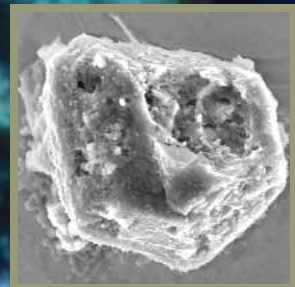
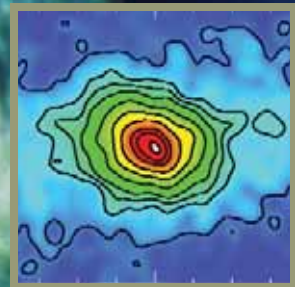
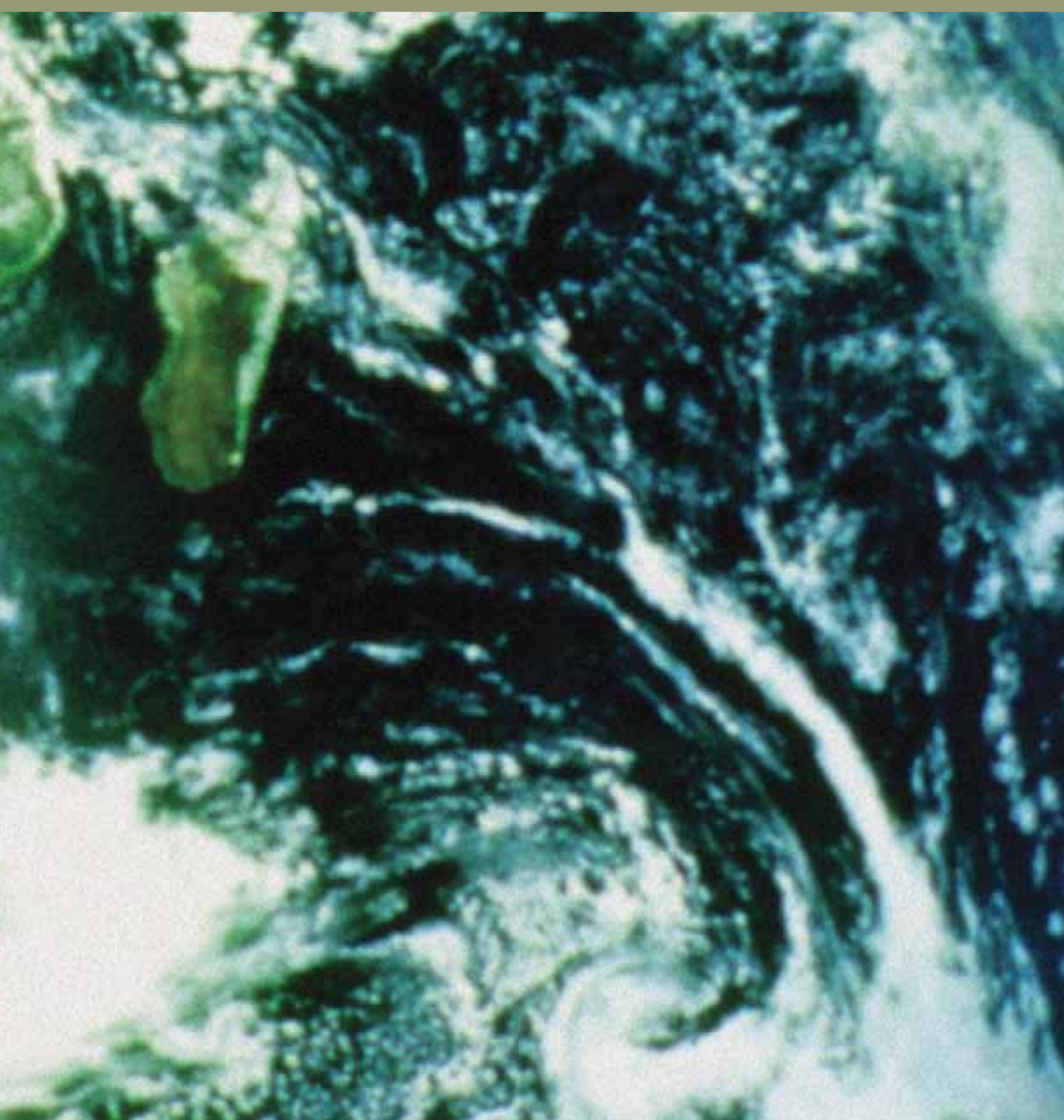


C A R N E G I E I N S T I T U T I O N  
*Department of Terrestrial Magnetism*



## About the Carnegie Institution of Washington

Andrew Carnegie founded the Carnegie Institution of Washington in 1902 as an organization for scientific discovery. Since then, Carnegie scientists have pioneered many fields. The institution is headquartered in Washington, D.C., and has six departments around the country devoted to research in plant biology, developmental biology, Earth and planetary sciences, astronomy, and global ecology.

Andrew Carnegie's intention was for the institution to be home to the exceptional person—an individual with imagination and dedication who worked at the cutting edge of a specialty. Some of the institution's exceptional individuals include Nobel laureate geneticists Barbara McClintock and Alfred Hershey, and Mount Wilson astronomer Edwin Hubble, for whom the Hubble Space Telescope is named.

Scientists at Carnegie today are free to investigate their specific areas of interest under the broad goals of an individual department. Researchers are given the support and equipment they need in a nurturing environment. This arrangement has produced unexpected benefits to society, among them hybrid corn and the proximity fuze.

The organization is an endowed, independent, nonprofit institution. Significant additional support comes from federal grants and private donations. A board of trustees, consisting of leaders in business, the sciences, education, and public service, oversees Carnegie's operations. Richard A. Meserve, president, presides over day-to-day administration. Each of the six departments is independently managed by a director, who is aided by support staff. In addition to the scientists on staff, there is a constantly changing roster of pre- and postdoctoral fellows and associates, as well as visiting investigators, at each facility.

Carnegie is also involved in education at the lower levels. In 1989 former president Maxine Singer launched First Light, a Saturday science school for children from the Washington, D.C., public schools. First Light encourages children to explore the world around them with the aid of a unique hands-on curriculum. The success of First Light led to CASE, the Carnegie Academy for Science Education, which is a training ground for elementary school teachers in the art of teaching science, mathematics, and technology.

ON THE COVER: Research at the department covers a wide range, from Earth science to astrophysics. At top right is a model of small-body formation in the asteroid belt. Second from top, an observer measures unusual magnetic disturbances in Alaska in 1907. Third from top, a mid-infrared image of the young star  $\beta$  Pictoris yields information on planet formation. Fourth from top, a tiny, two-micron presolar grain holds clues to the origin of the solar system. Carnegie scientists work in labs and in the field worldwide. At bottom, collaborators sit atop a broadband seismic station in the Azores.

*(Background image courtesy NASA.)*



# Contents

- 2 Department of Terrestrial Magnetism: A Brief History
- 3 Current Research
- 4 Postdoctoral and Predoctoral Programs
- 4 Facilities
- 6 Staff Scientists



Members of the Department of Terrestrial Magnetism staff in 2002 are shown on the steps of the Abelson Building. First row (from left): Jaime Sosa, Pedro Roa, Ambre Luguét, Pablo Esparza, Fouad Tera, Aki Roberge, Kathleen Flint, Brian Schleigh, George Wetherill. Second row: Janice Dunlap, Mary Horan, Daniela Power, Steven Desch, Timothy Mock, Petrus le Roux, Mark Behn, Peter Burkett, Richard Carlson, Derek Schutt, Mark Schmitz, David James, Louis Brown, Selwyn Sacks, Steven Shirey, Nelson McWhorter. Third row: Eugenio Rivera, Nader Haghighipour, Terry Stahl, Ben Pandit, Erik Hauri, Shaun Hardy, Michael Acierno, Myung Gyoon Lee, Alycia Weinberger, Mary Coder, Roy Scalco, Bill Key. Fourth row: Roy Dingus, Georg Bartels, Conel Alexander, Jay Bartlett, Gary Bors, Paul Butler, Kevin Burke, John Graham, Steven Hauck, Sean Solomon, Brooke Hunter, Vera Rubin.



# Department of Terrestrial Magnetism

## A Brief History

**T**wo years after the Carnegie Institution of Washington was formed in 1902, Louis Bauer, a scientist studying the Earth's magnetic field, was selected by the board of trustees to form the Department of Terrestrial Magnetism (DTM). Bauer was a man with big ambitions: he wanted to map the geomagnetic field of the entire Earth. Under his direction, "observers," as they were called, made worldwide expeditions to gather magnetic field data. They trekked through some of the remotest regions of the planet. The department also commissioned a ship, the *Carnegie*, fashioned primarily of nonmagnetic parts, to map the



*"The historic goal—to understand the physical Earth and its place in the universe—remains a compelling beacon."*

magnetic field at sea. By 1929, DTM researchers had collected volumes of data that were used to correct navigational charts and quantify the mysterious temporal variations in the geomagnetic field. The work was completed, and the department turned its attention to other questions.

In 1925 two DTM physicists, Gregory Breit and Merle Tuve, were already exploring new areas. They wanted to prove the existence of the ionosphere—the region of the upper atmosphere where the number of electrically charged particles, or ions, is large enough to affect the travel of radio waves. The collaborators directed pulsed radio waves into the atmosphere and, by observing the echoes, confirmed the existence of the ionosphere. The department managed a worldwide network of stations to monitor the condition of the ionosphere that allowed accurate prediction of the propagation of shortwave radio communications, an advance that was to become vitally important during World War II.

During the 1930s and 40s, studies in physics dominated research at the department, which was a world-class center for nuclear physics. DTM investigators made fundamental discoveries about atomic forces. Throughout World War II, department scientists—like scientists all over the country—became involved in the war effort. One project, the largest after the Manhattan Project and the MIT Radiation Laboratory, was directed by Tuve. Under his guidance, researchers engineered an invention called the proximity fuze into mass production. The device was a radio-controlled sensor installed in the nose of an artillery shell. It detected a radio-reflecting target and triggered a detonation when the shell was in close proximity to its mark.

After the war, DTM physicists began some of the earliest work in biophysics using radioactive tracers. Later came ventures in seismology, astronomy, theoretical astrophysics, planetary formation and evolution, and radioisotope geochronology. Science at the department has evolved to reflect the growing multidisciplinary nature of the Earth, planetary, and astronomical sciences. However, the historic goal—to understand the physical Earth and its place in the universe—remains a compelling beacon.

## \* Current Research

The multidisciplinary program at DTM is unhampered by the constraints typically found in university departments. Current research spans the disciplines of astronomy, astrophysics, geophysics, geochemistry, cosmochemistry, and planetary science. Department staff investigate their topics in a variety of ways that include field projects, astronomical and

spacecraft observations, and advanced laboratory analysis. They also develop and improve specialized instrumentation to accomplish their scientific goals.

Investigators at the department participate in a variety of collaborative efforts with other institutions around the world in addition to undertaking smaller projects tailored to individual interests. In one large collaboration, DTM, in conjunction with scientists from Carnegie's Geophysical Laboratory, is a lead member of the NASA Astrobiology Institute. The effort demands a diverse complement of researchers who are looking into the synthesis of organic materials and potential habitats for life beneath the Earth's land surface and seafloor, on other bodies in the solar system, and on extrasolar planets. As part of this program, Carnegie scientists are analyzing organic chemical synthesis in water-rock systems under varying conditions of temperature, pressure, and chemistry to mimic environments that may be encountered in terrestrial and extraterrestrial settings. In related work, Carnegie scientists are investigating the physical and chemical environments of circumstellar disks around young stars and the nature of early organic compounds in



Department staff work in the lab and in the field. Mass spectrometry laboratory manager Timothy Mock (bottom) works on the Plasma 54 inductively coupled plasma mass spectrometer. Seismic field technician Peter Burkett (top right), with collaborator Beat Rinderknecht (ETH, Zurich), is installing solar panels for a broadband seismic station on Graciosa, Azores. The instrumentation is part of a network to study the upper mantle structure beneath the Azores platform and hotspot.

At left, hunting the magnetic pole, an observer (probably L. A. Bauer) takes measurements of unusual magnetic disturbances at Treadwell Point, Alaska, 1907.

extraterrestrial materials, such as meteorites.

Geophysicists, geochemists, and seismologists in the department coordinate with other researchers internationally in the Kaapvaal Craton Project. This is a multidisciplinary, multi-institutional investigation into the formation and stabilization of cratons—the rootlike structures underlying the continents. The project is advancing our understanding of the deep structure and dynamics of the Earth. Some of these researchers are also studying other aspects of the Earth's interior to determine their connections to dynamic surface processes such as earthquakes and volcanoes. In addition, DTM staff are undertaking individual investigations to examine a number of fundamental problems in the fields of igneous geochemistry, geochronology, crustal evolution, seismology, volcano geophysics and geochemistry, and comparative planetary science.

Sean Solomon, director of the department, is the lead investigator of another large effort—a NASA mission that will teach us more about our solar system's innermost planet, Mercury. Understanding the unusual characteristics of Mercury, and the forces that have shaped it, is fundamental to understanding all of the terrestrial planets and their evolution. This mission, called MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging), is scheduled for launch in 2004 and will orbit Mercury for one Earth-year in 2009 after making two planetary flybys.

Astrophysicists in the department are leaders in the discovery of extrasolar planets, the study of their birthplaces, and the development of theories about their formation. A group co-led at DTM has found most of the approximately 100 currently known extrasolar planets in our galaxy using a technique called precision Doppler velocity. The method detects the subtle wobbles a star exhibits in response to the gravitational tug exerted by a large orbiting object. Other DTM scientists are using the characteristics of known planets and their environments to refine theories for how stars and planets form and evolve. DTM researchers actively use Carnegie's state-of-the-art telescope facilities at the Las Campanas Observatory in Chile to search for extrasolar planets and the disks from which they form and to study the large-scale motion of galaxies.

## ✧ Postdoctoral and Predoctoral Programs

The department offers a variety of postdoctoral fellowship and associate positions. Predoctoral and advanced undergraduate appointments are also available as opportunity determines. Fellows and associates can engage in a wide range of experiences that include designing and constructing specialized experimental devices; participating in seminars and symposia; and gathering and analyzing data. These pro-

jects are shaped to preserve maximum flexibility and to fit the scientific interests of both Staff Members and fellows.

Fellows at DTM are regarded as scientific colleagues, free to chart their individual research agendas. Every fellow has access to the full staff of DTM and the other departments of the Carnegie Institution, as well as to a group of nonresident collaborators and visiting investigators from all parts of the world. Cooperating institutions—universities, government agencies, and private organizations—provide further substantial resources for scholarship. There are also joint fellows of DTM and the Geophysical Laboratory in areas of mutual interest.

Predocctoral students may be accepted for training in an area of research leading to the preparation of a thesis for an advanced degree at a cooperating university. One or more of the DTM faculty usually serve as thesis advisors.

## ✧ Facilities

The department has well-equipped laboratories, offices, conference rooms, and workshops, all situated on a parklike nine-acre campus in northwest Washington, D.C., which it shares with Carnegie's Geophysical Laboratory. In addition to extensive commercially purchased instrumentation, DTM has a large number of unique instruments designed by the staff, including seismometers, strainmeters, mass spectrometers, and a large-radius ion probe. Geochemical facilities include three thermal ionization mass spectrometers, one of



which is a VG-354 multicollector; P54 and Axiom multicollector ICP mass spectrometers with multiple sample introduction systems including a Cetac LSX-200 laser system; a Cameca 6F ion probe; several clean wet chemistry laboratories for sample processing; and equipment for rock sample preparation and mineral separation.

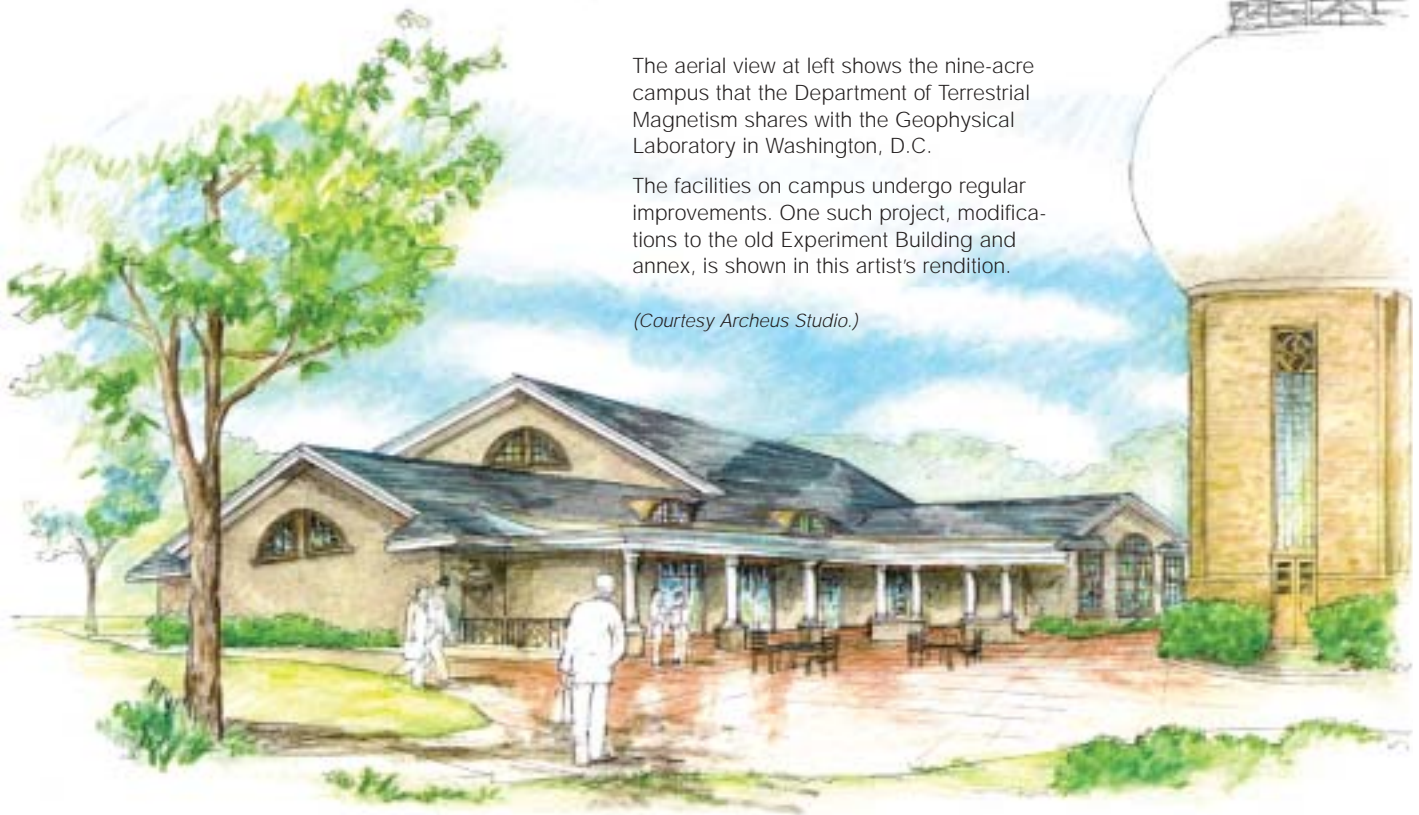
These instruments are used for a wide range of geochemical applications that require isotope ratio and trace element concentration measurements. Current research applications with the thermal and plasma ionization mass spectrometers include the analysis of lithium, boron, magnesium, strontium, silver, neodymium, hafnium, tungsten, osmium, lead, uranium, thorium, and radium isotopic compositions with isotope dilution concentration measurements of a number of elements. The Cameca 6F ion probe is used for a wide variety of applications where spatial resolution is critical. These applications range from trace element measurements on individual minerals and fluid/melt inclusions to isotopic measurements of carbon, oxygen, magnesium, silicon, sulfur, calcium, titanium, and iron in terrestrial, meteoritic, and extrasolar materials. Currently under construction is an addition to the ion probe that will use a 1-meter-radius magnet to provide additional dispersion, which will allow higher transmission at high mass resolution and the ability to use a 5-detector ion collector system.

Other facilities, including SEM (Scanning Electron Microscope), electron microprobe, and stable isotope mass spectrometers for sulfur, carbon, and oxygen, are available at

the Geophysical Laboratory. A thermal field-emission SEM, jointly operated by the two departments, permits sub-micrometer elemental mapping. DTM has well-equipped and well-staffed machine and electronics shops for the development and construction of new instruments.

DTM's modern computing facilities are used in all areas of training and research. Its local area network provides a distributed computing environment; all computers have high-speed access to the Internet. The platforms include approximately 60 Sun and Compaq workstations, Intel Pentium PCs, and Apple Macs. Theoretical calculations are carried out on the Carnegie Cluster of more than 40 Alpha CPUs and the Dynamics Cluster of 32 Intel Xeon CPUs. Equipment also exists for the production of computer-generated videos. High-quality color printers, high-resolution color scanners, and a large-format color printer are broadly available.

DTM and the Geophysical Laboratory have a joint library containing 40,000 volumes (including journals, books, and maps) as well as a variety of electronic databases related to the investigations conducted by the two departments. Library staff provide reference assistance to researchers, conduct online literature searches, and arrange interlibrary loans of material from several major research libraries in the area.



The aerial view at left shows the nine-acre campus that the Department of Terrestrial Magnetism shares with the Geophysical Laboratory in Washington, D.C.

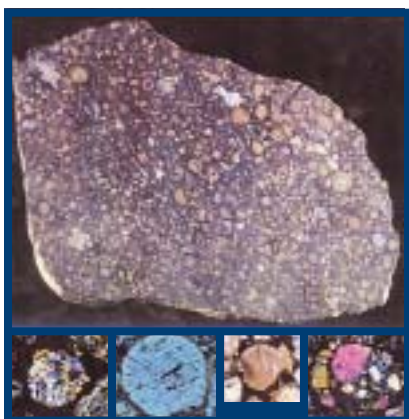
The facilities on campus undergo regular improvements. One such project, modifications to the old Experiment Building and annex, is shown in this artist's rendition.

*(Courtesy Archeus Studio.)*

## Conel M. O'D. Alexander



Among other affiliations, Conel Alexander is a member of the NASA Astrobiology Institute (NAI), an interdisciplinary research consortium made up of academic and nonprofit organizations and NASA centers. Astrobiology is the study of the origin, evolution, distribution, and future of life in the universe.



In his work on chondritic meteorites—the most primitive type of meteorites—Conel Alexander analyzes chondrules. Chondrules, the tiny, millimeter-size spheres that are the dominant constituent of chondritic meteorites, are seen here at varying magnifications.

Some 40 thousand tons of extraterrestrial material fall on Earth every year. This cosmic debris provides cosmochemist Conel Alexander with information about the formation of the solar system, the galaxy, and perhaps the origin of life.

Alexander studies meteorites to find the clues they provide to discern what went on before and during the formation of our solar system. Meteorites are fragments of asteroids—small bodies that originated between Mars and Jupiter and are likely the last remnants of objects that gave rise to the terrestrial planets. He is particularly interested in the analysis of chondrules, millimeter-size spherical objects that are the dominant constituent of the most primitive types of meteorites. Chondrules formed as molten droplets prior to the formation of the asteroids. Alexander develops techniques to measure precisely the isotopic species of the elements potassium, iron, magnesium, and oxygen in meteorite samples. Depending on the conditions, these elements may have evaporated and recondensed during chondrule formation. The isotopic compositions can indicate the extent of evaporation and recondensation, which can reveal the conditions present when chondrules formed.

Alexander's other major interest is presolar materials preserved in meteorites. These include the tiny grains that emerged around dying stars and interstellar organic matter. By deciphering these relics, he hopes to understand the processes of galaxy evolution, the formation of the elements inside stars via nucleosynthesis, and stellar evolution.

In recent years, evidence has mounted that meteorites may have played a role in the origin of life on Earth. Alexander studies this possibility as part of his work on the origin of interstellar organic matter in meteorites. Analysis has shown that meteorites contain more than 70 amino acids and three of the nucleic acids in RNA and DNA—the molecules that are essential to life. Many amino acids are chiral molecules, meaning that they come in two mirror-image forms—left-handed and right-handed. It is the left-handed forms that are almost exclusively present in living organisms and that are, in some instances, slightly more abundant in meteorites. With these objects constantly bombarding the Earth, it is possible that they ferried the precursors of life to this planet and that they played a role in the emergence of life elsewhere.

A small number of meteorites come from Mars. They have a wide age range and contain water-bearing minerals. By studying the hydrogen isotopes of this water, Alexander hopes to test ideas about what happened to the water that was originally on the planet.

#### SELECTED PUBLICATIONS

- Alexander, C. M. O'D. 2002. Application of MELTS to kinetic evaporation models of FeO-bearing silicate melts, *Meteoritics Planet. Sci.* 37, 245-256.
- Alexander, C. M. O'D., S. Taylor, J. S. Delaney, P. Ma, and G. F. Herzog. 2002. Mass-dependent fractionation of Mg, Si, and Fe isotopes in five stony cosmic spherules, *Geochim. Cosmochim. Acta* 66, 173-183.
- Grossman, J. N., C. M. O'D. Alexander, J. Wang, and A. J. Brearley. 2002. Zoned chondrules in Semarkona: evidence for high- and low-temperature processing, *Meteoritics Planet. Sci.* 37, 49-73.
- Alexander, C. M. O'D., A. P. Boss, and R. W. Carlson. 2001. The early evolution of the inner solar system: a meteoritic perspective, *Science* 293, 64-68.
- Krot, A. N., A. Meibom, S. S. Russell, C. M. O'D. Alexander, T. E. Jeffries, and K. Keil. 2001. A new astrophysical setting for chondrule formation, *Science* 291, 1776-1779.

## Alan Boss



Among his many affiliations, Alan Boss was selected to join the Science Working Group of NASA's Kepler mission—a space-borne telescope designed to search for habitable planets around nearby stars, scheduled for launch in 2006. Boss is also a member of the NASA Independent Review Team for the Navigator Program, which is charged with overseeing all NASA missions leading to the detection and characterization of habitable Earths. He is a fellow of the American Academy of Arts and Sciences, the American Geophysical Union, the American Association for the Advancement of Science, and the Meteoritical Society.



This image shows the equatorial density—after 373 years—for a protoplanetary disk with a mass 10% that of the Sun. The formation of a multiple-Jupiter mass clump can be seen as a tiny white dot at 12 o'clock (not to scale). The region has a radius of 20 AU. The surface density in this relatively low-mass disk is comparable to that required for gas giant planet formation by the core accretion mechanism.

In the past few years, some 100 gas giant planets have been detected orbiting nearby stars. Other objects with planet-size masses also have been discovered hovering alone in space. Many of these new finds have defied what we thought we knew about planetary and stellar formation. All this has kept astrophysicist Alan Boss hard at work refining his theories about how these objects came to be.

There are two main models to explain how gas giant planets formed—core accretion and disk instability. The most widely accepted is the core accretion model; but it is a slow process requiring millions of years. In this theory, collisions between small bodies of ice and rock form a massive, solid planetary core. Later, the solid core gains a gaseous atmosphere from the nebular disk, and the planet grows to its final size. Under this scenario, however, the time needed for the core to accrete is longer than the lifetime of the nebular gas from which our solar system formed.

To deal with this problem and others, Boss developed the disk instability model. It is a much faster process, requiring only about a thousand years for a protoplanet to form. Boss has devised several three-dimensional models to study what happens to protoplanetary disks under this scenario. All of the models account for the effects of gravity, radiative transfer, and thermodynamics. He shows that gravitational instabilities in the nebular disk cause the gas and dust to suddenly break up into clumps. Some of the clumps contract into a core and quickly grow into giant gaseous planets. Interestingly, these instabilities can occur in a marginally unstable disk with a mass as low as 10% of the Sun's mass inside a radius of 20 astronomical units (1 AU is the distance between Earth and the Sun)—a size similar to the mass of the disks thought to be needed to make planets by core accretion.

To address the debate about what the planetary-mass free-floating objects are, Boss recently considered the effects of magnetic fields in his formation calculations of low-mass stars called brown dwarfs. He found that magnetic-field tension stops a molecular cloud from collapsing into a single prestellar object at the cloud's center. This outcome results in smaller-mass objects that can then accrete into several stars. He also found that a close multiple protostar system is unstable to orbital decay, which can cause single objects to be ejected and float freely in space. He suggests that these objects be called sub-brown dwarfs.

## SELECTED PUBLICATIONS

- Boss, A. P. 2003. Formation of planetary-mass brown dwarfs in magnetic molecular clouds, in *Proceedings of International Astronomical Union Symposium 211: Brown Dwarfs*, E. L. Martin, ed., San Francisco, Astronomical Society of the Pacific, pp. 23-26.
- Boss, A. P. 2002. The formation of gas and ice giant planets, *Earth Planet. Sci. Lett.* **202**, 513-523.
- Boss, A. P. 2002. Stellar metallicity and the formation of extrasolar gas giant planets, *Astrophys. J. Lett.*, **567**, L149-L153.
- Boss, A. P. 2002. Collapse and fragmentation of molecular cloud cores VII: magnetic fields and multiple protostar formation, *Astrophys. J.* **568**, 743-753.
- Boss, A. P. 2002. Gas giant protoplanet formation: disk instability models with thermodynamics and radiative transfer, *Astrophys. J.* **563**, 367-373.
- Boss, A. P., G. W. Wetherill, and N. Haghighipour. 2002. Rapid formation of ice giant planets, *Icarus* **156**, 291-295.



Staff Member Emeritus Louis Brown is a fellow of the American Physical Society. In 1964 he received the Amerbach Prize from the University of Basel, Switzerland.

## Louis Brown



**L**ouis Brown has designed and built scientific instrumentation throughout his career. His research has spanned the spectrum of nuclear physics, optical and X-ray spectroscopy, and accelerator mass spectrometry. He is currently building a mass analyzer to be used to study the isotopic composition of meteorite components. The device will enhance the capability of the ion microprobe, which bombards samples with high-energy ions to evaporate atoms that are then analyzed by the mass spectrometer. This analysis allows scientists to determine the abundances of different isotopes. The new system is a significant improvement over the existing probe; it uses more of the beam and replaces a single detector with five detectors. These changes will greatly increase the speed of analysis, an important advancement because the samples are small and quickly used up.

Brown's research at the department began with the Carnegie Van de Graaff accelerator, a very large and, at the time, abandoned instrument capable of holding the large and heavy source of polarized protons. A collaboration with the University of Basel in Switzerland used the polarized beam to study a number of nuclear interactions. Beams of heavy ions were also produced to determine the lifetimes of excited atomic states and the X-ray spectra resulting from their collisions. With members of the Tandem Laboratory at the University of Pennsylvania, Brown helped develop and use the method of accelerator mass spectrometry. This technique allows the number of atoms of a given cosmogenic isotope in natural samples to be determined—as few as thousands of atoms per gram. This research demonstrated the presence of the cosmogenic isotope  $^{10}\text{Be}$  in the magmas of island-arc volcanoes, indicating that the magma contained deep-ocean sediment that had been carried into the mantle by the subduction of tectonic plates.

During his first six years of retirement, Brown studied the history of radar and wrote the book *A Radar History of World War II*. He has become the de facto historian of the department and wrote its centennial history.



Research in cosmochemistry requires determining the atomic species, or isotopes, of minute quantities of material found in meteorites. The electrostatic analyzer, which Louis Brown has worked on, is being tested for use with the ion microprobe.

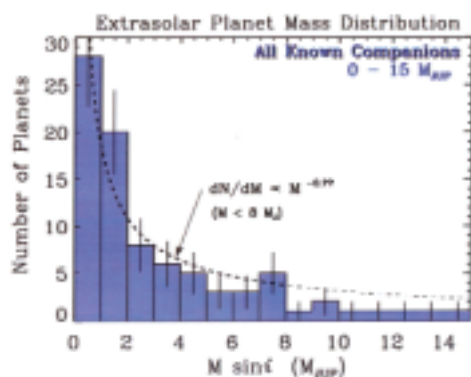
### SELECTED PUBLICATIONS

- Brown, L., J. Klein, R. Middleton, I. S. Sacks, and F. Tera. 1982.  $^{10}\text{Be}$  in island-arc volcanoes and implications for subduction, *Nature* 299, 718-720.
- Brown, L., G. E. Assousa, N. Thonnard, H. A. Van Rinsvelt, and C. K. Kumar. 1975. Characteristic and continuum x-rays with potassium ions of a few MeV, *Phys. Rev. A* 12, 425-433.
- Arnold, L. G., R. G. Seyler, L. Brown, T. I. Bonner, and E. Steiner. 1974. 2-threshold state in  $^9\text{Be}$ , *Phys. Rev. Lett.* 32, 895-898.
- Assousa, G. E., L. Brown, and W. K. Ford, Jr. 1970. Radiative lifetime measurements of excited levels in neon I and argon II, *J. Optic. Soc. Amer.* 60, 1311-1314.
- Baumgartner, E., L. Brown, P. Huber, H. Rudin, and H. R. Striebel. 1960. Source of polarized deuterons and the verification of alignment with the  $\text{T(d,n)}\text{He}^4$  reaction, *Phys. Rev. Lett.* 5, 154-156.

## R. Paul Butler



Paul Butler, collaborator Geoffrey Marcy of UC-Berkeley, and their team are the foremost extrasolar planet hunters in the world. In 1997 Butler and Marcy were awarded the Bioastronomy Medal of the International Astronomical Union. In 2001 they received the Henry Draper Medal from the National Academy of Sciences, and in 2002 they received the Carl Sagan Memorial Award given by the American Astronomical Society and the Planetary Society. Butler has also been acknowledged extensively in the popular press and by other organizations. He was an invited speaker at the World Economic Forum in Davos, Switzerland, in 2001, and in 1997 was cited as one of *Newsweek's* 100 Americans for the Next Century.



A histogram of extrasolar planets by mass, compiled by Paul Butler and his collaborators, illustrates important general aspects of planetary formational processes. The horizontal axis is not true planet mass, but rather the product of mass (in units of Jupiter masses) and the sine of the inclination ( $i$ ) of the planetary orbit to the Earth-star line. For only one extrasolar planet (HD 209458 b) is the inclination known independently (from transit observations). The distribution follows an inverse power law below 8 Jupiter masses.

While the planets in our solar system are astonishingly diverse, their orbital motion is extremely orderly. All of them move around the Sun in approximately the same orbital plane, in the same direction, and primarily in circular orbits. Since 1995, Paul Butler and his team have discovered over half of the planets found orbiting nearby stars. Unlike the situation in our own solar system, most of these extrasolar planets have elongated, eccentric orbits. However, some are very close to their parent stars in circular orbits with periods of as little as three days. Because the detection technique is limited to large planets, most of these newly found objects have masses on a par with those of Jupiter or Saturn.

Butler and colleagues have developed the most precise method to date for finding these remote bodies: the precision Doppler velocity technique. The system works by detecting, via the Doppler effect, the wobble of a star caused by the gravitational attraction of a massive orbiting object. The information also allows the team to infer the planet's mass, its orbital period, and the size of the orbit.

After further refinements to their method, in 2002 Butler and team announced the smallest planetary find yet—one with a mass just 40 times that of Earth. They also announced the discovery of the first true analogue to our own solar system—three planets in mostly circular orbits around the star 55 Cancri. The outermost planet in the system, at between 3.5 and 5 times Jupiter's mass and at a distance of 5.9 astronomical units (AU) from its star, is analogous to Jupiter, which is 5.2 AU from our Sun (1 astronomical unit is the distance from the Earth to the Sun).

Butler's work is part of a multiyear project to carry out the first reconnaissance of all 2,000 nearby Sun-like stars within 150 light-years of the solar system (1 light-year is about 9.4 trillion kilometers). His team is currently monitoring about 1,700 stars, including 1,000 Northern Hemisphere stars with the Keck telescope in Hawaii and the UCO Lick Observatory telescope in California, and 300 Southern Hemisphere stars with the Anglo-Australian telescope in New South Wales, Australia. The remaining Southern Hemisphere stars are being surveyed with Carnegie's new Magellan telescopes in Chile. By 2010 the researchers hope to have completed their planetary census. They will then be able to tell what percentage of stars have planets, how many systems are similar to our own, and the different characteristics these systems exhibit. The ultimate goal is to find planets that resemble the Earth.

### SELECTED PUBLICATIONS

- Butler, R. P., G. W. Marcy, S. S. Vogt, D. A. Fischer, G. W. Henry, G. Laughlin, and J. T. Wright. 2003. Seven new Keck planets orbiting G & K dwarfs, *Astrophys. J.* 582, 455-466.
- Tinney, C. G., R. P. Butler, G. W. Marcy, H. R. A. Jones, A. J. Penny, C. McCarthy, B. D. Carter, and J. Bond. 2003. Four new planets orbiting somewhat metal-enriched stars, *Astrophys. J.* 587, 423-428.
- Butler, R. P., G. W. Marcy, S. S. Vogt, C. G. Tinney, H. R. A. Jones, C. McCarthy, A. J. Penny, K. Apps, and B. D. Carter. 2002. On the double planet system around HD 83443, *Astrophys. J.* 578, 565-572.
- Jones, H. R. A., R. P. Butler, G. W. Marcy, C. G. Tinney, A. J. Penny, C. McCarthy, and B. D. Carter. 2002. Extrasolar planets around HD 196050, HD 216437, and HD 160691, *Mon. Not. Roy. Astron. Soc.* 337, 1170-1178.
- Marcy, G. W., R. P. Butler, D. A. Fischer, G. Laughlin, S. S. Vogt, G. W. Henry, and D. Pourbaix. 2002. A planet at 5 AU around 55 Cancri, *Astrophys. J.* 581, 1375-1388.

## Richard Carlson



Richard Carlson is a fellow of the American Geophysical Union and the Geochemical Society. He is also Principal Investigator on the Kaapvaal Craton Project, funded by the National Science Foundation. This large-scale multidisciplinary project combines geological, geochemical, and geophysical studies of a portion of Earth's oldest crust found in southern Africa. The project involves colleagues from the Department of Terrestrial Magnetism, the Geophysical Laboratory, and the Massachusetts Institute of Technology in conjunction with university and industry collaborators from South Africa, Zimbabwe, and Botswana.



Fieldwork is integral to Richard Carlson's research. Here he uses a specially adapted chain saw to drill samples from a 3.4-billion-year-old lava flow in South Africa.

**R**ocks reveal Earth's history, including the origin of mountains, the dynamics of the deep mantle and crust, and the formation of cratons—ancient rootlike structures that are the oldest and most stable parts of the continents. Geochemist Richard Carlson studies these topics and more in a variety of ways, but especially by analyzing the different atomic species, or isotopes, of elements found in rocks that he collects from around the world.

Natural radioactive isotopes decay at a predictable rate. Using radiometric dating techniques, scientists measure the products of this decay in ancient rocks to determine their absolute ages. This high-precision analysis, coupled with chemical investigations, helps Carlson explore the geochemical evolution of the Earth. He also applies these techniques to the study of meteorites, which provides information on the history of the materials from which our planet formed.

To understand how the oldest continental crust formed and stabilized, Carlson leads an investigation into the Kaapvaal Craton in southern Africa. Through radiometric analyses of mantle xenoliths—fragments of mantle brought to the surface by volcanic eruptions from as deep as 220 km—and from seismic imaging, the scientists found that the geological evolution of the crust of the craton is strongly tied to that of the underlying mantle to depths of at least 180 to 200 km. The analyses indicate that thick mantle roots date to the Archean era (3.9 to 2.5 billion years ago), suggesting that the Kaapvaal Craton has not changed significantly over the last 3 billion years. In work on the northern Canada cratons, Carlson found a similar long-term stability; however, he found that mantle portions of cratons in China and Wyoming have been lost through collisions between continental plates.

In his research on meteorites, Carlson tests theories of solar system formation. With colleague Erik Hauri, he has looked at the silver isotopic composition of meteorites to learn about the solar system's early chronology. Palladium has a comparatively short-lived isotope ( $^{107}\text{Pd}$ ) that decays to a silver isotope ( $^{107}\text{Ag}$ ), with a half-life of 6.5 million years. The researchers developed a new means for high-precision isotope ratio analysis, which provides ages precise to within a million years or less on meteorites that are 4.56 billion years old. This advance means that the Pd-Ag dating technique can now be used on a broader range of meteorites, as well as on terrestrial rocks to determine when Earth's iron-metal core segregated to the center of the planet.

#### SELECTED PUBLICATIONS

- Carlson, R. W., ed. 2003. *Treatise on Geochemistry, Vol. 2: The Mantle and Core*, Elsevier Science.
- Carlson, R. W., and E. H. Hauri. 2001. Extending the  $^{107}\text{Pd}$ - $^{107}\text{Ag}$  chronometer to low Pd/Ag meteorites with the MC-ICPMS, *Geochim. Cosmochim. Acta* 65, 1839-1848.
- Carlson, R. W., F. R. Boyd, S. B. Shirey, P. E. Janney, T. L. Grove, S. A. Bowring, M. D. Schmitz, J. C. Dann, D. R. Bell, J. J. Gurney, S. H. Richardson, M. Tredoux, A. H. Menzies, D. G. Pearson, R. J. Hart, A. H. Wilson, and D. Moser. 2000. Continental growth, preservation, and modification in southern Africa, *GSA Today* 10, 1-7.
- Carlson, R. W., and G. W. Lugmair. 2000. Timescales of planetesimal formation and differentiation based on extinct and extant radioisotopes, in *Origin of the Earth and Moon*, K. Righter and R. M. Canup, eds., Tucson, University of Arizona Press, pp. 25-44.
- Carlson, R. W., D. G. Pearson, F. R. Boyd, S. B. Shirey, G. Irvine, A. H. Menzies, and J. J. Gurney. 1999. Re-Os systematics of lithospheric peridotites: implications for lithosphere formation and preservation, *Proc. 7th Int. Kimberlite Conf.*, 99-108.

# John Chambers



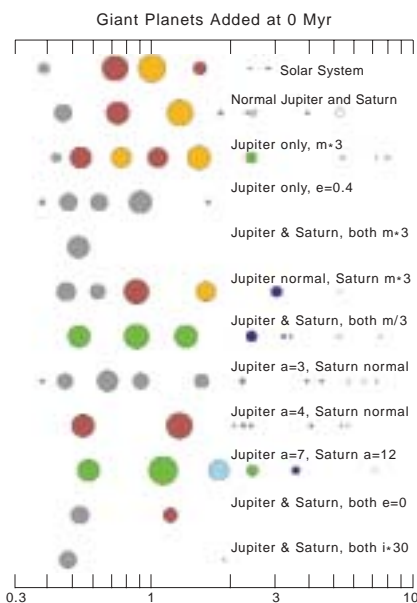
John Chambers is one of the world leaders in the dynamics of terrestrial planet formation. Prior to his Carnegie appointment, he was a research scientist at the Search for Extraterrestrial Intelligence Institute in Mountain View, California.

With the proliferation of extrasolar planet discoveries, the race is on to find habitable worlds akin to the Earth. At present, however, extrasolar planets less massive than Saturn cannot be reliably detected. Astrophysicist John Chambers models the dynamics of these newly found giant planetary systems to understand their formation history and to determine the best way to predict the existence and frequency of smaller Earth-like worlds. As part of this research he explores the basic physical, chemical, and dynamical aspects that led to the formation of our own solar system—an event that is still poorly understood. His ultimate goal is to determine if similar processes could be at work in the newly discovered planetary systems, which could then help predict smaller, extrasolar bodies that might harbor life.

It is generally believed that the Earth and other terrestrial planets formed by the accretion of many rocky planetesimals. Water and other life-giving volatile materials are thought to have originally accreted in planetesimals located beyond 1 astronomical unit (AU) from the Sun in the early solar nebula (1 AU = distance from the Earth to the Sun). These small bodies were subsequently driven toward the inner solar system by the gravitational perturbations from Jupiter and Saturn. Chambers's models consider both observed and hypothetical planetary systems. He and colleagues recently calculated that the evolution of the terrestrial planets and the asteroid belt was heavily dependent on the orbital characteristics of the giant planets. He further demonstrated that the amount of volatiles present was affected by the timing of giant-planet formation.

Based on evidence of the rate of impact cratering on the Moon, Chambers recently proposed a bold hypothesis about our early solar system: five planets instead of four originally accreted inside the asteroid belt. He believes that the missing fifth planet was in an unstable orbit between Mars and the asteroid belt and was ejected by 600 million years of gravitational perturbations induced by the other planets. He proposes that the missing planet's exodus disrupted asteroid fields, creating an increase in lunar impacts.

Chambers devises innovative numerical simulations in his work. Some of his calculations are based on a scheme used by Carnegie's George Wetherill, who pioneered studies in planetary accretion. In 1999 Chambers combined two integration algorithms to develop a new mathematical technique he named *Mercury*. This technique is able to simulate planetary and asteroid accretion faster and more accurately than previous methods and is now used by different research groups worldwide.



These simulations show types of terrestrial planets that form in giant-planet systems. Only terrestrial planets are indicated. Earth-like planets can form at different distances in different systems. The colors indicate the fraction of the planet's mass consisting of water, going from gray (no water), through red, yellow, green, light blue, dark blue, and white. Each progressive color implies 5 times more water. Earth (top line) is yellow, with relatively little water. (The scale is astronomical units—the Earth-Sun distance.)

## SELECTED PUBLICATIONS

- Chambers, J. E., and P. Cassen. 2002. The effects of nebula surface density profile and giant-planet eccentricities on planetary accretion in the inner solar system, *Meteoritics Plan. Sci.* 37, 1523-1540.
- Chambers, J. E., E. V. Quintana, M. J. Duncan, and J. J. Lissauer. 2002. Symplectic integrator algorithms for modeling planetary accretion in binary star systems, *Astron. J.* 123, 2884-2894.
- Laughlin, G., and J. E. Chambers. 2002. Extrasolar trojans: the viability and detectability of planets in the 1:1 resonance, *Astron. J.* 124, 592-600.
- Laughlin, G., J. Chambers, and D. Fischer. 2002. A dynamical analysis of the 47 Ursae Majoris planetary system, *Astron. J.* 579, 455-467.
- Quintana, E. V., J. J. Lissauer, J. E. Chambers, and M. J. Duncan. 2002. Terrestrial planet formation in the Alpha Centauri system, *Astrophys. J.* 576, 982-996.

## John A. Graham



John Graham has been active in a variety of astronomical societies over the years, among them the American Astronomical Society, where he was vice president between 1984 and 1986, and the Astronomical Society of the Pacific, where he chaired the editorial board from 1988 to 1991. Concurrent with his work at Carnegie, he served as a program director for the Division of Astronomical Sciences at the National Science Foundation from 2000 to 2001.

The nearby galaxy NGC 5128 is one of the most peculiar in the sky. It is among the brightest emitters of radio waves and, for this reason, is also known as Centaurus A (Cen A). John Graham, Staff Member Emeritus, has discovered groups of young, blue stars within the extended areas of the galaxy's radio emission. By studying these stars, which originated in an unusual environment, he can gain a deeper insight into the whole process of star formation.

The entire Cen A structure stretches over several degrees in the sky. It is believed that the radio emission is powered by particle jets, which stream at relativistic velocities from the galaxy's core. If the radio jet happens to hit a stray cloud of dust and gas, material may be compressed to the extent that gravitational collapse of the cloud is initiated and loose chains of young, luminous blue stars are produced. The brightness and colors of the blue stars can be used to estimate their ages and predict their destinies. Part of the cloud may be swept up by the jet and, energized by the impact, can be seen as a long stream of faint filaments.

In our Milky Way galaxy, star formation is believed to be triggered by shocks generated during supernova outbursts—the spectacular explosions that end a star's life. However, in these cases the supernova, its remnant, and the attendant shocks have long disappeared by the time the new stars manifest themselves about a million years later. In Cen A, in contrast, researchers can see both the triggering mechanism and the consequent star formation at the same time because of the long life of the radio jet.

Graham and summer intern Caleb Fassett used images taken with a CCD detector on the du Pont 2.5-meter telescope at Carnegie's Las Campanas Observatory in this research. Different glass filters permit color information to be obtained. A blue image, for example, highlights the main concentrations of blue stars in Cen A. The brightest blue stars in the loose groups are close to magnitude 20 and appear to be quite normal and similar to the brightest stars in our neighboring galaxy, the Large Magellanic Cloud. Interpolation of theoretical stellar models leads to an estimation of ages for these stars. A significant age range emerges, extending from less than a million years to more than 15 million years, showing that, in this instance, star formation is a continuing process.



The radio galaxy Centaurus A is shown with contours of the inner radio structure at 1407 MHz. The outer radio lobes extend beyond the image frame. The direction of the radio jet is indicated by the orientation of the inner radio lobes. The outer boundary of a neighboring cloud of dust and gas is shown as a single broad white contour. The square box shows the location of a region where shock-triggered star formation is observed.

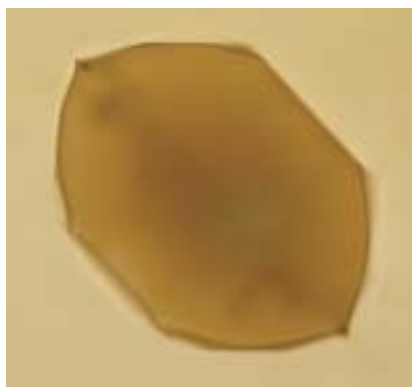
### SELECTED PUBLICATIONS

- Graham, J. A., and C. I. Fassett. 2002. Star formation associated with the X-ray jet in Centaurus A, *Astrophys. J.* 575, 712-720.
- Fassett, C. I., and J. A. Graham. 2000. Age, evolution, and dispersion of the loose groups of blue stars in the northeast radio lobe of Centaurus A, *Astrophys. J.* 538, 594-607.
- Graham, J. A. 1998. Shocked gas and star formation in the Centaurus A radio galaxy, *Astrophys. J.* 502, 245-252.

## Erik Hauri



In 2000 Erik Hauri received the F. G. Houtermans Medal from the European Association of Geochemistry for his outstanding contributions to geochemistry as a young researcher. That same year he was also awarded the James B. Macelwane Medal by the American Geophysical Union.



Erik Hauri studies melt inclusions (tiny bits of melt trapped in crystals) with the ion microprobe to determine the origins of volatile elements in the Earth's interior. This melt inclusion is from mid-ocean-ridge magma from the Siqueiros Fracture Zone, Pacific Ocean.

(Photo courtesy Alberto Saal, Brown University.)

**M**aterial in the atmosphere, the oceans, and the interior of the Earth circulates as a result of convection—the fluid motion that is driven by temperature variations and gravity. Geochemist Erik Hauri studies the movement of matter in planetary interiors and the origin and role of water in volcanic systems on Earth and the other terrestrial planets. Analysis of different atomic species, or isotopes, combined with numerical modeling and seismic imaging techniques are revealing what goes on inside the rocky planets and the timing of processes that occurred during planetary evolution. Hauri uses high-precision, highly sensitive mass spectrometry and other methods to analyze the composition of magma samples from Earth and meteorites and determine their implication for the composition and evolution of solar system bodies. He also directs the Carnegie-National Science Foundation National Ion Microprobe Facility—a resource for scientists from around the world to make in situ geochemical measurements at the micron scale.

Plate tectonics powers the convective process in Earth's interior, and the presence of liquid water at the surface is thought to be a primary factor in keeping this system active. By investigating magmas, Hauri's analyses have revealed that water plays a significant role in magma generation and differentiation in a variety of planetary environments. His work also sheds light on the primordial conditions under which the Earth formed. When the Earth was accreting, it became a sea of molten rock. The interior became partly depleted in the volatile elements—hydrogen, carbon, nitrogen, and sulfur—a loss that continues today through the eruption and outgassing from active volcanoes.

Venus has outgassed water, but atmospheric water has been broken down by solar ultraviolet radiation and the hydrogen lost to space. Water on Mars is believed to be partly frozen as ice and trapped in the crust. The lack of active plate tectonics on the other terrestrial planets and other factors have led scientists to believe that water from the Earth's surface is carried into the interior by plate subduction—the process in which the edge of one plate descends below another—and serves as the lubricant that facilitates continued plate motions. Water-rich explosive volcanism occurring at subduction zones confirms that water is carried down with the descending plate. But two major questions about the water budget at subduction zones remain unanswered: How much of the water that goes down into subduction zones comes back up at volcanic eruptions, and how much water is left in the subducting plate? Hauri is currently exploring these and related questions.

## SELECTED PUBLICATIONS

- Hauri, E. H. 2002. Osmium isotopes and mantle convection, *Phil. Trans. Roy. Soc. London Ser. A* 360, 2371-2382.
- Hauri, E. H. 2002. SIMS investigations of volatiles in silicate glasses 2: abundances and isotopes in Hawaiian melt inclusions, *Chem. Geol.* 183, 115-141.
- Saal, A., E. H. Hauri, C. H. Langmuir, and M. Perfit. 2002. Vapor undersaturation in primitive mid-ocean ridge basalt and the volatile content of the Earth's upper mantle, *Nature* 419, 451-455.
- Van Keken, P. E., E. H. Hauri, and C. J. Ballentine. 2002. Mantle mixing: generation, preservation, and destruction of chemical heterogeneity, *Annu. Rev. Earth Planet. Sci.* 30, 493-525.
- Hauri, E. H. 1996. Major element variability in the Hawaiian mantle plume, *Nature* 382, 415-419.

## David James

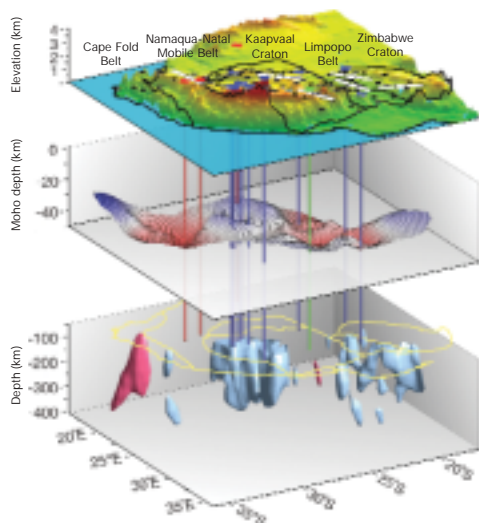


David James is a member of the American Geophysical Union (AGU), the Seismological Society of America (SSA), and the Society of Exploration Geophysicists and a fellow of the Royal Astronomical Society. He is also chairman of the PASSCAL Standing Committee and a distinguished IRIS/SSA Lecturer. He was also an editor for the AGU, and a member of the Advisory Committee for Earth Sciences to the National Science Foundation.

**M**ultidisciplinary research has been a mainstay at the Department of Terrestrial Magnetism (DTM) for decades. In this tradition, geophysicist David James uses both geophysics and geochemistry to study the structure, formation, and evolution of the continents. Much of his early work was dedicated to the study of subduction zones, where the tectonic plates collide to form mountain ranges, earthquakes, and volcanoes. In this work James used both geophysics and geochemistry to investigate how subduction processes created new crust and modified existing crust along the active Andean margin of South America—the modern analogue to the formation of old mountain belts such as the Appalachians. He produced the first three-dimensional seismic image of crustal structure beneath the central Andes and, in the early 1970s, published the first comprehensive plate tectonic model for the evolution of the area that synthesized seismic, gravitational, geochemical, and geological data. As part of his Andean research, James also devoted more than a decade to isotopic and trace element studies, where he helped pioneer the use of stable oxygen isotopes combined with radiogenic isotopes to understand the origin of subduction zone magmas.

James was foremost among those who advocated harnessing revolutionary digital and microelectronics technology to design and build a powerful new class of portable broadband seismometer systems. He was a leader in promoting the development of portable broadband array instrumentation and methodology that DTM and others now use worldwide to make 3-D images of the Earth's crust and deep interior. As part of his portable broadband seismic studies, James was a principal organizer of the Southern Africa Seismic Experiment, the largest of its kind ever undertaken and a centerpiece of the multidisciplinary Kaapvaal Craton Project, which addresses how cratons—the earliest continental masses on Earth—formed and evolved. James published 3-D images of the crust-mantle boundary beneath the cratons and their deep mantle “roots,” showing that the Archean cratons have a unique signature compared with continents that formed later in geologic time.

James continues to investigate the origin of the continental lithosphere and how processes of continental formation and growth have changed over time. He is currently planning a major experiment with DTM colleague Richard Carlson and others to determine how a large and entirely new block of continental lithosphere was created in central and eastern Oregon over the past 20 million years.



Measurements from the Kaapvaal Craton area help determine the evolution of the region. On top, black circles show broadband seismic stations. White circles with white bars show the direction of fast mantle shear-wave propagation. Black lines are geological province boundaries; and the filled diamonds denote major kimberlite localities keyed by Re/Os model ages of mantle xenoliths (blue, > 2.5 Byr; green, 2-2.5 Byr; red, < 2 Byr). The middle panel is the base of the continental crust; blue denotes thin crust, red thick crust. At bottom are P-wave anomalies in the upper mantle. Anomalies in blue outline the deep mantle root of the craton.

## SELECTED PUBLICATIONS

- Assumpção, M., D. E. James, and J. A. Snoke. 2002. Crustal thicknesses in SE Brazilian shield by receiver function analysis: implications for isostatic compensation, *J. Geophys. Res.* 107 (no. B1), 10.1029/2001JB000422.
- James, D. E., and M. J. Fouch. 2002. Formation and evolution of Archean cratons: insights from southern Africa, in *The Early Earth: Physical, Chemical, and Biological Development* (Special Publication no. 199), C. M. R. Fowler, C. J. Ebinger, and C. J. Hawkesworth, eds., London, Geological Society, pp. 1-26.
- Niu, F., and D. E. James. 2002. Fine structure of the lowermost crust beneath the Kaapvaal craton and its implications for crustal formation and evolution, *Earth Planet. Sci. Lett.* 200, 121-130.
- James, D. E., M. J. Fouch, J. C. VanDecar, S. van der Lee, and Kaapvaal Seismic Group. 2001. Tectospheric structure beneath southern Africa, *Geophys. Res. Lett.* 28, 2485-2488.
- James, D. E., and I. S. Sacks. 1999. Cenozoic formation of the central Andes: a geophysical perspective, in *Geology and Ore Deposits of the Central Andes* (Special Publication no. 7), B. J. Skinner, ed., Littleton, Society of Economic Geologists, pp. 1-25.

## Alan Linde



In 2002 Alan Linde was elected a fellow of the American Geophysical Union. Over the years he has traveled to seismically active areas across the globe to install strainmeters—devices that detect small, long-term crustal movements—and other instrumentation. He and colleagues have deployed instruments in Iceland, in Peru, in China, along the San Andreas Fault in California, and beneath the ocean floor near the Japan Trench.



This international team, aboard a ship near Japan in 1999, installed two packages of geological measuring equipment 1 km below the Pacific Ocean floor in waters 2 km deep. Team members from left to right are Ben Pandit, Alan Linde, Eiichiro Araki, Masanao Shinohara, Kiyoshi Suyehiro, Nelson McWhorter, and Selwyn Sacks.

Changes inside the Earth lead to earthquakes, volcanoes, and deformations on the surface of the planet. For a number of years, geophysicist Alan Linde, working with Department of Terrestrial Magnetism (DTM) collaborator Selwyn Sacks, has been involved in a program to measure these disturbances in tectonically active areas around the world. The goal is to understand the processes at work at different depths in the Earth's interior. Most of the data for this program have come from Sacks-Evertson borehole strainmeters—instruments developed at DTM that detect small, long-term crustal movements. Over the last few decades strainmeters have been installed in seismically active areas, including California, Japan, and Iceland. The high-resolution data have led to the detection of new processes, such as slow earthquakes in seismogenic zones—areas where earthquakes occur—and changes in magma reservoirs during episodes of volcanic activity.

Linde, Sacks, and colleagues from the Japan Meteorological Agency (JMA) are analyzing strainmeter data on the deformations caused by the 1986 eruption of Miharayama on the island Izu-Oshima in Japan. The instruments are part of a network installed by the JMA for its earthquake prediction research program. The data show that during the first stage of the eruption the relatively shallow reservoir—the ultimate source of magma for the eruption—was continuously replenished from a much deeper source about 30 km below the surface. The scientists noted that the rate of replenishment changed at the time of small volcanic earthquakes. Strain changes preceding the second stage of the eruption occurred at depths to 50 km and came from the formation and propagation of dikes originating several kilometers below the surface. Surprisingly, most of the magma movement from the reservoir did not come to the surface but instead flowed into a large subterranean dike.

In 1999 Linde and collaborators installed borehole strainmeters, tiltmeters, and seismometers in drill holes about 1,100 meters below the ocean bottom near Japan. Data from these sites will provide new insights into the processes of plate motion and earthquake generation. The team has installed five new strainmeters in the San Francisco Bay area in a joint effort with the U.S. Geological Survey and the University of California at Berkeley and San Diego. A practical by-product of Linde's science is the development of early warning systems for impending eruptions.

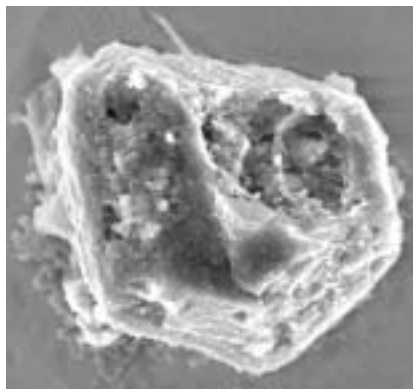
### SELECTED PUBLICATIONS

- Linde, A. T., and I. S. Sacks. 2002. Slow earthquakes and great earthquakes along the Nankai trough, *Earth Planet. Sci. Lett.* 203, 265-275.
- Ágústsson, K., A. T. Linde, R. Stefánsson, and I. S. Sacks. 1999. Strain changes for the 1987 Vatnafjöll earthquake in south Iceland and possible magmatic triggering, *J. Geophys. Res.* 104, 1151-1161.
- Linde, A. T., and I. S. Sacks. 1998. Triggering of volcanic eruptions, *Nature* 395, 888-890.
- Linde, A. T., M. T. Gladwin, M. J. S. Johnston, R. L. Gwyther, and R. G. Bilham. 1996. A slow earthquake sequence on the San Andreas Fault, *Nature* 383, 65-68.
- Linde, A. T., I. S. Sacks, M. J. S. Johnston, D. P. Hill, and R. Bilham. 1994. Increased pressure from rising bubbles as a mechanism for remotely triggered seismicity, *Nature* 371, 408-410.

## Larry Nittler



The Meteoritical Society recently created the Nier Prize for scientists under the age of 35 who have "made a significant contribution in the field of meteorites and closely allied fields of research." Larry Nittler received the award in 2001.



The best-investigated presolar grains are the silicon carbide (SiC) type (above). They typically range in size from 1 to 20 millionths of a meter (micron). This one, from the Murchison meteorite, is about 2 microns across. The isotopic signatures of most presolar SiC grains suggest an origin in old red giant stars or supernova explosions.

Cosmochemist Larry Nittler studies extraterrestrial materials, including meteorites and interplanetary dust particles (IDPs), to understand the formation of the solar system, the galaxy, and the universe and to identify the materials involved. He is particularly interested in developing new techniques to analyze different atomic species, or isotopes, in small samples. In related studies, he uses space-based X-ray and gamma-ray spectrometers to determine the composition of planetary surfaces, and he was part of the 2000-2001 scientific team to hunt for meteorites in Antarctica.

Nittler is especially interested in presolar grains contained in meteorites and in what they can tell us about our cosmic origins. He develops and uses advanced microanalytical techniques to locate and analyze these particles. The solar system formed about 4.5 billion years ago from a cloud of gas and dust. Most of the original dust grains were vaporized during solar system formation, but in the 1980s, researchers discovered that a fraction of these particles survived, trapped in meteorites. Presolar grains are tiny—about one thousandth of a millimeter in diameter. They predate other solid material in the solar system and are believed to have formed in winds and explosions of ancient dying stars. The unusual abundance ratios of different isotopes in presolar grains compared with other solar system products are their defining feature. They give researchers information about a number of processes, including how elements are synthesized inside stars, how the Milky Way galaxy evolves, and what the first solar system materials were.

Nittler recently worked on NASA's Near Earth Asteroid Rendezvous (NEAR) mission to advance our understanding of the relationship of asteroids to meteorites. Although it is known from both calculations and observations that most meteorites originated from asteroids, it has been difficult to link specific asteroid classes to specific meteorite classes. NEAR orbited the 30-km-diameter asteroid Eros for a period of one year during 2000 and 2001. Nittler, with collaborators, reduced and interpreted data from the X-ray spectrometer aboard NEAR to determine the elemental composition of the asteroid's surface. The data clearly showed that Eros is primitive; it has not differentiated into a core, mantle, and crust. Except for the ratio of sulfur to silicon, the elemental ratios agree with those measured in ordinary chondrites—the most common type of meteorite—indicating a possible relationship. The sulfur/silicon ratio, however, is much lower than in chondrites, a fact that most likely reflects some sort of "space-weathering" processes causing sulfur to volatilize and escape. Nittler continues to explore this and related questions in his research.

#### SELECTED PUBLICATIONS

- Messenger, S., F. J. Stadermann, C. Floss, L.R. Nittler, and S. Mukhopadhyay. 2003. Isotopic signatures of presolar materials in interplanetary dust, *Space Sci. Rev.*, 106, 155-172.
- Nittler, L. R. 2003. Presolar stardust in meteorites: recent advances and scientific frontiers, *Earth Planet. Sci. Lett.* 209, 259-273.
- Amari, S., L. R. Nittler, E. Zinner, K. Lodders, and R. S. Lewis. 2001. Presolar SiC grains of type A and B: their isotopic compositions and stellar origins, *Astrophys. J.* 559, 463-483.
- Nittler, L. R., R. D. Starr, L. Lim, T. J. McCoy, T. H. Burbine, R. C. Reedy, J. I. Trombka, P. Gorenstein, S. W. Squyres, W. V. Boynton, T. P. McClanahan, J. S. Bhangoo, P. E. Clark, M. E. Murphy, and R. Killen. 2001. X-ray fluorescence measurements of the surface composition of asteroid 433 Eros, *Meteoritics Planet. Sci.* 36, 1673-1695.



In 1993 Vera Rubin received the National Medal of Science—the nation's highest scientific award—for “her pioneering research...which demonstrated that much of the matter in the universe is dark...” She was elected to the National Academy of Sciences in 1981, and in 1996 she became the first woman to receive the Royal Astronomical Society's Gold Medal since Caroline Herschel, who was awarded the prize in 1828. Among her other honors, Rubin was chosen to be the American Astronomical Society's Henry Norris Russell Lecturer in 1994, she won the Cosmology Prize of the Peter Gruber Foundation in 2002, and in 2003 she received the Catherine Wolfe Bruce Medal from the Astronomical Society of the Pacific.

## Vera Rubin

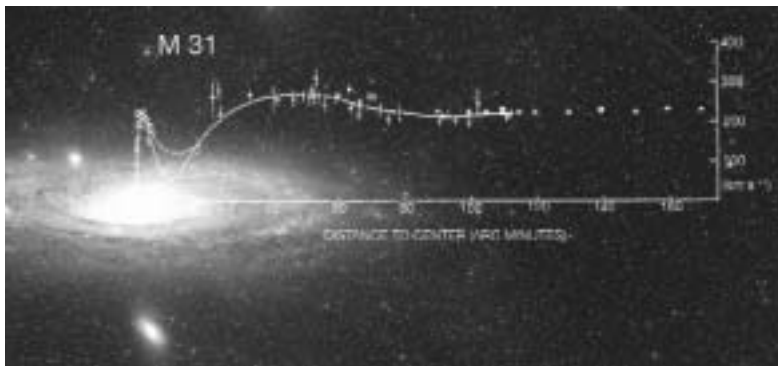


When Vera Rubin arrived in 1965, the Department of Terrestrial Magnetism (DTM) was a hands-on physics laboratory, and Kent Ford, a young Staff Member, had just designed and built an image tube spectrograph. This state-of-the-art instrument allowed telescopes to observe objects that were many times fainter than those that had previously been studied. Rubin's interest in how stars orbit their galactic centers led her and Ford to study the nearby spiral M31, the Andromeda galaxy. The two researchers hoped to determine the distribution of mass in M31 from the orbital speeds of stars and gas at different distances from the galaxy's center. Newtonian gravitational theory states that an object farther from its central mass will orbit slower. But, to their surprise, the scientists found that stars far from the center traveled as fast as those near the center.

By the late 1970s, after Rubin and her colleagues had observed dozens of spirals, it was clear that something other than the visible mass was responsible for the stars' motions. Analysis showed that each spiral galaxy is embedded in a spheroidal distribution of dark matter—a “halo.” The matter is not luminous, it extends beyond the optical galaxy, and it contains 5 to 10 times as much mass as the luminous galaxy. The stars' response to the gravitational attraction of the matter produces the high velocities. As a result of Rubin's groundbreaking work, it has become apparent that more than 90% of the universe is composed of dark matter. Defining it is one of astronomy's most important pursuits.

During the 1970s, Rubin and DTM collaborators Ford, Norbert Thonnard, and John Graham were among the first astronomers to examine the systemic velocities of galaxies to see if there are large-scale motions of galaxies, superposed on the general expansion of the universe. Their early work, and more recent work by others, suggests that such motions exist. Accurate details of these motions require large data sets for thousands of galaxies. Several large astronomical consortia are now making extensive observations to address this question.

Recently Rubin has been observing low-surface-brightness galaxies, objects that are fainter than the night sky. In these galaxies, the stars contribute little to the total mass; most of the mass is composed of dark matter. Because the inner rise of the rotation curve will differ depending upon the properties of the dark matter, Rubin and colleagues are using their observations to attempt to discriminate between various models for the composition of the dark halos.



This is an image of the Andromeda galaxy (M31), the companion spiral to our own, copied from the Palomar Sky Survey. The measured optical velocities from ionized gas clouds are indicated as open and filled circles. Velocities from neutral hydrogen radio observations are shown as filled triangles. Note that the velocities remain high far beyond the optical disk.

(Montage by Vera Rubin and Janice Dunlap, based on Roberts.)

### SELECTED PUBLICATIONS

- Swaters R. A., and V. C. Rubin. 2003. Stellar motions in the Polar Ring Galaxy NGC 4650A, *Astrophys. J. Lett.* 587, L23.
- Rubin, V. C. 2002. Why does an optical astronomer study something she cannot see? in *Beyond Earth: Mapping the Universe*, D. DeVorkin, ed., Washington, D.C., National Geographic Press, pp. 186-203.
- de Blok, W. J. G., S. McGaugh, A. Bosma, and V. C. Rubin. 2001. Mass density profiles of low surface brightness galaxies, *Astrophys. J. Lett.* 552, L23.
- Rubin, V. C., and J. Haltiwanger. 2001. Disturbed kinematics in Virgo Cluster spirals, in *Galaxy Disks and Disk Galaxies*, ASP Conference Series 230, J. G. Funes and E. M. Corsini, eds., pp. 421-424, Astronomical Society of the Pacific, San Francisco.
- Sofue, Y., and V. C. Rubin. 2001. Rotation curves of spiral galaxies, *Annu. Rev. Astron. Astr.* 39, 137.

## Selwyn Sacks



Selwyn Sacks, a fellow of the American Geophysical Union, has held a number of committee appointments over the years, including chairman of the National Research Council Panel on Real Time Earthquake Warning of the National Academy of Sciences and cochairman of Lithosphere–Asthenosphere Sounding of the International Association of Geomagnetism and Aeronomy.



More than 30 years ago, Carnegie's Selwyn Sacks and his colleague Dale Evertson of the University of Texas invented the Sacks-Evertson borehole strainmeter—an extremely sensitive instrument that, when cemented in place about 200 meters below the Earth's surface, is able to detect minute changes in rock deformation. Borehole strainmeters have been installed worldwide and are advancing our understanding of what small stresses deep inside the Earth can tell us about earthquakes and volcanic eruptions. Sacks (far right) and colleagues are standing at a hole for a strainmeter they installed on Trizonia, an island in the Gulf of Corinth, in 2002.

**T**he interaction of the mobile tectonic plates, which make up the Earth's surface, causes stresses that result in deformation and rock failure. When these stresses are released rapidly, earthquakes can result. The stresses then diffuse slowly away from the source. Geophysicist Selwyn Sacks studies the slow deformations that are a result of strain diffusion from large earthquakes, volcanic eruptions, and spreading events at the plate boundaries.

Sacks's analyses have helped determine the viscosity of the crust and uppermost mantle for Japan, California, and Iceland. Some of the deformations resulting from great earthquakes can be measured hundreds of kilometers from the source even after a century. In fact, it appears that the present-day strain field cannot be reliably estimated without allowing for the effects of past powerful earthquakes. As an example, Sacks and colleagues showed that the devastating earthquake in Kobe, Japan, in 1995 was probably triggered by strain diffusing from large earthquakes in 1944 and 1946.

Strain pulses are also capable of inhibiting earthquakes in instances where faults have many different orientations. Because of the orientation sensitivity, it is possible to calculate the probability of fault failures in these circumstances. In a region in south central Japan, for instance, Sacks and collaborators found that all earthquakes during the period 1901-1969 occurred where the probability of fault failure was enhanced by strain diffusion that mostly resulted from the 1891 Nobi earthquake. No earthquakes occurred where the strain pulses increased fault clamping.

Although the physics of strain diffusion is reasonably well understood, the physics of slow earthquake rupture is not. Recent observations using highly sensitive borehole strainmeters—instruments coinvented by Selwyn Sacks—enabled the discovery of slow events that were not seen on instrumentation available earlier. Strainmeters can measure tiny deformations within the Earth. Sacks recognized and analyzed the slower events and deformations. He and longtime colleague Alan Linde of DTM discovered that slow events can occur on the same faults that fail rapidly at other times. One of the most dramatic examples of this phenomenon occurs off northeast Japan, where there are subduction events as large as magnitude 8. Most of the plate motion there is released as slow, nondestructive events that could not even be detected until recently. To study this phenomenon more, Sacks and his team installed measuring instruments below the seafloor in 1999.

### SELECTED PUBLICATIONS

- Rydelek, P. A., and I. S. Sacks. 2003. Triggering and inhibition of great Japanese earthquakes: the effect of Nobi 1891 on Tonankai 1944, Nankaido 1946, and Tokai, *Earth Planet. Sci. Lett.* 206, 289-296.
- Rydelek, P. A., and I. S. Sacks. 2001. Migration of large earthquakes along the San Jacinto fault; stress diffusion from the 1857 Fort Tejon earthquake, *Geophys. Res. Lett.* 28, 3079-3082.
- Sacks, I. S., K. Suyehiro, G. D. Acton, et al. 2000. *Western Pacific Geophysical Observatories, Sites 1150 and 1151*, Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 186, College Station, ODP/Texas A&M University.
- Suyehiro, K., I. S. Sacks, G. Acton, and the Leg 186 Scientific Party. 2000. Japan Trench geophysical observatories: ODP Leg 186, *JOIDES Journal* 26 (no. 1), 10-16.
- Takanami, T., I. S. Sacks, and A. Hasegawa. 2000. Attenuation structure beneath the volcanic front in northeastern Japan from broad-band seismograms, *Phys. Earth Planet. Inter.* 121, 339-357.

## Sara Seager



Sara Seager comes to Carnegie from the Institute for Advanced Study in Princeton, where she was a long-term member and a Keck Fellow.

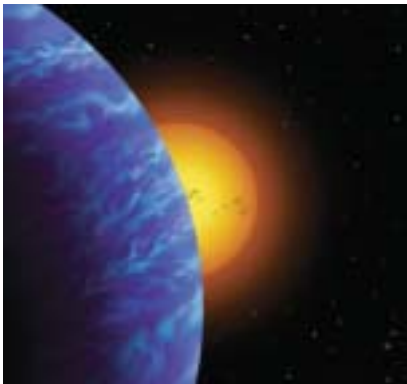
A decade ago, few scientists imagined that it would become almost commonplace to find planets orbiting nearby stars. To learn more about the physical characteristics of these objects, Sara Seager searches for *transiting* extrasolar planets and models extrasolar planet atmospheres.

One extrasolar giant planet transits its parent star every 3.5 days. As it passes in front of the star, the star's light dims by the ratio of the planet-to-star areas, allowing a measurement of the planet's radius. The radius gives modelers, such as Seager, information on the planet's evolution, composition, atmosphere, and interior properties. With postdoctoral fellow Kaspar von Braun and colleague Gabriela Mallén-Ornelas, Seager is leading a search for more of these objects by monitoring tens to hundreds of thousands of stars simultaneously. Using several telescopes, including Carnegie's Swope telescope, she investigates field stars and open star clusters to find short-period planets by identifying their characteristic dips in brightness.

Extrasolar giant planets orbiting very close to their parent stars are called close-in extrasolar giant planets (CEGPs). The star and planet light cannot be spatially separated, but the planets are very hot and possibly very bright due to their proximity to the parent stars. Seager models the atmospheres of CEGPs and predicts their signatures in reflected, thermally emitted, and transmitted light. Her models are used by observational astronomers to design experiments to make specific measurements. Her work led to the first successful detection of an extrasolar planet atmosphere in November 2001. Seager is working on additional models to help interpret observational results.

Seager's interest extends to finding and characterizing Earth-like extrasolar planets. Of particular interest is detecting atmospheres with severe chemical disequilibrium and specific chemical species that are indicative of habitable conditions. Because the parent star is millions to billions of times brighter than the planet, these objects are very difficult to detect and study. Around the year 2015, NASA is planning to launch the Terrestrial Planet Finder mission for this effort. Seager is working on atmospheric models to help determine the mission goals, the instrument design, and the best wavelengths for study.

Seager also studies cosmology. She investigates the early universe when electrons and protons combined to form hydrogen and helium during the "recombination epoch," some 300,000 years after the Big Bang. This era—when photons last interacted with matter—is seen today as the cosmic background radiation. In 2000 Seager and colleagues published a paper on this subject that has become the new standard for this research.



This artist's conception of an extrasolar planet shows a view from a close-in extrasolar giant planet looking toward the Sun-like parent star. The colors or banded structures of extrasolar giant planets are not yet known, but Seager's models, used to predict and interpret observations, are working toward this goal.

(Illustration courtesy Lynnette Cook.)

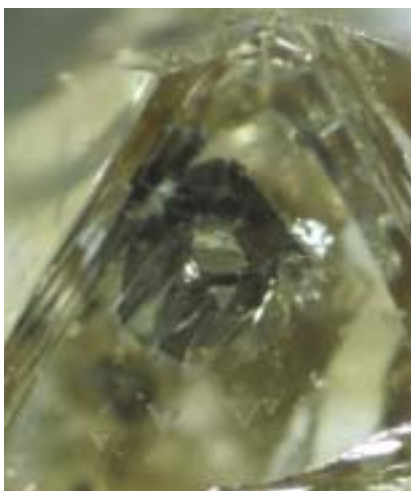
### SELECTED PUBLICATIONS

- Seager, S. and G. Mallén-Ornelas. 2003. A unique solution of planet and star parameters from an extrasolar planet transit light curve, *Astrophys. J.* 585, 1038-1055
- Seager, S., and L. Hui. 2002. Constraining the rotation rate of transiting extrasolar planets by oblateness measurements, *Astrophys. J.* 574, 1004-1010.
- Ford, E. B., S. Seager, and E. L. Turner. 2001. Characterization of extrasolar terrestrial planets from diurnal photometric variability, *Nature* 412, 885-887.
- Seager, S., and D. D. Sasselov. 2000. Theoretical transmission spectra during an extrasolar giant planet transit, *Astrophys. J.* 537, 916-921.
- Seager, S., D. D. Sasselov, and D. Scott. 2000. How exactly did the universe become neutral? *Astrophys. J. Supp.* 128, 407-430.

## Steven B. Shirey



Steven Shirey is a fellow of the Geological Society of America and a past president of the Geological Society of Washington. He has been a Staff Member at the department since 1985.



This is an optical photomicrograph of a sulfide-inclusion-bearing rough diamond from the Jwaneng Mine, Botswana. Below the natural diamond growth surface, at center, is a hexagonal grain of iron sulfide (Fe-S) surrounded by an irregular black rim. This rim is caused by internal fracture of the diamond on its 150-km ascent to the Earth's surface in the explosive volcanism of the kimberlitic magma. Sulfide grains like these are removed for rhenium-osmium isotopic analysis to reveal the age of the diamond and the composition of the sulfide. The diameters of these sulfide grains are about 300 microns.

(Image courtesy J. W. Harris.)

**I**gneous rocks are formed when molten material, often rising from great depths, solidifies. These rocks contain clues of past processes in Earth's interior in the form of different radioactive isotopes. Over time, these isotopes decay and beget daughter isotopes. Measuring these changes provides scientists with information about ancient geologic events. Geochemist Steven Shirey uses isotopic analyses to learn about the evolution and composition of the Earth's crust and mantle, as well as the history of the continents and ocean basins. He travels the world to search for rock samples and develops new tools and techniques in the laboratory to extract this valuable information. One of his goals is to understand how the continents were first created from the ancient mantle.

Shirey is particularly interested in the rhenium-osmium (Re-Os) isotopic decay system and has contributed significantly to its development and application. The Re-Os method is enormously useful for studying geological problems because Re and Os behave differently during melting than the elements used in other dating systems. Shirey, DTM colleague Richard Carlson, and others have applied the Re-Os method to a diversity of volcanic/magmatic processes and to the formation of the stable interiors of continents, called cratons. Cratons, containing the oldest rocks on Earth, anchor the amalgamation of younger continental material and contain much of the planet's mineral wealth, including diamonds, gold, and platinum.

Shirey and colleagues recently developed a microchemical technique to determine the Re-Os composition of single small sulfide inclusions (at  $10^{-15}$  grams) embedded in diamonds from the Kaapvaal Craton in Botswana and South Africa. These inclusions are the most informative capsules of materials from the deep mantle. Their analyses have led to the construction of a geochronological framework for diamonds and have provided a link to their source regions in the cratonic mantle keel. The results are important to diamond exploration and represent an important way to sample and analyze mantle material. Scientists now can link diamond growth to geological processes, such as craton stabilization, and to the role mantle keels played in continent development.

Shirey is also interested in specific magmatic processes in the ancient and modern Earth. To investigate this area, he has studied unique 2.7- to 3.3-billion-year-old high-temperature volcanic rocks known as komatiites. Recently he has turned his attention to the rocks from the volcanically active midocean ridges and helped develop new methods for measuring their boron isotopic composition in situ.

#### SELECTED PUBLICATIONS

- Wilson, A. H., S. B. Shirey, and R. W. Carlson. 2003. Archean ultra-depleted komatiites formed by hydrous melting of cratonic mantle, *Nature* 423, 858-861.
- Shirey, S. B., J. W. Harris, S. H. Richardson, M. J. Fouch, D. E. James, P. Cartigny, P. Deines, and F. Viljoen. 2002. Diamond genesis, seismic structure, and evolution of the Kaapvaal-Zimbabwe craton, *Science* 297, 1683-1686.
- Richardson, S. H., S. B. Shirey, J. W. Harris, and R. W. Carlson. 2001. Archean subduction recorded by Re-Os isotopes in eclogitic sulfide inclusions in Kimberley diamonds, *Earth Planet. Sci. Lett.* 191, 257-266.
- Shirey, S. B., R. W. Carlson, S. H. Richardson, A. Menzies, J. J. Gurney, G. D. Pearson, J. W. Harris, and U. Wiechert. 2001. Archean emplacement of eclogitic components into the lithospheric mantle during formation of the Kaapvaal Craton, *Geophys. Res. Lett.* 28, 2509-2512.
- Shirey, S. B., and R. J. Walker. 1998. The Re-Os isotope system in cosmochemistry and high-temperature geochemistry, *Annu. Rev. Earth Planet. Sci.* 26, 423-500.

## Paul Silver



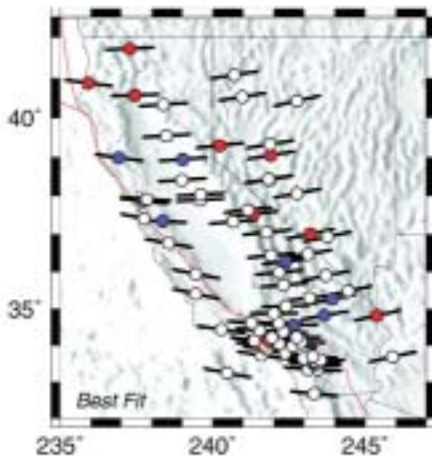
A fellow of the American Geophysical Union and the Geological Society of America, Paul Silver also serves on many committees and boards. He is president-elect of the Seismology Section of the American Geophysical Union. Silver has also taken a lead role in the conception, development, and ultimate funding of the Plate Boundary Observatory (PBO), an initiative to monitor and understand the Earth's movements and earthquakes between the North American and the Pacific plates.

**H**ow are earthquakes triggered, and how do they interact with each other? Geophysicist Paul Silver believes that by observing the slow redistribution of stress and strain that accompanies earthquakes he can help answer these questions. Silver uses several approaches to detect and characterize slow deformation. He also studies seismic anisotropy—the fact that seismic wave velocity depends on the direction and polarization of the waves as they propagate through a material. Because seismic anisotropy is produced by deformation and flow in the Earth's mantle, Silver uses the phenomenon to understand how the mantle is involved in mountain building, to map convection in the mantle, and to study how this flow interacts with the tectonic plates.

Silver and colleagues assembled an unprecedented 10-year data set on the strain behavior of a portion of the San Andreas Fault in central California—an area that is expected to experience a magnitude 6 earthquake soon. The strain records show that slow motion on the fault began to speed up in 1993, which started a complex multiyear slow earthquake involving the redistribution of stress along the fault and four moderate-size earthquakes. It is the best-documented slow earthquake so far observed. Through especially sensitive seismic imaging of the crust, Silver and team also found that fluid in the fault zone was redistributed in association with the slow earthquake.

The magnitude 7.3 Landers, California, earthquake of 1992 triggered increased levels of seismic activity in regions as far as several hundred kilometers away. By investigating all of the earthquakes in these areas over time, Silver and collaborators found that an elevated state of earthquake activity persisted for five years. They also discovered that the triggered activity had an annual cycle: fall had the greatest number of earthquakes, spring the least. The scientists concluded that the annual variations resulted from changes in barometric pressure—less pressure yields reduced stress on the faults, which can therefore move more frequently.

Using several hundred global seismic stations, Silver has also mapped the deformation of the upper mantle using a manifestation of anisotropy known as shear-wave splitting, or birefringence. In addition to showing that the mantle plays a role in mountain building and continent formation, Silver used this technique to study the flow associated with mantle convection beneath surface plates. With collaborators, he developed the first method to measure this flow field directly and determined how and why the mantle is moving in various places, including western North America and Iceland.



By combining data on surface deformation and seismic anisotropy (see text at right), Silver is able to estimate the mantle flow field beneath western North America. Shown are the directions of fast shear wave polarization directions predicted from a best-fitting flow model at sites where shear wave splitting has been measured. White symbols denote good fits of predicted and observed directions; red shows sites where predicted directions are more than 14° clockwise than observed; blue indicates a similar counterclockwise misfit. In the best-fitting model the mantle moves eastward at  $5.5 \pm 1.5$  centimeters per year, opposite to the motion of the North American plate. (Reprinted with permission from *Science* 295, 1055. Copyright 2002 AAAS.)

## SELECTED PUBLICATIONS

- Sipkin, S., and P. G. Silver. 2003. Characterization of the time-dependent strain field at seismogenic depths using first-motion focal mechanisms: can changes in the regional stress field trigger earthquakes? *J. Geophys. Res.*, in press.
- Bjarnason, I. Th., P. G. Silver, G. Rumpker, and S. C. Solomon. 2002. Shear wave splitting across the Iceland hotspot: results from the ICEMELT experiment, *J. Geophys. Res.* 107 (B12), 10.1029/2001JB000916.
- Silver, P. G., and W. E. Holt. 2002. The mantle flow field beneath western North America, *Science* 295, 1054-1057.
- Gao, S. S., P. G. Silver, and A. T. Linde. 2000. Analysis of deformation data at Parkfield, California: detection of a long-term strain transient, *J. Geophys. Res.* 105, 2955-2967.
- Gao, S. S., P. G. Silver, A. T. Linde, and I. S. Sacks. 2000. Annual modulation of triggered seismicity following the 1992 Landers earthquake in California, *Nature* 406, 500-504.

## Sean Solomon



Sean Solomon, a member of the National Academy of Sciences, was awarded the Arthur L. Day Prize and Lectureship from the National Academies in 1999. He was also awarded the G. K. Gilbert Award from the Geological Society of America that year. He was president of the American Geophysical Union from 1996 to 1998 and has served on many editorial boards for publications in the Earth and planetary sciences.



Mercury, the closest planet to the Sun, is a world of extremes. Its diurnal temperature varies from  $-184^{\circ}\text{C}$  ( $-300^{\circ}\text{F}$ ) at night to  $450^{\circ}\text{C}$  ( $840^{\circ}\text{F}$ ) during the day. The compact MESSENGER spacecraft (1.62 x 1.62 x 1.32 meters) and its seven-instrument suite are specially outfitted for these exceptional conditions. As an additional precaution, the craft will pass through the hottest areas of its orbit for only short periods.

(Image courtesy The Johns Hopkins University Applied Physics Laboratory.)

Sean Solomon balances his position as director of the Department of Terrestrial Magnetism (DTM) with research in planetary geology and geophysics, seismology, marine geophysics, and geodynamics. His experience ranges from oceanographic expeditions on Earth to spacecraft missions to Venus, Mars, and Mercury.

As Principal Investigator for the Mercury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, Solomon heads a multi-institutional consortium of scientists and engineers who will launch the small, efficient MESSENGER spacecraft in 2004 to reach its target orbit in 2009.

To date, the only craft sent to Mercury was *Mariner 10* in the 1970s, and it imaged less than half of the planet. With a suite of seven miniaturized instruments, MESSENGER will address questions that are key to understanding terrestrial planet evolution. Solomon's particular interests are to learn more about Mercury's bulk composition and what that tells us about planet formation in general; to investigate its volcanic, tectonic, and internal evolution; and to understand how the planet's magnetic field originated and determine whether there is a liquid outer core. *Mariner 10* discovered that Mercury has a weak magnetic field, a phenomenon that is thought to arise from an electromagnetic dynamo created in a liquid metallic outer core. Because the planet is small, scientists had thought that the core had cooled and solidified long ago. MESSENGER will investigate this question as well as the nature of the planet's thin atmosphere and the composition of the permanently shadowed polar deposits.

Solomon is also Principal Investigator for Carnegie's research as part of the NASA Astrobiology Institute (NAI). Astrobiology is an interdisciplinary approach to understanding the origin of life on Earth and its potential for existing elsewhere. Scientists from DTM and the Geophysical Laboratory are looking at the nature of deep hydrothermal systems and their possible role in the origin of life.

Solomon is also a team member on a variety of other projects including the Mars Orbiter Laser Altimeter (MOLA) investigation and the Plume-Lithosphere Undersea Mantle Experiment (PLUME). Data from MOLA, an instrument on the *Mars Global Surveyor* spacecraft, have been used to construct precise topographical maps to understand Martian geology, geophysics, and atmospheric circulation. PLUME is a combined land and ocean-bottom seismic experiment to image the mantle beneath the Hawaiian hotspot. Solomon is leading the land section of this project.

### SELECTED PUBLICATIONS

- McGovern, P. J., S. C. Solomon, D. E. Smith, M. T. Zuber, M. Simons, M. A. Wieczorek, R. J. Phillips, G. A. Neumann, O. Aharonson, and J. W. Head. 2002. Localized gravity/topography admittance and correlation spectra on Mars: implications for regional and global evolution, *J. Geophys. Res.* **107** (E12), 10.1029/2002JE001854.
- Niu, F., S. C. Solomon, P. G. Silver, D. Suetsugu, and H. Inoue. 2002. Mantle transition-zone structure beneath the South Pacific Superswell and evidence for a mantle plume underlying the Society hotspot, *Earth Planet. Sci. Lett.* **198**, 371-380.
- Shen, Y., S. C. Solomon, I. Th. Bjarnason, G. Nolet, W. J. Morgan, R. M. Allen, K. Vogfjörð, S. Jakobsdóttir, R. Stefánsson, B. R. Julian, and G. R. Foulger. 2002. Seismic evidence for a tilted mantle plume and north-south mantle flow beneath Iceland, *Earth Planet. Sci. Lett.* **197**, 261-272.
- Solomon, S. C., R. L. McNutt, Jr., R. E. Gold, M. H. Acuña, D. N. Baker, W. V. Boynton, C. R. Chapman, A. F. Cheng, G. Gloeckler, J. W. Head III, S. M. Krimigis, W. E. McClintock, S. L. Murchie, S. J. Peale, R. J. Phillips, M. S. Robinson, J. A. Slavin, D. E. Smith, R. G. Strom, J. I. Trombka, and M. T. Zuber. 2001. The MESSENGER mission to Mercury: scientific objectives and implementation, *Planet. Space Sci.* **49**, 1445-1465.

## Alycia Weinberger



In 2000 Alycia Weinberger was honored with the Annie Jump Cannon Award from the American Astronomical Society. The award, established in 1934, is given to outstanding postdoctoral astronomers for "significant research in astronomy." She was also cowinner of the 2000 Vainu Bappu Gold Medal of the Astronomical Society of India in recognition of her exceptional contributions as a young astronomer.

Unfortunately, we can't go back in time to watch our infant solar system as it formed the planets we know so well today. The next best thing, as the work of astronomer Alycia Weinberger illustrates, is to study the disks surrounding nearby young stars as analogues to help us determine what the conditions for planet formation really are.

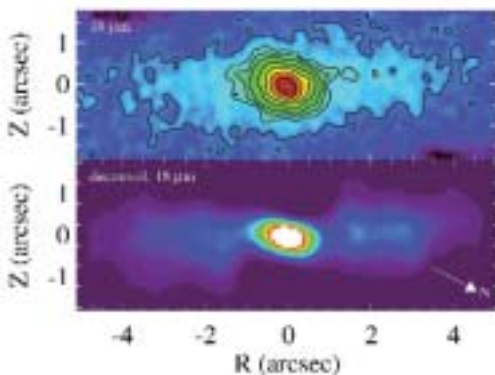
Young disks contain the raw materials for building planets, including lots of dust. This dust absorbs light from the star, heats up, and radiates in the infrared (IR), leaving a telltale signature for Weinberger to seek in looking for new disks. To determine how protoplanets form, Weinberger tries to measure how much dust there is over time around stars of different masses. The dust also reflects shorter wavelength light from the star. Weinberger uses this mirroring property of disks to determine their structures, finding such features as rings, gaps, and warps. Some of these distortions may be due to the influence of orbiting planets. For her many kinds of disk observations, she uses space-based and ground-based instruments, including two different imagers on the Hubble Space Telescope (HST), a mid-infrared camera and spectrograph at the W. M. Keck Observatory in Hawaii, and now Carnegie's 6.5-meter Magellan telescopes at Las Campanas, Chile.

Weinberger also looks at the chemistry of disk dust at varying distances from the central star to discover how materials are formed and distributed during early planet formation. Using large ground-based telescopes for infrared spectra, she studies the distribution of silicate dust, an important constituent of our own solar system, in other disks. In addition, she was the Principal Investigator of an HST program to take visual spectra of dust disks, which had been nearly impossible in the past because of contamination of the disk region by scattered light from the central stars.

Weinberger is working with high-angular-resolution imaging techniques on large ground-based telescopes to remove the distorting effects of atmospheric turbulence. To study the orbital motions of binary stars, she uses the techniques of speckle imaging—where many short exposures of an object are subjected to algorithms, eliminating the atmospheric effects—and adaptive optics, where real-time corrections are made for the same purpose. Weinberger also collaborates on searches for massive planets and brown dwarfs around nearby stars and studies active galactic nuclei—massive black holes at the centers of galaxies.

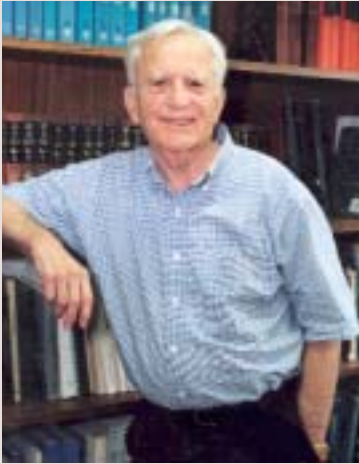
## SELECTED PUBLICATIONS

- Weinberger, A. J., E. E. Becklin, and B. Zuckerman. 2003. The first spatially resolved mid-infrared spectra of  $\beta$  Pictoris, *Astrophys. J. Lett.* 584, L33-L37.
- Weinberger, A. J. 2002. Planetary disks: A dusty business, *Science* 295, 2027-2028.
- Weinberger, A. J., E. E. Becklin, G. Schneider, E. I. Chiang, P. J. Lowrance, M. Silverstone, B. Zuckerman, D. C. Hines, and B. A. Smith. 2002. Infrared views of the TW Hydra disk, *Astrophys. J.* 566, 409-418.
- Schneider, G., E. E. Becklin, B. A. Smith, A. J. Weinberger, M. Silverstone, and D. C. Hines. 2001. NICMOS coronagraphic observations of 55 Cancri, *Astron. J.* 121, 525-537.
- Soifer, B. T., G. Neugebauer, K. Matthews, E. Egami, A. J. Weinberger, M. Ressler, N. Z. Scoville, S. R. Stolovy, J. J. Condon, and E. E. Becklin. 2001. High-resolution mid-infrared imaging of infrared-luminous starburst galaxies, *Astron. J.* 122, 1213-1237.

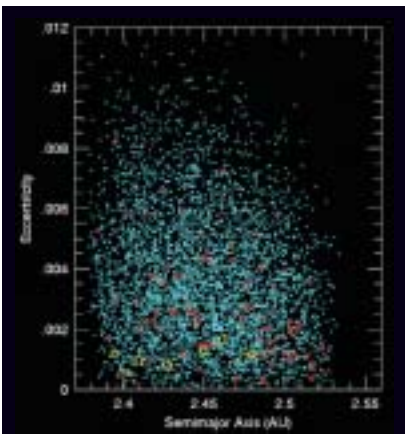


Mid-infrared imaging of the young star  $\beta$  Pictoris by Alycia Weinberger and colleagues reveals spatial asymmetries in its dusty circumstellar disk. Visible for the first time is an inner (within about 1 arcsecond, or 20 AU, of the star) warp in the disk (tilting at about  $15^\circ$  from upper left to lower right) that is aligned differently from a larger-scale warp seen in scattered light by the Hubble Space Telescope. At the top is a false-color image, at a wavelength of about  $18 \mu\text{m}$ , of dust heated by the star to temperatures of 150-500 K; the bottom version of the image incorporates a deconvolution procedure to sharpen resolution.

## George Wetherill



In 1997 George Wetherill received the highest scientific award in the nation—the National Medal of Science. He was elected to the National Academy of Sciences in 1974. He received the 1984 G. K. Gilbert Award of the Geological Society of America, the 1986 G. P. Kuiper Prize of the American Astronomical Society, and the 1991 Harry H. Hess Medal of the American Geophysical Union. In 2003 Wetherill was awarded the Henry Norris Russell Lectureship, the highest honor bestowed by the American Astronomical Society.



The asteroid region between Mars and Jupiter contains only small bodies. It is not known if only small bodies formed there, or if planets as large as Mars were formed and later removed. Knowing this answer will help clarify the evolution of other regions of the solar system. The illustrated “standard” model assumes that few planet-forming small solid bodies were in the region near 2.5 AU (the distance between the Earth and the Sun). Under these circumstances, after only a few million years bodies the size of today’s largest asteroids (yellow circles) are formed, along with intermediate (red) and small (blue) ones. Unlike the observed asteroids, these modeled orbits are fairly circular.

**E**arly in his career, George Wetherill and his Carnegie coworkers used an improved technique for dating Earth rocks using the fact that uranium ores provide two isotopic systems, which permit testing for unwanted geological disturbances the minerals may have experienced when they were deep inside the Earth. Along with coworkers at the department and the Geophysical Laboratory, Wetherill determined the poorly known decay constant of the half-life of very long-lived radioactive rubidium by comparing it with well-dated uranium and thorium ages that came from the same rocks. This knowledge made it possible to use rubidium to date the formation of ordinary rocks, such as granite, instead of having to use only rare uranium ores. Later, Wetherill became interested in the origin of meteorites, and this led him to explore the dynamics of the asteroid belt and the formation of the solar system.

Inspired by the research of Russian scientist Victor Safronov, who showed that groups of tiny planetesimals could grow into large bodies such as the terrestrial planets, Wetherill was one of the first to develop calculations of the orbital evolution and dynamics of planetesimal accretion and growth. These calculations result in the formation of a large group of probabilistic outcomes from a very similar initial condition. Along with the work of others, this result enabled him to make predictions of the size and orbits of the inner planets, as well as how collisions between bodies in the asteroid belt could result in asteroid impacts on Earth, such as the one that led to the extinction of the dinosaurs.

Wetherill’s computations have revealed how important Jupiter may be in protecting the Earth and other inner planets from bombardment. The gravitational field from Jupiter’s enormous mass effectively provides a shield from asteroids and comets. The discoveries of planets orbiting other stars by DTM’s Paul Butler and others are providing further challenges. Wetherill is considering if giant planets may form under different conditions, such as those proposed by DTM’s Alan Boss, rather than those of the standard model. Collaborative work with the former post-doctoral fellows Satoshi Inaba and M. Ikoma is testing whether the standard model can explain the formation of the outer planets.

Wetherill came to the department as a Staff Member in 1953. Between 1960 and 1975 he was a professor and department chairman at the University of California, Los Angeles. He came back to Carnegie in 1975 as director of the department, a position he held until 1991.

## SELECTED PUBLICATIONS

- Chambers, J. E., and G. W. Wetherill. 2001. Planets in the asteroid belt, *Meteoritics Planet. Sci.* 36, 381-399.
- Inaba, S., H. Tanaka, K. Nakazawa, G. W. Wetherill, and E. Kokubo. 2001. High-accuracy statistical simulation of planetary accretion II: comparison with *N*-body simulation, *Icarus* 149, 235-250.
- Kortenkamp, S. J., G. W. Wetherill, and S. Inaba. 2001. Runaway growth of planetary embryos facilitated by massive bodies in a protoplanetary disk, *Science* 293, 1127-1129.
- Kortenkamp, S. J., and G. W. Wetherill. 2000. Terrestrial planet and asteroid formation in the presence of giant planets I: relative velocities of planetesimals subject to Jupiter and Saturn perturbations, *Icarus* 143, 60-73.
- Wetherill, G. W., and S. Inaba. 2000. Planetary accumulation with a continuous supply of planetesimals, *Space Sci. Rev.* 92, 311-320.

# Scientific Staff Directory

## Department of Terrestrial Magnetism

Main Telephone Number: 202-478-8820    Main Fax Number: 202-478-8821

---

**Thomas Aldrich**  
(*Ph.D. 1948, University of Minnesota*)  
e-mail: aldrich@dtm.ciw.edu  
Phone: 202-478-8814

**Conel Alexander**  
(*Ph.D. 1987, University of Essex*)  
e-mail: alexander@dtm.ciw.edu  
Phone: 202-478-8478

**Alan Boss**  
(*Ph.D. 1979, University of California, Santa Barbara*)  
e-mail: boss@dtm.ciw.edu  
Phone: 202-478-8858

**Louis Brown**  
(*Ph.D. 1958, University of Texas*)  
e-mail brown@dtm.ciw.edu  
Phone: 202-478-8470

**R. Paul Butler**  
(*Ph.D. 1993, University of Maryland*)  
e-mail: paul@dtm.ciw.edu  
Phone: 202-478-8866

**Richard Carlson**  
(*Ph.D. 1980, Scripps Institution of Oceanography*)  
e-mail: carlson@dtm.ciw.edu  
Phone: 202-478-8474

**John Chambers**  
(*Ph.D. 1994, University of Manchester*)  
e-mail: chambers@dtm.ciw.edu  
Phone: 202-478-8851

**John Graham**  
(*Ph.D. 1964, Australian National University*)  
e-mail: graham@dtm.ciw.edu  
Phone: 202-478-8867

**Erik Hauri**  
(*Ph.D. 1992, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution*)  
e-mail: hauri@dtm.ciw.edu  
Phone: 202-478-8471

**David James**  
(*Ph.D. 1967, Stanford University*)  
e-mail: james@dtm.ciw.edu  
Phone: 202-478-8838

**Alan Linde**  
(*Ph.D. 1972, University of Queensland*)  
e-mail: linde@dtm.ciw.edu  
Phone: 202-478-8835

**Larry Nittler**  
(*Ph.D. 1996, Washington University*)  
e-mail: lrn@dtm.ciw.edu  
Phone: 202-478-8460

**Vera Rubin**  
(*Ph.D. 1954, Georgetown University*)  
e-mail: rubin@dtm.ciw.edu  
Phone: 202-478-8861

**I. Selwyn Sacks**  
(*Ph.D. 1961, University of Witwatersrand*)  
e-mail: sacks@dtm.ciw.edu  
Phone: 202-478-8839

**Sara Seager**  
(*Ph.D. 1999, Harvard University*)  
e-mail: seager@dtm.ciw.edu  
Phone: 202-478-8868

**Steven Shirey**  
(*Ph.D. 1984, State University of New York, Stony Brook*)  
e-mail: shirey@dtm.ciw.edu  
Phone: 202-478-8473

**Paul Silver**  
(*Ph.D. 1982, University of California, San Diego*)  
e-mail: silver@dtm.ciw.edu  
Phone: 202-478-8834

**Sean Solomon**  
(*Ph.D. 1971, Massachusetts Institute of Technology*)  
e-mail: scs@dtm.ciw.edu  
Phone: 202-478-8850

**Fouad Tera**  
(*Ph.D. 1962, University of Vienna*)  
e-mail: tera@dtm.ciw.edu  
Phone: 202-478-8472

**Alycia Weinberger**  
(*Ph.D. 1998, California Institute of Technology*)  
e-mail: alycia@dtm.ciw.edu  
Phone: 202-478-8852

**George Wetherill**  
(*Ph.D. 1953, University of Chicago*)  
e-mail: wetherill@dtm.ciw.edu  
Phone: 202-478-8855

A satellite image of Earth showing the Americas. The top portion shows the northern part of South America and the northern part of North America, with a color scale from green (low elevation) to yellow and orange (high elevation). The bottom portion shows a more detailed view of North America, including the United States and Canada, with a color scale from blue (low elevation) to red and white (high elevation).

**CARNEGIE  
INSTITUTION  
OF WASHINGTON**

**Department of Terrestrial Magnetism**  
5241 Broad Branch Road, NW  
Washington, DC 20015-1305

Phone: 202-478-8820  
Fax: 202-478-8821  
Web: [www.ciw.edu/DTM](http://www.ciw.edu/DTM)