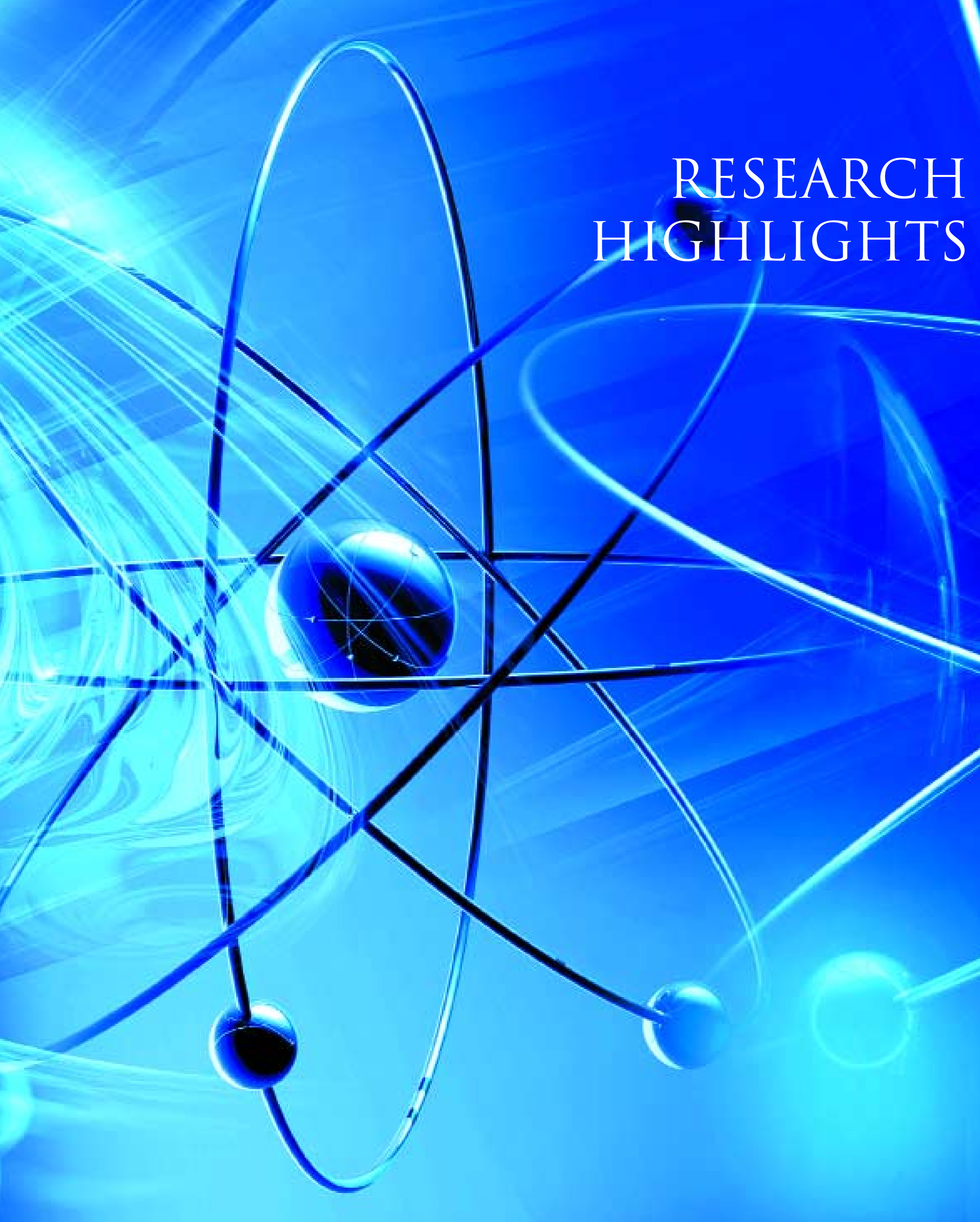
RESEARCH HIGHLIGHTS



EMBRYOLOGY

Deciphering the Complexity of Cellular, Developmental, and Genetic Biology

Seeking a Framework for Cell Division

Cell division, or mitosis, might look simple from our end of the microscope, but it is actually a painstaking process. As in a carefully managed divorce settlement, each resulting cell receives half of everything, including the parent cell's DNA.

Yixian Zheng and her colleagues at Embryology have found that a protein with an established role in interphase—the period that separates phases of mitosis—is also vital for cell division. The discovery fills in some important missing facts about the process and could have a significant impact on studies of tissue and organ development, stem cell biology, and cancer.

Scientists have long known about microtubules—the protein "ropes" that tug at chromosomes during cell division. But they are still looking for a structure called the spindle matrix, which acts as a framework to keep microtubules and DNA (in the form of chromosomes) organized during division. So far, most attempts to identify the matrix have focused on proteins that only function in mitosis.

Logical though this strategy might be, it excludes any protein that is active at all times. Zheng and colleagues reasoned that double-duty proteins might form the spindle matrix in dividing cells, and then convert to another function when the cells are in interphase. One protein, called lamin B, is known to help organize the cell's nucleus. When a cell divides, the nucleus temporarily disintegrates, and so researchers had thought that lamin B was simply inactive during mitosis.

Zheng's team tagged lamin B molecules in frog's eggs with fluorescent antibodies and found that the protein collects near the chromosome-splitting microtubules—too close to be a coincidence. Then they interfered with the lamin B gene in cultured human cells and observed severe disruption of cell division. Several more experiments strengthened the case for lamin B's role in the long-sought spindle matrix.

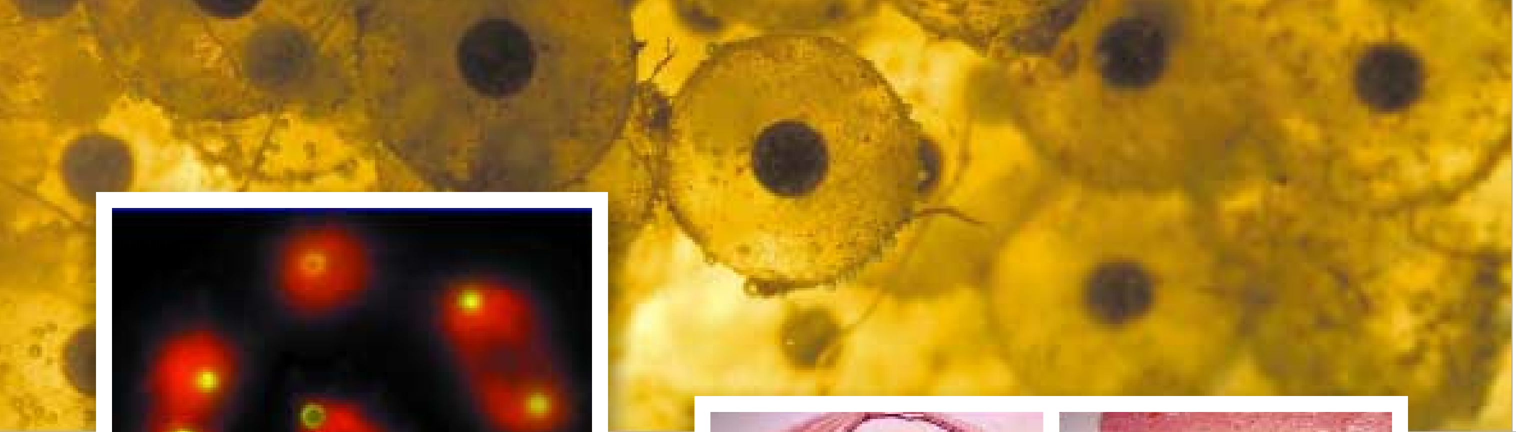
Mutations in lamin proteins have already been implicated in a number of conditions such as premature aging, and more research is likely to strengthen such connections. Nonetheless, the discovery of lamin B's role in the spindle matrix is a leap forward in the study of cell division, with clear implications for human biology and health.

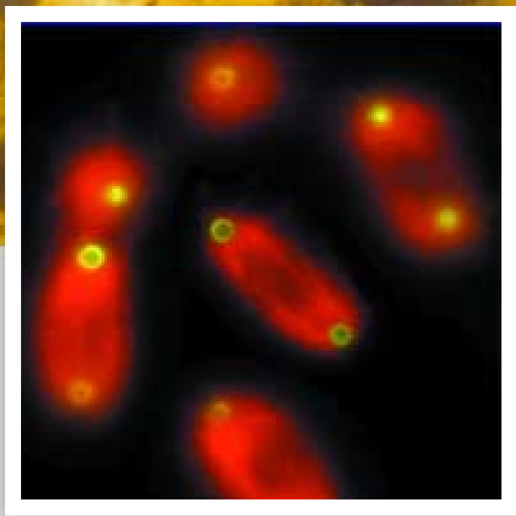
Mice Aid the Study of Human Eye Cancer

Every year in the United States, a malignant cancer called retinoblastoma causes retinal tumors in about 300 children under the age of three. The condition is rare; leukemia, by contrast, affects 10 times as many children. Yet retinoblastoma is among the most heritable human cancers known, and has been traced to a defect in a critical gene called *Rb*.

Laboratory mice with this defect do not develop tumors as humans do, which initially made it difficult to study the condition. Embryology staff associate David MacPherson and colleagues have engineered the first breedable mice that develop such tumors. They now use these mice to study retinoblastoma.

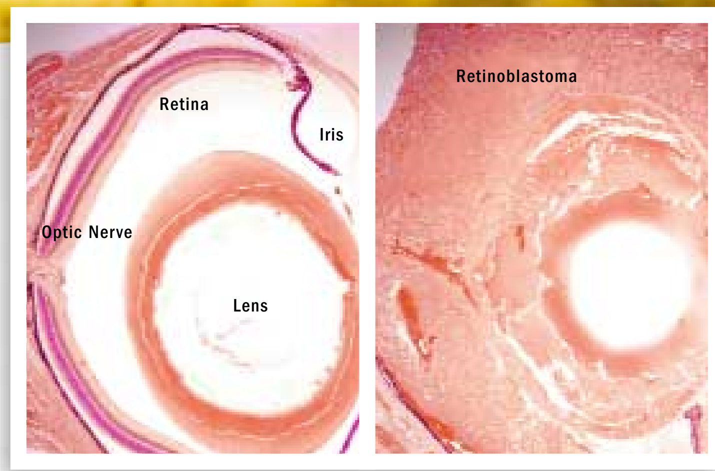
The *Rb* gene was the first to be identified as a tumor suppressor—a gene that contributes to cancer when inactivated. As with all genes, tumor suppressor genes have two copies; both copies must be damaged, or





This image contains several spindles—the structures that carefully divide a cell's genetic material. To better understand their function, Yixian Zheng and colleagues stimulate spindle formation using protein-linked magnetic beads (green/yellow dots). The red fibers are microtubules—protein "ropes" that tug at chromosomes during cell division.

(Image courtesy Yixian Zheng,)



A normal mouse eye (left) is shown in side view next to one with the malignant eye cancer called retinoblastoma. Cancer cells make up the large amount of extra material between the lens and the retina.

(Image courtesy David MacPherson.)

mutated, for cancer to result. In human retinoblastoma, the pattern of mutation—either inherited or spontaneous—determines whether multiple tumors will form in both eyes or a single tumor will form in one eye.

There are many unanswered questions about retinoblastoma. MacPherson's highest priority is to identify the specific retinal cell type from which these tumors arise and to understand how these cells become altered in the process. To answer such questions, researchers need a model organism. Since *Rb* mutations alone do not lead to retinoblastomas in mice, researchers began by looking for other genes that are similar to *Rb*. For his graduate work, MacPherson focused on one such gene, called *p130*. This "retinoblastoma-like" gene seems to compensate for a defective *Rb* gene and protects the mouse from tumor growth. However, when *p130* is mutated in combination with *Rb*, tumors form.

The MacPherson lab is using the retinoblastoma-prone mice to study when and where tumors originate and how they advance. Using technology that allows a comparison of genes in a cancer cell to those of normal cells, the researchers found that some tumors have extra copies of certain DNA regions. Instead of having only two copies of certain genes, as normal cells have, some retinoblastoma cells have multiple or "amplified" genes.

MacPherson's team traced one of the amplified regions to a specific gene called N-*myc*, which is known to cause cancer. However, other amplified regions do not contain known cancer genes. MacPherson believes the mouse data will help in the identification of other cancer-causing genes that influence retinoblastoma.

The mice should help the study of *Rb*'s role in normal retinal development as well as tumor formation. Such work could aid in the design of therapies to save the sight of children with retinoblastoma, and could possibly help to combat many other malignancies in which *Rb* is inactivated. •

GEOPHYSICAL LABORATORY

Probing Planet Interiors, Origins, and Extreme States of Matter

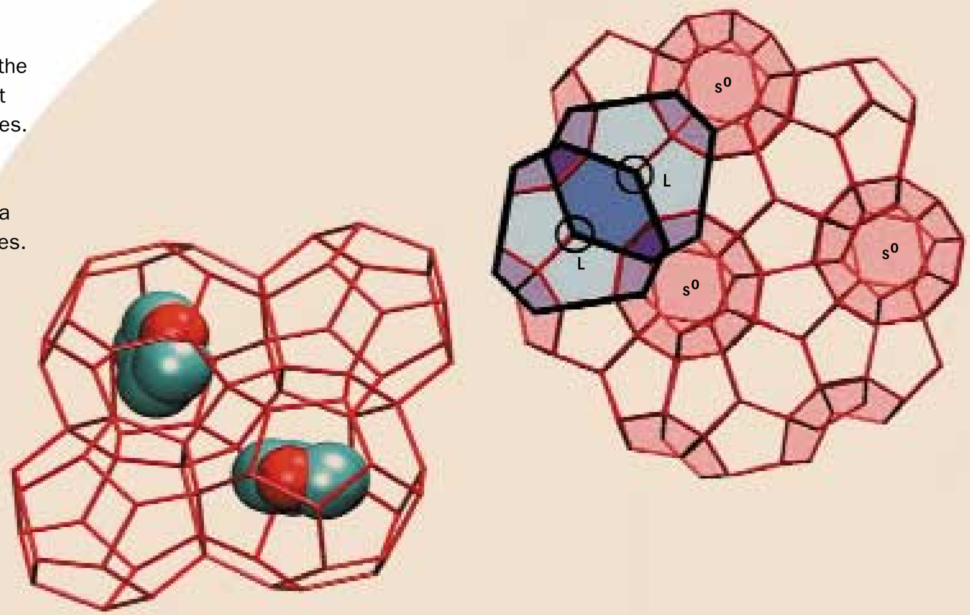
Beyond Petroleum: Into the Hydrogen Era

With sticker shock at the gas pump and an unsettled Middle East, there is intensified interest in finding alternative ways to power our cars. Using theory and experimentation, researchers at the Geophysical Laboratory (GL) have made significant progress in harnessing hydrogen gas (H_2), an environmentally friendly alternative to polluting fossil fuels. Although hydrogen is the most abundant gas in the universe, it has proven difficult to store practically, especially in tanks small enough for cars.

GL researchers Viktor Struzhkin, Burkhard Militzer, Tim Jenkins, Ho-kwang (Dave) Mao, Russell Hemley, Wendy Mao (now at Los Alamos National Laboratory), and collaborators are refining the use of molecule-sized, multicompartment cages of water ice, called clathrate hydrates, to encase and store hydrogen gas at practical temperatures and pressures.

Building on the 2002 experiments by Dave Mao and Wendy Mao, which trapped hydrogen gas inside the water ice structures under high pressure and low temperature, researchers at GL have been testing different clathrate structures to identify bigger cages with more capacity as well as to find additional components that will stabilize the structures under normal temperatures and pressures.

Clathrate compounds are typically stable under high pressure or at low temperatures (-189°F, or 150 K). They



Tetrahydrofurane (THF) (left) occupies the larger cages, leaving the hydrogen (not shown) free to occupy the smaller cages. These type II clathrate structures—molecule-sized cages (right)—consist of 16 small and eight large cages in a cubic unit cell with 136 water molecules. *(Image courtesy B. Militzer and T. Jenkins.)*

Burkhard Militzer (left) and Viktor Struzhkin at the Geophysical Laboratory

(Image courtesy Viktor Struzhkin.)

come in two main structures: type I and type II—each of which has two types of cavities capable of storing different "guest" molecules. The scientists found that if they added tetrahydrofurane (THF), a chemical used in industry, to type II clathrates, the structure could trap more hydrogen molecules under lower pressure (about 3,000 times the atmospheric pressure at sea level, or 300 MPa) and at a temperature closer to ambient (9.6°F, or 250 K). The use of the chemical also made the structures more stable. Type II clathrates have a set of small and larger cavities. The THF occupied the larger cavities, providing structural integrity for the hydrogen, which resided in the smaller cavities.

Although a primary benefit of this research is to help solve the energy dilemmas facing the nation, the work has a bonus. It points to the possibility that hydrogen might exist in icy bodies in our solar system thought incapable of retaining it.

Making the Materials of Tomorrow Today

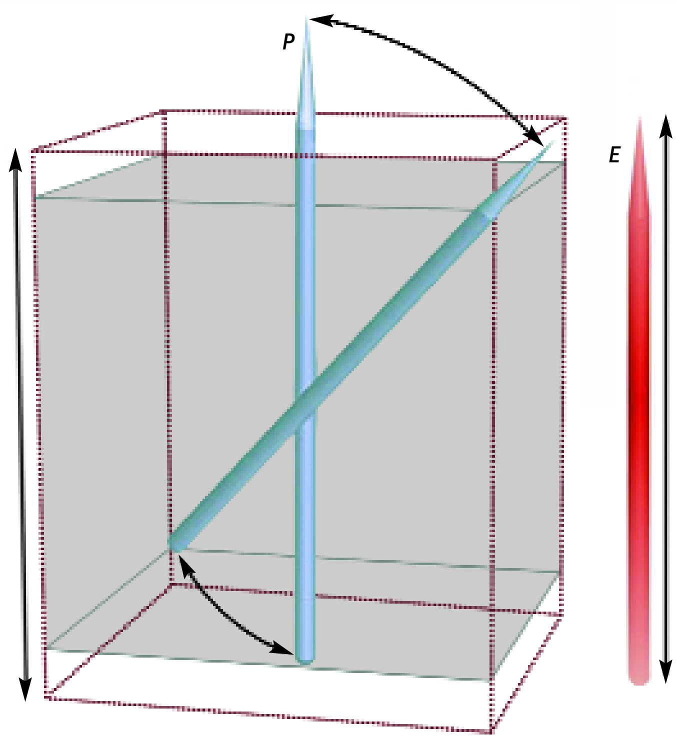
Have you ever wondered how car buzzers or medical ultrasound works? They, and other gadgets, depend on materials known as piezoelectrics, crystals that translate electrical energy into mechanical energy and vice versa—a characteristic known as the piezoelectric effect. The best piezoelectrics tend to be ferroelectric, which means that they have an electric polarization (dipole moment per volume) that is switchable with an applied electric field. Theoretician Ronald Cohen and colleagues have developed a fundamental understanding of these complex materials. They have developed a theory for the origin of ferroelectricity that has enabled detailed predictions of electromechanical properties as well as explanations of the behavior of a new class of these substances that has 10 times the power of currently used materials. Their work not only reveals how these important substances work; it is also used to screen new potential ferroelectrics and is helping to revolutionize devices in fields as diverse as knifeless surgery, sonar, and homeland security.

Using sophisticated computer simulations, Ronald Cohen, Huaxiang Fu, and their colleagues proposed that the secret of these supersubstances lies in the way their polarization behaves in the presence of an electrical field. Cohen and his team model the behavior of matter using first-principles calculations. They begin with the most fundamental properties of a system, such as the nuclear charges of the atoms, and then calculate what happens to matter under different physical conditions. The group has modeled countless ferroelectrics and has even created

Geophysical Laboratory, CONTINUED

In a standard application of piezoelectrics—crystals that translate electrical energy into mechanical energy and vice versa—an electric field is applied in the same direction as the polarization: the field and polarization are collinear. Carnegie theoreticians Ron Cohen and Huaxiang Fu modeled the outcome of an electrical field that is applied obliquely (the electric field is the diagonal axis in the cube) to the direction of the polarization (vertical axis *P* in the cube). They found that the polarization easily rotates from the diagonal position to align with the field (vertical direction) in a phenomenon they called polarization rotation, giving a much larger piezoelectric effect. The large shape and strain changes from the movement are responsible for the giant piezoelectric effect in new strong coupling materials called relaxor piezoelectrics as well as in PZT, the most commonly used piezoelectric.

(Image courtesy Nature 441, 941, © Nature Publishing, June 22, 2006.)



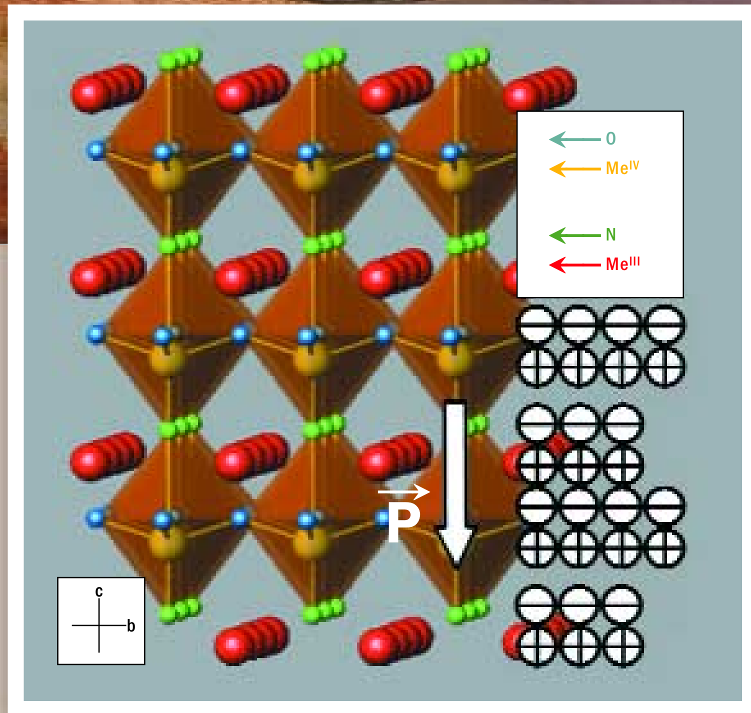
new ones in an effort to understand the mysteries of the piezoelectric effect and to design new, useful materials. To devise new candidate materials and help interpret results from experiments, Cohen's team works closely with experimentalists at the Geophysical Lab and elsewhere.

In the standard use of a piezoelectric, an electric field is applied parallel to the polarization—the field and polarization are collinear. The scientists modeled what would happen when an electrical field was applied obliquely to the direction of the polarization. They found that the polarization easily rotated, a phenomenon they dubbed polarization rotation. Cohen's team showed that this rotation is responsible for the large strain in materials called relaxor ferroelectrics. Since their prediction, dozens of lab experiments have corroborated the team's findings. It is now clear that all large coupling piezoelectrics operate through this mechanism.

Most of the ferroelectric materials today are perovskites, or perovskite-related oxides. Perovskite is a mineral with the same structure as the most common mineral in the Earth, silicate perovskite. Cohen and former Carnegie Fellow Razvan Caracas began theoretical "experiments" by changing the chemistry of these materials through substituting some of the oxygen atoms with nitrogen. They followed by changing the other atoms to obtain stable insulators (dielectrics). They designed a new class of ordered oxynitride perovskites, which have some of the largest polarization values thus far predicted or measured for any solid material. All the structures are perovskite-like or perovskite-derived, and their potential applications are manifold.

Ronald Cohen, Huaxiang Fu, and colleagues created a model for understanding the enormous piezoelectric effect of some of these important crystals. This image is a three-dimensional plot of the dependence of strain on the direction of an applied electric field of a classic ferroelectric, barium titanate ($BaTiO_3$). The bulging areas are the large strain in response to polarization rotation. The inset shows PZN-PT crystals, relaxor ferroelectric single crystals with giant electromechanical coupling.

(Image courtesy Ronald Cohen; inset courtesy TRS Technologies, Inc.)



Like well-practiced soldiers, these atoms displace to create a huge polarization effect (depicted by the big arrow with P), which is the key to a new class of superstrong piezoelectrics called oxynitride perovskites, developed by former Carnegie Fellow Razvan Caracas with staff member Ronald Cohen.

(Image courtesy Razvan Caracas.)

A Chemical Journey Back to Our Origins

For more than 4.5 billion years, comets have preserved the dust and ice left over from the formation of our solar system, making them exciting targets for research into our own origins. Seven years ago, NASA launched the Stardust mission on a 3-billion-mile journey to retrieve dust from comet Wild 2 and bring it back to Earth for analysis. On January 15, 2006, the spacecraft's sample canister touched down in the Utah desert, carrying with it the first comet samples ever studied by humans.

The micron-sized comet grains came embedded in slabs of aerogel, a special "foamed glass" that is 99.8% air by volume. The satellite gathered less than 1/1000 of an ounce of comet material. After successfully clearing the hurdle of collecting the samples and bringing them back to Earth, members of the Stardust team had to carefully sort, clean, and prepare the minuscule grains for study.

Geophysical Laboratory staff member George Cody and postdoctoral fellow Hikaru Yabuta are using the Scanning Transmission X-ray Microscope (STXM) at Lawrence Berkeley Laboratory's Advanced Light Source to analyze the organic, or carbon-based, chemistry of these samples. The STXM's remarkable optical system focuses an X-ray beam onto a spot 30 nanometers in

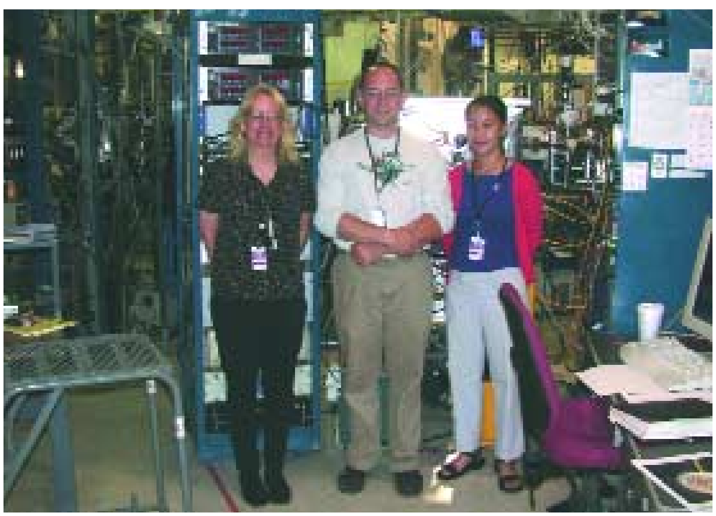
Former Carnegie Fellow Razvan Caracas (pictured) and colleagues are developing new materials with countless applications from medicine to defense. Caracas is now at the Bayerisches Geoinstitut, Universität Bayreuth, Germany.

(Image courtesy Razvan Caracas.)

diameter—about the size of the virus that causes the common cold. The STXM makes it possible to analyze comet particles that contain only a few hundred attograms of carbon. (One attogram equals 1 billionth of a billionth of a gram, or 10^{-18} g.)

Cody and Yabuta's preliminary work has revealed that the organic matter in comets is complex in structure and has a rich variety of nitrogen- and/or oxygen-containing functional groups—assemblies of atoms that give a molecule some of its characteristic properties. In fact, it appears that comets carry more of these functional groups than meteorites do, while also carrying fewer compounds with aromatic, or ringed, carbon structures. These preliminary results fly in the face of many astrochemical theories that predict that organic matter in a young solar system should contain abundant aromatic carbon.

If the Stardust samples from comet Wild 2 can be likened to a book on the early, low-temperature history of our solar system, then Cody, Yabuta, and other collaborators (including GL's Andrew Steele and Marc Fries, and Terrestrial Magnetism's Larry Nittler and Conel Alexander) have read only the first few chapters. Time will tell what exciting plot twists might surface in the future. •



From left to right, Susan Wirick of the National Synchrotron Light Source, George Cody of Carnegie's Geophysical Laboratory, and Tham Vu of Monash University in Australia pose with the Scanning Transmission X-ray Microscope (STXM) at the National Synchrotron Light Source, Brookhaven National Laboratory.

(Image courtesy George Cody.)

GLOBAL ECOLOGY

Exploring Ecosystems from the Smallest to the Largest Scale

Filling the Gaps in the Global Carbon Cycle

As the consequences of global climate change increasingly worry scientists and policymakers, the focus on monitoring causes and devising solutions has been directed to the industrialized nations of Eurasia and North America—the dominant sources of fossil-fuel emissions and attendant greenhouse gases like carbon dioxide (CO_2). But air has no borders. The lack of monitoring over other parts of the planet significantly impairs the ability to understand the dynamics of the entire global carbon cycle. Joe Berry and collaborators are working to define the large-scale carbon "budget" of a neglected part of the world that represents some 20% of the planet's land mass—Africa.

With 14% of the world's population but only 3% of fossil emissions, Africa poses an interesting case. In contrast to more-developed continents, most of Africa's anthropomorphic carbon emissions come from fires, land-use changes, and ecosystem degradation by overgrazing and desertification. However, without a dedicated monitoring system, the magnitude of this contribution is unknown. To date, estimates of the amount of CO_2 from Africa have been based largely on computer models, but such models yield uncertain results because of the continent's diverse and complicated ecosystems—from the Sahara Desert to savannas and jungles.

Berry, with collaborators at NASA, at Colorado State University, and in South Africa, has embarked on the continental-scale African Carbon Exchange project to help define Africa's role in this critical cycle. Vegetation uses CO_2 to grow and then releases it when it decomposes or burns. To measure how carbon wends its way between vegetation and the atmosphere, the researchers are setting up monitoring stations to catalog concentrations of CO_2 on the ground and above the tree canopy. They are also monitoring stable isotopes, forms of carbon and oxygen that differ in the number of neutrons in the nucleus. Because plants and microorganisms use and release stable isotopes in ratios that depend on vegetation type, soil characteristics, seasonal changes, short-term weather, and the composition of the atmosphere, the isotopes in the atmosphere provide telltale signs conveying vital information about how carbon, oxygen, and water are cycled through ecosystems. The researchers are also gathering high-resolution data from NASA satellites to characterize ecosystems, and all of this information helps them calibrate their computer models.

So far, there are CO_2 measurement sites in South Africa and Mali, and another will soon be located in Zambia. With existing infrastructure and technical support, other types of measurement sites will provide information to be used in combination with the project's other tools. This blend is designed to fill in information between scattered sites and to check its accuracy by comparing the measurements with the results of a model that predicts the CO_2 concentration at observation sites around the globe.

An Uncertain Future as the Oceans Turn to Acid

Sixty-five million years ago, a catastrophe of global proportions—possibly the aftermath of a colossal meteorite impact—wiped the dinosaurs from the face of the Earth. But they were not the only casualties. Fossil records also

Global Ecology, CONTINUED

This tower is an experimental setup for meteorological measurements of CO_2 exchange by a savanna ecosystem in Kruger Park, South Africa.

reveal a massive die-off of corals in the world's oceans, most likely the result of a drastic shift in ocean chemistry.

Now it seems that history might repeat itself. Increased carbon dioxide emissions are rapidly making the world's oceans more acidic and, if unabated, could cause a mass extinction of marine life similar to the one that occurred when the dinosaurs disappeared.

Using computer models, Ken Caldeira has predicted that the oceans will become far more acidic within the next century. He has found some startling similarities between these data and evidence from the fossil record. While the chemical effects of ocean acidification are likely to last tens of thousands of years, Caldeira estimates that biological recovery from another chemical catastrophe could take millions of years.

Some of the carbon dioxide from the burning of fossil fuels dissolves in the ocean and becomes carbonic acid, increasing the acidity of ocean water. When acid input is modest, sediments from the ocean floor can dissolve and buffer it. But at the current rate of input—nearly 50 times the natural background from volcanoes and other sources—this buffering system is overwhelmed. If current trends in carbon dioxide emissions continue, Caldeira's model predicts that high-latitude ocean waters will become acid enough to start dissolving the shells of some marine organisms.

Ocean acidification threatens all marine organisms that use calcium carbonate to make their shells, including corals. Under normal conditions, the ocean is supersaturated with this mineral, making it easy for these creatures to grow. However, an increasingly acidic ocean decreases

Walter Kubheka, a technician employed in South Africa by the project, stands by a precision gas analysis system constructed by Larry Giles at Global Ecology. The system conducts accurate measurements of CO_2 concentrations that are cross-calibrated with the global CO_2 monitoring network.

the concentration of the carbonate ion that serves as raw material for shells, putting these species at risk.

The oceans endured a similarly drastic change in chemistry roughly 65 million years ago. Many researchers believe that a meteorite smacked into what is now the Yucatan Peninsula and struck a carbonate platform rich in calcium sulfate, releasing a large amount of sulfur. This material would have later rained down on the ocean as sulfuric acid. In addition, the impact likely released carbon dioxide, which further acidified the oceans.

The fossil record reveals a precipitous drop in the number of calcium carbonate-shelled species, especially corals and plankton, in the upper ocean at this time—a pattern consistent with the effects of drastically acidified seawater. Species with shells made from resistant silicate minerals were more likely to survive.

Caldeira believes that the only remedy for ocean acidification is to cultivate nonfossil energy sources, such as wind, solar, and nuclear power, which can fuel economic growth without releasing dangerous carbon dioxide into the environment. •

Global Ecology's Ken Caldeira's work on ocean acidification was featured in an *LA Times* series called "Altered Oceans." He poses on the beach during a break from the photo shoot.

(Image courtesy Ken Caldeira.)

OBSERVATORIES

Investigating the Birth, Structure, and Fate of the Universe

The Social Life of Galaxies

Galaxies rarely stand alone—instead they tend to gather in small collections called galaxy groups. These groups can get crowded, and galaxies commonly brush up against one another. Sometimes, two galaxies get close enough to merge into a single galaxy. New evidence suggests that this phenomenon is common in the life cycle of galaxy groups, and that some groups might eventually coalesce into one large galaxy.

In the mid-1990s, astronomers discovered groups that emit X-rays. Using the space-based X-ray telescope ROSAT, John Mulchaey and collaborators showed that this radiation is spread over the entire volume of a group—several hundreds of thousands of light-years. This result suggests that X-rays originate in low-density gas heated to about 10 million degrees. At these temperatures, gas should quickly disperse unless it is confined by another force.

Astronomers believe this force is gravity. However, it would take an immense amount of mass to generate the gravity required to confine this gas—far more than the matter visible in groups. This finding led Mulchaey and team to deduce that galaxy groups contain dark matter, the elusive material that exerts a strong gravitational pull but does not emit light.

Mulchaey has undertaken the most detailed study of galaxy groups yet. He has found that only about 20% of groups actually emit X-rays, making it a relatively rare phenomenon. He believes that all groups contain gas, but that the gas is too cool to produce X-rays in most cases. Using the Magellan telescopes, Mulchaey found that X-ray–emitting groups contain mostly old, red galaxies, while the nonemitting groups include many young, blue galaxies.

Mulchaey has proposed an evolutionary sequence for groups. At first, they contain many gas-rich galaxies, but over time these galaxies merge and use up some of their gas reservoirs in the production of new stars. The resulting groups are mostly made up of old, red galaxies. They also increase in mass as they age, and eventually produce enough gravity to retain high-temperature, X-ray–emitting gas. Some such groups may continue growing and merging until they form a single enormous galaxy.

In the last few years Mulchaey has discovered several of these galaxies, which he calls fossil groups. His work offers a window into the future of our Milky Way galaxy, which is part of a small group in the early stages of formation; it is likely that we will one day merge with the Andromeda galaxy, our biggest neighbor.

Chemical Archaeology of the Heavens

Our bodies and the world we live in are intimately connected to stars. Although the lightest elements—hydrogen, most of the helium, and traces of lithium—were made in the Big Bang, some 14 billion years ago, nearly all of the remaining elements were produced by nuclear reactions inside stars.

When stars die, either by spectacularly violent supernova explosions or by a gradual detachment of the stellar envelope, they return newly synthesized elements to the interstellar gas clouds. As successive generations of stars form out of these gas clouds, the fraction of new elements (sometimes referred to as the metal content) increases with time.

Thus, the overall metal content and the detailed chemical abundance patterns form a "fossil" record of chemical evolution. Andrew McWilliam and collaborators are studying the origin and evolution of the chemical elements by looking at the composition of the envelopes of long-lived stars. Their observations, made with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph on the 6.5-meter Clay telescope at Carnegie's Las Campanas Observatory, are refining theoretical models, which until now have relied heavily on the composition of the Sun and its nearby neighbors.

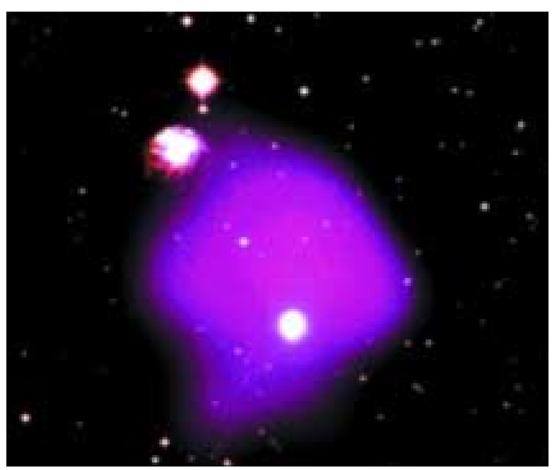
McWilliam's results show that the galactic bulge is strongly enhanced in products from supernovae events of especially massive stars. As these objects careened toward a self-destructive core collapse they produced many elements, including oxygen, aluminum, silicon, calcium, and titanium, that are characteristic of an origin from short-lived progenitor stars. These signatures suggest that the bulge evolved very quickly, in less than 500 million years. The research also shows a surprising decrease in oxygen relative to magnesium. The astronomers believe the depletion is due to "winds," or gas outflows, from

This Hubble Space Telescope (HST) image above shows the nearby Stephen's Quintet group of galaxies; it is representative of interacting galaxy groups.

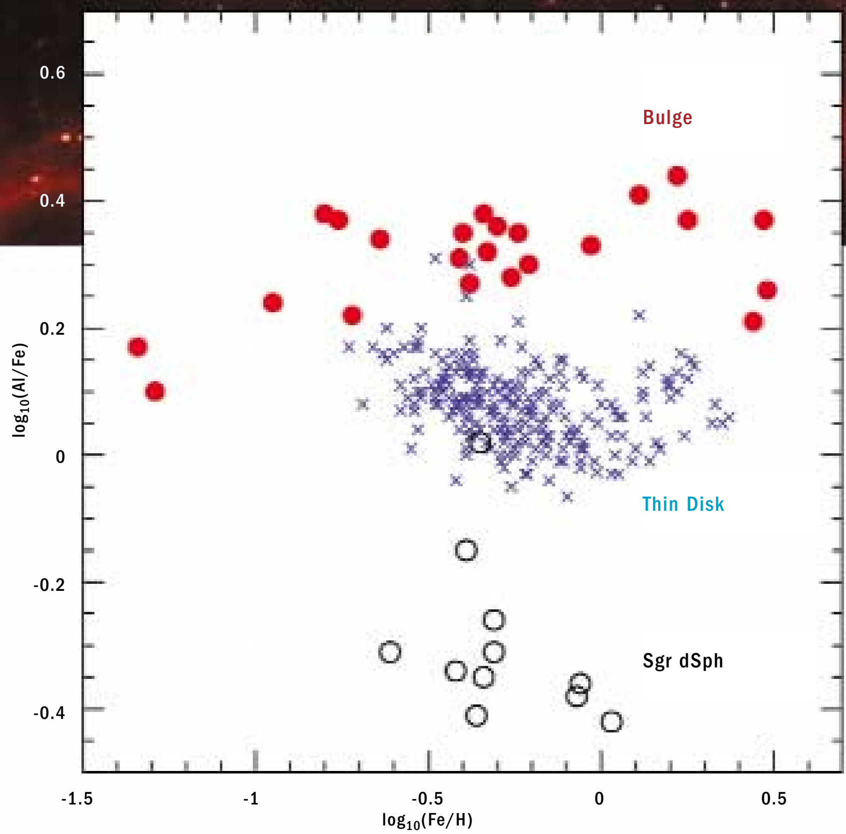
(Image courtesy Space Telescope Science Institute.)

This image below depicts the first discovery of X-ray emission in galaxy groups. It shows X-ray emission (pink) overlaid on an optical image of the NGC 2300 group of galaxies.

(Image courtesy John Mulchaey and NASA.)



Observatories, CONTINUED



The figure compares the trend of the aluminum to iron ratio (in solar units) versus metal content (measured by iron/hydrogen) in the Milky Way's bulge and thin disk, and the Sagittarius dwarf galaxy. The different chemical path taken by these systems is due to the decrease in aluminum to iron yield as the formation time increases. These results present much-needed observational clarity on theoretical nucleosynthesis and chemical evolution models, which until now relied heavily on the composition of the Sun and nearby stars.

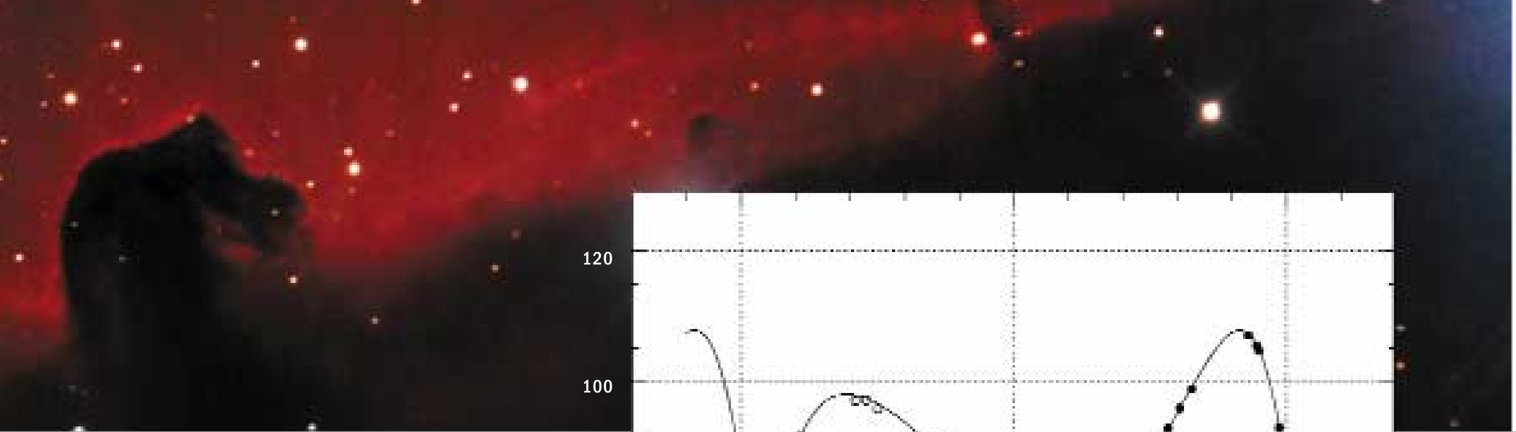
(Image courtesy Andrew McWilliam.)

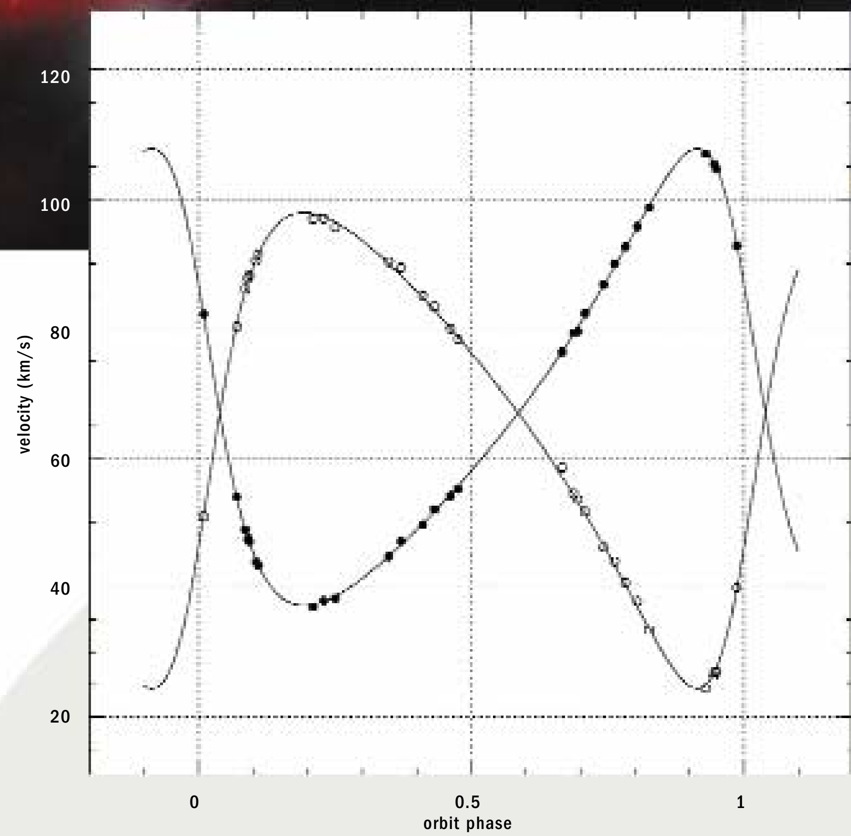
massive metal-rich stars. Although the winds are understood somewhat, they have thus far been omitted from models of supernova nucleosynthesis.

McWilliam also looked at stars in the Sagittarius dwarf galaxy, which is currently colliding with our galaxy. These stars show a paucity of products from core-collapse supernovae, but have strong signatures from a different process called slow neutron capture, where an atomic nucleus collides with a neutron to form a heavier nucleus. Because slow neutron capture elements, such as barium and lanthanum, are predominately produced by very long-lived stars, the enhancements indicate that this galaxy chemically evolved over several billions of years. Details of the pattern of neutron-capture element abundances indicate that the Sagittarius dwarf galaxy must have lost a significant fraction of its initial mass during its evolution.

Unlocking the Secrets of Elusive Double Stars

Since the beginning of humankind, people have peered into the night sky and wondered how the universe began. Some astronomers grapple with this question by studying how stars form, evolve, and die. Ian Thompson explores stellar evolution by measuring the fundamental properties of stars—their masses, luminosities, and radii—in very rare systems called detached eclipsing binary stars. These are systems in which two stars orbit each other in an orbital plane along our line of sight. While such observations have been made for many young stars in our galaxy, until this research none of these binaries had been found among so-called population II stars, the oldest stars in the Milky Way. Thompson, with colleagues, has found 16 of these binary systems in eight southern





How do astronomers measure the masses of old binary stars? This figure shows the velocities for the variable V23900 in the globular cluster M4. Since the inclination of the orbit is known, the masses can be determined from the amplitudes of the two velocity curves and the period of the orbit. V23900 has a period of 48.2 days, and the masses are 0.75 and 0.72 the mass of our Sun. This data set is the first empirical collection of luminosities, radii, and masses for these objects, a milestone in understanding stellar evolution.

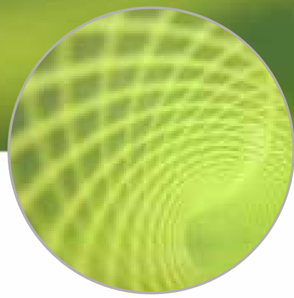
galactic globular clusters, ancient spherical systems of more than 100,000 stars each.

Astronomers need to know a star's mass, radius, and brightness to study and test theoretical models of stellar evolution. Observations of binary systems provide a means to determine these data. When one star passes in front of the other, the total light changes, and the shape of the plot is used to discern the relative sizes and separation of the stars. Thompson and team then derive the absolute dimensions of the system, and the radii and masses of the two stars, by measuring the stars' velocities and by applying Kepler's laws of gravity. They determine total and apparent luminosities by relying on a relation between the surface brightness of the star and its color, as measured in the visible and infrared regions of the spectrum. The total luminosity of the star is derived from its radius and its surface brightness, and the distance is calculated by comparing this total luminosity with its apparent luminosity. Finally, the ages of the stars can be ascertained if they find that one of the stars is at the end of its main sequence life; this period is a function of the star's mass.

Using a suite of telescopes at Carnegie's Las Campanas Observatory, Thompson and colleagues have studied these evasive systems for several years. With the Swope 1-meter telescope they are monitoring a sample of nearby southern globular clusters to detect the stellar eclipses and define their orbital periods. They use the du Pont 2.5-meter telescope to capture the changing light during the eclipse, and they harness the Magellan Inamori Kyocera Echelle spectrograph to observe stellar velocities. They plan to study similar stellar systems in the Large Magellanic Cloud, a southern galactic neighbor of the Milky Way. •

PLANT BIOLOGY

Characterizing the Genes of Plant Growth and Development



A Better Understanding of Botanical Bodybuilding

Unlike many animals, plants cannot depend on a skeleton to help them keep their shape. Instead, they stand up straight by building stiff walls around their cells, each of which is tightly glued to its neighbors. The cells within maintain a steady fluid pressure that presses against the walls, keeping the whole cell rigid in much the same way an inner tube keeps a bicycle tire inflated. It is difficult for a plant cell to change its shape once it is in place, so plants rely on carefully organized cell division and growth during development.

Plant Biology director Christopher Somerville studies how plant cells weave together a variety of molecules—mostly large, fibrous carbohydrates such as cellulose—to make and arrange their cell walls. Although these molecules make up more than half of the land-based biomass on Earth, researchers know surprisingly little about how plants manufacture them, and how their chemistry contributes to the function of cell walls.

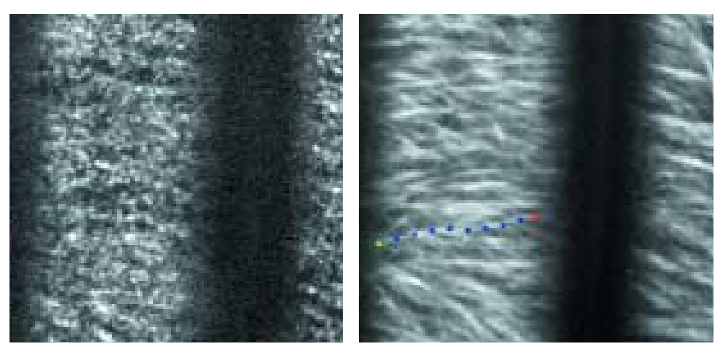
Cellulose, by far the most abundant of cell wall components, consists of about 36 parallel chains of glucose that form long microfibrils. These polymers, which can reach more than 10 micrometers in length, wrap around the surface of plant cells as they form outside the cell membrane. The fibers are extremely strong and durable, and provide much of the cell wall's resistance to expansion.

Somerville, with graduate student Alex Paredez and staff member David Ehrhardt, engineered a plant that produces fluorescent cellulose synthase—part of the enzyme complex that makes cellulose. As a result, the team could watch while individual complexes actively made cellulose in living cells. With a different fluorescent marker, the team also labeled proteins in the cortical microtubules—the scaffolding that helps to shape actively dividing cells.

By simultaneously visualizing both types of proteins, the group determined that the position and orientation of the microtubule scaffolding largely controls where and in what direction the cellulose synthase complex makes cellulose. So far, they are unsure of exactly how the microtubules guide the enzyme complexes, but it seems likely

This pair of images shows fluorescently labeled cellulose synthase—the enzyme that makes cellulose—at work in live cells. Left, an average of five images of the cell membrane taken 10 seconds apart shows the position of individual cellulose synthase complexes. (The particles are actually much smaller than they appear in the image.) Right, an average of 61 images shows particles movement during a 10-minute span; the colored dots highlight the track of a single enzyme complex. The researchers determined that a single enzyme complex links gluclose molecules into cellulose fibrils at the rate of nearly 25,000 per minute.

(Image reprinted with permission from Science *312, 1491-1495, 2006.)*



they are in direct contact with each other.

Somerville and Ehrhardt's research groups are now studying cellulose formation from two different, yet complementary, angles: Somerville's team is working to understand the cellulose synthase complex, and Ehrhardt's crew is focused on the organization and orientation of the microtubules. Together the groups hope to discover the functional relationship between the two structures. While a better understanding of cellulose formation will certainly lead to a better understanding of plant growth, it might also aid the effort to produce biofuels from cellulose.

Some members of The Arabidopsis Information Resource (TAIR) team (left to right) are Julie Tacklind (Webmaster), Margarita Garcia-Hernandez (curator), Eva Huala (director), and Sue Rhee.

(Image courtesy Sue Rhee.)

Cultivating Plant Data in the Information Age

TAIR (The Arabidopsis Information Resource), a biological database directed by Plant Biology's Seung (Sue) Rhee, is an information age tour de force. *Arabidopsis*, a relative of the mustard plant, is the most widely used research plant today. Developed by Rhee and colleagues at Carnegie and the National Center for Genome Resources, TAIR is among the most accessed "bioinformatics" resources in all of biology. Although the database focuses on *Arabidopsis*, it also helps researchers understand the genes governing growth, development, disease, and more in all plants. The database has grown from 100,000 page hits per month in 2000, to 1 million per month in 2005. Rhee's work has helped set the standard for biological databases worldwide, and she is now mining the information to conduct plant experiments without actually growing a thing.

TAIR is accessible via commonly used Web browsers (http://www.arabidopsis.org/). Researchers can review the *Arabidopsis* literature and find information about genes, genetic markers, nucleotide sequences, clones, proteins, gene families, biochemical pathways, researchers, notes, and can even order seed and DNA stocks using an online shopping-cart system. The database's flexible architecture allows Rhee and colleagues to adapt it as more information is learned about plants and the relationships among their molecular components.

In addition to directing TAIR, Rhee is leading the charge for improving and standardizing the vast array of bioinformatics resources. Currently, different biological databases have inconsistent nomenclature, organization, annotation, and displays. Rhee seeks a seamless connection among related databases, public repositories, and journals in an effort to make the data explosion more accessible to biologists all over the world.

Rhee sees the future of bioinformatics as a primary source for virtual experiments. Toward this end, she and colleagues have been using the enormous databank to investigate the molecular mechanisms of plant responses to environmental stresses, such as excess salt, drought, wounds, cold, heat, and more. Using the bioinformatic infrastructure she developed and in collaboration with others, she started to tackle the problem by analyzing data from experiments that use state-of-the art technologies such as microarrays. Preliminary results from her statistical analyses show that the genes affected by these stresses fall into two general types. She foresees using the data to model the network of regulatory molecules that govern how genes are turned on and to identify the regulatory genes that control the biochemical processes that enable plants to adapt and respond to changes in the environment. To corroborate the findings, she will verify her virtual experiments by testing actual plants.

Genetic Defenders on the Front Lines

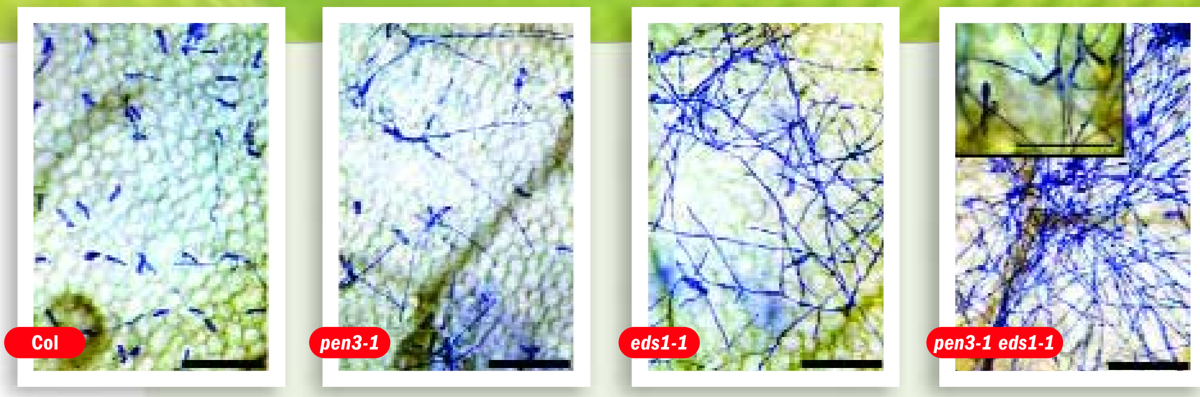
Like soldiers guarding a castle gate, multiple genetic defenders protect plant cells against powdery mildew disease—a common fungal infection that attacks more than 9,000 plant species, including important crops and horticultural plants. Shauna Somerville, postdoctoral fellows Laurent Zimmerli and Matt Humphry, and graduate student Monica Stein of Carnegie's Department of Plant Biology are among the first to document these defense genes in plants. Their discovery could help combat fungal pathogens and save billions of dollars in pesticides and crop losses every year.

Each species of powdery mildew can infect some plant species but not others. Somerville and Zimmerli discovered that a species of powdery mildew that attacks the mustard relative *Arabidopsis thaliana* works by somehow suppressing (or failing to activate) a common defense pathway. Another mildew species that normally infects barley, however, is unable to suppress this pathway. Somerville, Stein, Humphry, and colleagues built on this work by disabling certain protective genes in *Arabidopsis*; as a result, they were able to infect these plants with the barley mildew as well as another type that normally attacks pea plants. Identifying these genes has provided crucial insight into how plants defend against multiple pathogens.

Once a powdery mildew infection takes hold, it covers the plant with fuzzy splotches, and the fungal spores invade healthy plant cells with rootlike feeding structures that sap precious nutrients. A suite of defense genes called *PEN1*, *PEN2, PEN3,* and *MLO2* prevent the fungus from penetrating the cells' first line of defense: the cell wall.

Depending on the mildew species, some mildew succeeds in breaking through the cell wall in about 5% to 25% of normal *Arabidopsis* cells. At this point a complex of three genes, *EDS1*, *PAD4*, and *SAG101*, can signal infected cells to die. By sacrificing these fallen cells, the defense genes can spare healthy ones from infection.

Somerville, Stein, and colleagues at the Max Planck Institute for Plant Breeding in Cologne disabled the protective genes in *Arabidopsis* by introducing mutations in various combinations. They infected these mutants with one of two species of powdery mildew, one that attacks barley and one that attacks pea plants. The pea powdery



These micrographs show *Arabidopsis* leaves inoculated with the fungal parasite *Erysiphe pisi*, which is stained blue in this image. From left to right, plants with no mutations (Col), a disabled *PEN3* gene (*pen3-1*), a disabled *EDS1* gene (*eds1-1*), and both genes disabled together are increasingly vulnerable to the fungus. The last variant of *Arabidopsis* is the most susceptible to infection; it allowed *E. pisi* to reproduce, thus completing the pathogen's life cycle.

(Image reprinted with permission from Plant Cell *18, 731-746.)*

mildew reproduced as well on triple-mutant *Arabidopsis* as on its normal host, suggesting that resistance barriers rely on just a limited number of genes.

The *EDS1*, *PAD4*, and *SAG101* gene complex's ability to signal cell death was relatively well known to scientists. However, very little was known about how the *PEN* genes function. The researchers demonstrated that the PEN3 protein is a transporter—a protein that exports molecules to the cell wall—although the molecules it transports remain unknown. Their research expands on previous work on *PEN1*, which seems to share a common purpose with *PEN3*. However, *PEN3* appears to protect against a wider range of fungal pathogens; for example, *PEN3*-mutant *Arabidopsis* is more susceptible than normal plants to *Phytopthora infestans*, the fungus responsible for the notorious Irish Potato Famine of the mid-19th century.

The genetic mechanisms that protect plants from fungal pathogens appear to be relatively simple, relying on only a handful of genes. It might be possible to engineer crops with these hardy *Arabidopsis* genes to help control powdery mildew and other destructive diseases, thus minimizing the need for pesticides. •

TERRESTRIAL MAGNETISM

Understanding the Earth, Other Planets, and Their Place in the Cosmos

One Natural Force Provokes Another: Typhoons and Slow Earthquakes in Taiwan

DTM instrument maker Nelson McWhorter (front) checks a strainmeter before it is transported to the study site for installation in Hualien, eastern Taiwan. Selwyn Sacks (DTM, middle) and Chi-Ching Liu (Academia Sinica, left) check the electronic components. *(Image courtesy Alan Linde.)*

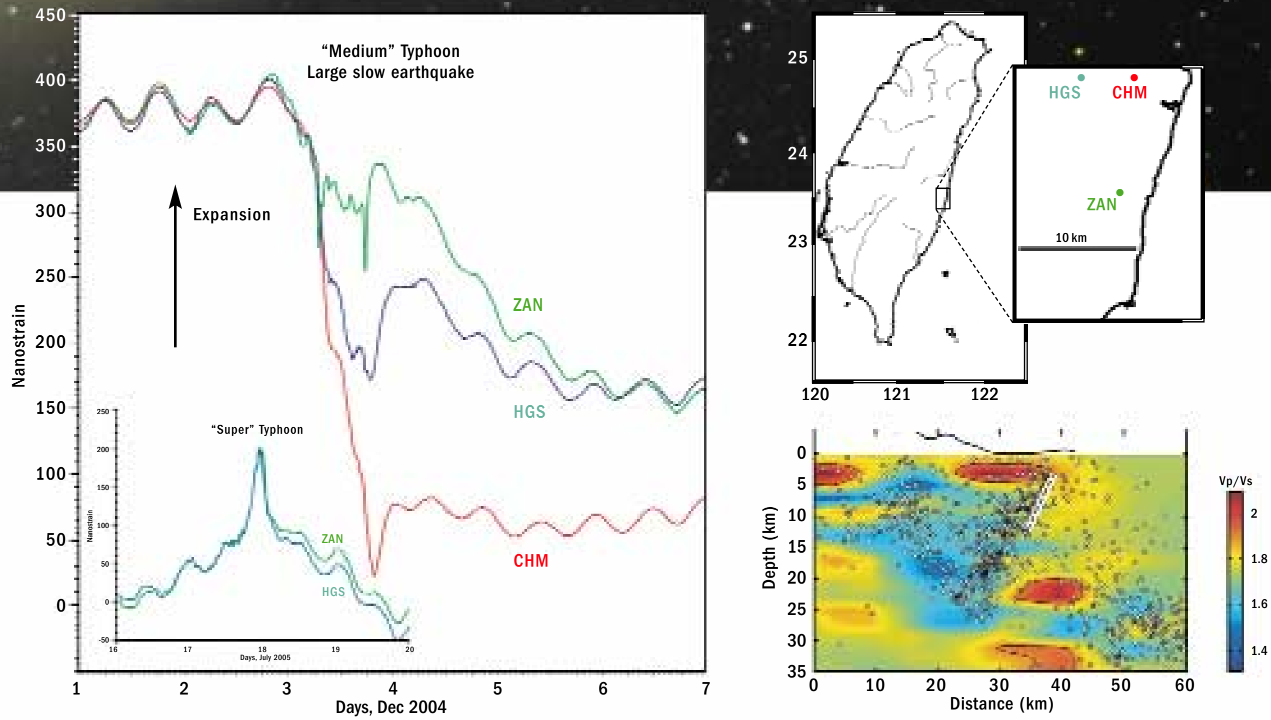
Eastern Taiwan experiences relatively few massive, headline-grabbing earthquakes, despite being one of the most rapidly deforming tectonic regions on Earth. New research has revealed that "slow" earthquakes—subtle tectonic shifts that last for hours or even days and do not show up on standard seismographs—relieve some of the strain built up as the Philippine Sea Plate forces itself west into and beneath the Eurasian Plate. Unexpectedly, it seems that these slow quakes can be triggered by typhoons—tropical storms that originate in the western Pacific Ocean.

To study the fault system, Selwyn Sacks and Alan Linde of the Department of Terrestrial Magnetism (DTM) and their team installed a small network of strainmeters—devices embedded in boreholes that can track otherwise imperceptible distortions in rock—beginning in 2003. The project is in collaboration with Chi-Ching Liu of the Academia Sinica in Taipei.

Global Positioning System data have revealed that eastern Taiwan's Longitudinal Valley narrows by nearly an inch per year along a 6-mile section of the coast, building up a great deal of strain in the process. By contrast, the deformation along the San Andreas Fault in California is spread over a distance at least 10 times larger. Strain meter data have shown that some of the strain in the Longitudinal Valley is released via slow earthquakes. Sacks, Linde, and Liu were surprised to find that these quakes seemed to occur when typhoons made landfall near the fault. It became clear that this was far more than just coincidence; the typhoons were, in fact, triggering the quakes.

The explanation lies partly in the nature of typhoons and partly in the geometry of the eastern Taiwan fault system. A typhoon is not only a potentially deadly cyclonic juggernaut; it is also a slow-moving zone of low atmospheric pressure. The relevant fault in eastern Taiwan traces the coastline, with one side of the fault on land and one under the sea.

As a typhoon passes over the fault, it reduces the atmospheric pressure on land. This change in atmospheric pressure does not affect the pressure at the bottom of the ocean



These figures show the effect of typhoons on a section of the Longitudinal Valley fault in eastern Taiwan. At left, strainmeter data show that typhoons cause a decrease in atmospheric pressure, which results in expansion of the rock. The inset graph depicts a typhoon in mid-July 2005; the lower-pressure eye of the hurricane can be seen as peaks in the middle of the graph. The larger graph shows a typhoon in December 2004 that triggered a slow earthquake; the shift in the fault resulted in compression at the strain-measuring stations, as seen in the dip in the strain traces. At bottom right, a vertical section through the fault area shows the orientation of the fault, which dips 65° westward. Black dots indicate earthquake locations, colors denote different ratios of the speeds of compressional (P) and shear (S) waves, and the dashed line shows the path of the December quake, which began less than 2 miles (~3 kilometers) below the surface and spread to a depth of over 6 miles (~10 kilometers). At top right, the map shows the study area with strainmeter locations labeled.

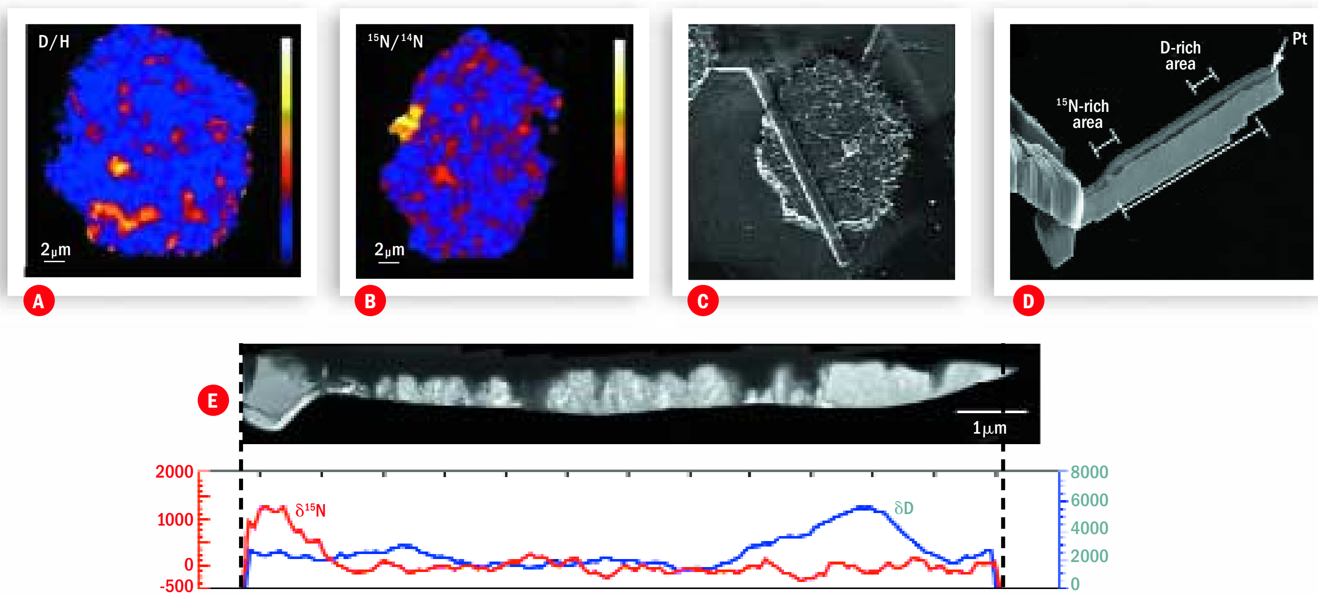
because water moves to equalize the pressure; only the land side of the fault experiences a significant pressure drop.

Depending on how much strain is stored in the fault, this one-sided decrease in pressure can cause a slow earthquake. High levels of strain make it more likely that the fault will "unclamp," resulting in slippage. Earthquake or not, the changes in strain are easily detected by the strainmeter network. The data reveal that four of nine typhoons during a yearlong study triggered significant slow earthquakes; these four typhoon-triggered quakes were the only ones that occurred during this time.

Sacks, Linde, and Liu speculate that typhoons could account for the peculiar rarity of big earthquakes in eastern Taiwan. The frequent storms on the island might trigger many subtle temblors, which could act as "pressure valves" to relieve much of the tectonic stress in the fault system. In this case, the fault would rarely build up enough strain to power a major earthquake.

Survival of the Fittest: Organic Matter from the Ancient Solar System

Spectacular shooting stars that make it to Earth—meteorites— are fragments of objects originating in the asteroid belt located between Mars and Jupiter. Meteorites bring extraterrestrial materials to our planet including, some believe, the building blocks of life—complex organic material. Now, Henner Busemann, Larry Nittler, and Conel Alexander at DTM, with colleagues, have found the best evidence yet that at least some organic particles in meteorites originated in interstellar space or, perhaps,



These images show different analyses needed to understand the origin of insoluble organic matter from very ancient meteorites called carbonaceous chondrites. The bright yellow spots on image A indicate the amount of heavy hydrogen (D) relative to the lighter hydrogen isotope (H). On image B, the glows indicate the higher abundance of the heavy isotope of nitrogen ^{15}N relative to ^{14}N. The relative proportions of hydrogen and nitrogen isotopes point to how and where the meteorite organic matter was generated. Image C is a scanning electron microscope image of a tiny fragment held in place with a microscopic strap before the sample is cut. Microscopic tweezers (left on image D) hold an ultrathin section of the material, which was extracted by a focused ion beam. Image E was produced by transmission electron microscopy (TEM), in which a beam of electrons passes through a specimen, resulting in a high-resolution image. It is aligned with a graph profiling the ratios of the hydrogen and nitrogen isotopes.

(Image courtesy Henner Busemann, Rhonda Stroud, and Tom Zega.)

in the cold, outer solar system as it was beginning to coalesce from gas and dust some 4.5 billion years ago. Their work also suggests that organic matter in asteroids is more closely related to that in comets, which formed much farther out in the solar system than scientists had previously thought.

The key to these discoveries was the team's use of novel techniques to analyze, at minute scales, the isotopic compositions of organic material from some of the most primitive meteorites known. Isotopes are different forms of an element's atoms. The relative proportions of an element's isotopes in the organic matter depend on formation conditions, such as temperature and chemical reactions.

In this work, the relative proportion of isotopes nitrogen (^{14}N and ^{15}N) and hydrogen (H and D) provide clues to how and where the meteorite organic matter was generated. The telltale sign of primitive organics is the high abundance, relative to terrestrial materials, of the heavy isotopes of hydrogen (deuterium, or D) and nitrogen (^{15}N) chemically bonded to the carbon.

Tiny interplanetary dust particles (IDPs) collected in the Earth's upper atmosphere often contain huge excesses of these isotopes, which points to the formation of their organic matter in the interstellar medium. IDPs also have characteristics indicating that they come from comets, and therefore experienced less severe processing after formation than did the asteroids from which meteorites originate.

Busemann and team found that their meteorite samples, when examined at the same tiny scales as interplanetary dust particles, have similar or even higher abundances of ^{15}N and D than those reported for IDPs, which suggests that asteroids and comets may belong to the same family tree. The team will further test this result via their analyses of the samples recently returned by the Stardust mission from comet Wild 2.

Department of Terrestrial Magnetism scientists Larry Nittler, Conel Alexander, and Henner Busemann (left to right) stand in front of the NanoSIMS ion probe. Ion probes can reveal the chemical makeup of a sample by vaporizing tiny target areas with a stream of ions. The NanoSIMS allows a more accurate count of the elements emitted than previous ion probes and is ideal for analyzing minuscule grains from meteorites, interstellar dust particles, and comets, such as those from Wild 2 obtained via the Stardust mission.

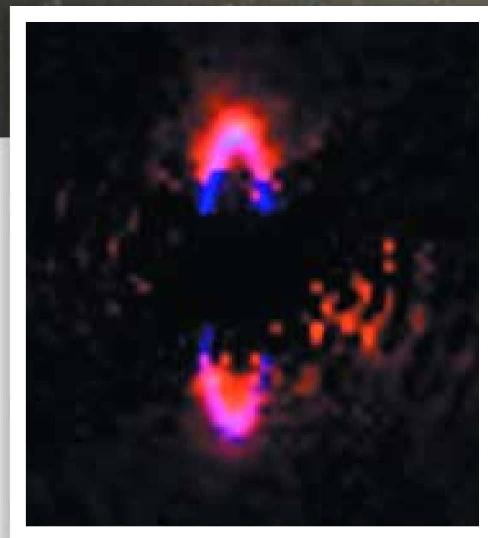
(Image courtesy Henner Busemann.)

Can Dusty Disks Beget Other Earths?

As gas, dust, and rocky chunks swirled around the Sun during the first few tens of millions of years of our solar system's history, comets or asteroids ferried life-giving water and possibly complex hydrocarbons to the young Earth. To understand what leads to life-bearing worlds, Alycia Weinberger and colleagues look to distant stars and their young planetary systems—circumstellar disks of dust and gas. Weinberger and coworkers are deciphering the composition of these disks and are determining whether the ingredients for life are present. It turns out that Earth's chemistry might not be that rare.

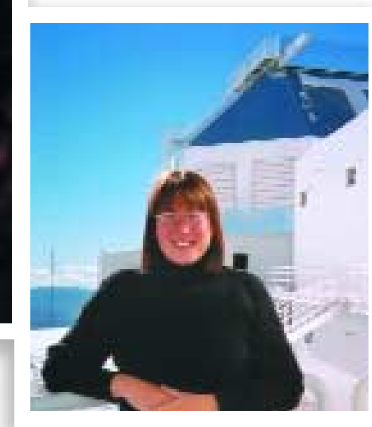
Dust and gas in circumstellar disks reflect or absorb the light from their stars in specific ways. Different

Terrestrial Magnetism, CONTINUED



This young disk system around star HR 4796A appears red, which suggests the presence of long organic chains, possibly similar to the tholins found in the red rings of Saturn and in the atmosphere of its moon Titan. The color indirectly suggests the possibility of methane ice, such as that believed to be on the surface of a distant icy body in our own system named Centaur Pholus 5145.

(Image courtesy John Debes, Alycia Weinberger, and Glenn Schneider.)



Department of Terrestrial Magnetism astronomer Alycia Weinberger at Carnegie's Las Campanas Observatory

(Image courtesy Alycia Weinberger.)

molecules, such as water and methane ices, can coat the dust and reflect light at characteristic wavelengths. Carbon-rich materials can appear red and not very reflective, for instance. By analyzing the light from a distant disk around HR 4796A, a 10-million-year-old star some 2.5 times as massive as the Sun, Weinberger, postdoctoral researcher John Debes, and their team recently found it to be very red and dark, indicating the presence of organic materials. They suspect long organic chains similar to the tholins found in the red rings of Saturn and in the atmosphere of its moon Titan—a promising location in the search for life. The results also closely match the color of a distant icy body in our own system named Centaur Pholus 5145, believed to have a surface composed of water and methane ice—more evidence hinting that HR 4796A may be able to produce Earth-like planets.

Other evidence for this rich, carbon chemistry comes from Beta Pictoris, a star that is a little less massive and just a bit older than HR 4796A. For years, it has been known that small orbiting bodies break up to enrich the disk in gas and dust. Using NASA's Far Ultraviolet Spectroscopic Explorer and the Hubble Space Telescope, former Carnegie Fellow Aki Roberge, with Weinberger and colleagues, analyzed the disk's gas and detected unusually high quantities of life-essential carbon, more than in our solar system's comets and asteroids or in the star itself. The researchers pose several possible explanations for this abundance: the vaporization of unusually carbon-rich asteroids or comets; the difference between young and old comets and asteroids, where the young may be more carbon rich; or evaporation from cold methane-rich bodies.

For more tantalizing clues to early solar system chemistry, Weinberger and colleagues have embarked on new programs using the Spitzer Space Telescope, the Hubble Space Telescope, and Carnegie's Las Campanas Observatory to find other young solar systems potentially amenable to extraterrestrial life. •

FIRST LIGHT & THE CARNEGIE ACADEMY FOR SCIENCE EDUCATION

Teaching the Art of Teaching Science

Science Education at CASE: Full Steam Ahead

The Carnegie Academy for Science Education's (CASE) venture into the secondary school arena received a huge boost in 2006. The Division of Undergraduate Education of the National Science Foundation (NSF) awarded it an $820,000 three-year grant to support D.C. Biotech: Improving Opportunities for Urban Minority Students. The project is designed to improve science competencies of D.C. high school students through biotechnology certification, the broadening of students' career opportunities, and the improvement of biotech workforce diversity. CASE is the lead organization in developing the program. Other consortium members include the D.C. Public Schools (DCPS) Office of Career and Technical Education, McKinley Technology High School, Ballou Senior High School, Montgomery College, the Biotechnology Industry Advisory Committee, Walter Reed Army Medical Center, and numerous other regional research and educational institutions.

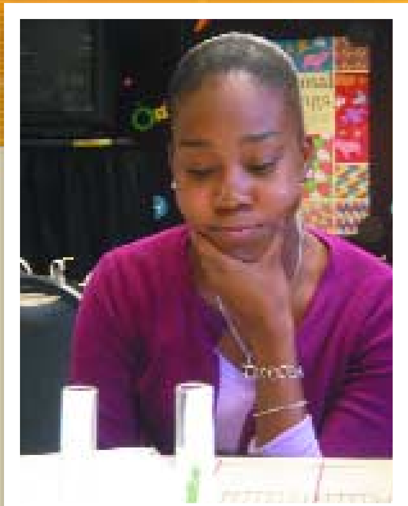
The CASE summer 2006 program had some new dimensions. It marked the second year in which D.C. elementary school teachers, formerly trained by CASE, successfully "soloed" in the teaching of other D.C. public school teachers in the art of teaching science, mathematics, and technology. Maxine Singer, Carnegie president emerita and CASE senior scientific advisor, designed and taught the second year of a program that was developed by CASE for middle school science and math teachers.

The new program is designed to teach science through the study of astrobiology, a multidisciplinary examination of the chemical and biological conditions that led to life on Earth and the circumstances that are most likely required for it to exist elsewhere. Teachers learned through experimentation, field trips, and classroom visits by Carnegie astrobiologists Paul Butler and Marilyn Fogel. Following CASE's long tradition of nurturing outstanding mentor teachers, a 2005 Astrobiology Institute alumnus, Guy Brandenburg, cotaught the 2006 institute with Singer.

President emerita and senior scientific advisor to CASE Maxine Singer (left) shows middle school teacher Martha Harris laboratory techniques during the 2006 Astrobiology Institute.

First Light & the Carnegie Academy for Sciene Education, CONTINUED

CASE codirectors Toby Horn and Julie Edmonds are principal instructors in the D.C. Biotech summer work experience. The students are paid by the D.C. Government's Department of Employment Services as part of its summer employment program for teens. Some 24 rising juniors and 16 rising seniors from McKinley Technology High School, as well as five DCPS teachers, learned biotechnology workplace practices and procedures. With coteachers from DCPS, Horn instructed the seniors, while Edmonds and coteachers taught the juniors. The juniors learned basic biotech skills that culminated in weeklong group projects—either forensic DNA fingerprinting or deciphering the concentrations of pigments in soft drinks. The seniors worked on numerous projects throughout the summer. Some chose to investigate the best conditions needed to cut DNA specifically or to determine which vegetable seeds could germinate in high-salt conditions, while others compared the sensitivity of different forensic tests or looked at the effect of purified yogurt bacteria on protein patterns of milk whey. All of the students used state-of-the-art laboratory equipment, rarely seen in high school labs, purchased for the school by the DCPS Office of Career and Technical Education. •



(Top) Middle school teacher Kendra Neal compares chlorophyll chromatography patterns during the 2006 Astrobiology Institute.

(Bottom) Rising senior Monica Artis shows visitors a protein assay as part of the D.C. Biotech project open house. From left to right are Monica Artis; Moses Shanfield, chairman of Forensic Science at George Washington University; and David Hanych, project director at NSF.

(Images courtesy Toby Horn.)