-chair of the COI and IPC.

USRA management was also heavily involved. During meetings of the IPC, members shared their concerns on focus issues with USRA president Fred Tarantino, who incorporated these concerns in his congressional testimonies. For example, Tarantino stressed the concern of universities over ITAR issues in his briefing of the Congressional Export Control Working Group in September of 2008.

Professor Scott Pace (George Washington University), who joined the USRA Board of Trustees in 2008, advised USRA management and the IPC on tactical approaches in further efforts to reform US export regulations affecting space researchers. Pace had worked in the White House Office of Science and Technology Policy and had served as Associate Administrator for Program Analysis and Evaluation at NASA Headquarters. In the summer of 2008, Pace became the Director of the Space Policy Institute at George Washington University, which subsequently collaborated with USRA in organizing important symposia on space issues.

In advocating for the university space research community, the IPC explained to members of Congress and their staffs that Category XV of ITAR engulfed the US university space research community in a "perfect storm" with three elements:

- **COX COMMITTEE REPORT**—Congress's mandate casting a broad net that "satellites and related items," irrespective of military utility, be transferred from the Department of Commerce to the State Department and be covered as defense articles under ITAR.
- **CONCEPT OF DEEMED EXPORTS**—An export can be "deemed" to have taken place when information is conveyed to a foreign national, including through conversation or classroom teaching.
- **SIGNIFICANT PRESENCE OF FOREIGN NATIONALS ON UNIVERSITY CAMPUSES**—In space research, university scientists work in teams with colleagues and students, who may be foreign nationals, including foreign students at US universities.

The IPC further pointed out to Congress:

- Professors were being forced to choose between excluding non-US students from their courses and research projects, or "dumbing down" the curriculum for all students, so that the risk of being accused of transferring technological information is eliminated.
- Students and able young faculty members were avoiding space-related fields, where the uncertainties and burdens of ITAR compliance and the ITAR approval process are so acute.
- Universities were weighing the costs and risks of conducting research and teaching students in disciplines associated with space science and technology, versus opting out and placing investments in non-space related fields.

During visits to the offices of members of Congress, the IPC found that many staff members were unaware of these unintended consequences.

SCHMADEL'S WHITE PAPER — COI RESOLUTION

In late 2008, Kevin Schmadel of USRA drafted a white paper on ITAR on behalf of the IPC, distributing it for review by the IPC on 5 December. Among other things, Schmadel's paper called for a review and scrubbing of the US Munitions List (USML) and the Commerce Control List (CCL) to remove items that were inconsistent with the guidance of National Security Decision Directive (NSDD) 189.[20] This directive, signed by President Ronald Reagan in 1985, established "national policy for controlling the flow of science, technology, and engineering information produced in federally-funded fundamental research at colleges, universities, and laboratories." Schmadel pointed out that NSDD 189 formally recognized the open nature of fundamental research, which it defined as:

> *Basic and applied research in science and engineering, the results of which ordinarily are published and shared broadly within the scientific community, as distinguished from proprietary research and from industrial development, design, production, and product utilization, the results of which ordinarily are restricted for proprietary or national security reasons.*[21]

Schmadel further pointed out that NSDD 189 specified that classification should be the means of control of the products of fundamental research, when it was required for national security reasons:

> *It is the policy of this Administration that, to the maximum extent possible, the products of fundamental research remain unrestricted. It is also the policy of this Administration that, where the national security requires control, the mechanism for control of information generated during federally-funded fundamental research in science, technology and engineering at colleges, universities, and laboratories is classification. … No restriction may be placed upon the conduct or reporting of federally-funded fundamental research that has not received national security classification, except as provided in applicable US Statutes.*[22]

Schmadel's paper was approved by the IPC, and a corresponding draft resolution was prepared for consideration by the COI at their annual meeting in the spring of 2009. In the meantime, another report from the National Academies was published, titled "Beyond 'Fortress America:' National Security Controls on Science and Technology in a Globalized World," which found that:

> *– The current system of export controls now harms our national and homeland security, as well as our ability to compete economically;*
>
> *– The system of export controls on the international flow of science, technology, and commerce is fundamentally broken and cannot be fixed by incremental changes below the presidential level; and*
>
> *– US national security and economic prosperity depend on full global engagement in science, technology, and commerce.*[23]

At the USRA annual meeting in the spring of 2009, the COI resolved that:

> *– The US Government should apply the basic research exclusion in the International Traffic in Arms Regulations (ITAR) to universities and university researchers as originally intended and further, should modify the basic research exclusion so that it extends to US aerospace firms, Federal laboratories, and non-profit organizations when they are interacting with universities in pursuit of fundamental space research; that*
>
> *– The US Government should undertake an interagency review of export controls as a high priority, that the National Security Council should lead this review with support from the Office of Science and Technology Policy and/or a future National Space Council, and that it should include a top-to-bottom scrubbing of the items on the US Munitions List (USML) and the Commerce Control List (CCL); and that*
>
> *– The US Government should identify needed legislative and administrative actions that will revise the current export regime to more effectively protect sensitive technology and minimize adverse effects on other important areas and that this legislation should put the responsibility back in the Executive Branch for determining articles and services to be included on export control lists.*[24]

These three items were included in a letter from USRA president Fred Tarantino to the NASA Presidential Transition Team for the Obama administration in early 2009. Tarantino also sent letters on the ITAR issue to Dr. John Holdren, Assistant to the President for Science and Technology; General James Jones, Assistant to the President for National Security Affairs; and Dr. Lawrence Summers, Director of the National Economic Council and the Assistant to the President for Economic Policy.

The Foreign Relations Authorization Act for fiscal years 2010 and 2011 (H.R. 2410) contained language for which USRA advocated. The act authorized the President to remove satellites and related components from the USML, and called for the President to conduct a "strategic review and assessment of the United States export control

THOMAS ZURBUCHEN

VICTORIA COVERSTONE

system." The act passed the US House of Representatives on 10 June 2009, and while the bill was not taken up by the Senate, President Obama issued an executive order on 13 August 2009 that initiated an interagency review of the US export control system.

The National Defense Authorization Act of 2010 gave relief to the university space research community vis-à-vis export control. Section 1248 of this act directed the secretaries of defense and state to assess the risks associated with removing satellites and related items from the USML.[25]

USRA COLLABORATES WITH OTHER ASSOCIATIONS

The language in both authorizations mirrored the language in the COI resolution of 2009. The IPC found that encouraging and determined to continue its efforts. On 10 January 2010, the IPC met with Mr. Brian Nilsson of the National Security Council to convey the adverse impact that export control regulations were having on university research and education. On the same day, the IPC met with Ms. Patricia Cooper, president of the Satellite Industry Association (SIA), which was advocating for export control reform in collaboration with the Aerospace Industries Association (AIA). The IPC agreed to cooperate with the SIA and the AIA on the needed reform.

Following the annual meeting of USRA's COI in the spring of 2010, Zurbuchen succeeded to the chair of the COI and the IPC and Professor Victoria Coverstone (University of Illinois at Urbana-Champaign) was elected to be the vice chair. The IPC continued advocating for export control reform, as Schmadel, now the USRA Vice President for Government Relations, met with various congressional staffs and arranged meetings between these offices and members of the IPC. For the spring meeting of the COI in 2011, the IPC and the Space Policy Institute organized a symposium titled "US Export Control and Space Science."

Following this meeting and throughout 2012, USRA worked more closely with the Satellite Industry Association, the Commercial Spaceflight Federation, and the American Association of Universities, undertaking joint visits to congressional offices. This coalition advocated for broad reform, not limited to commercial satellites.

SOME RELIEF

In March 2012, the Departments of Defense and State issued a final report in which they recommended removing commercial communications satellites from the USML, controlling these items instead through the Export Administration Regulations (EAR) of the Department of State. The final report did not mention scientific satellites, but it recommended that authority to determine the export control status of satellites and other space-related items be returned to the President. This authority was established in law when Congress passed, and President Obama signed, the National Defense Authorization Act for Fiscal Year 2013 on 2 January 2013. The Department of Defense then began a review of the space-related items covered by Category XV of its USML. Following this review, the Department of State published proposed regulations related to space-related export reform in the Federal Register on 24 May 2013. USRA provided comments on these proposed regulations and persuaded other industry associations to include USRA's comments within their own.

The final regulations were published on 13 May 2014 and became effective on 10 November 2014, though revisions continued to be made through the remainder of the Obama presidency. In general, these regulations limited space-related items on the USML to those that were narrowly and clearly related to defense needs, e.g., to spacecraft that:

- Are specially designed to mitigate effects (e.g., scintillation) of or for detection of a nuclear detonation
- Autonomously detect and track moving ground, airborne, missile, or space objects other than celestial bodies, in real-time using imaging, infrared, radar, or laser systems
- Conduct signals intelligence (SIGINT) or measurement and signatures intelligence (MASINT)
- Are anti-satellite or anti-spacecraft (e.g., kinetic, RF, laser, charged particle)
- Have space-to-ground weapons systems (e.g., kinetic or directed energy)
- Are specially designed to provide inspection or surveillance of another spacecraft, or service another spacecraft via grappling or docking (excluding the NASA Docking System)
- Are classified[26]

But other types of spacecraft that could be of interest to the university space research community remained on the USML, e.g., those that:

- Are specially designed to be used in a constellation or formation that when operated together, in essence or effect, form a virtual satellite (e.g., functioning as if one satellite) with the characteristics or functions of other items [shown above]
- Have [certain specified] electro-optical remote sensing capabilities or characteristics
- Have [certain] radar remote sensing capabilities or characteristics such as synthetic aperture radar
- Provide Positioning, Navigation, and Timing (PNT) signals
- Autonomously perform collision avoidance
- Are sub-orbital, incorporate [certain specified] propulsion systems, and are specially designed for atmospheric entry or re-entry[27]

In addition, some of the USML-controlled spacecraft parts, components, accessories, attachments, equipment, or systems are of interest to university space researchers, including certain specified antenna systems, space-qualified optics, space-qualified focal plane arrays, and several other advanced space systems.

IN CONCLUSION

The impact of ITAR on university space research hasn't been, and likely never will be, totally removed. But, as noted by Kevin Schmadel, after several years of effort on the part of USRA, at least the items on Category XV of the USML are now narrowly defined and applicable to clear military purposes.

> *Industry had sought, for a decade, to try to reverse the "Cox mandate." After USRA joined with industry to form a coalition, Congress learned how the mandate was affecting space-related university research and education. Congress correctly saw impairment of space workforce development as a national security concern. These combined efforts of industry and academia eventually led to a reversal of the Cox mandate, in the sense that the new law restored to the President authority for removal of satellites and related items from the USML. Furthermore, it was a complete reform of the language of Category XV of the USML, not just some kind of reform limited to communication satellites or excluding scientific and research and experimental satellites.*[28]

Since the passage of the National Defense Authorization Act for Fiscal Year 2013 and the subsequent regulatory implementation, congressional offices have sought the input of USRA on how well the reform has lessened the adverse effects on space workforce development. USRA continues to turn to its member universities through the IPC to gather constructive feedback for Congress and executive agencies.

SINCE THE PASSAGE OF THE NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 2013, CONGRESSIONAL OFFICES HAVE SOUGHT THE INPUT OF USRA ON HOW WELL THE REFORM HAS LESSENED THE ADVERSE EFFECTS ON SPACE WORKFORCE DEVELOPMENT.

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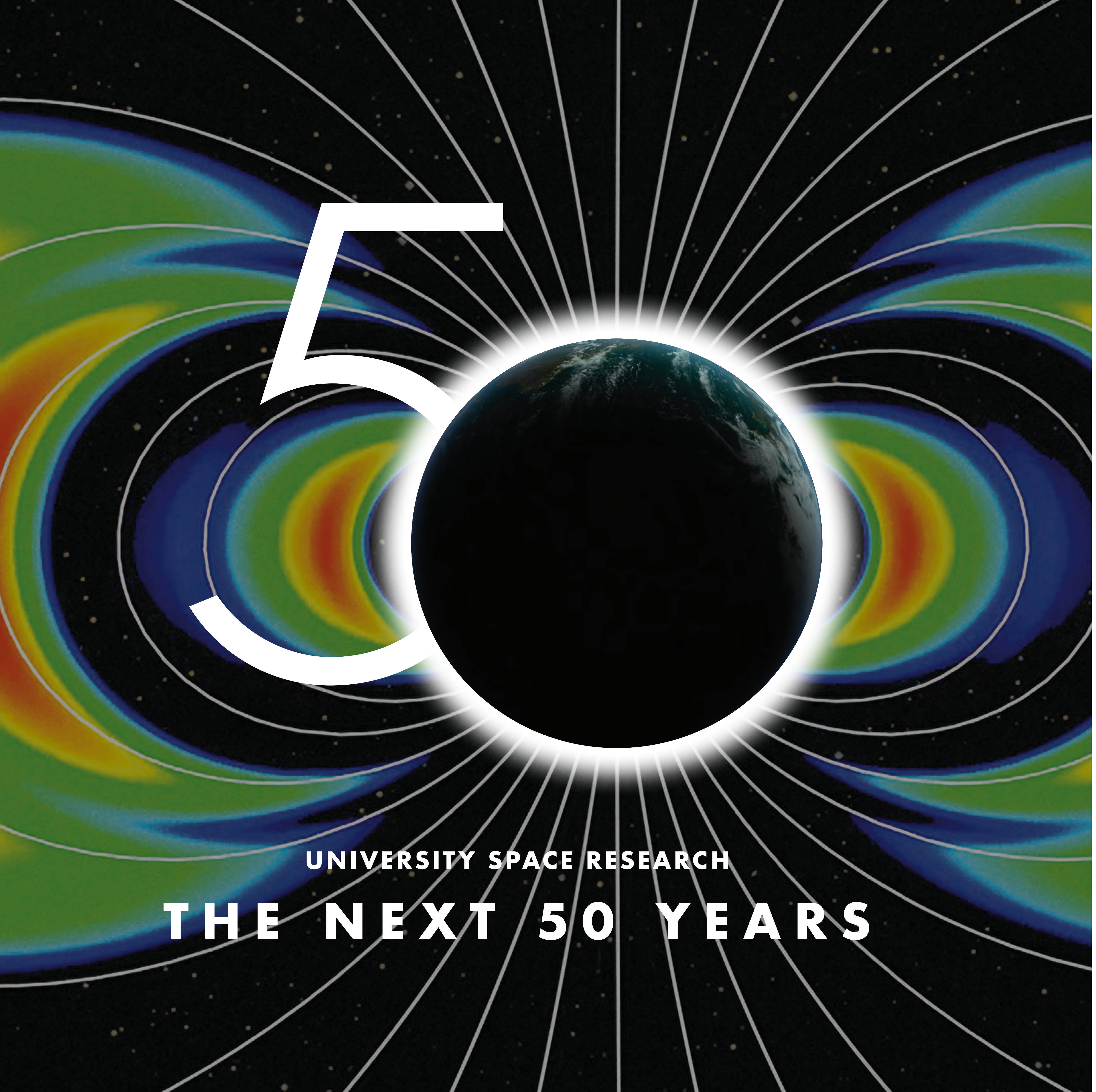
LOOKING TO THE FUTURE



UNIVERSITY SPACE RESEARCH

THE NEXT 50 YEARS

President Kennedy speaking at Rice University in 1962
Credit Wikipedia

ARGUABLY, UNIVERSITY SPACE RESEARCH BEGAN with the discovery of belts of high-energy particles trapped in the Earth's magnetic field. Professor James A. Van Allen and his graduate students at the University of Iowa made the discovery of what came to be called the Van Allen radiation belts by using data from their instruments on the Explorers 1 and 3 satellites, launched in the winter and spring of 1958.

Other university research groups began to conduct space experiments with satellites and space probes following the creation of the National Aeronautics and Space Administration (NASA) on 29 July 1958. A little more than ten years later, the Universities Space Research Association (USRA) was formed[1] to assist both NASA and university researchers as the discipline of space research grew. Prior sections of this book have highlighted some of USRA's work on behalf of university space research during the first fifty years of the Association.

What about the next fifty years? What is the future for university space research and for USRA, which has a charter[2] that ties it to university space research? These questions cannot be answered with certainty, but examining three trends dating back to the beginning of university space research might inform judgments about the future.

US SUPPORT OF SPACE EXPLORATION

Over the past sixty years, US citizens and their elected representatives have generally been very supportive of space exploration. NASA was created in the midst of the "space race" with the Soviet Union, however, and now that the space race is largely historical, one might question whether there is sufficient motivation for the nation to continue the exploration of space.

In a speech at Rice University on 12 September 1962, President John F. Kennedy announced his decision to direct the US to begin the exploration of the Moon and pledged to send astronauts to the Moon.

> *We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, …*[3]

Kennedy's view seems to have prevailed; the US has continued to undertake space exploration because it is challenging, and mastering the exploration of space keeps the nation competitive along a broad and important technical front. Added to that, and perhaps more importantly, space-related discoveries during the past six decades have demonstrated to the scientific community, as well as the general public, the importance of continuing space exploration. Certainly, much exploration remains to be done. As President Kennedy noted in his speech at Rice University, "The greater our knowledge increases, the more our ignorance unfolds."[4]

SPACE-RELATED DISCOVERIES DURING THE PAST SIX DECADES HAVE DEMONSTRATED THE IMPORTANCE OF CONTINUING SPACE EXPLORATION.

STRIKING DISCOVERIES HAVE LED TO MANY MORE UNANSWERED QUESTIONS.

SEVERAL EXAMPLES ILLUSTRATE HOW STRIKING DISCOVERIES HAVE LED TO MANY MORE UNANSWERED QUESTIONS.

- On 20 May 1964, Robert Wilson and Arno Penzias of the Bell Laboratories measured the cosmic microwave background (CMB) radiation. Satellite observations have since revealed tiny fluctuations in the temperature of the CMB that are likely the signature of random quantum fluctuations at the time of the beginning of an enormous inflation of the universe. That increase in our knowledge has uncovered a perhaps greater ignorance. As noted by those tasked with identifying future critical areas of research in astronomy and astrophysics, "… the underlying detailed physics of inflation is still a complete mystery."[5]
- Recent satellite and ground-based observations have revealed many stars with planetary systems; one star (TRAPPIST 1) has been shown to have seven planets in its stellar system.[6] Three of these planets are in the so-called habitable zone for the star. This discovery and others like it will guide future work on finding signs of life outside our solar system.
- On 25 August 2012, the Voyager 1 spacecraft crossed the heliopause at a distance from the Sun of about 122 astronomical units. (One astronomical unit is the average distance from the Earth to the Sun.) The heliopause is the outer boundary of the region of space known as the heliosphere, which contains particles and fields that have their origin in the Sun. It was a great achievement to finally measure this boundary after Voyager 1 had travelled through the solar system for more than 35 years. Researchers were surprised that the direction of the magnetic field didn't change as Voyager 1 passed through the heliopause. The Voyager in situ measurement and subsequent remote observations by the Intersteller Boundary Explorer and Cassini spacecrafts have raised other questions, such as whether the heliosphere is shaped like a bubble or like a comet with a long tail.[7]
- Interplanetary spacecraft have encountered a remarkable variety of moons of the outer planets, among them some have come to be called "ocean worlds," because of the evidence for liquid oceans below shells of ice, e.g., Europa, Ganymede, Callisto, Enceladus and Titan.[8] These discoveries beg the question, "Are there life forms in the oceans of these moons?"
- Over the past decades, satellites have made increasingly accurate measurements of the flows beneath the solar surface and more sophisticated models of the dynamo that drives solar activity, but this understanding leaves ignorance in its wake. Those charged with planning for future work in solar physics acknowledge that, "What triggers catastrophic energy release in a flare or coronal mass ejection remains a puzzle."[9]
- The initial exploration of the Moon by US astronauts advanced our understanding of how and when the Moon was formed, its thermal history, and its surface and internal structure. The discovery that the Earth-Moon system was likely formed by a collision between the proto-Earth and another planetary body has prompted broader questions about how the inner planets of the solar system were formed. Those charged with laying out a roadmap for future planetary research are asking, "What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?"[10]
- Following the discovery of the Van Allen radiation belts and the theoretical work by Professor Eugene Parker of the University of Chicago on the solar wind and its embedded magnetic field, space researchers continued to discover and describe how the solar wind shapes the Earth's magnetic field, the magnetosphere. These Earth-focused studies have helped researchers better understand measurements made on other planetary magnetospheres and more distant astrophysical objects. For most of the past exploration of near-Earth space, research efforts have focused on individual elements of a system that includes the upper atmosphere, ionosphere, and magnetosphere. Projections by space physicists indicate that future efforts will be increasingly designed to "determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs."[11]

LEFT

TOP: Tiny fluctuations in temperature of the cosmic background radiation as observed by the WMAP satellite *Credit NASA*

MIDDLE: The cosmic timeline *Credit the NASA Wilkinson Microwave Anisotropy Probe Science Team*

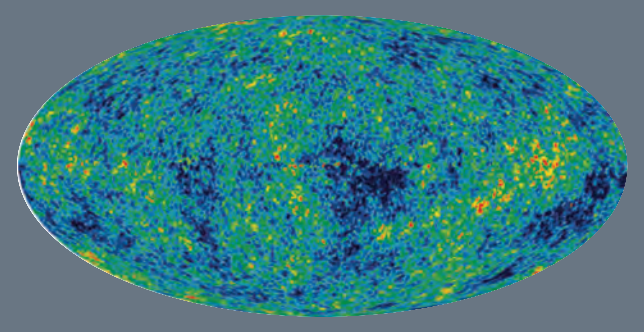
BOTTOM: The Earth's magnetosphere. *Credit NASA*

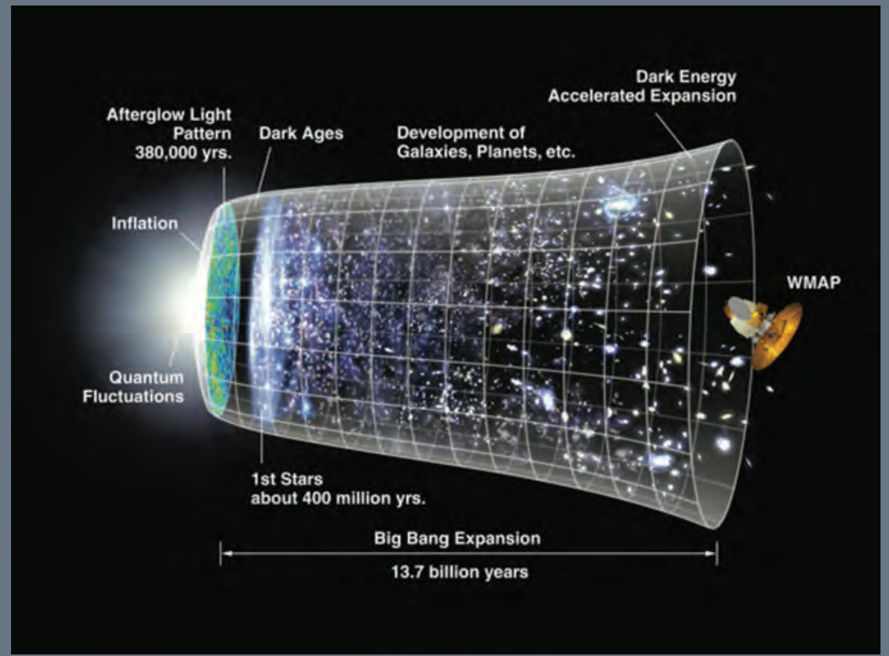
RIGHT

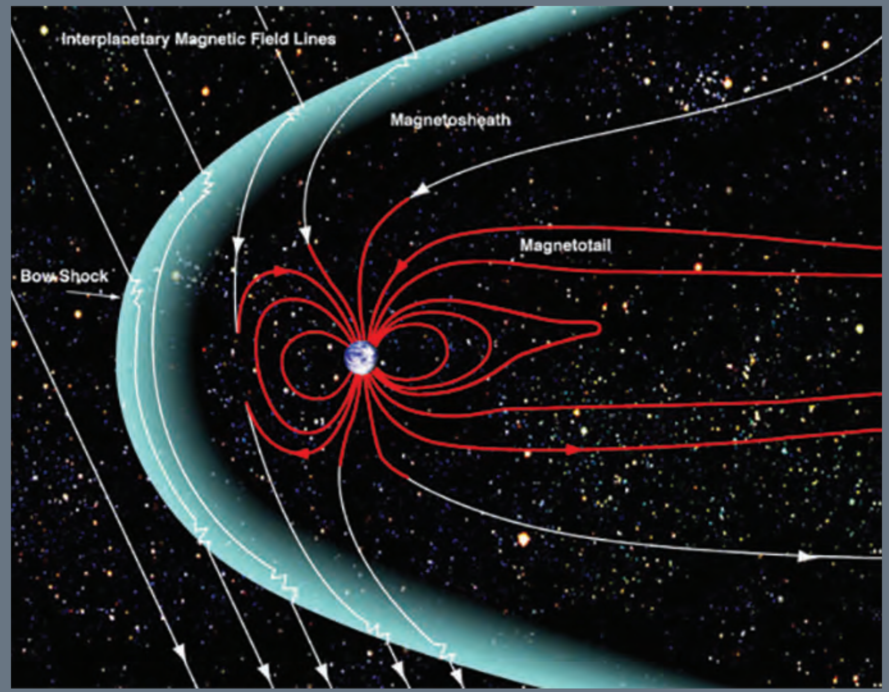
TOP: Some moons of the outer planets (plus the Pluto system), with known icy worlds labeled in blue. *Credit Emily Lakdawall/ Planetary Society*

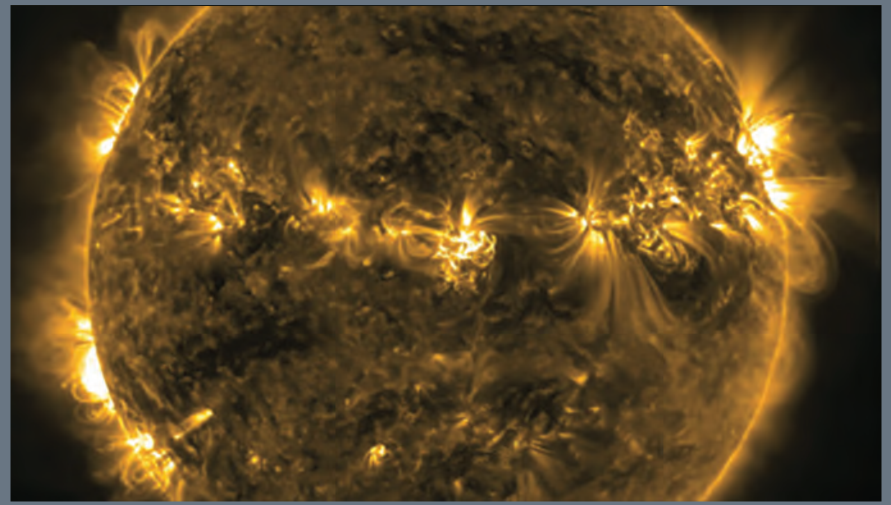
MIDDLE: The Sun as seen in extreme ultraviolet light from NASA's Solar Dynamics Observatory *Credit NASA*

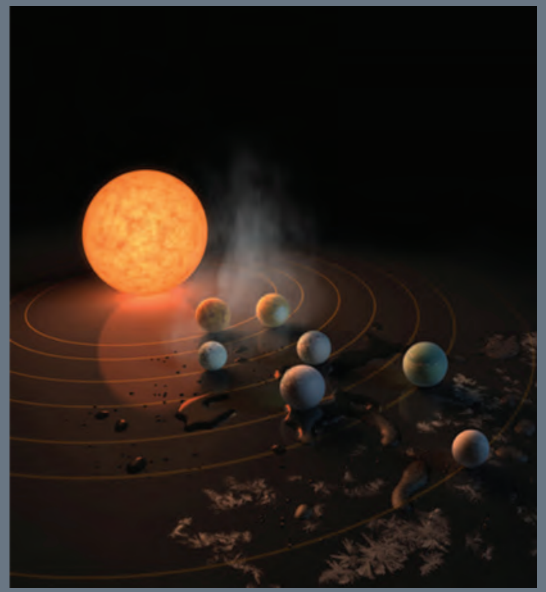
BOTTOM: An artist's conception of TRAPPIST-1 and its seven planets, with vapor, water, and ice crystals shown to indicate the likely environments for the planets. *Credit NASA*
Apollo 17 astronaut Gene Cernan on the Moon's surface *Credit NASA*

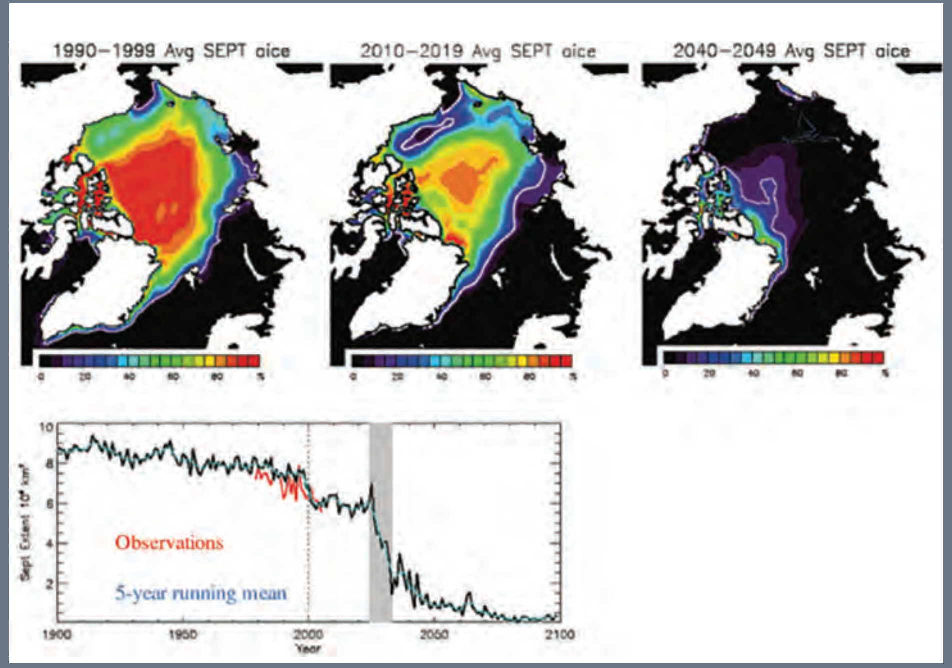


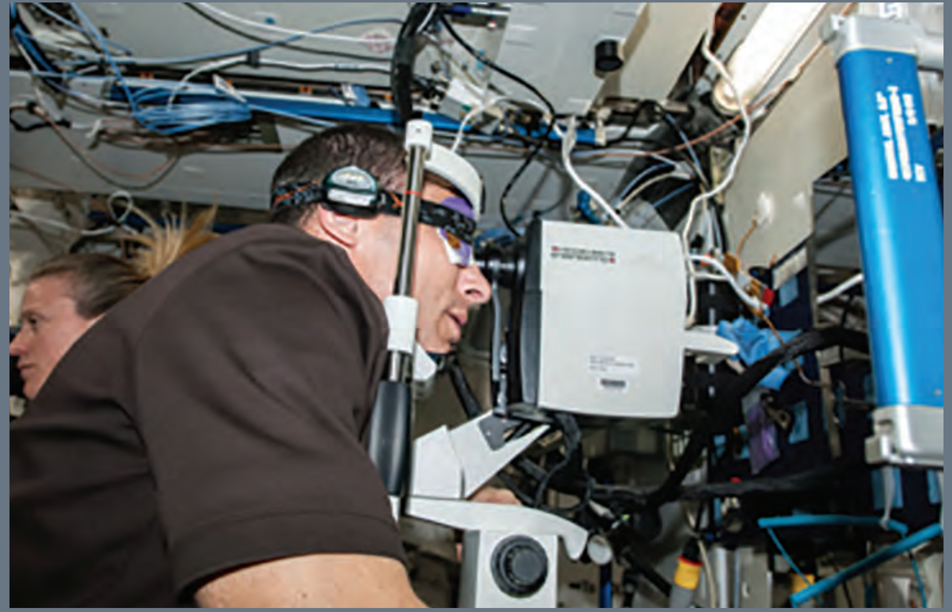












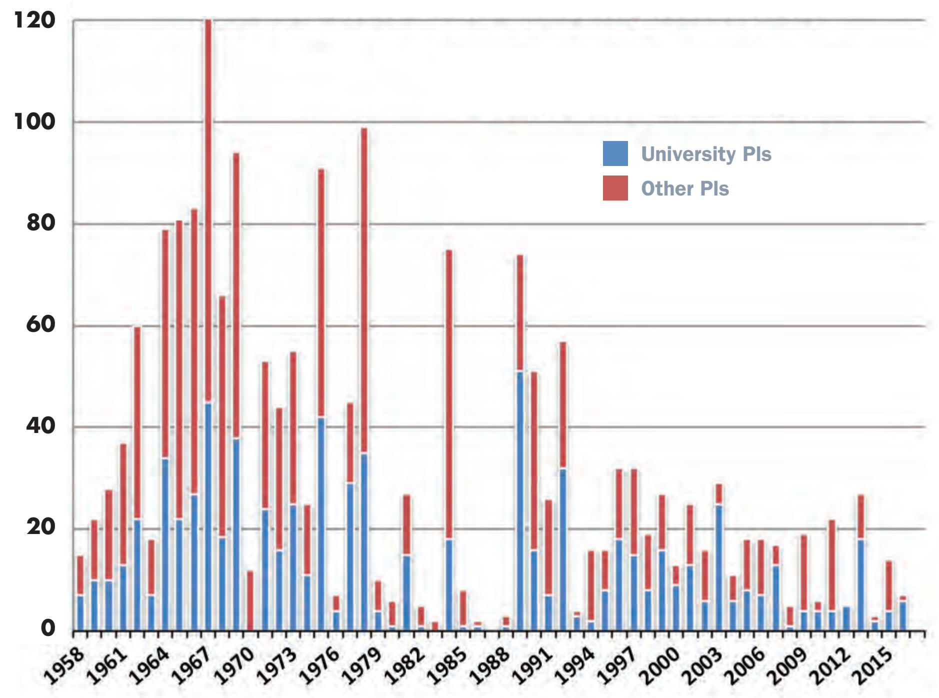
TOP: Past and projected sea ice cover in the Arctic ocean. *Credit the American Geophysical Union.*

BOTTOM; Astronauts Karen Nyberg and Michael Hopkins using the Optical Coherence Tomography apparatus on the ISS. *Credit NASA*

- Earth-observing satellites have played a key role in determining the rates of glacial and sea ice retreat, particularly in the Arctic region. The next questions for Earth scientists are, "Will there be catastrophic collapse of the major ice sheets, including those of Greenland and West Antarctic and, if so, how rapidly will this occur? What will be the time patterns of sea-level rise as a result?"[12]
- Space research on human physiology over the past few decades has succeeded in identifying significant challenges posed for humans who are trying to operate in the space environment. These challenges include heightened exposure to space radiation, as well as the effects of microgravity on human skeletal structure and human organs, such as the eyes. Research in the next decades will determine whether or how these challenges can be surmounted.[13]
- Laboratory research on the International Space Station has demonstrated that in a microgravity environment micron-sized hard spheres of the same size can form crystals even without any attractive or repulsive forces between the particles. This crystal formation had been predicted, but the transition could not be seen in laboratories on the Earth because of gravity-related interference. "The ability to work with colloids in this new regime has led to a focus on colloidal engineering – how to apply these new insights: building functional materials and machines that can do work and transport materials that are much smaller than the diameter of a fine human hair. Getting colloids to self-assemble and in some cases self-replicate plays an important role and enables the scaling up of this new resource."[14]

As predicted by President Kennedy, the discoveries of the past sixty years have opened many exciting avenues of space research to pursue. Largely because of these discoveries, it seems likely that space exploration has now been woven into the fabric of the nation's overall research and development effort. In practical terms, the space research enterprise is fueled by the existence of NASA, which has the federal mandate for space exploration. The associated congressional oversight and budget committees, as well as the space-related committee structure of the National Academies of Sciences, Engineering, and Medicine helps to sustain a long-term future for space research in the US. The foundation for this optimistic outlook, however, is the continued support by US citizens for the nation's space program.

US PIs ON ROBOTIC SPACEFLIGHT MISSIONS



UNIVERSITY ENGAGEMENT IN US SPACE EXPLORATION.

Will universities continue to be a central part of US space exploration during the next fifty years? Van Allen and his students, as well as other university professors and their students after them, had frequent launch opportunities of spacecraft that carried experiments designed and developed on a university campus in many cases. Over the years, spacecraft and the instruments that they carried became more complicated, and the launch opportunities less frequent. One might ask if space exploration during the next fifty years will be compatible with the requirements of a university to train students while advancing knowledge.

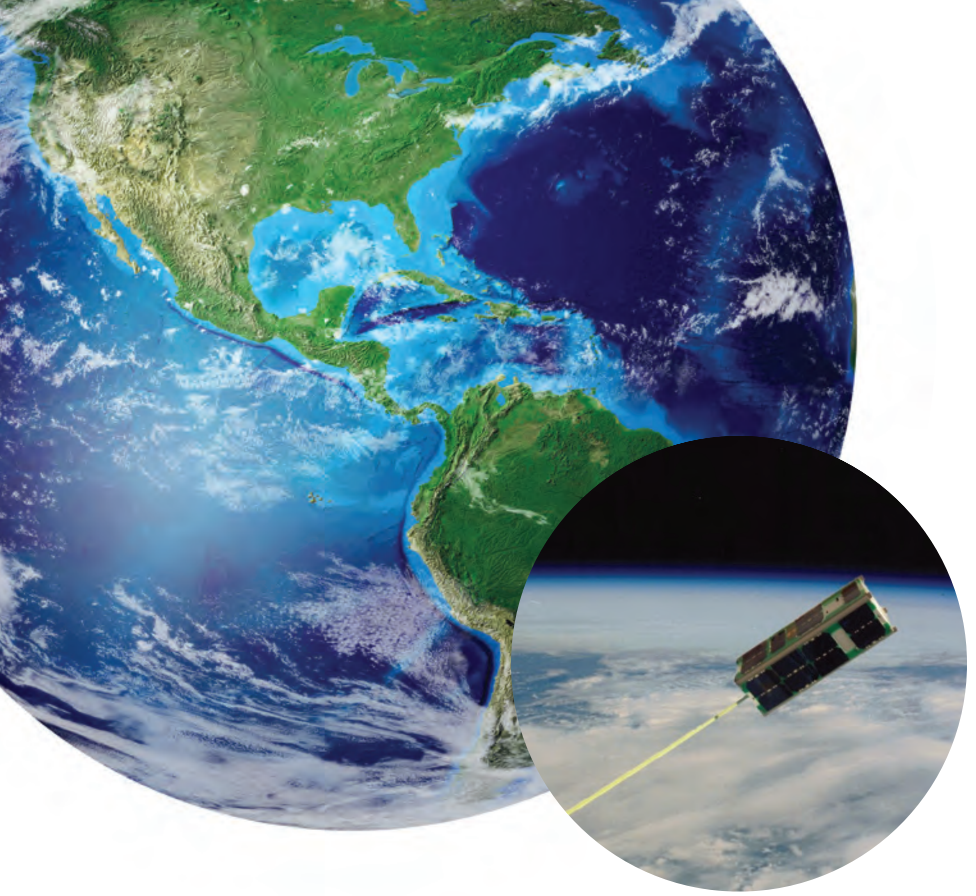
One way to measure how well NASA has involved universities in space research over the past sixty years is to look at the annual number of instrument and mission principal investigators (PIs) on robotic space flight missions and to note how many of these PIs were affiliated with universities. As shown in the accompanying chart[15], over the past sixty years there has been a decline in the number of principal investigators (PIs) for science missions conducted by NASA using traditional free-flying spacecraft, such as the series of Explorer spacecraft. Often a spacecraft carries several different science instruments, so that a single space flight mission might include several instrument PIs, as well as an overall mission PI. One might have thought that the trend toward larger and more complicated robotic space missions, though less frequently launched, might have involved more PIs per mission, ensuring the average number of PIs per year would not decline. But the above chart shows that this has not been the case. The percentage of PIs with university affiliations has been relatively steady at 40% to 50% of the total number, but the annual number of university PIs on traditional NASA-sponsored robotic space flight missions has been declining.

The decline is concerning for the future of university space research.[16] These missions are not the only means universities have for conducting space research. Suborbital programs, which include sounding rockets, research balloons, and airborne research platforms have been very important means for research and training of graduate students. The Space Shuttle was also used, as well as the International Space Station. But free-flying spacecraft have been the mainstay of university space research activities since the inception of NASA.

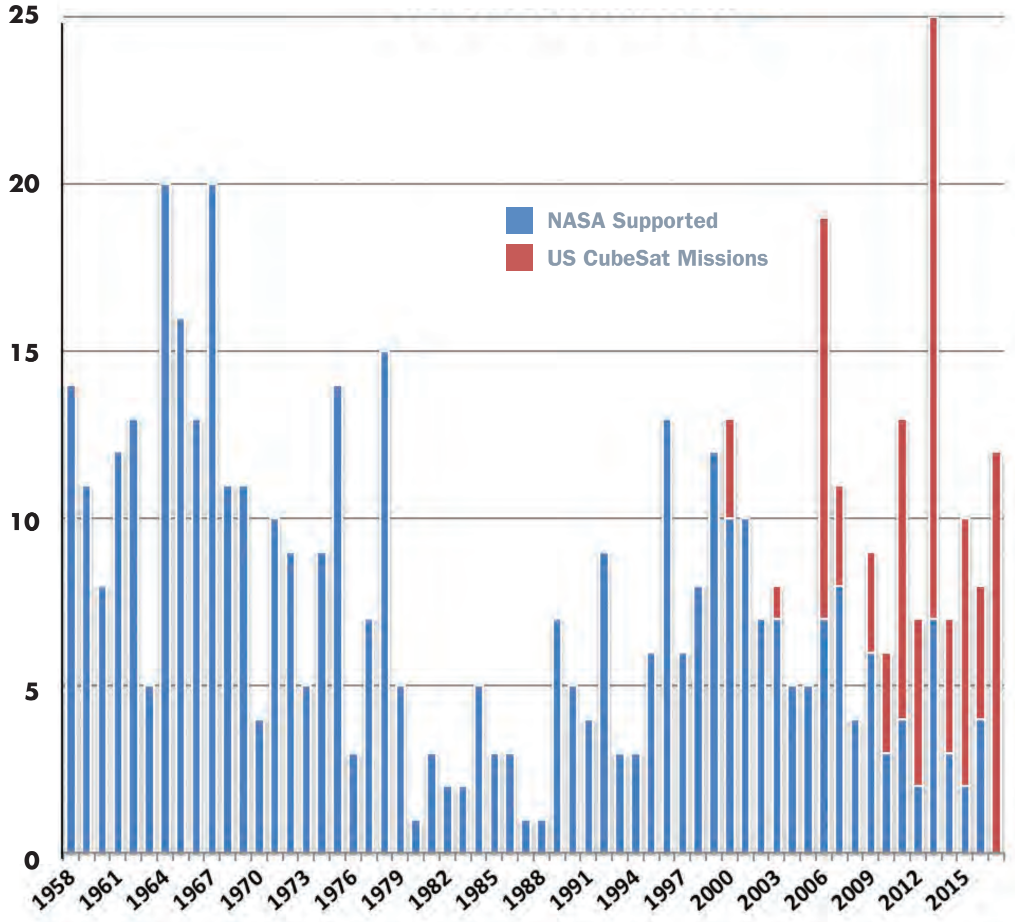
Fortunately, there is an emerging trend involving a new class of free-flying spacecraft. As shown in the accompanying chart[17] (page 222) low-cost CubeSats have begun to represent a significant part of NASA-supported flight opportunities. CubeSats conform to a standard size and mass. The basic unit (1U) is a ten centimeter cube with a mass that cannot exceed 1 kg. Satellites can be constructed in multiples of this basic unit, i.e., 2U, 3U, 4U etc., CubeSats. The reduced cost of CubeSat deployment and the ability to use excess capacity of larger launch vehicles has allowed for greater university student involvement in space research, on par with rocket and balloon opportunities.

AS PRESIDENT KENNEDY PREDICTED, THE DISCOVERIES OF THE PAST SIXTY YEARS HAVE OPENED MANY EXCITING AVENUES OF SPACE RESEARCH TO PURSUE.

The Colorado Student Space Weather Experiment 3U CubeSat. *(Credit Orbital Wisdom)*



NASA SUPPORTED SCIENCE SPACEFLIGHT MISSIONS AND US CubeSat MISSIONS



CubeSats are increasingly sophisticated and are already producing good science. A recent example is the confirmation by instruments on the Colorado Student Space Weather Experiment CubeSat that the source of electrons in the inner Van Allen belt is the result of a process in which cosmic rays that impinge on the Earth's atmosphere create high energy neutrons, some of which are reflected back into the magnetosphere where they decay into protons and electrons.[18]

The trends suggest, therefore, that with continued university involvement as PIs on large robotic missions, the continuation of NASA's suborbital programs, and the continued expansion of the use of CubeSats, universities will play a substantial role in the US space program of the future. The foundation for this optimistic outlook, however, is the continued support of university space research by NASA and/or other federal agencies.

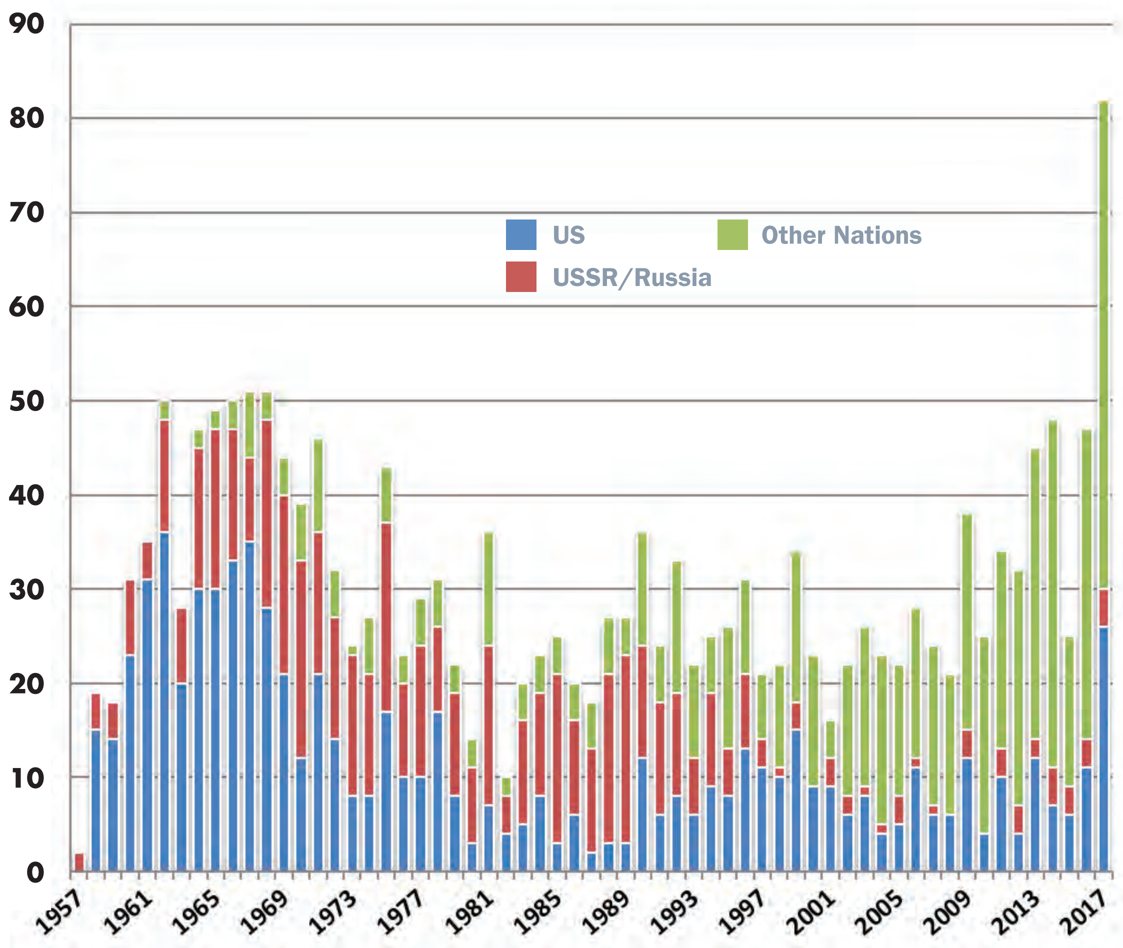
THE INTERNATIONAL CONTEXT OF SPACE RESEARCH

During the two decades following the launch of the first Earth satellite by the USSR, most participants in space research were located in the US and the Soviet Union. There wasn't much international collaboration between these countries during the space race until the Apollo-Soyuz mission in 1975, when US and USSR space vehicles were joined to form a laboratory in which astronauts and cosmonauts could carry out research.

In subsequent decades, international collaborations became common, particularly for large, expensive missions. The Hubble Space Telescope, for example, was launched in 1990 as a collaborative effort between NASA and the European Space Agency (ESA). In the same year, the sun-orbiting spacecraft Ulysses was launched as a joint venture between ESA and the US with participation from Canada as well. The Russian space station MIR was collaborative in the sense that US astronauts visited the station via the US Space Shuttle beginning in 1995, and US astronauts operated within MIR for various periods over the life of the station. The Cassini-Huygens mission to Saturn, launched in 1997, was a joint effort by NASA, ESA, and the Italian Space Agency. The construction of the International Space Station began in 1998, with participation from NASA, ESA, and the space agencies of the Russia, Japan, and Canada.

International collaborations on large missions have continued into the 21st century. For example, the Stratospheric Observatory for Infrared Astronomy (SOFIA), using a telescope carried by a Boeing 747 aircraft, flew for the first time in 2010. SOFIA is a joint effort between NASA and the German Aerospace Center (DLR), which oversaw the construction of the mirror system for the observatory.

SCIENCE-CAPABLE (CIVILIAN) ROBOTIC SPACECRAFT BY YEAR OF LAUNCH/DEPLOYMENT



THERE HAS ALWAYS BEEN AN INTERNATIONAL ASPECT TO SPACE RESEARCH ON MANY LEVELS AND USRA HAS SERVED RESEARCHERS FROM AROUND THE WORLD.

Besides international collaborations on large space projects, there has always been an international aspect to space research. During the first few years of the space race the USSR and the US were the only nations to launch spacecraft. In 1962, the UK and Canada began to fly their own satellites, and other nations soon followed suit. Future internationalization seems likely, manifesting through the participation in space research of many different countries. The above chart[19] shows the number of space research launches by year of the US, USSR/Russia, and "Other Nations." The last category includes prominently China and Japan, but 50 other nations (including ESA) as well. Much of the upward trend of late is due to the emergence of CubeSats.

USRA has always served researchers from around the world, and one of the metrics annually measured by USRA Headquarters is the amount and quality of international activities in the Association's sponsored programs. For example, visiting scientists from abroad commonly participate in USRA institutes and other programs. There has always been a vital contingent of non-US scientists at the annual Lunar and Planetary Science Conferences and on the LPI's staff as visiting scientists, visiting post docs, and summer interns. As noted above, SOFIA is jointly supported by NASA and the DLR. There are two SOFIA research centers, one managed by USRA, and the other, the German SOFIA Institute, at the University of Stuttgart. USRA provides a SOFIA Science Council that serves as a forum and as an advisory body for both US and German interests in SOFIA and has participants from both countries.

Finally, there have always been non-US member universities in USRA, so there have always been non-US members on USRA's Council of Institutions, which elects USRA's Board of Trustees. Since 2007, one of USRA's nine regional groups of universities has contained only non-US universities, which means that one of the nine Regional Trustees on USRA's board is from a non-US university. In 2017, the USRA Council of Institutions changed the Association's bylaws to allow a larger number of non-US universities in its membership.

It is not yet clear what international roles USRA might play in a future when many different countries are active in space exploration. But, in such an environment, having member universities from countries around the globe would seem to be a necessary condition for USRA to be effective in international collaborative efforts.

DURING THE NEXT FIFTY YEARS THERE SHOULD BE MANY OPPORTUNITIES TO CONTINUE TO SERVE UNIVERSITIES, FEDERAL AGENCIES, AND PRIVATE COMPANIES. THE FUTURE SUCCESS OF USRA COULD DEPEND ON ITS CONTINUED ABILITY TO THOROUGHLY ENGAGE UNIVERSITY RESEARCHERS IN THE MANAGEMENT AND EXECUTION OF ITS PROGRAMS.

USRA

CONCLUSIONS

From the forgoing examination of trends over the past sixty years, one can perhaps be guardedly optimistic about the future of university space research. The environment for university space research is likely to be different than it has been over the past decades, however, not only because of the internationalization of space activities, but perhaps also because of a larger role for the private sector.

Space-related companies have always played important roles in space exploration. They have built the rockets and much of the space hardware that NASA and other federal agencies have used for their missions. Almost all the work done by the private sector in the past, however, has been under contract with the federal government. Private companies will likely continue to support federal agencies through contracted work, but there are indications that in the future private companies will more and more operate independently in pursuit of commercial goals. There have been setbacks and delays for some of these companies, but spectacular success as well. During the next fifty years university space research could benefit from the availability of competing companies for launch services and the provision of data from large numbers of Earth-observing satellites.

Regardless of the details of the environment for the future of university space research, an important question is whether and how USRA will continue to thoroughly engage university space researchers in the management and execution of its programs. USRA was created by the National Academy of Sciences after lengthy deliberations by representatives from the university community,[20] and distinguished members of the university space research community have been deeply and widely involved in USRA's activities since its founding. A significant strength of the Association has come from active participation by Institutional Representatives on the USRA Council of Institutions, by members of USRA's Board of Trustees, and from service by university researchers on various USRA science and technology advisory councils.

It seems likely that members of the university space research community have been willing to devote their energy and expertise to USRA's efforts because USRA has continued to operate with a guiding philosophy that it inherited from James E. Webb, the second NASA Administrator. Webb was consistent in expressing the importance of strengthening universities.[21] He wanted substantial participation of university researchers in NASA's explorations, because he knew that NASA would need to draw on university expertise as the agency encountered a wide variety of scientific and technical challenges. Webb wanted the university participation to be accomplished with minimal impact on faculty members as they fulfilled their teaching and training responsibilities at their universities.

USRA was born from Webb's vision, and the historical essays of this book illustrate how the association has supported the needs of NASA and other federal agencies as well as making it easier for university space researchers to participate in the nation's space program.

During the next fifty years there should be many opportunities for USRA to continue to serve universities, federal agencies, and perhaps private companies. The future success of USRA could well depend on its continued ability to thoroughly engage university researchers in the management and execution of its programs.

ENDNOTES

1. Cummings, W.D., 2009. A Documentary History of the Formation of USRA, USRA. Columbia, Maryland.
2. The non-profit charter for USRA is:
   To constitute an entity by means of which universities and other research organizations may cooperate with one another, with the governments of the United States and other nations, and with other organizations toward the development and application of space-related science, technology and engineering.
   To develop and manage programs and facilities, and provide other services as required under contract, or otherwise, with the governments of the United States and other nations, and other organizations for space-related education, research, development, and operations.
3. Kennedy, J.F., 1962. John F. Kennedy Address at Rice University on the Space Effort. *Public Papers of the Presidents of the United States,* v. 1, 1962, pp.669–670, p.670. Rice University.
4. Ibid., 669.
5. Astronomy, National Research Council, 2010. New Worlds, New Horizons in Astronomy and Astrophysics, p.48.
6. Gillon, M., Triaud, A.H., Demory, B.O., Jehin, E., Agol, E., Deck, K.M., Lederer, S.M., De Wit, J., Burdanov, A., Ingalls, J.G. and Bolmont, E., 2017. Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. *Nature, 542*(7642), p.456.
7. Personal communication from Dr. Alan Cummings.
8. Nimmo, F. and Pappalardo, R.T., 2016. Ocean worlds in the outer solar system. *Journal of Geophysical Research: Planets, 121*(8), pp.1378–1399.
9. Board, S.S. and National Research Council, 2013. *Solar and space physics: A science for a technological society.* National Academies Press, p.25.
10. Board, S.S. and National Research Council, 2012. *Vision and voyages for planetary science in the decade 2013-2022.* National Academies Press, p.71.
11. Ibid.
12. Board, S.S. and National Research Council, 2007. *Earth science and applications from space: national imperatives for the next decade and beyond.* National Academies Press, p.2.
13. Board, S.S. and National Research Council, 2012. *Recapturing a future for space exploration: life and physical sciences research for a new era.* National Academies Press, p.2.
14. Personal communication from Dr. William Meyer.
15. Data for this chart on US PIs were obtained primarily from the NASA Space Science Data Coordinated Archive. The research affiliations of PIs were determined by referring to research papers written by the PIs at or around the year of the space flight. CubeSat missions and experiments on the Space Shuttle and the International Space Station (ISS) were not included, except for missions that used the Space Shuttle or the ISS as points of departure for free flight. Experiments on the Gemini and Apollo missions were also excluded. A national policy decision to use the Space Shuttle as the primary space launch system for the US resulted in a dearth of NASA missions after the Space Shuttle Challenger accident occurred on 28 January 1986. Following this accident, there was a thirty-two month stand down of the Shuttles while the cause of the failure was being investigated.
16. According to the NASA Space Science Data Coordinated Archive, the only NASA-sponsored space science-related spacecraft to be launched in 2017 was the Microwave Radiometer Technology Acceleration (MiRaTa) satellite, which is a CubeSat developed at MIT.
17. The NASA Space Science Data Coordinated Archive was used to obtain data for this chart on NASA-supported science spaceflight missions. Data on CubeSat launches were obtained from the websites of Michael Swartwout (https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database#database) and Gunter Krebs (https://space.skyrocket.de/directories/chronology.htm).
18. Li, X., Selesnick, R., Schiller, Q., Zhang, K., Zhao, H., Baker, D.N. and Temerin, M.A., 2017. Measurement of electrons from albedo neutron decay and neutron density in near-Earth space. *Nature, 552*(7685), p.382.
19. Data for this chart on science-capable (civilian) robotic spacecraft were obtained from the NASA Space Science Data Coordinated Archive and the Swartwout and Krebs websites (See endnote 16.).
20. Cummings, A Documentary History.
21. Lambright, W.H., 1995. Powering Apollo: James E. Webb of NASA. *The John Hopkins University Press,* p.136.

APPENDIX

MEMBERS OF USRA'S BOARD OF TRUSTEES

The Universities Space Research Association (USRA) was incorporated in the District of Columbia on 12 March 1969 as a nonprofit corporation. The members of USRA are universities, and a representative from each member university sits on the USRA Council of Institutions (COI). The COI elects its Chair and other officers, including members of USRA's board of directors, which is called the Board of Trustees. The Chair of the COI is a member of the Board of Trustees.

The first meeting of the USRA Council of Institutions was held on 9 June 1969, with representatives from forty–one universities in attendance. Professor Donald MacRae of the University of Toronto was elected as the initial Chair of the COI. The succession of Chairs of the COI since this first meeting is shown in the table below.

CHAIRS OF THE USRA COUNCIL OF INSTITUTIONS

1969–1971	Donald A. MacRae	University of Toronto
1971–1974	Frederick Seitz	Rockefeller University
1974–1975	Frederick T. Wall	Rice University
1975–1976	Alexander J. Dessler	Rice University
1976–1977	Simon Ostrach	Case Western Reserve University
1977–1978	Frederick W. Crawford	Stanford University
1978–1979	James J. Papike	State University of New York at Stony Brook
1979–1980	Robert L. Carovillano	Boston College
1980–1981	James W. Head III	Brown University
1981–1982	Albert P. Sheppard	Georgia Institute of Technology
1982–1983	Donald R. Johnson	University of Wisconsin–Madison
1983–1984	James R. Arnold	University of California, San Diego
1984–1985	Frank J. Kerr	University of Maryland, College Park
1985–1986	Carle M. Pieters	Brown University
1986–1987	Robert L. Carovillano	Boston College
1987–1988	Saul S. Abarbanel	Tel–Aviv University
1988–1989	Thomas P. Armstrong	University of Kansas
1989–1990	Paul W. Weiblen	University of Minnesota
1990–1991	William A. Cassidy	University of Pittsburgh
1991–1992	Eugene H. Levy	University of Arizona
1992–1993	Jeremy D. Dunning	Indiana University Bloomington
1993–1994	Laurence W. Fredrick	University of Virginia

CHAIRS OF THE USRA COUNCIL OF INSTITUTIONS (CONTINUED)

1994–1995	Saul S. Abarbanel	Tel–Aviv University
1995–1996	Norman F. Ness	University of Delaware
1996–1997	Daniel N. Baker	University of Colorado Boulder
1997–1998	Simon Ostrach	Case Western Reserve University
1998–1999	W. Jeffrey Hughes	Boston University
1999–2000	Sabatino Sofia	Yale University
2000–2002	George R. Carignan	University of Michigan
2002–2004	Patricia H. Reiff	Rice University
2004–2006	Carolyn B. Morgan	Hampton University
2006–2008	W. Jeffrey Hughes	Boston University
2008–2010	Edward J. Groth III	Princeton University
2010–2012	Thomas H. Zurbuchen	University of Michigan
2012–2014	Victoria L. Coverstone	University of Illinois at Urbana–Champaign
2014–2016	Robert H. Holzworth	University of Washington
2016–2018	Steven A. Ackerman	University of Wisconsin–Madison
2018–2020	Daniel N. Baker	University of Colorado Boulder

During the deliberations that led to the formation of USRA, the National Academy of Sciences formed the Universities Organizing Committee for Space Sciences (UOCSS). The thirteen members of this committee became the initial Board of Trustees for USRA. The board had its first meeting in conjunction with the third meeting of the UOCSS on 31 March 1969.

INITIAL BOARD OF TRUSTEES (1969)

Albert L. Babb	University of Washington
Arthur D. Code	University of Wisconsin–Madison
Bruno J. Giletti	Brown University
William E. Gordon	Rice University
Lucius P. Gregg Jr.	Northwestern University
A. Robert Kuhlthau	University of Virginia
Donald A. MacRae	University of Toronto
Ernest C. Pollard	Pennsylvania State University
William W. Rubey	University of California, Los Angeles
Henry C. Torrey	Rutgers University
Wolf V. Vishniac	University of Rochester
Robert M. Walker	Washington University in St. Louis
Frederick T. Wall	University of California, San Diego; American Chemical Society

APPENDIX

At the second meeting of the USRA COI, held on 27 March 1970, member universities were organized into nine regional groups (I – IX), with one Regional Trustee to be elected to the USRA Board of Trustees from each region. As USRA's membership grew, regional boundaries were adjusted from time to time so that approximately the same number of member universities would be in each regional group. In 2007, the COI designated Regional Group V as the one that would be populated only by universities from outside the United States. In 2017 the USRA bylaws were changed to allow up to three such regional groups.

The succession of Regional Trustees since 1970 is shown in the following tables.

REGIONAL TRUSTEES

REGIONAL GROUP I

1970–1976	Bruno J. Giletti	Brown University	**1994–1997**	Carle M. Pieters	Brown University
1976–1979	Donald L. Turcott	Cornell University	**1997–2003**	Robert L. Carovillano	Boston College
1979–1985	Martin E. Glicksman	Rensselaer Polytechnic Institute	**2003–2009**	Richard P. Binzel	Massachusetts Institute of Technology
1985–1988	Joseph F. Veverka	Cornell University	**2009–2015**	Wesley L. Harris	Massachusetts Institute of Technology
1988–1994	Roger L. Arnoldy	University of New Hampshire	**2015–2021**	Patricia H. Doherty	Boston College

REGIONAL GROUP II

1970–1978	Oliver A. Shaeffer	State University of New York at Stony Brook	**1999–2005**	James P. Ferris	Rensselaer Polytechnic Institute
1978–1983	Robert L. Carovillano	Boston College	**2005–2011**	Stefi A. Baum	Rochester Institute of Technology
1983–1990	Eugene Isaacson	New York University	**2011-2017**	Judith L. Pipher	University of Rochester
1990–1993	Steven W. Squyres	Cornell University	**2017–2020**	Louis J. Lanzerotti	New Jersey Institute of Technology
1993–1999	Mary A. Bisson	State University of New York at Buffalo			

REGIONAL TRUSTEES (CONTINUED)

REGIONAL GROUP III

1970–1973	Ernest C. Pollard	Pennsylvania State University	**1994–2000**	Burton I. Edelson	George Washington University
1973–1975	Randal M. Robertson	Virginia Polytechnic Institute and State University	**2000–2006**	Roger A. Chevalier	University of Virginia
1975–1982	William A. Cassidy	University of Pittsburgh	**2006–2009**	Menas C. Kafatos	George Mason University
1982–1988	Bruce W. Arden	Princeton University	**2009–2015**	Scott N. Pace	George Washington University
1988–1994	Paul D. Feldman	Johns Hopkins University	**2015–2021**	Pascale Ehrenfreund	George Washington University

REGIONAL GROUP IV

1970	A. Robert Kuhlthau	University of Virginia	**1991–1992**	Donald P. Giddens	Georgia Institute of Technology
1970–1973	Alfred B. Garrett	Ohio State University	**1992–1997**	Robert A. Cassanova	Georgia Institute of Technology
1973–1976	Urho A. K. Uotila	Ohio State University	**1997–2003**	John C. Kelly Jr.	North Carolina A&T State University
1976–1979	A. Robert Kuhlthau	University of Virginia	**2003–2005**	Reza Abbaschian	University of Florida
1979–1985	Laurence W. Fredrick	University of Virginia	**2005–2009**	Peggy L. Evanich	University of Florida
1985–1990	Albert P. Sheppard	Georgia Institute of Technology	**2009–2015**	Eric J. Sheppard	Hampton University
1990–1991	Kenneth E. Harwell	University of Alabama in Huntsville	**2015–2021**	Carolyn B. Morgan	Hampton University

REGIONAL GROUP V

1970–1975	James T. Wilson	University of Michigan	**1993–1999**	Joe G. Eisley	University of Michigan
1975–1978	David A. Landgrebe	Purdue University	**1999–2005**	Alexander Solan	Technion, Israel Institute of Technology
1978–1984	Thomas M. Donahue	University of Michigan	**2005–2011**	Alan A. Wells	Leicester University
1984–1987	Warren G. Meinschein	Indiana University Bloomington	**2011–2014**	Hans–Peter Roser	University of Stuttgart
1987–1993	Simon Ostrach	Case Western Reserve University	**2015–2020**	Alfred B. Krabbe	University of Stuttgart

APPENDIX

REGIONAL TRUSTEES (CONTINUED)

REGIONAL GROUP VI

1970–1971	Robert M. Walker	Washington University in St. Louis
1971–1974	Robert O. Pepin	University of Minnesota
1974–1977	Homer T. Mantis	University of Minnesota
1977–1981	Eugene N. Parker	University of Chicago
1981–1983	Frank Scherb	University of Wisconsin–Madison
1983–1989	C. William Gear	University of Illinois at Urbana–Champaign
1989–1995	Donald R. Johnson	University of Wisconsin–Madison
1995–2001	Dietrich Müller	University of Chicago
2001–2007	Fred W. Turek	Northwestern University
2007–2013	Gary R. Swenson	University of Illinois at Urbana–Champaign
2013–2019	John E. Carlstrom	University of Chicago

REGIONAL GROUP VII

1970–1973	William E. Gordon	Rice University
1973–1974	Elbert A. King	University of Houston
1974–1975	Jesse H. Poore Jr.	Florida State University
1975–1977	Elbert A. King	University of Houston
1977–1978	Harlan J. Smith	University of Texas at Austin
1978–1983	Joseph M. Reynold	Louisiana State University
1983–1989	Richard W. Newton	Texas A&M University
1989–1995	John H. Hoffman	University of Texas at Dallas
1995–1996	Louis C. Sheppard	University of Texas Medical Branch at Galveston
1996–1998	Patricia A. Santy	University of Texas Medical Branch at Galveston
1998–1999	Kenneth E. Harwell	University of Alabama in Huntsville
1999–2001	Robert C. Harriss	Texas A&M University
2001–2007	Gerald R. North	Texas A&M University
2007–2013	John D. Fix	University of Alabama in Huntsville
2013–2019	Elizabeth J. Protas	University of Texas Medical Branch at Galveston

REGIONAL TRUSTEES (CONTINUED)

REGIONAL GROUP VIII

1970–1971	Albert L. Babb	University of Washington
1971–1974	Albert B. Weaver	University of Arizona
1974–1977	George W. Farwell	University of Washington
1977–1983	Charles P. Sonett	University of Arizona
1983–1985	Gunter E. Weller	University of Alaska
1985–1992	Thomas P. Armstrong	University of Kansas
1992–1998	Eugene H. Levy	University of Arizona
1998–2004	Robert B. Schnabel	University of Colorado Boulder
2004–2005	Helen L. Reed	Arizona State University
2005–2007	M. Kay Jeppesen	Utah State University
2007–2011	Michael J. Drake	University of Arizona
2012–2019	Edward J. Weiler	University of Colorado Boulder

REGIONAL GROUP IX

1970	Frederick T. Wall	University of California, San Diego
1970–1972	James R. Arnold	University of California, San Diego
1972–1975	Robert L. Kovach	Stanford University
1975–1981	Frederick W. Crawford	Stanford University
1981–1987	George M. Homsy	Stanford University
1987–1993	Thomas B. McCord	University of Hawai'i at Manoa
1993–1996	Catherine Gautier–Downes	University of California, Santa Barbara
1996–2002	Darrell L. Judge	University of Southern California
2002–2008	B. Thomas Soifer	California Institute of Technology
2008–2014	Stephen M. Kahn	Stanford University
2014–2020	B. Thomas Soifer	California Institute of Technology

APPENDIX

At the second meeting of the USRA COI, three strands of At–large Trustees were established. In 2007 a fourth strand was added, to be occupied by individuals with financial expertise. The succession of these trustees is shown in the following tables.

AT-LARGE TRUSTEES

AT–LARGE TRUSTEES – STRAND 1

1970–1971	William W. Rubey	University of California, Los Angeles
1971–1977	Donald A. MacRae	University of Toronto
1977–1983	T. Stephen Cheston	Georgetown University
1983–1986	Michael C. Lesch	Northwestern University
1986–1992	Abraham Peled	International Business Machines Corporation
1992–1995	Abraham J. Callegari	Exxon Corporation
1995–2001	Ralph H. Jacobson	Major General, USAF, Retired
2001	Eberhardt Rechtin	Aerospace Corporation, Retired
2002–2011	Peter M. Banks	Institute for the Future
2010–2016	Jan A. Van Prooyen	Major General, USA, Retired
2016–2019	John A. Montgomery	Naval Research Laboratory, Retired

AT–LARGE TRUSTEES – STRAND 2

1970–1975	Wilmot N. Hess	National Oceanic and Atmospheric Administration
1975–1979	F. Curtis Michel	Rice University
1979–1984	Ursula B. Marvin	Harvard University/ Smithsonian Astrophysics Observatory
1984–1990	Richard J. O'Connell	Harvard University
1990–1993	James B. Odom	Applied Research Incorporated
1993–1999	Robert W. Hager	Boeing Corporation
1999–2005	Gerald D. Griffin	Director, NASA JSC, Retired
2005–2011	Ivette Falto–Heck	Lockheed Martin Corporation
2011–2017	James H. Crocker	Lockheed Martin Corporation
2017–2020	Natalie W. Crawford	RAND Corporation

AT-LARGE TRUSTEES (CONTINUED)

AT–LARGE TRUSTEES – STRAND 3

1970–1973	Frederick T. Wall	University of California, San Diego; American Chemical Society; Rice University
1973–1976	Joseph M. Reynolds	Louisiana State University
1976–1979	Samuel D. Conte	Purdue University
1979–1981	Richard S. Shevell	Stanford University
1981–1985	Ramon L. Espino	Exxon Corporation
1985–1987	William C. Norris	Control Data Corporation
1987–1991	Morley R. Kare	Monell Chemical Sensor Center
1991–1994	Bobby R. Alford	Baylor College of Medicine
1994–2000	Burton I. Edelson	George Washington University
2000–2006	M. Rhea Seddon	Vanderbilt University
2006–2009	Edward D. McCullogh	Boeing Corporation
2009–2015	David E. Frost	Vice Admiral, USN, Retired
2015–2021	William F. Ballhaus Jr.	Aerospace Corporation, Retired

AT–LARGE TRUSTEES – STRAND 4

2007–2013	M. Kay Jeppesen	Utah State University
2013–2019	James P. Johnson	Los Alamos National Laboratory, Retired

APPENDIX

The Chairs of the USRA Board of Trustees are elected by the board members.
The Chairs since 1969 are shown in the following table.

CHAIRS OF THE USRA BOARD OF TRUSTEES

1969–1973	Frederick T. Wall	University of California, San Diego; American Chemical Society; Rice University
1973–1975	Donald A. MacRae	University of Toronto
1975–1976	Joseph M. Reynolds	Louisiana State University
1976–1977	Frederick W. Crawford	Stanford University
1977–1978	A. Robert Kuhlthau	University of Virginia
1978–1979	William A. Cassidy	University of Pittsburgh
1979–1981	Thomas M. Donahue	University of Michigan
1981–1982	T. Stephen Cheston	Georgetown University
1982–1983	Ursula B. Marvin	Harvard University/ Smithsonian Astrophysics Observatory
1983–1984	Martin E. Glicksman	Rensselaer Polytechnic Institute
1984–1985	Ramon L. Espino	Exxon Corporation
1985–1986	C. William Gear	University of Illinois at Urbana–Champaign
1986–1987	George M. Homsy	Stanford University
1987–1988	Albert P. Sheppard	Georgia Institute of Technology
1988–1989	Thomas P. Armstrong	University of Kansas
1989–1990	Richard J. O'Connell	Harvard University
1990–1991	Simon Ostrach	Case Western Reserve University
1991–1992	Thomas P. Armstrong	University of Kansas
1992–1993	John H. Hoffman	University of Texas at Dallas
1993–1997	Robert A. Cassanova	Georgia Institute of Technology
1997–1999	Robert W. Hager	Boeing Corporation
1999–2001	John C. Kelly Jr.	North Carolina A&T State University
2001–2003	Robert L. Carovillano	Boston College
2003–2005	Robert B. Schnabel	University of Colorado Boulder
2005–2011	Peter M. Banks	Institute for the Future
2011–2015	Jan A. Van Prooyen	Major General, USA, Retired
2015–2017	James H. Crocker	Lockheed Martin Corporation
2017–2019	William F. Ballhaus Jr.	Aerospace Corporation, Retired

The Presidents of USRA are appointed by the Board of Trustees.
The Presidents since 1969 are shown in the following table.

PRESIDENTS OF USRA

1969–1976	A. Robert Kuhlthau
1976–1981	Alexander J. Dessler
1981–2000	Paul J. Coleman Jr.
2000–2006	David C. Black
2006–2014	Frederick A. Tarantino
2014	Donald Kniffen
2014–present	Jeffrey A. Isaacson

ABOUT THE AUTHOR

Dr. W. David Cummings was the first PhD to graduate from the Space Science Department of Rice University. He then joined the faculty of the Department of Planetary and Space Science at UCLA. Dr. Cummings later served as Head of the Physics Department at Grambling State University before becoming the Executive Director of the Universities Space Research Association (USRA), serving in this latter capacity for 31 years. He is currently Senior Advisor and Historian at USRA.

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