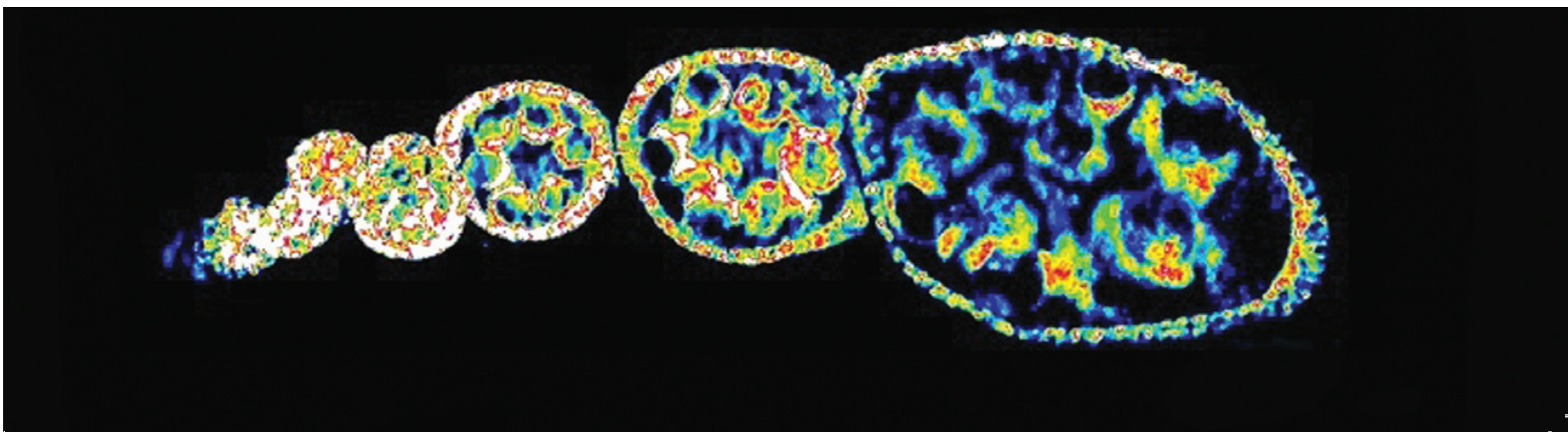
CarnegieScience

The Newsletter of the Carnegie Institution

SUMMER 2016

EMBRYOLOGY ▫ GEOPHYSICAL LABORATORY ▫ GLOBAL ECOLOGY ▫ THE OBSERVATORIES ▫ PLANT BIOLOGY ▫ TERRESTRIAL MAGNETISM ▫ CASE: CARNEGIE ACADEMY FOR SCIENCE EDUCATION

On the Inside



CARNEGIE SCIENCE

CARNEGIE INSTITUTION FOR SCIENCE

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Déjà Vu in the Realm of Genetic Engineering

Carnegie biological scientists employ powerful tools for studying the growth, physiology, and adaptations of plants, animals, and microbes. Modern genetics explores how genes control these processes. Traditional genetics identifies genes needed for a certain function, such as formation of proper muscles, by looking for mutants that have muscle defects. Modern molecular geneticists have invented tools for engineering genes to test ideas about how they work.

On May 9, Carnegie Science cosponsored, with the Council of Scientific Society Presidents and the Kavli Foundation, a talk by Professor Jennifer Doudna of the University of California, Berkeley. Dr. Doudna has made pioneering and fundamental discoveries about how bacteria protect themselves from viral infections. Viruses insert their own genes into bacteria, and bacteria have, in turn, evolved defense systems that detect and destroy these viral genes. Even more impressively, the bacteria retain a memory of past viral infections, allowing more effective responses to new infections by an old enemy.

About 550 people arrived at our P Street headquarters in Washington, D.C., to hear Dr. Doudna describe the defense system she studies, called CRISPR. Why would these people, mostly nonbiologists, want to hear about this seemingly esoteric subject? The work of Dr. Doudna and others in the field has allowed the adaptation of CRISPR as the most powerful gene-engineering tool yet devised, and it works in all organisms. Dr. Doudna did a superb job of first explaining the origin

Dr. Maxine Singer of the National Institutes of Health with Dr. Paul Berg of Stanford, a Nobel Prize winner
Image courtesy NIH

of the CRISPR tool as the outcome of pure curiosity…with no application in sight. Then she traced the dawning realization that highly precise changes in genes of flies and plants and mice…anything…could be made by adapting the bacterial defense system in fairly simple ways. A revolution in genetic engineering is upon us, she demonstrated.

Dr. Doudna described discussing CRISPR engineering possibilities with the coworkers in her own lab group. Some said "that's amazing," and some said "that's scary." Some said both, and both were right. CRISPR can be used for good purposes, such as modifying genes in the lab to ask questions about how they work. Many Carnegie scientists in our Departments of Embryology and of Plant Biology routinely use CRISPR and related engineering tools, much as an instrument designer in our Observatories would use a milling machine. Shape it, try it, change it, try it. Beyond research on lab plants and animals, where CRISPR is used today, it could next be employed for engineering cells for agricultural purposes. Although a long way off, there is also considerable potential for repairing damaged genes to correct in human disease. In crops, there is the potential to change crop plants to make them more resistant to pathogens that cause devastating crop loss, or to design plants that prosper in difficult conditions such as low light, drought, or heat. Plant dependency on fertilizer or pesticide use may be reduced. There may be ways to engineer farm animals to make them more resistant to disease and require fewer antibiotics.

Genetic engineering has been going on ever since humans started cultivating plants and domesticating animals. It was done (and often still is done) by searching for accidental variants that seem useful. Get seeds from the plant in the back of the garden that produces the best-tasting fruit, not from the one in front with bitter-tasting fruit. Choose horses for breeding that have the greatest endurance and don't bite. Over hundreds of generations, this has had a huge effect on our domesticated plants and animals. Look at the variations of dogs, for example, or the tiny ears of ancestral corn in comparison to the huge sugar-filled cobs of modern sweet corn. This is not an efficient process, since you need to be lucky to get something useful. A better way is to understand what genes matter, like for disease resistance or protein production, and then modify those genes to boost resistance or protein. This knowledge-based modification requires understanding what genes do, a goal of work done by many Carnegie biologists.

One objection to advanced gene engineering is the potential for unknown events resulting from transferring a piece of one organism's DNA into another. CRISPR and techniques like it can be used for inter-species transfers, but can also modify an organism's own genes—without transfer between species. Another objection is that targeted gene modifications will be used to alter plants or animals in ways that are potentially risky or objectionable. Given the vast number of possible manipulations, such objections are well worth debating. Wondrous and harmless things can be done in medicine and agriculture, I believe, using genetic engineering, but that certainly does not mean I would support all uses of the technology.

CRISPR can be used for manipulating human genes. Potential human genetic modification troubled some of Dr. Doudna's coworkers, and many other people feel the same way. While the potential for treating genetic disease is thrilling, the potential for crossing ethical boundaries is fairly obvious. This was the reason for a National Academies CRISPR conference this past year, and for many other ongoing discussions among ethicists, the public, and scientists.

Why my title of "Déjà vu"? In 1975, a group of molecular geneticists realized that they had devised the first powerful ways to clone DNA, which meant that specific genes from any organism could be purified, grown in bacteria, reproduced as

Why my title of "Déjà vu"? In 1975, a group of molecular geneticists realized that they had devised the first powerful ways to clone DNA, which meant that specific genes from any organism could be purified, grown in bacteria, reproduced as vast numbers of copies, and manipulated. Could that lead to a dangerous outcome?

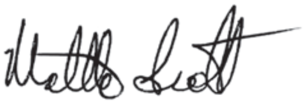
vast numbers of copies, and manipulated. Could that lead to a dangerous outcome? At a now-famous conference held at Asilomar (in California), the scientists decided to self-regulate this new technology. They classified different types of experiments across a range from safe to a matter of concern to ones that should not be done at all. They prescribed types of containment laboratories for possibly dangerous experiments, and specified types of host bacteria that should be used to reduce hazards. For example, cloning genes from viruses that cause cancer in mice was viewed as something that should await proper safeguards. That Asilomar event was viewed as remarkable by science historians, since scientists regulating themselves was a new phenomenon. Among those scientists was our own Dr. Maxine Singer of the National Institutes of Health, a future president of Carnegie Institution for Science and a present trustee. She is shown in 1975 with Dr. Paul Berg of Stanford, a Nobel Prize winner and another leader of the conference (page 2).

Now, with echoes of Asilomar, scientists debate the uses of CRISPR. The concerns now focus on ethically undesirable applications of this exceptionally powerful engineering tool. Like the public and ethicists who have begun to examine complex issues arising from CRISPR, scientists have diverse views.

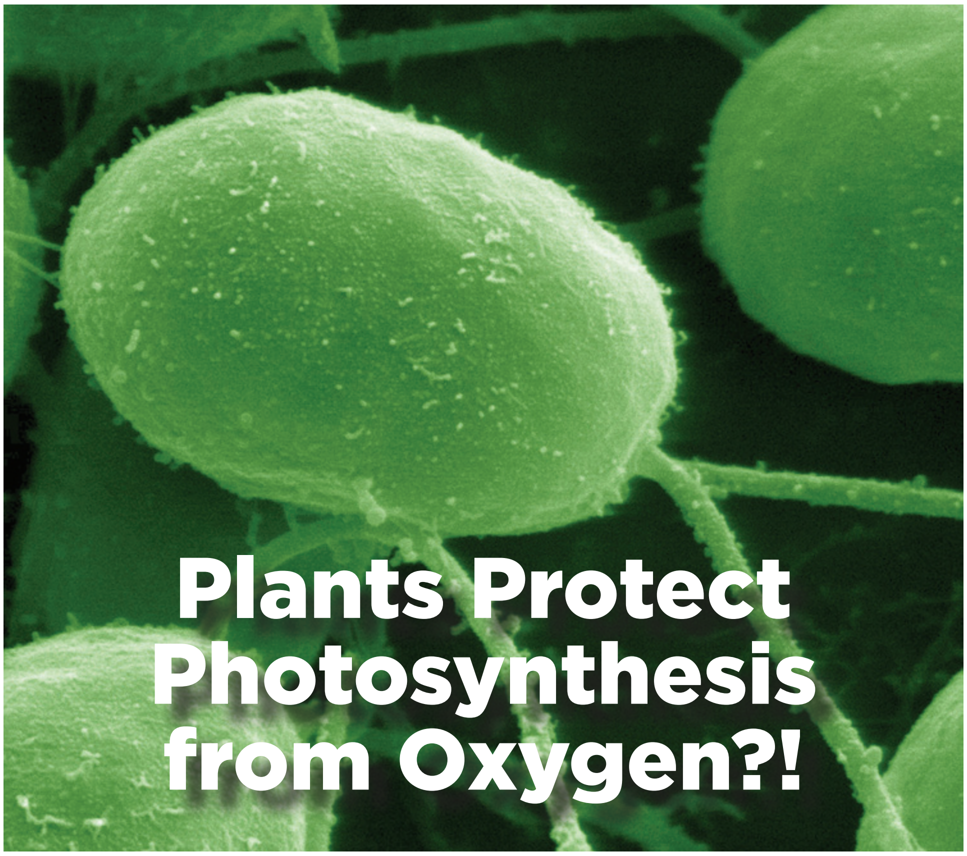
Last year, a group of biologists including Paul Berg published a recommendation that no manipulation for clinical applications should be done using human germline cells, i.e., cells involved in reproduction like sperm and eggs. (*Science* volume 348, pages 36-38). They wrote "it would be wise to begin a discussion that bridges the research community, relevant industries, medical centers, regulatory bodies, and the public to explore responsible uses of this technology." They reasoned that the ethical implications have not been sufficiently addressed, nor is the science advanced enough to rule out unexpected problems caused by well-intentioned modifications. While that view is widely shared, four countries (Japan, England, China, and Sweden) now allow some degree of manipulation of human germline cells. For example, to suppress cancer, should only human blood cells or other specific afflicted tissues be modified, or should germline cells be edited to prevent traumatic inherited genetic diseases (including cancers)? What risks are acceptable? And looking ahead, do we want engineered children?

Our Carnegie plant and animal scientists explore gene functions and networks of genes involved in complex developmental and physiological events. CRISPR is proving to be a dream-come-true tool for exploring gene functions, with the goal of understanding how things work, how evolution happens, and how gene editing can serve humankind. Possibilities for treating cancer, infectious disease, and agricultural blights are *real*. It is good to see emerging, however, a vigorous and healthy public discussion of which ideas are great and which carry dangers or otherwise cross ethical lines.

I am delighted that the audience at our headquarters asked spectacularly excellent questions in post-talk discussions. Carnegie Science convenes such discussions as a responsibility and mission, to spur debate and spread ideas, and thus to help shape a healthy future for all of us. Simple answers to questions raised by new technologies are rarely sufficient. In the case of CRISPR, we will continue, in our labs and in our events, to engage in deep thought about how and when it should be used. I want to close by thanking our guest speaker Jennifer Doudna for presenting a talk that was fascinating...and responsible.



Matthew Scott, *President*



Plants Protect Photosynthesis from Oxygen?!

During the daytime, plants convert the Sun's energy into sugars using photosynthesis, a complex, multistage biochemical process. New work from a team including Carnegie's Mark Heinnickel, Wenqiang Yang, and Arthur Grossman identified a protein needed for assembling the photosynthetic apparatus, which may help us understand the early days of photosynthesis on Earth when oxygen was not abundant in the atmosphere. *Proceedings of the National Academy of Sciences* published their work.

Photosynthesis takes place in stages. In the first stage light is absorbed and used to produce energy molecules, with oxygen as a byproduct. These energy molecules are then used to power the second stage of photosynthesis, in which carbon dioxide from the air is fixed into carbon-based sugars, such as glucose and sucrose.

Working with the green alga *Chlamydomonas*, the research team—which also included graduate students Rick Kim and Tyler Wittkopp of Stanford University, Karim Walters of Pennsylvania State University, and visiting professor Stephen Herbert of the University of Wyoming—focused on a protein, CGL71. This protein was already known to be involved in assembling the array of proteins that make up the part of the photosynthetic apparatus involved in the first stage of photosynthesis, the one that turns sunlight into the energy molecules that power the second stage and that also has an oxygen byproduct. But little about CGL71's role in this assembly process was understood until now.

The team was able to figure out that at least one aspect of CGL71's job is to protect the photosynthetic apparatus from oxygen during its assembly. Yes, that's right, from oxygen. You see, photosynthesis first evolved in bacteria about 3 billion years ago, a time when the Earth's atmosphere had very little oxygen. Of course, as photosynthetic bacteria became more and more populous on ancient Earth, the atmosphere changed, eventually creating the oxygen-rich air that we breathe today.

Oxygen is a very reactive molecule that can disrupt the iron-and-sulfur-containing clusters of proteins that are crucial to photosynthesis. Like CGL71, these clusters are critical for the first stage of photosynthesis, where they move electrons to create the energy molecules. Just as oxygen can rust iron, it can damage the iron-and-sulfur proteins of the photosynthetic apparatus.

So as oxygen accumulated in the Earth's atmosphere, the photosynthetic mechanism needed protection from its own byproduct, and CGL71 is one component that evolved to keep the photosynthetic apparatus stable under these new conditions.

"When we look at this critical assembly protein, CGL71, it's as if we are looking back in time to the era when photosynthetic apparatus had to gradually adjust to the changing atmospheric conditions of our planet," Grossman said. ■

Arthur Grossman

Mark Heinnickel

Wenqiang Yang

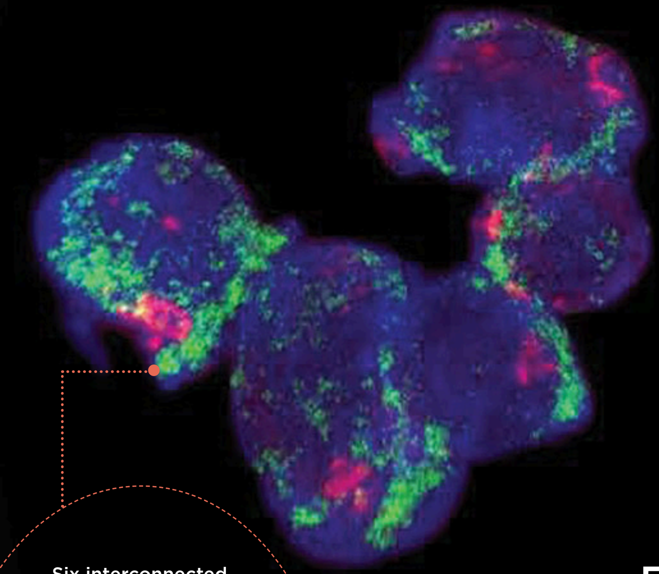
(Above right) The false-color scanning electron microscope image shows *Chlamydomonas*, a blue-green alga that is used widely in plant science research including for this study.

Image courtesy NSF, Louisa Howard, Dartmouth College

SUPPORT

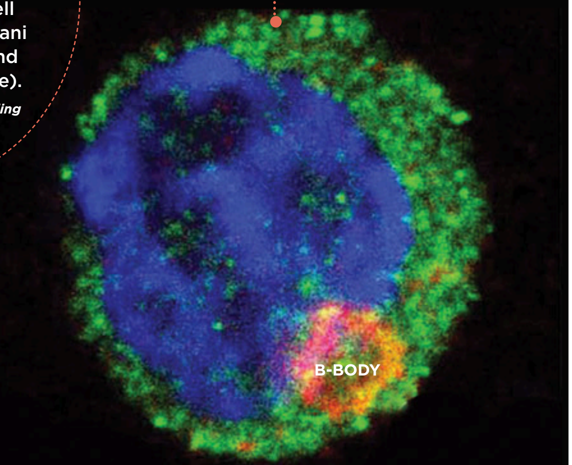
NSF, Stanford Graduate Fellowships, Stanford U.'s Biology Department, Carnegie's Department of Plant Biology, DOE, and the College of Agriculture and Natural Resources and the Agricultural Experiment Station at U. Wyoming supported this work.

The ENIGMATIC EGG



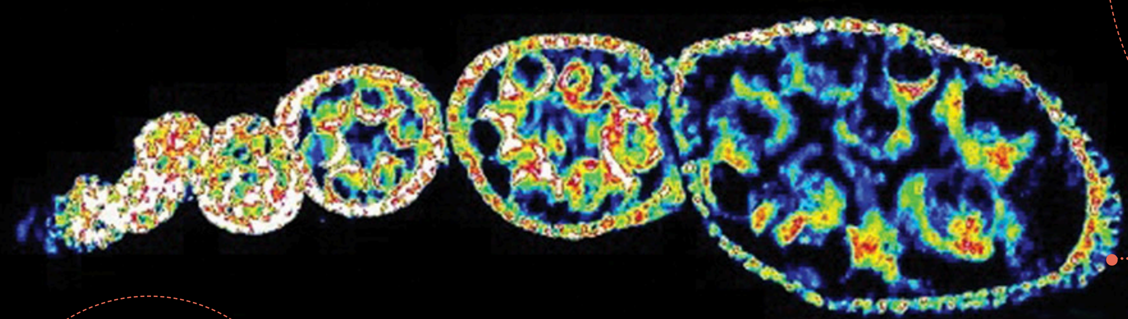
Six interconnected sister germ cells from a developing mouse ovary are shown, and organelles of two types are highlighted: Golgi elements (red) and mitochondria (green). The germ cell at the far left has received organelle donations and is becoming an oocyte with an increased number of Golgi and mitochondria, which are forming a Balbiani body. Transfer is not yet complete.

Image courtesy Allan Spradling



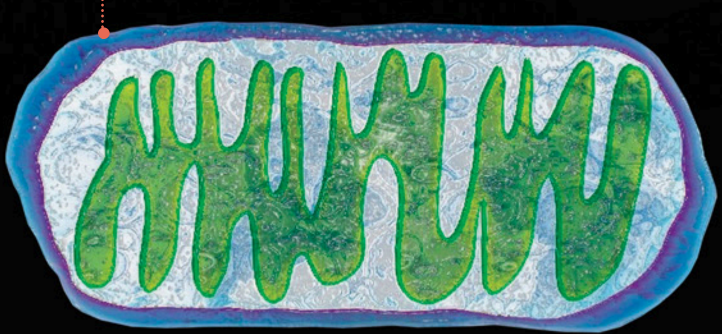
This image shows a mouse egg cell after transfers from nurse cells are complete. Note the nucleus (DNA, blue), cytoplasm (germ cell marker, green), Balbiani body ("B-Body"), and Golgi marker (orange).

Image courtesy Allan Spradling



Insect ovaries are composed of tubes, called ovarioles, one of which is shown here. It is stained with a mitochondrial membrane-potential stain. The more red/white the color is, the higher the mitochondrial membrane potential, and in turn the higher mitochondrial activity it represents. White/red colors indicate the highest activity, while blue/black colors indicate the lowest activity.

Image courtesy Matt Sieber



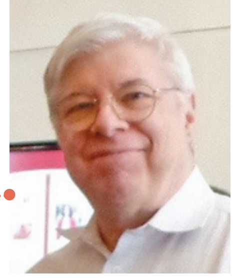
This is an artist's depiction of mitochondria. The purple on the outside border represents the outer mitochondrial membrane. The blue on the inside depicts the mitochondrial inner membrane space.

Image courtesy Matt Sieber

Allan Spradling was the director of the Department of Embryology from 1994 until this spring. He now conducts his research full time.

Image courtesy Christine Pratt

Allan Spradling's lab studies the biology of reproduction, particularly egg cells. His lab members have unraveled some mysteries about how this unique cell operates.



Cells Sacrifice to Make an Egg

Spradling and former postdoctoral associate Lei Lei demonstrated that mammalian egg cells gain crucial cellular components at an early stage from their undifferentiated sister cells, called germ cells. This mechanism had previously only been documented in lower animals and may be a key to understanding the egg's unique properties. *Science First Release* published their work.

Egg cells are the only cells that are capable of developing into a new individual. Yet only a small number of egg cells are produced by a female, so they are a limiting factor in many aspects of reproductive science. Understanding how eggs gain the power to develop into a new individual is crucial to scientists and to doctors interested in improving a female's reproductive odds by increasing their egg supply.

Working with mice, Lei and Spradling tested their belief that certain undifferentiated germ cells learn to develop into eggs very early during their production in the ovary, when germ cells are found in small clusters of interconnected sister cells, all daughters of the same parent cell.

Similar clusters have been observed in lower animals such as the fruit fly. In flies, most of the germ cells, known as nurse cells, transfer their cellular organs—called organelles—and cytoplasm—the fluid solution in which the organelles are suspended—to just one cell, which then becomes an egg.

Until now, the germ cell clusters in mammalian ovaries were thought by most researchers to be nonfunctional, evolutionary relics. But Lei and Spradling found that as in fruit flies, these connected, mammalian sister germ cells also exchange cytoplasm and organelles—including mitochondria, the cell's energy factory; Golgi, the cell's packaging service; and centrosomes, which manage cell division.

Among the five germ cells in an average mouse cluster, four cells transfer most of their organelles into the fifth, which alone becomes an egg cell. The new organelles coalesce into a structure called a Balbiani body, a dark, circular blob seen only in young eggs and whose origin was previously unknown.

When the researchers blocked this transfer, few egg cells were able to form, demonstrating that, like insects and invertebrates, mammals undergo an ancient process of organelle transfer from the nurse cells to the future egg.

How might this sacrifice by the nurse cells help the egg cell gain the power to develop?

The acquisition of so much cellular material from its sisters almost certainly helps the egg start a program of growth through which it becomes the largest cell in the mammalian body. Lei and Spradling also hypothesize that the transfer includes additional factors that "reprogram" the egg's chromosomes and give it the capacity to develop into an embryo. The Balbiani body, itself generated by the transfer, might further support egg development by producing nutrients or hormones. Finally, damaged cellular organelles might be moved outward during transfer, away from the egg, purifying it.

"Understanding how mammalian oocytes are built will greatly assist efforts to combat human infertility and to improve animal husbandry," Lei commented.

"This work also shows the importance of using model organisms such as the fruit fly *Drosophila* to study subjects of medical importance," Spradling added. "Research on *Drosophila* guided this work and will be essential to identifying the specific human factors and their genes that reprogram egg cells and make development possible."

SUPPORT
The Howard Hughes Medical Institute (HHMI) funded this work.

Metabolism Linked to Egg Development

Reproduction is highly dependent on diet and the use of nutrients to grow and generate energy. This is seen in women, who must provide all the nutritional building blocks required to support a growing embryo. As a result, metabolic diseases like diabetes and obesity are closely linked with several female reproductive disorders such as infertility, polycystic ovary syndrome, and ovarian cancer. The precise links between reproductive processes and metabolism remains poorly understood, however.

In a recent study, published in *Cell*, Carnegie's Matthew Sieber, Michael Thomsen, and Allan Spradling used the fruit fly to unravel the links between metabolism and egg development. As eggs (oocytes) enter the final stages of development, they accumulate large amounts of proteins, lipids and sugars to fuel the embryo. The team was able to identify a functional and biochemical change in the developing oocytes that triggers carbohydrate storage.

The cellular structures mitochondria convert nutrients, such as sugar, into energy to fuel the cell. The team found that during the final stages of oocyte development, insulin signaling is inactivated in oocytes, causing a fundamental change in the biochemical properties of the mitochondria and reducing mitochondrial activity. This change leads to a build-up of sugars in the oocyte that can then be used after fertilization to fuel the developing embryo.

Their findings are consistent with previous observations that show mammalian oocytes also display low levels of mitochondrial activity, suggesting similar changes in mitochondrial function and sugar storage may be an essential aspect of oocyte production in many species.

"We believe our findings are directly applicable to understanding human infertility," Spradling said. "Polycystic ovary syndrome is the leading cause of female infertility, and it is strongly associated with diabetes and insulin resistance, which suggests that defects in the metabolic aspects of oocyte maturation may be the underlying source of the disorder."

Furthermore, the team believes that mitochondrial defects during oocyte development may contribute to oocytes that fail during *in vitro* fertilization (IVF) treatment, although further research is required. ■

SUPPORT
HHMI, the Carnegie Institution for Science, and the Jane Coffin Childs Memorial Fund supported this work.

Janice Dunlap (left) and Bill Kupiec (middle) receive 2016 Service to Science Awards from Carnegie's president, Matt Scott.

Janice Dunlap & Bill Kupiec Receive 2016 Service to Science Awards

Janice Dunlap of the Department of Terrestrial Magnetism (DTM) and Bill Kupiec of the Department of Embryology received the 2016 Service to Science Awards at this year's Carnegie Evening on May 5 at the administration building. The Carnegie Service to Science Award was created to recognize outstanding and/or unique contributions to science by Carnegie employees who work in administration, support, and technical positions. Any individual at Carnegie may nominate an eligible employee for this award, which is selected by an internal review panel.

Janice Dunlap has worked at the Department of Terrestrial Magnetism for over 30 years. She began her career as editorial assistant to David James for the national seismic program known as PASSCAL. She then became assistant to the director, providing exemplary service to four DTM directors. She was a key staff person for the MESSENGER mission to Mercury and the NASA Astrobiology project, working with Director Sean Solomon. Beyond her service to the directors she is largely responsible for setting the tone of the department, which has remained consistently collegial, collaborative, productive, and supportive of young and older staff and postdocs. She was recognized for her many contributions to making DTM such an efficient and enjoyable place to work.

Bill Kupiec has been the information technology manager at Embryology for over 24 years. He manages all the computers, network infrastructure, network security, web servers, e-mail servers, file servers, telephone systems, building security systems, audio/visual systems, and he oversees the department's microscopy efforts. In 2000, Bill left the institution to become a project engineer in commercial architectural millwork. During this time, Bill gained experience in engineering and project management for many high-end projects. Bill returned to Embryology in 2002, again as information technology manager. This was at a time when plans for the new Singer Building were beginning to take shape. He was recognized for his efforts to go above-and-beyond the call of duty and for his tireless work on behalf of the Embryology staff.

Disk-Covering Planet Formation

Department of Terrestrial Magnetism staff astronomer Alycia Weinberger was the 2016 Carnegie Evening speaker. Weinberger talked about looking for and uncovering young Milky Way stars and their disks, which is where planets are born. Disks provide raw dust and gas for protoplanets, which over time are swept up to form larger and larger objects. Researchers have dealt with numerous challenges in this research, such as masking out the light from the star.

Once the excess radiation from a star is subtracted, astronomers can determine an object's distance, composition, and timescales for planet formation. These disks do not last long in astronomical terms, some 3 to 10 million years.

Weinberger gave a tour of different disk orientations, and different methods for studying them. She uses both the spaced-based Hubble telescope and ground-based telescopes, including Carnegie's Magellan and the Atacama Large Millimeter Array (ALMA), both in Chile. Astronomers preferentially look for young stars with surrounding disks; however, the youngest ones are not that close to us. She discussed the advantages of the different telescopes. On the ground, disturbances from the atmosphere have to be corrected, which requires adaptive optics, such as the Magellan Adaptive Optics Secondary Mirror (MagAO), which eliminate disturbances in real time.

Astronomers focus on gaps that are seen in disks, which could indicate that a planet is sweeping up the debris. She cautioned that other reasons for the gap, like less reflective ice particles, also have to be considered.

After discussing how researchers have overcome some of the technical challenges, Weinberger talked about what researchers have discovered about planet formation. For instance, forming an Earth takes between 30 million to 100 million years. Researchers' ultimate goal, however, is to find a disk like our own, which is extremely tenuous. Such very thin disks are out of reach now, but she emphasized that they could be reachable with a new generation of telescopes like the Giant Magellan Telescope. ■

Department of Terrestrial Magnetism staff astronomer Alycia Weinberger talked about her work studying disks around other stars to learn about planetary formation.

Michael Stambaugh Appointed Carnegie's First Chief Investment Officer

Michael Stambaugh, formerly Managing Director of Investments at the Alfred P. Sloan Foundation, joined Carnegie Science as its first Chief Investment Officer on March 28, 2016.

Stambaugh brings over 15 years of experience managing endowment assets. He began his career in commercial banking and moved to endowment management with the Metropolitan Museum of Art in 2000, where he was part of a five-person team managing the Met's $2.5 billion endowment and the museum's treasury function. American University in Cairo recruited him to establish an in-house investment office for their $600 million endowment. At the Sloan Foundation he was in a senior position on a four-person team driving all aspects of the investment process, including the formulation of investment strategy, strategic asset allocation, manager selection, and risk management for their $1.8 billion endowment.

"We are extremely excited to welcome Mike to Carnegie as we expand the stewardship of our endowment," remarked Carnegie Chief Operating Officer Timothy Doyle. "He brings deep experience in all aspects of asset allocation, manager selection, portfolio construction, and risk management, along with a strong interest in the scientific mission of Carnegie."

Carnegie president Matthew Scott commented: "I am delighted that Mike is joining Carnegie. His skills and experience will be a tremendous addition. Andrew Carnegie established our endowment in 1902 as a way of giving scientists freedom to pursue their ideas with minimum pressures from outside influences. This has led to an extraordinary century-plus of discoveries and inventions. Our current scientists continue in that tradition, and skilled management of our investments is fundamental to their sustained success."

Stambaugh received a B.S. in finance from Florida State University and an M.B.A. from Pepperdine University. He is a Chartered Financial Analyst (CFA). ■

Rebecca Albright Honored with 2nd Carnegie "Postdoctoral Innovation and Excellence" Award

Rebecca Albright at work
Images courtesy Rebecca Albright

Rebecca Albright, a postdoc in the Caldeira lab at Global Ecology since 2014, is the latest recipient of the newly formed Carnegie Postdoctoral Innovation and Excellence (PIE) Awards. She has been working on ocean acidification, specifically the effects of ocean acidification on corals and coral reef systems.

To this end, the lab had been trying to succeed with an experiment to add alkalinity to seawater flowing over a natural coral reef to buffer acidification for the past five years.

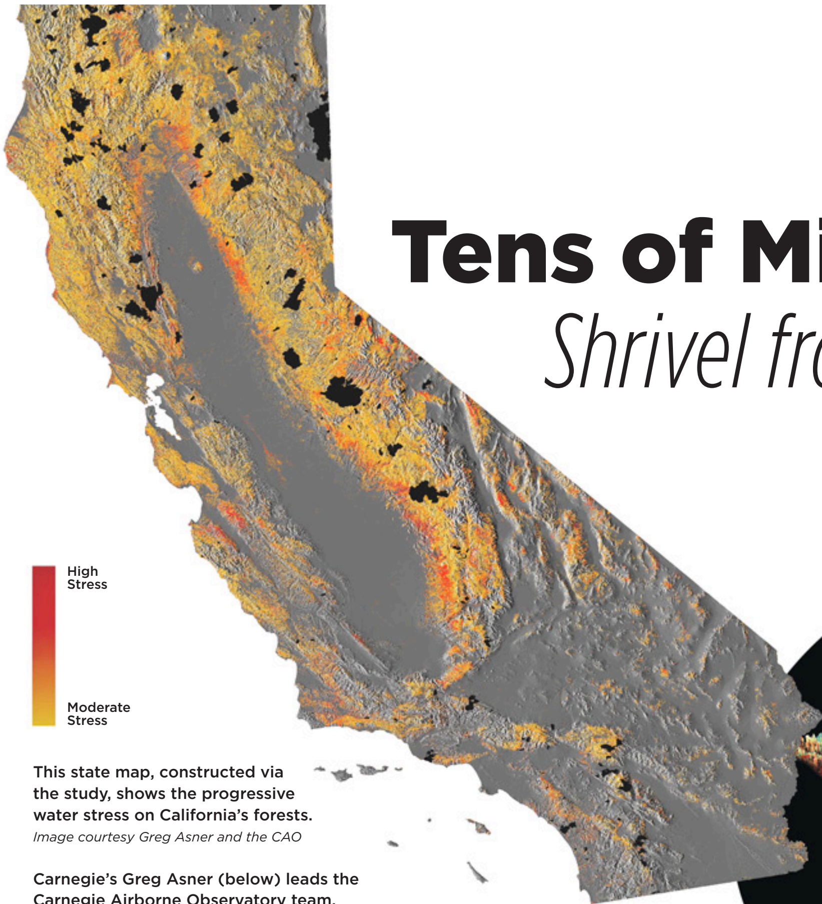
Rebecca was the scientific leader of the third attempt at the experiment. It was the first one to succeed, in no small part due to Rebecca's leadership. A paper describing the experiment, with Rebecca as first author, was published in *Nature*. The accompanying news story "Landmark experiment confirms ocean acidification's toll on Great Barrier Reef" featured the work.

Rebecca also recently led a successful proposal for the first Carnegie Venture Grant competition, which links different Carnegie researchers from different disciplines to address a common problem.

Postdoctoral Innovation and Excellence Awards are made through nominations from the department directors. The recipient is chosen by the Office of the President. One postdoc is honored every quarter for their extraordinary accomplishments with a prize of $1000, and being guest of honor at a departmental gathering with celebratory pies.

Carnegie President Matt Scott remarked, "Rebecca has the vigorous spirit of adventure, intense curiosity and imagination, and the passionate leadership and drive that we look for in Carnegie researchers. She fits the bill in all categories and is very deserving of this award. Join me in congratulating her." ■

Tens of Millions of Trees
Shrivel from California Drought



This state map, constructed via the study, shows the progressive water stress on California's forests.
Image courtesy Greg Asner and the CAO

Carnegie's Greg Asner (below) leads the Carnegie Airborne Observatory team.
Image courtesy Robin Kempster

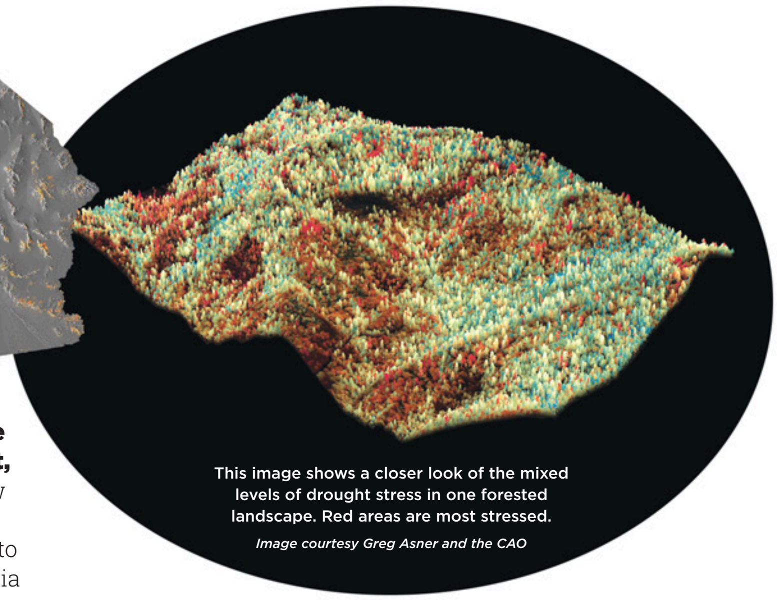
California's forests are home to the planet's oldest, tallest, and most-massive trees. New research from Carnegie's Greg Asner and team reveals that up to 58 million large trees in California experienced severe canopy water loss between 2011 and 2015 from the state's historic drought. *Proceedings of the National Academy of Sciences* published their results and the story was covered widely by the media.

In addition to the persistently low rainfall and high temperatures, outbreaks of the destructive bark beetle increased forest mortality risk. But the team gained more than just a picture of trees that had already died.

To obtain a large-scale understanding a forest's responses to the drought, and ongoing changes in climate, required a higher-tech approach. Asner's team used the laser-guided imaging spectroscopy tools on the Carnegie Airborne Observatory (CAO) to measure for the first time the full impact of the drought on California's forests. They combined the CAO data with more traditional satellite data going back to 2011.

The team's new approach revealed a progressive loss of water in California's forest canopies over the four-year span. Mapping changes in canopy water content tells scientists when trees are under drought stress and greatly aids in predicting which trees are at greatest risk of death and fire.

"California relies on its forests for water provisioning and carbon storage, as well as timber products, tourism, and recreation, so they are tremendously important ecologically, economically, and culturally," Asner explained. "The drought put the forests in tremendous peril, a situation that may cause long-term changes in ecosystems that could impact animal habitats and biodiversity."



This image shows a closer look of the mixed levels of drought stress in one forested landscape. Red areas are most stressed.
Image courtesy Greg Asner and the CAO

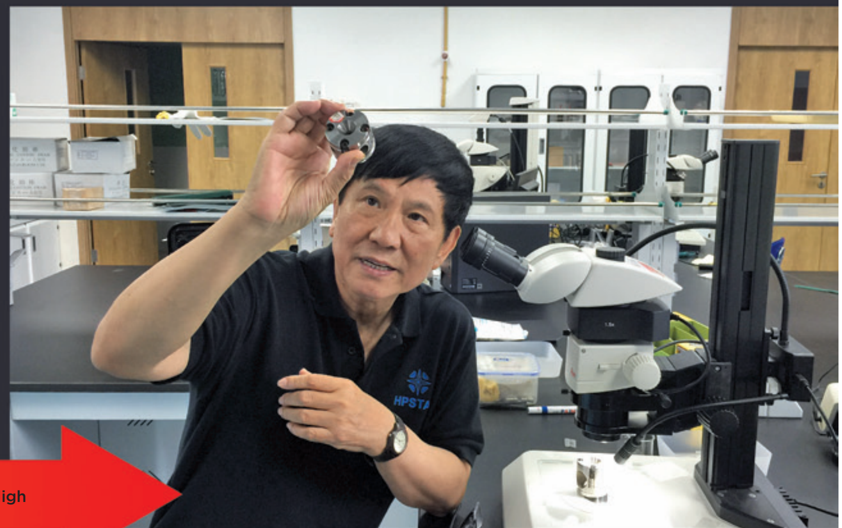
The team's advanced tools showed that about 41,000 square miles (10.6 million hectares) of forest containing up to 888 million large trees experienced measurable losses of canopy water between 2011 and 2015. Up to 58 million large trees reached water loss thresholds that were extremely threatening to long-term forest health. Given the severity of the situation, even with increased precipitation due to El Niño, if drought conditions reoccur in the near future, the team predicts that there would be substantial changes to already significantly weakened forest structures and systems.

"The Carnegie Airborne Observatory's research provides invaluable insight into the severity of drought impacts in California's iconic forests. It will be important to bring their cutting-edge data and expertise to bear as the state seeks to address the effects of this epidemic of dying trees and aid in the recovery of our forests," said Ashley Conrad-Saydah, deputy secretary for climate policy at the California Environmental Protection Agency (EPA).

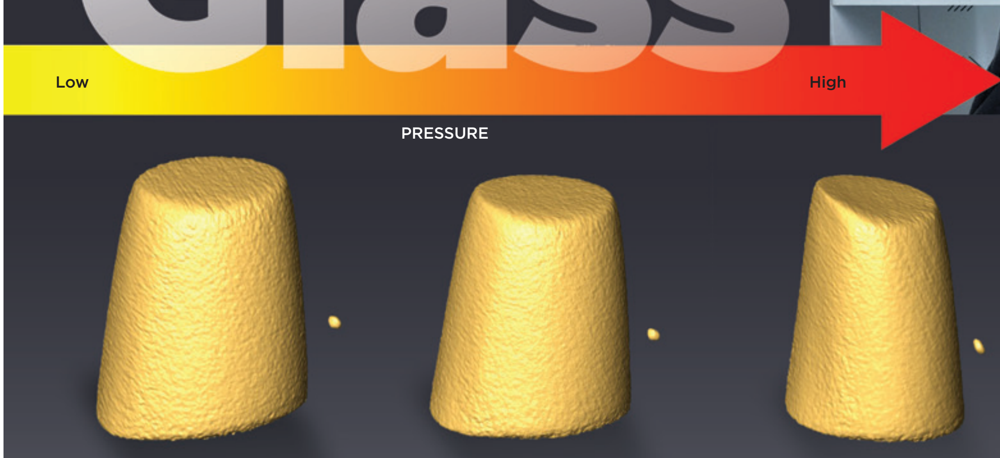
Since day one of CAO flight operations, Asner has been engaged with forest managers and officials from the California EPA and Department of Forestry and Fire Protection to inform decision makers on the severity of forest water losses from the drought and beetle outbreaks. The team's results also helped motivate the California governor's recent proclamation of a state of emergency for dead and dying trees across the state. The latest CAO maps of forest vulnerability were recently transmitted to both state and federal partners. ■

SUPPORT
The David and Lucile Packard Foundation supported this study. The Avatar Alliance Foundation, the John D. and Catherine T. MacArthur Foundation, Mary Anne Nyburg Baker and G. Leonard Baker Jr., and William R. Hearst III currently support the Carnegie Airborne Observatory.

Scrutinizing Metallic Glass



Ho-kwang "Dave" Mao



The progressive volume change of cerium-based metallic glass during compression is shown in this sequence, as measured by transmission X-ray microscopy technique in a diamond anvil cell.
Image courtesy Qiaoshi "Charles" Zeng

Qiaoshi "Charles" Zeng

Everyday glass easily shatters, but not so with metallic glass. Any liquid frozen fast enough, even liquid metal, can become a glass. Metallic glasses, called vitrified metals, are at the frontier of materials science because they are so strong. Metallic glasses have been made by rapidly cooling alloys of metals such as zirconium, palladium, iron, titanium, copper, and magnesium, and they are used for items ranging from golf clubs to aerospace construction. But much about them remains poorly understood.

A team including Carnegie's Qiaoshi "Charles" Zeng and Ho-kwang "Dave" Mao, with others, is trying to figure out the rules that govern metallic glass's creation by looking at metallic glasses under extreme pressures. High-pressure research probes structure on an atomic level to understand a material's state of order or disorder.

Crystals are structured in repeating patterns that extend in every direction; glasses lack this strict organization. Crystalline metals often have weaknesses at the boundaries between crystal grains. But metallic glasses lack these defects, which makes them stronger.

Practically speaking, metallic glasses are extremely strong, hard, and resistant to wear and corrosion, which make them good potential candidates for engineering products including electronics casings and medical tools such as surgical pins and stents. But so far, their creation is time-consuming and expensive because scientists lack a general metallic glass theory. Discovering fundamental rules governing metallic glasses could be revolutionary.

The team—which also included Carnegie's Zhidan Zeng, Stanislav Sinogeikin, Yoshio Kono, Curtis Kenney-Benson, Changyong Park, and Wenge Yang—probed glass made from alloys of the metal cerium under pressure. High-pressure research teams at Carnegie have probed cerium alloys extensively. Their goal this time was to look for fundamental rules correlating the structure and properties of metallic glasses that could aid their further discovery and synthesis. *Proceedings of the National Academy of Sciences* published their findings.

"High-pressure compression is an extremely powerful tool for fine-tuning both the structures and the properties of materials such as metallic glasses and for looking for information that is consistent across samples," said lead author Zeng. "By accurately measuring the evolution of structure and properties during compression, we could establish a relationship between them. The more we learn about this structure-property relationship, the better we can predict the properties of other potential metallic glasses."

Using advanced X-ray tools on cerium-based metallic glass, the team was able to discover a consistent rule that establishes an exact numeric relationship between the decrease in volume of metallic glass under pressure in relation to changes in its atomic structure. This numeric relationship held for metallic glasses at ambient pressure, too.

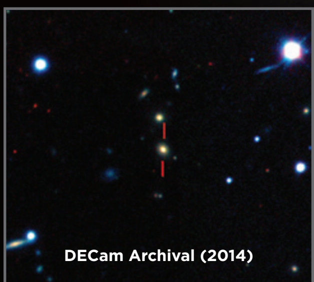
"The exactness and universality of this rule we've discovered indicates that the atomic structures of metallic glasses are not totally random, even if they aren't as regularly packed as crystalline metals; they may share some predictable structural features. This is an important step in understanding what controls the formation of these materials," Zeng said. ■

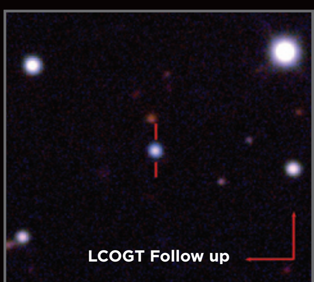
SUPPORT
DOE, NSF, and the National Natural Science Foundation of China supported this work.

The astronomers used the Magellan Clay telescope, one of the twin Magellans (shown) at Carnegie's Las Campanas Observatory for the follow-up work. The new supernova's galaxy is more luminous than our own Milky Way, visible above the telescopes.

Image courtesy Yuri Beletsky

Most-Luminous Supernova Ever





These images show the comparison between a false-color pre-explosion image from the Dark Energy Survey and false-color follow-up image from the LCOGT 1 m network.

Image courtesy Benjamin Shappee

A team of astronomers, including Carnegie's Benjamin Shappee, Nidia Morrell, and Ian Thompson, has discovered the most-luminous supernova ever observed, called ASAS-SN-15lh. *Science* published their findings.

Supernovae are violent stellar explosions and some of the brightest objects in the universe. Human records noting their existence date back nearly 2,000 years. Within the past two decades a rare new category of super-luminous supernovae has been discovered. They shine one hundred to a thousand times brighter than the more-common supernovae. It has been theorized that these super-luminous supernovae are powered by so-called magnetars, neutron stars with extremely powerful magnetic fields, with the magnetism providing the engine for the immense luminosity. According to this theory, the magnetic field's spin magnifies the energy of the explosion, increasing the luminosity.

As counterintuitive as it may sound, super-luminous supernovae are difficult for astronomers to spot. This is because they are rare and tend to form in low-luminosity galaxies with vigorous star formation, whereas the sky surveys that have been traditionally used to locate supernovae target bright galaxies with low rates of star formation.

The newly found super-luminous supernova was discovered by the All-Sky Automated Survey for Supernovae (ASAS-SN) team, an international collaboration headquartered at the Ohio State University. It uses a network of 14-centimeter telescopes around the world to scan the visible sky every two or three nights looking for very bright supernovae. The only all-sky variability survey in existence, it is capable of finding normal supernovae out to about 350 million light-years from Earth.

"On June 14, we spotted a newly occurring explosion in a galaxy of an unknown distance," Shappee said. "Subsequent observations—including those made at our Las Campanas Observatory by Nidia Morrell and Ian Thompson—allowed the team to confirm the existence of the supernova ASAS-SN-15lh."

The supernova's light spectra matched that of other hydrogen-poor super-luminous supernovae. But it wasn't until further follow-up was conducted that the study's lead author Subo Dong of the Kavli Institute for Astronomy and Astrophysics (KIAA) at Peking University and the rest of the team realized how unusual the supernova is: it is two times more luminous than any supernova previously discovered. In fact, ASAS-SN-15lh at peak was almost 50 times more luminous than the entire Milky Way galaxy.

"When the first du Pont spectrum was available, as usual, I quickly checked what kind of supernova it was. To my surprise, I was not able to even tell for sure it was a supernova. My first reaction was: 'this is interesting, we should get more data,'" Morrell said. "It was only when we obtained higher resolution spectra from the Southern African Large Telescope and the Magellan Clay Telescope that I realized how distant the host galaxy is and consequently, how luminous the supernova."

What's more, they determined that the galaxy where ASAS-SN-15lh formed is very atypical for a super-luminous supernova, which raises questions about how these types of supernovae form. Its host galaxy isn't the typical low-luminosity, star-forming galaxy where previous super-luminous supernovae have been spotted. ASAS-SN-15lh's galaxy is, in fact, more luminous than our own Milky Way.

"The astounding amount of energy released by this supernova strains the magnetar-formation theory," Shappee explained. "More work will be necessary to understand this extraordinary object's power source and whether there are other similar supernovae out there in the universe." ■

The discovery was made possible via a global network of 14-centimeter telescopes (one shown) that scan the visible sky every two or three nights looking for very bright supernovae. The system is capable of finding normal supernovae out to about 350 million light-years from Earth.

Image courtesy Benjamin Shappee

Benjamin Shappee (far left) is the Hubble, Carnegie-Princeton fellow at the Carnegie Observatories.

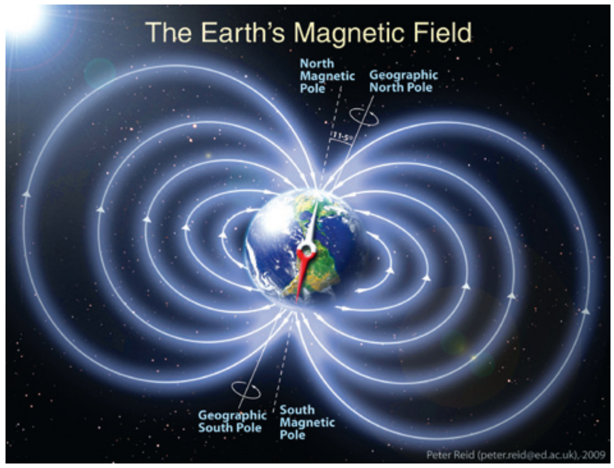
SUPPORT

The other coauthors are José Luis Prieto of U. Diego Portales and Millennium Institute of Astrophysics; S. W. Jha of Rutgers U.; Kris Stanek, Tom Holoien, Chris Kochanek, Todd Thompson, Udit Basu, John Beacom, Jon Brown, A. Bianca Danilet, and Greg Simonian of the Ohio State U. (OSU); David Bersier of Liverpool John Moores U. (LJMU); Joseph Brimacombe of Coral Towers Observatory (CTO); Ping Chen of Peking U.; E. Conseil of the Observatoire de Strasbourg; E. Falco of the Harvard-Smithsonian Center for Astrophysics (CfA); D. Grupe of Morehead State U.; S. Kiyota of the Variable Star Observers League in Japan (VSOLJ); G. Masi of the Virtual Telescope Project; B. Nicholls of Mt. Vernon Observatory; F. Olivares and G. Pignata of U. Andres Bello and the Millennium Institute of Astrophysics; G. Pojmanski and D. M. Szczygiel of Warsaw U. Astronomical Observatory; P. R. Woźniak of Los Alamos National Laboratory (LANL).

ASAS-SN is an international collaboration of astronomers from the Ohio State U., the Carnegie Observatories, U. Diego Portales, Kavli Institute for Astronomy and Astrophysics-Peking U. (KIAA-PKU), Warsaw U. Astronomical Observatory, CTO, LJMU, KIAA-PKU, CfA, and LANL.

The team acknowledges support from Las Cumbres Observatory Global Telescope (LCOGT), NSF, OSU CCAPP, Mt. Cuba Astronomical Foundation, TAP, European Southern Observatory (ESO), SAO, Las Campanas Observatory (LCO), a CAS grant, a NASA Hubble Fellowship, a Fondo Nacional de Desarrollo Científico y Tecnológico (FONDECYT) grant, MAS, an NSF CAREER award, DOE, and the LANL Laboratory Directed Research and Development program.

Surprising History of Earth's Magnetic Field



Earth's dipole magnetic field is generated by the motion of liquid iron in the planet's core and acts like a bar magnet. The north and south magnetic poles periodically swap places. These reversals can happen from some tens of thousands to tens of millions of years apart.

Image courtesy Peter Reid, U. Edinburgh

Earth's magnetic field is generated by the motion of liquid iron in the planet's core. This "geodynamo" occasionally reverses its polarity, i.e., the magnetic north and south poles swap places. The switch occurs over a few thousand years, and the time between reversals can vary from some tens of thousands to tens of millions of years.

Peter Driscoll joined the Carnegie staff in 2015. He studies the evolution of the Earth's core and magnetic field, magnetic polarity reversals, inner core structure, and core-mantle coupling among other aspects of the Earth's interior.

Image courtesy Peter Driscoll

When magnetic polarity remains stable in one orientation for more than 10 million years the interval is dubbed a "superchron." Within the last 540 million years—the time when animals have roamed the Earth's land and seas—there are three known superchron periods, occurring about once every 200 million years.

The question of how frequently reversals and superchrons occurred over a longer segment of Earth's history is important for understanding the long-term evolution of the internal and surface conditions of our planet. But so far, such information has only been pieced together with fragmentary evidence.

New work from Carnegie's Peter Driscoll and David Evans of Yale University now identifies as many as 10 additional superchrons over a 1.3 billion-year stretch of time during the Proterozoic Eon, or Earth's middle age, which occurred 2.5 to 0.54 billion years ago. *Earth and Planetary Science Letters* published their work.

Records of magnetic field reversals can be found in rocks that maintain the magnetic polarity of the era in which they formed. To establish evidence of a polarity shift, this kind of ancient magnetic, or "paleomagnetic," data must be gathered from around the globe, ideally sampling every tectonic plate.

Driscoll and Evans compiled a database of global paleomagnetic data from the Proterozoic Eon, coordinating their reversal records with the movements of the tectonic plates to look for long periods with either strongly northern or southern polarity dominance. These super-long periods of polarity bias then revealed the previously unknown ancient superchrons.

"Our study points the way towards new questions about fundamental aspects of Earth's evolution," Driscoll said. "One of the major implications of these findings is that geodynamo-driven superchrons have occurred at a similar rate for most of the past two billion years."

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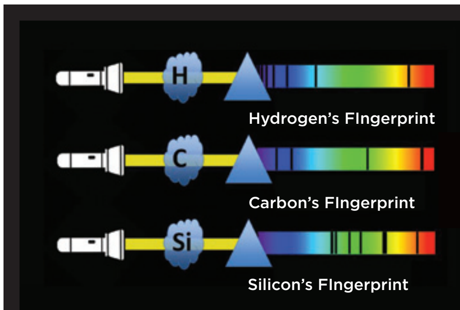
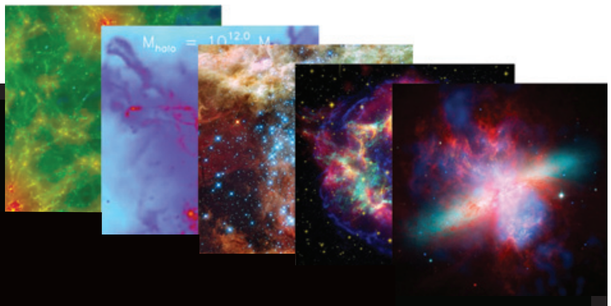
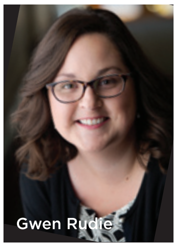
SCIENTISTS UPDATE TRUSTEES

TRUSTEE NEWS





YOUNG GALAXIES FAR, FAR AWAY


Gwen Rudie

Director John Mulchaey kicked off the updates by describing his top priorities for the Observatories—to rebuild the scientific staff, grow the theory group, and find young instrumentalists. He also gave a status report on the postdoc program, educational initiatives, and the Giant Magellan Telescope—all going strong.

Mulchaey turned the floor over to new staff astronomer Gwen Rudie who talked about her work observing the formation of galaxies from 10 billion years ago, when the universe was particularly active. This era was vital to the process of churning out galaxies, stars, and planets out of enormous clouds of gas (above right). Distant gas is so faint that large telescopes, like Magellan, and the state-of-the-art instrument FourStar are necessary to see products of the gas cycle—galaxies and stars. Only the lightest elements were produced by the Big Bang. Heavier elements were produced later in stars that then exploded as supernovae, which circulated the newly, processed gas. Rudie studies gas by looking for its "shadows." She observes quasars, the very brightest objects. The chemical fingerprints of the gas can be detected in quasar light (above left). Astronomers can then determine the gas's chemistry, age, velocity, and direction. Rudie ended with what her future research could look like using the Giant Magellan Telescope.

Astronomers see products of the gas cycle—galaxies and stars—directly, but they can only detect the gas by analyzing its "shadow" illuminated by bright quasar light. Bright quasar light acts like flashlights (above left) passing through the gas. When the light is broken into a spectrum, different elements in the gas produce different absorption and emission lines, which are unique fingerprints to those elements.

CHALLENGES ASSESSING CLIMATE CHANGE

Global Ecology director Chris Field introduced Katharine Mach, after identifying some areas that will be the future of global ecology: carbon accounting, understanding how the frozen Earth and microbes affect carbon fluxes, and assessment science. The latter has to pull information from different disciplines, bridge that information, and then integrate it with qualitative data to make it more useful to society. Mach, a senior research associate, described the fundamental features of assessment science. She talked about the complex science-policy landscape of climate change and the intense, consensus process undertaken by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). She described the group's "key risk" approach to identify likely future impacts of climate change and the continuing evolution of the discipline. It is becoming more inclusive, particularly by bringing the private sector into the process with scientists and decision makers.

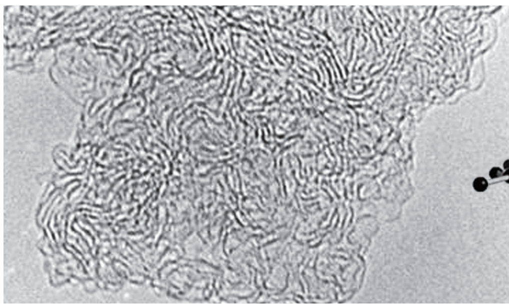
Chris Field (above left) was cochair of Working Group II of the Intergovernmental Panel on Climate Change (IPCC). The group assessed "the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it." Katharine Mach, senior research associate (right), was science codirector of Working Group II.

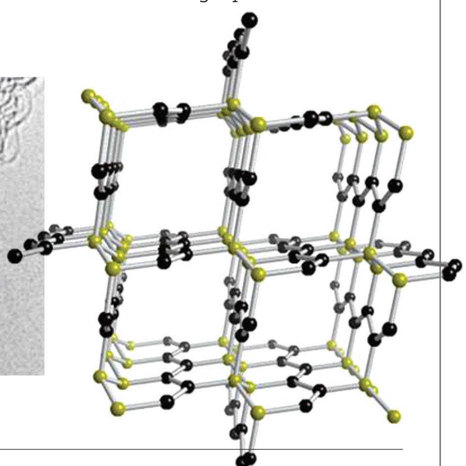
Image courtesy Katharine Mach

Tim Strobel

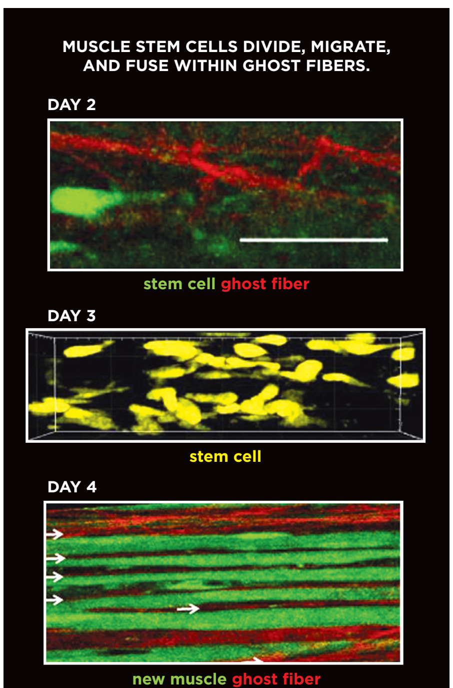
NEW FORM OF CARBON

George Cody, acting director of the Geophysical Lab, presented highlights of the department and introduced Timothy Strobel who described a new form of carbon. Strobel explores new states of matter. He began with a primer on the difference between a material's stable state—the thermodynamic ground state—and metastable states, which are more excited or energetic states of a material. He said theoretically there are thousands of potential states of matter. He then described how to induce metastable states with pressure in the lab. His portfolio includes a new form of silicon that has the best solar absorption of any yet. More recently he and collaborators used high-pressure techniques to transform an amorphous form of carbon into a new state by putting it under pressure and different temperatures. The new form of carbon is extremely hard, but it retains elasticity and has exceptional stress and strain properties. It is harder than ceramics but more elastic than rubber! The team suggests that cross-linked graphene sheets could give rise to these properties.





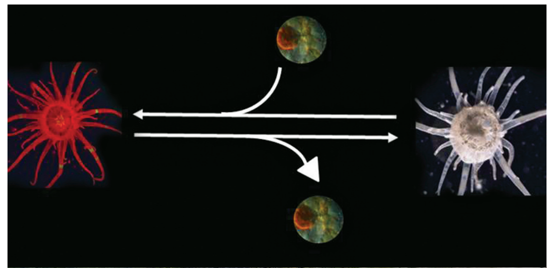
This image and illustration show the material's structure before (left) and after (right) Strobel and team applied high-pressure techniques in the lab.
Image courtesy Tim Strobel



Chen-Ming Fan (shown above right) and team used a cell marking and tracking technique to discover that muscle stem cells are only activated with an injury. When injured, they divide, move, and fuse within "ghost fibers" to grow new muscle.

TRACKING STEM CELLS

Acting director of Embryology Yixian Zheng talked about her philosophy for the department in the era of big labs. She then introduced Chen-Ming Fan who spoke about the role that muscle stem cells play in repairing muscle after injury and its role in muscle degradation due to disease and aging. Interestingly, without injury, muscle stem cells are immobile. Fan and team used a genetic tool to label and follow cells. They found that, when injured, stem cells divide, move, and fuse within "ghost fibers" to grow new muscle. The process requires an essential protein called integrin, which is a glue-like substance necessary for adhesion in the regeneration process. The team believes that altered integrin activity may be at the root of muscular dystrophy and aging muscles.

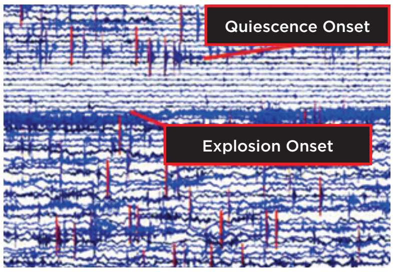


CORAL BLEACHING AND A MICROBIAL "ARMS RACE"

The new director of Plant Biology Sue Rhee talked about her vision and some of the current research at that department, including the causes and processes of the coral bleaching epidemic. Bleaching is actually caused by alterations of the photosynthetic organisms that live in the coral. Art Grossman and team are studying the molecular mechanisms of this symbiotic relationship. Global warming, pollutants, disease, acidity, and more can cause the photosynthetic organism to abandon the coral (above top). Rhee also described work by Devaki Bhaya to understand how microbial communities in very hot springs adapt and evolve under the extreme conditions. She outlined the "arms race" between bacteria and viruses. This race involves the gene editing, or snipping tool, called CRISPR, which confers immunity to the bacteria to ward off viral infection. Rhee then identified four Stanford faculty who are now adjunct Carnegie faculty and described the Stanford branch of the Carnegie Postdoc Association, which brings together Carnegie postdocs on the Stanford campus, bolstering that community.

Art Grossman (below left) is studying the molecular pathways behind the coral and photosynthetic organisms' symbiotic relationship. He focuses on the molecular processes that happen when the algae leave, resulting in bleached coral (above top).

Devaki Bhaya (below right) studies how cyanobacteria thrive and adapt in the extreme environments of roiling hot springs (above botom).



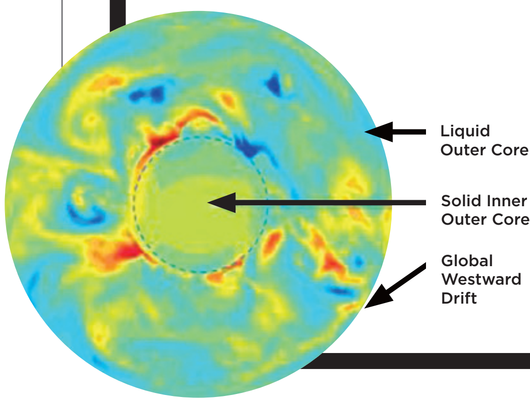
FORECASTING VOLCANOS

Director of Terrestrial Magnetism (DTM) Rick Carlson described some highlights of his department, including new staff members and the department's approach to interdisciplinary research. He introduced Diana Roman who described how researchers in the department couple direct observations, such as hers, with computational modeling of Earth processes. She focused on her work to identify precursors to volcanic eruptions at the Telica volcano in Nicaragua. At Telica, there is a period of seismic quiet immediately preceding an explosion, which can be used to forecast eruptions—the longer the quiet, the bigger the bang. This is important information for evacuation plans. She also described how using the water cycle in the deep Earth "slab to surface fluid transfer" could be used to image the "plumbing" systems below a suite of volcanoes in the Central Aleutians and how geochemistry and geophysics are being integrated at the department.

Diana Roman (above) and team found that at the Telica volcano in Nicaragua there is a period of seismic quiet immediately preceding an explosion. This finding can be useful to forecast eruptions.
Images courtesy Diana Roman

FLIP FLOPPING MAGNETIC POLES

New DTM staff scientist Peter Driscoll talked about Earth's magnetic field. Driscoll integrates observation with modeling to understand how Earth evolved, particularly how the magnetic field evolved. He began with a tutorial about Earth's deep interior, describing the layers: the top crust, the upper and lower mantle, and the outer and inner core. He described how heat- and motion-driven convection in the liquid iron outer core generates a dynamo, which translates mechanical energy to electrical energy, creating the magnetic field with its north and south poles. On average, every 250,000 years the north and south poles reverse. However, the reversal is not periodic. The last reversal was 780,000 years ago and took between 1,000 and 5,000 years. Driscoll conducts numerical modeling of the geodynamic evolution to look at the processes that produce this magnetic-field modulation.



Peter Driscoll integrates observations with modeling to understand how Earth's magnetic field evolved and what causes the poles to reverse. This is a snapshot of a model of Earth's geodynamo activity, which gives rise to the magnetic field. He simulated the processes over 50,000 years. Red indicates positive magnetic field, blue indicates negative.
Images courtesy Peter Discoll

CONTINUED FROM PAGE 13

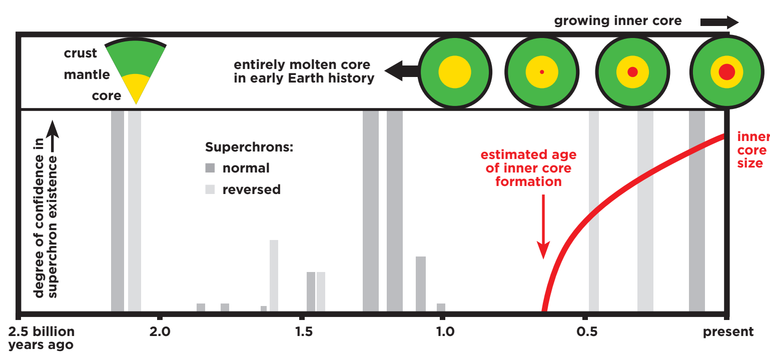
Surprising History of Earth's Magnetic-Field

This was surprising, because geophysicists have good reason to suspect that there was a major change in Earth's core within that time interval. Due to Earth steadily cooling, losing heat to space since the time of its formation, the planet's inner core—a giant mass of solid iron at the center of the planet—should have started to crystallize between about a half billion and one billion years ago. The growth of the solid inner core is fundamental to the physics of the geodynamo. Computer simulations of reversal rates are very different depending on whether or not the planet has a solid inner core.

One possible explanation for Driscoll and Evans's new result is that the Earth's inner core is actually much older than previously estimated, but this idea would conflict strongly with the most-reasonable planetary cooling models. Another explanation invokes an unexpected resilience of the geodynamo in the face of dramatic changes to its structure, including something as fundamental as the solidification of the inner core.

"We think the latter is more likely," Driscoll added. "But regardless of which answer is correct, these results mean that we may need to rethink our models for either core evolution or the geodynamo process." ■

"...these results mean that we may need to rethink our models for either core evolution or the geodynamo process."



This figure illustrates superchrons of both normal and reversed polarity over time as the Earth's molten core formed and solidified.
Image courtesy Peter Driscoll and David Evans

SUPPORT
The Bateman Fellowship in the Department of Geology & Geophysics at Yale U. partly funded this study.

Mercury's Mysterious "Darkness" Revealed

Carnegie's Larry Nittler is the deputy principal investigator of the MESSENGER mission and coauthor of the study.

Scientists have long been puzzled about what makes Mercury's surface so dark. The innermost planet reflects much less sunlight than the Moon, a body on which surface darkness is controlled by the abundance of iron-rich minerals. These are rare at Mercury's surface, so what is the "darkening agent"?

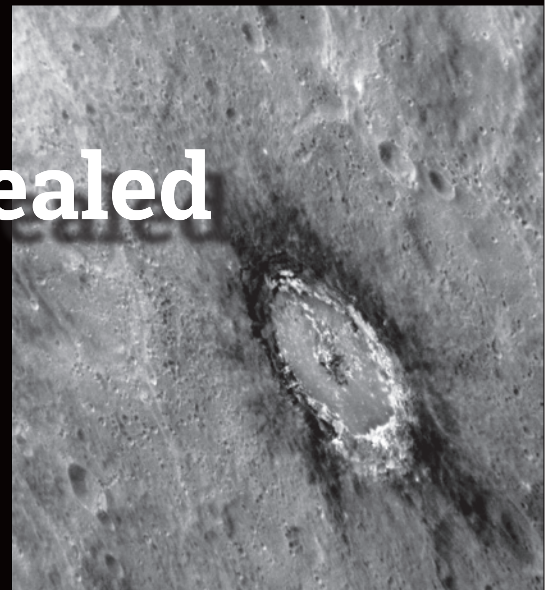
About a year ago, scientists proposed that Mercury's darkness was due to carbon that gradually accumulated from the impact of comets. Now scientists, including Carnegie's Larry Nittler, led by Patrick Peplowski of the Johns Hopkins University Applied Physics Laboratory, used data from the MESSENGER mission* to confirm that a high abundance of carbon is present at Mercury's surface. However, they also found that, rather than being delivered by comets, the carbon most likely originated deep below the surface, in the form of a now-disrupted and buried ancient graphite-rich crust. Some of it was later brought to the surface by impact processes after most of Mercury's current crust had formed. The Advanced Online Publication of *Nature Geoscience* published the results.

Nittler, deputy principal investigator of the MESSENGER mission, explained, "The previous proposal of comets delivering carbon to Mercury was based on modeling and simulation. Although we had prior suggestions that carbon may be the darkening agent, we had no direct evidence. We used MESSENGER's neutron spectrometer to spatially resolve the distribution of carbon and found that it is correlated with the darkest material on Mercury, and this material most likely originated deep in the crust. Moreover, we used both neutrons and X-rays to confirm that the dark material is not enriched in iron, in contrast to the Moon where iron-rich minerals darken the surface."

MESSENGER obtained the data via many orbits with the spacecraft passing lower than 60 miles (100 km) above the surface of the planet during its last year of operation. The data used to identify carbon included measurements taken just days before MESSENGER impacted Mercury in April 2015. Repeated neutron spectrometer measurements showed higher amounts of low-energy neutrons, a signature consistent with the presence of elevated carbon, coming from the surface when the spacecraft passed over concentrations of the darkest material. Estimating the amount of carbon present required combining the neutron measurements with other MESSENGER data sets, including X-ray measurements and reflectance spectra. Together, the data indicate that Mercury's surface rocks are made up of as much as a few percent graphitic carbon (by weight), much higher than on other planets. Graphite has the best fit to the reflectance spectra, at visible wavelengths, and the likely conditions that produced the material.

When Mercury was very young, much of the planet was likely so hot that there was a global "ocean" of molten magma. From laboratory experiments and modeling, scientists have suggested that as this magma ocean cooled, most minerals that solidified would sink. A notable exception is graphite, which would have been buoyant and floated to form the original crust of Mercury.

"The finding of abundant carbon on the surface suggests that we may be seeing remnants of Mercury's original ancient crust mixed into the volcanic rocks and impact ejecta that form the surface we see today. This result is a testament to the phenomenal success of the MESSENGER mission and adds to a long list of ways the innermost planet differs from its planetary neighbors and provides additional clues to the origin and early evolution of the inner Solar System," concluded Nittler. ■



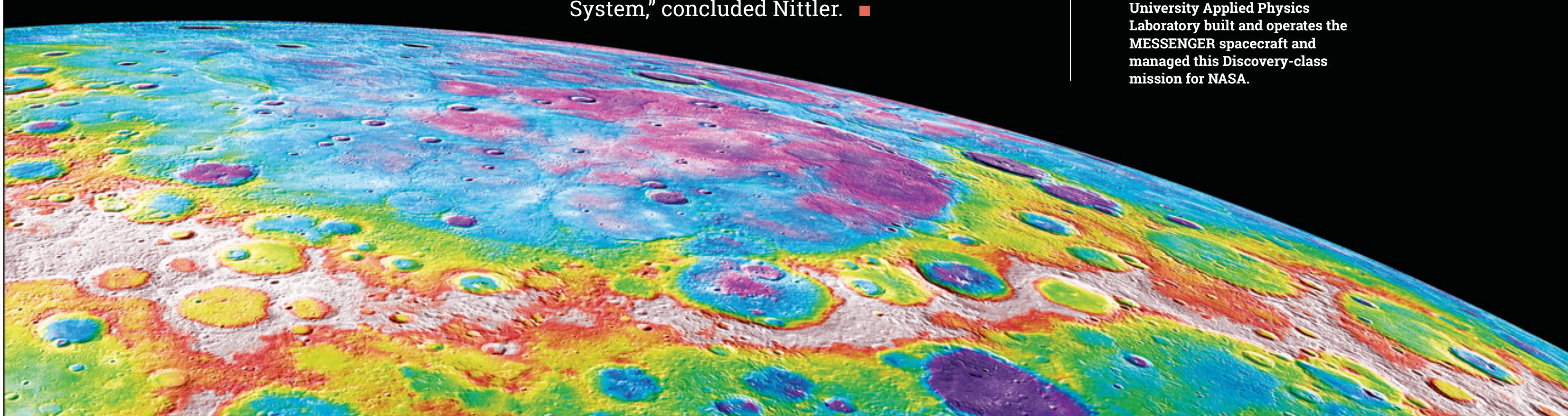
(Above) This is an image of Mercury's Basho crater with a distinctive dark halo that encircles it. The halo is composed of so-called low reflectance material (LRM). It was excavated from depths when the crater was formed. Basho is also renowned for its bright ray craters, which makes it easily visible from a distance.

(Below) This MESSENGER image looks toward Mercury's northern plains. The colors indicate the surface height, with purples showing the lowest elevations while white is the highest.

Images courtesy NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution

BACKGROUND

*Authors on this paper are Patrick Peplowski, Rachel Klima, David Lawrence, Carolyn Ernst, Brett Denevi, Elizabeth Frank, John Goldsten, Scott Murchie, Larry Nittler, and Sean Solomon. MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) is a NASA-sponsored scientific investigation of the planet Mercury and the first space mission designed to orbit the planet closest to the Sun. The MESSENGER spacecraft launched on August 3, 2004, and entered orbit about Mercury on March 17, 2011 (March 18, 2011 UTC), to begin a yearlong study of its target planet. MESSENGER's extended mission began on March 18, 2012. It ended in April 2015. Dr. Sean C. Solomon, formerly a department director at the Carnegie Institution and now at the Lamont-Doherty Earth Observatory of Columbia University, leads the mission as Principal Investigator. The Johns Hopkins University Applied Physics Laboratory built and operates the MESSENGER spacecraft and managed this Discovery-class mission for NASA.



Global Ecology's Environmental Entrepreneurs

Carnegie's Department of Global Ecology is on Stanford University's campus, the world-renowned breeding ground for Northern California start-ups. And now something interesting is happening to students who pass through Global Ecology. A number of postdocs and Ph.D.s are joining and forming start-up businesses as well, focused on agriculture and natural resource management.

Joe Mascaro from Greg Asner's lab joined Planet Labs

Based in San Francisco, Planet Labs was founded in 2010 by ex-NASA scientists to image the entire Earth every day. Planet Labs operates the largest constellation of small, Earth-imaging satellites (over 100) to assist with everything from first-responders dealing with natural disasters to monitoring natural resources. Their mission is to advance social impact "using space to help life on Earth." Planet Labs works with partners in environmental, social, and humanitarian sectors. Their objective is "to help collaborators strengthen their data literacy, develop progressive monitoring tools, and gain meaningful insights about our changing planet."

Joe Mascaro, formerly a postdoctoral ecologist with Asner's Carnegie Airborne Observatory (CAO) team, developed and used LiDAR (laser-ranging) remote-sensing methods to improve our understanding of tropical forest carbon stocks and emissions that cause climate change, in addition to the basic ecology of forest structure. At Planet Labs he directs the Ambassadors Program. The program looks for innovative researchers, scientists, and nonprofits to "unlock the power of Planet's one-of-a-kind dataset," with innovative uses of geospatial data collected by their satellites. Ambassador partners gain access to Planet Lab's data for six months. Mascaro looks for projects that have possibility for social, humanitarian, and environmental impacts or that could develop new analytical techniques for using geospatial data. Projects that have the potential for quick, peer-review publication or open-source code development are particularly desirable.

The CAO's one-of-a-kind system has state-of-the-art sensors for monitoring ecosystems. The inaugural Ambassadors Program was a partnership with Asner's CAO team to enhance its leading-edge work. By enabling access to Planet's frequent satellite coverage of the Earth's surface, the CAO data can significantly scale up across space and time.

(Above) Former Carnegie postdoc Joe Mascaro
Image courtesy Joe Mascaro

Adam Wolf conducted his Ph.D. research with Chris Field and Joe Berry then started his own business, Arable

Adam Wolf did his Ph.D. at Stanford, developing plant growth forecasts with Carnegie's Joe Berry. Berry is a world leader in understanding photosynthesis and plant water use. He also pioneered the use of satellites to measure Earth from space for monitoring and crop-growth forecasting.

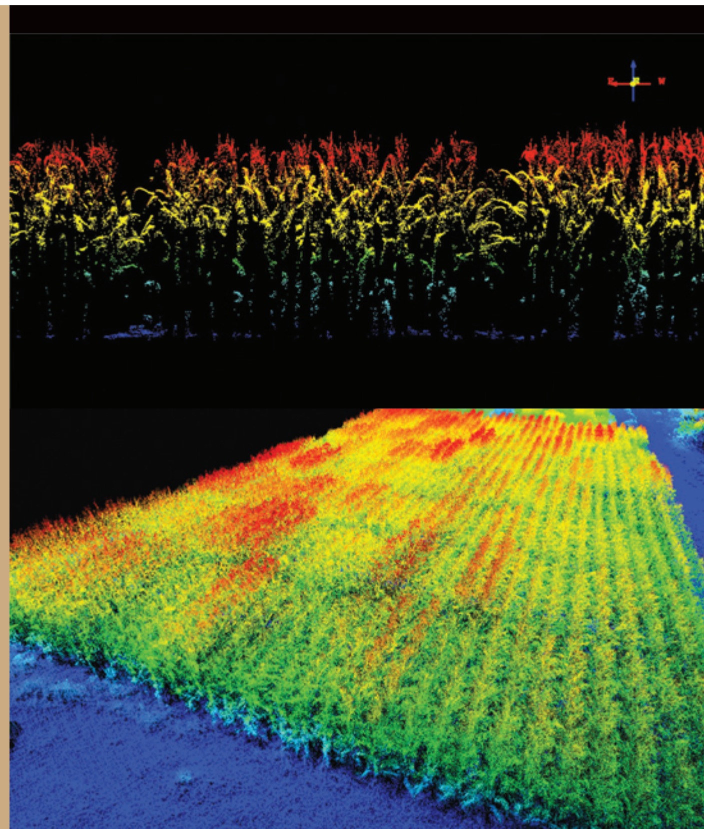
Wolf realized during his Ph.D. research with Berry and Chris Field that there was an absence of granular, individual plant-level data to understand the impacts of global change on crops, water, and weather. While he was at Carnegie, he started developing small devices to measure impacts of weather on plants for crop forecasting. This work eventually became the Pulsepod, a 6½-inch diameter, lightweight, solar-powered device that measures rainfall, crop water demand, water stress, microclimate, canopy biomass, light-use efficiency, and more. It has six spectral bands, more than most satellites, and thermal detectors. It is the only instrument in the world that measures both the plant and the weather, making it ideal for crop forecasting. The main advantage of local measurements is that it helps understand why plants are growing the way they do. The software continuously learns and adjusts the predictive algorithm. Furthermore, shadows, clouds, and aerosols are not an issue, as they are with satellites, which allows Pulsepod to measure true reflectance, removing a lot of error.

Wolf went on to cofound Arable in September of 2014, with Pulsepod as its main product. He is Arable's CEO. Arable is now based in Princeton, New Jersey, with an office in Oakland, California. Early on, the venture secured funding from an NSF grant and then private investors came on board. In May 2016 Pulsepod was scheduled to be field tested at Stanford's Jasper Ridge Biological Preserve, which is directed by Chris Field.

Matt Colgan from Greg Asner's lab joined
Blue River Technology

Matt Colgan, formerly a doctoral student and postdoctoral researcher with Greg Asner's Carnegie Airborne Observatory (CAO) team, developed object-based and machine-learning algorithms using CAO imagery to estimate the biomass and species of millions of individual trees in South African savannas. The carbon and species maps provided the foundation for research on the influence of climate, soils, and disturbances on savanna woody plants and the impact of land-use change on savanna carbon emissions and canopy structure.

Colgan is the project manager for Blue River Technology's drone project. It aims to improve plant breeding by measuring plant traits in the field. He develops airborne drone-imaging systems to measure crop features. Blue River serves the agricultural industry with computer-vision-based robotics designed to unlock greater crop yield. Their systems perform a range of tasks, from making real-time plant thinning decisions to processing large amounts of plant-image data to generate metrics for plant breeders. The current DOE-funded project focuses on improving sorghum for biofuel production on marginal lands. The multirotor drone uses a combination of LiDAR and multispectral cameras to measure height, leaf area, biomass, and other traits in corn, sorghum, and lettuce, among other crops. The phenotypic, or observable, traits measured by the drone are then linked to their genotypes—the organism's gentic makeup—using genomic modeling, with the goal to select for drought tolerance and resistance to other stresses while maximing yield.



(Top) Matt Colgan holds Blue River's drone for measuring crop traits. It is equipped with LiDAR and multispectral cameras, which is designed to improve sorghum breeding for biofuels on marginal land at the Kearney Agricultural Research Extension near Fresno, California.

The top image above shows a side profile of a row of 10-feet tall mature corn using downward-facing LiDAR, extracted from the full field (bottom). Color represents height, with red indicating tallest, followed by yellow and blue. The bottom image shows drone-based 3-D LiDAR data of an experimental corn field. Height is shown across 14 varieties of corn, with the same color designations. This technology is used to breed crops with improved drought tolerance, disease resistance, and resilience to other stresses.

Images courtesy Matt Colgan

Adam Wolf (right, in photo at left) is in a field in Salinas, California, with the first-of-its kind Pulsepod, produced by Arable, a company that he cofounded. The 6½-inch diameter, solar-powered tool (above) measures rainfall, water demand and water stress, microclimate, canopy biomass, light-use efficiency, and more.

Images courtesy Adam Wolf/Arable

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