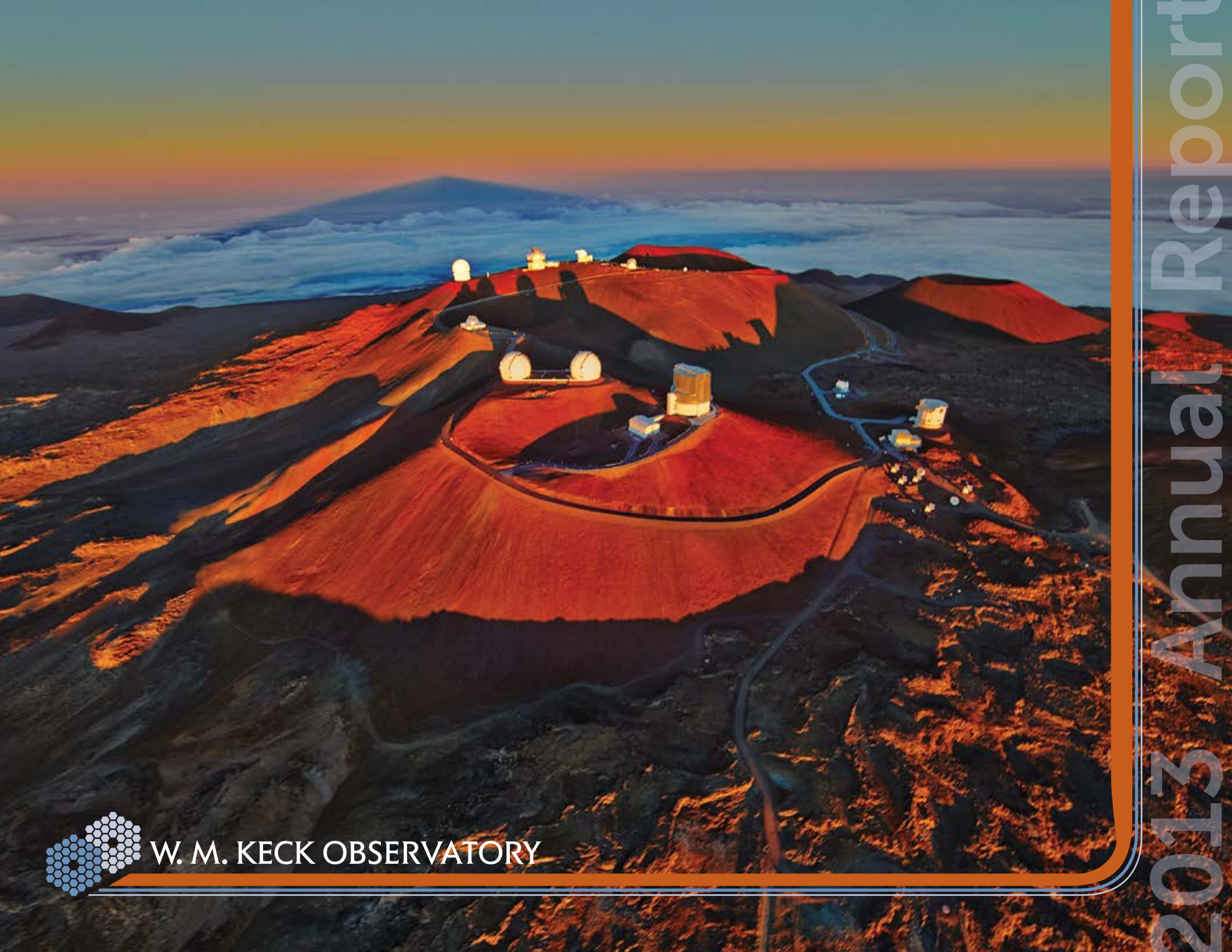

2013 Annual Report

W. M. KECK OBSERVATORY

W. M. KECK OBSERVATORY

On the summit of Mauna Kea, Island of Hawai'i

HEADQUARTERS LOCATION:
Kamuela, Hawaii, USA

MANAGEMENT:
California Association for Research in Astronomy

PARTNER INSTITUTIONS:
California Institute of Technology (CIT/Caltech)
University of California (UC)
National Aeronautics and Space Administration (NASA)

OBSERVATORY DIRECTOR:
Taft E. Armandroff

DEPUTY DIRECTOR:
Hilton A. Lewis

Observatory Groundbreaking:	1985
First light Keck I telescope:	1992
First light Keck II telescope:	1996

Federal Identification Number: 95-3972799

mission

To advance the frontiers of astronomy and share our discoveries, inspiring the imagination of all.

vision

A world in which all humankind is inspired and united by the pursuit of knowledge of the infinite variety and richness of the Universe.

Cover: A spectacular aerial view of this extraordinary wheelhouse of discovery with the shadow of Mauna Kea in the far distance.

FY2013

Fiscal Year begins October 1

489

Observing Astronomers

434

Keck Science Investigations

309

Refereed Articles

118

Full-time Employees

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Celebrating 20 years of revolutionary science from the W. M. Keck Observatory, Keck Week was a unique astronomy event that included a two-day science meeting. Here representing the Institute for Astronomy, University of Hawaii, Director Guenther Hasinger introduces Taft Armandroff for his closing talk, Census of Discovery.

Director's Report

Taft E. Armandroff

Keck Observatory's Annual Report highlights our organization's achievements and scientific advances over the past fiscal year, and I am pleased to introduce you to our report for 2013. For this occasion, we have the rare opportunity to look back on two decades of accomplishments while simultaneously making impressive progress towards future goals.

Keck Observatory's scientific productivity has remained excellent. In 2013 we set new records in refereed publications per telescope per year and citations per telescope per year. Keck continues to lead the observatory community worldwide in both of these widely accepted performance metrics. The observatory's role in graduate education remains strong; at least 287 students have each earned their Ph.D. based on data from Keck Observatory over the observatory's lifetime.

Since the first scientific observations were made with the Keck I telescope and its Near-Infrared Camera (NIRC), on March 16, 1993, the aggregate astronomical discoveries from Keck Observatory are humbling. I am very proud of what the Keck Observatory staff and the broader astronomy community have accomplished.

In March 2013, Keck Observatory marked its 20th anniversary with a week of celebratory events. Keck Week featured a science meeting, a fundraising gala, the dedication of our new Multi-Object Spectrograph for Infrared Exploration (MOSFIRE), an open house at Keck Observatory headquarters, a staff party, and even a tennis tournament. In addition to raising funds for our newest instrument in development, the Keck Cosmic Web Imager (KCWI), these events were successful in engaging the key constituencies of the observatory, including research astronomers, partner-university leadership, private donors, federal funders, Keck Observatory staff, the public and the media.

Keck Observatory's contributions to blockbuster science are stronger than ever, with recent discoveries making headline news across the globe reporting new results about exoplanets, the black hole at the Galactic Center, the high-redshift universe, and the intergalactic medium.

One of the hallmarks of Keck Observatory's leadership in astronomy is delivering new instrumentation as well as upgraded observing capabilities that advance the scientific frontiers.

On Keck II's adaptive optics (AO) system, we installed the laser's new center launch telescope, which will improve the overall performance of the system. All the hardware was completed this past summer. We then installed all the electronic and opto-mechanical components on the telescope and were able to successfully complete the alignment checks. This launch telescope also will be used for Keck II's next generation laser, which started its preliminary

design phase in 2013. This new laser will greatly improve AO performance and set the groundwork for the observatory's Next Generation Adaptive Optics system.

Our newest observing tool in development, KCWI, made significant progress over the past year. This unique optical integral-field spectrograph will be used on Keck II to probe new fields of observations about the cosmos, including the cosmic web of matter interconnecting galaxies, called the intergalactic medium, and explore how galaxies and the intergalactic medium co-evolve over the history of the universe.

On Keck I, a deployable mirror system is being designed that will optimize flexibility for time domain astronomy. It will allow switching between a number of instruments to respond quickly to rapidly unfolding phenomena such as gamma-ray bursts, supernovae, and events at the galactic center.

A major upgrade of our telescope control system is under way that will improve the precision of the telescopes' pointing and replace aging computers, electronics and software, thereby enhancing reliability and sustainability. In on-sky testing of a prototype, this system has demonstrated the impressive and ambitious pointing accuracy that we set as our goal.

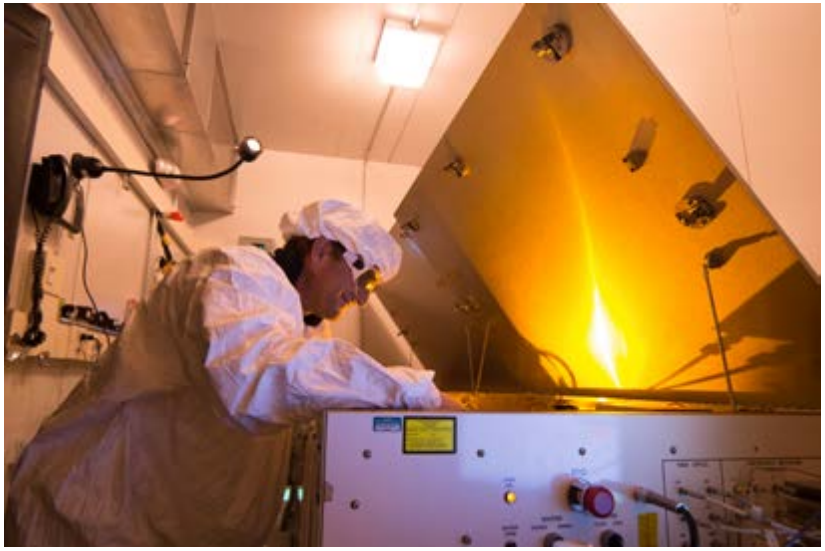
Keck Observatory relies on grants from federal and private sources to develop new observing capabilities and to upgrade existing instruments. The past year has been very successful for attracting new funding for priority programs. The National Science Foundation (NSF) Major Research Instrumentation program funded our proposal for $1.5 million to build a new tertiary mirror and its mount for the Keck I telescope. This will make its full instrumental capabilities available for time-sensitive scientific programs.

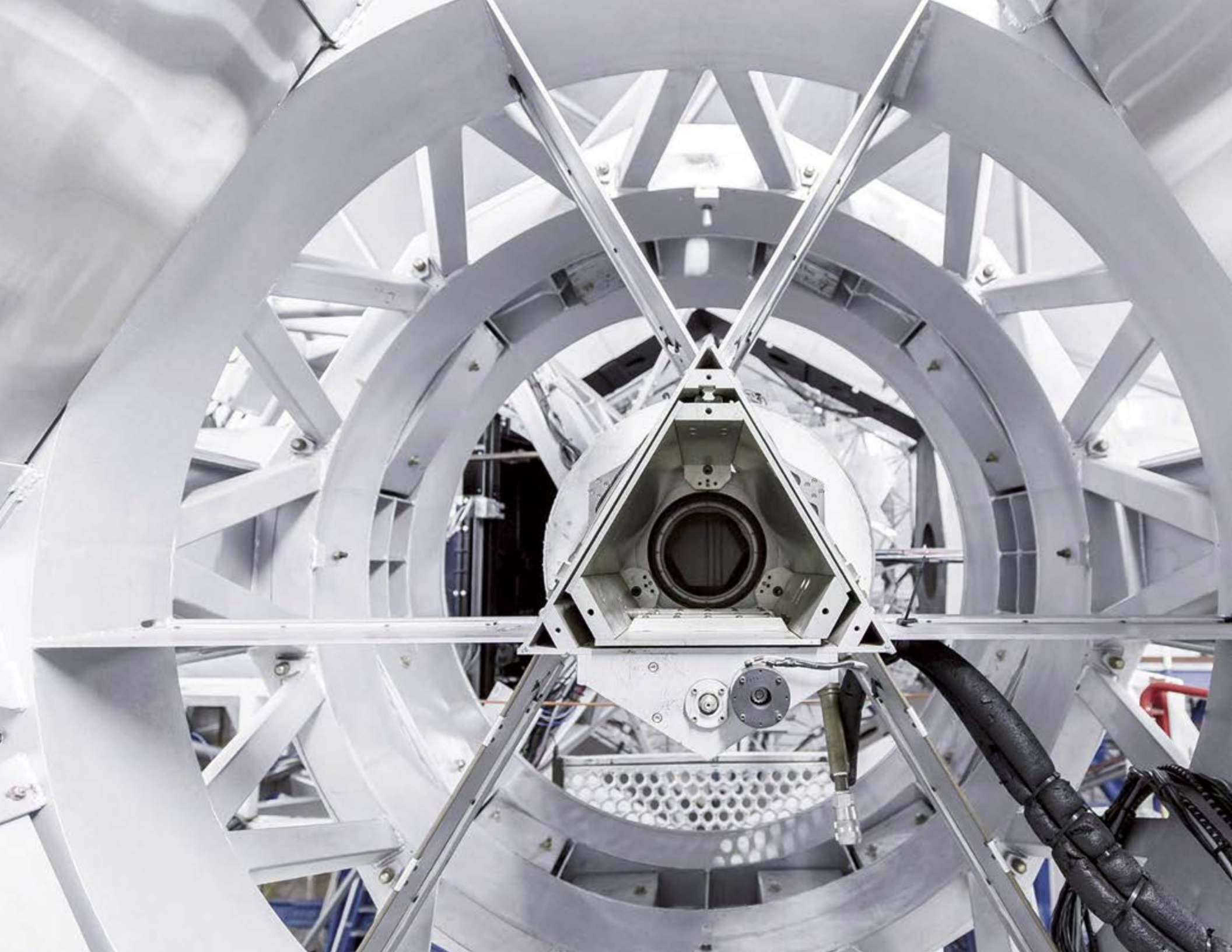
NSF's Advanced Technologies and Instrumentation program also funded our proposal for $968,000 to upgrade the science detector for Keck Observatory's OH-Suppressing Infra-Red Imaging Spectrograph (OSIRIS) from a Hawaii-2 to a Hawaii-2RG, providing higher sensitivity and a significant reduction in detector artifact, and to upgrade related electronics and software. In addition, astronomers Andrea Ghez and Michael Fitzgerald from the University of California, Los Angeles, attracted funding from the Gordon and Betty Moore Foundation to further upgrade the OSIRIS imaging performance, improving field of view, sensitivity and distortion. Together, these two projects will yield a fully revitalized instrument.

It takes a world-class team to achieve world-class results. I remain grateful for the inspired contributions of the Keck Observatory staff, our Board of Directors, our Science Steering Committee, NASA, NSF, our philanthropic contributors, and our creative observer community.

In closing, the opportunities for major scientific advances from Keck Observatory remain rich and profound. We maintain strong ties to both the national funding agencies and our donor base, and look forward to another year of groundbreaking scientific discoveries.

Pete Tucker, Laser Engineer, aligns the adaptive optics laser system on the Keck I telescope to ensure another night of groundbreaking discoveries.





Triumph of Science: The Universe According to the W. M. Keck Observatory

Science textbooks about our Universe have literally been rewritten in the 20 years since the W. M. Keck Observatory gathered its first scientific data. Much of our new knowledge about planets, stars, galaxies and cosmology has come from the twin 10-meter telescopes. Observations from Keck I and Keck II have given astronomers an unprecedented look at the formation and evolution of the near and distant Universe. Data from Keck Observatory has helped scientists resolve weather systems on nearby planets, put the definition of "planet" on the world stage, and helped discover and characterize galaxies at the edge of the observable universe.

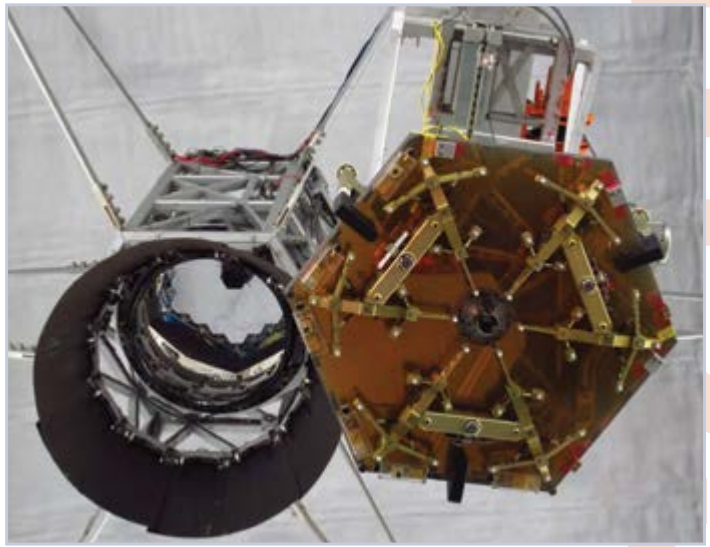
In March 2013, a group of leading astronomers gathered on the Kohala Coast of Hawaii to report on the past two decades of revolutionary science from Keck Observatory. In the audience were astronomers who had begun their professional careers using Keck Observatory data, as well as others who had completed their dissertations long before the twin Keck domes joined the Mauna Kea landscape. Also attending were Keck's technical staff, distinguished federal-funding representatives and philanthropic supporters of the organization.

The meeting was the cornerstone of Keck Week, a one of a kind astronomy event organized to reflect on the observatory's accomplishments and build support for a vibrant future.

Those who who gave presentations at the two-day science meeting were each renowned for their achievements, illuminating one or two subfields of astronomy. Together they highlighted the enormous range of scientific achievements made possible by Keck Observatory. All of their presentations were streamed live to thousands of enthusiastic Friends and Fans of Keck and are archived on Keck Observatory's website. What follows are brief highlights of the work made possible by the cosmic explorers of Keck Observatory.

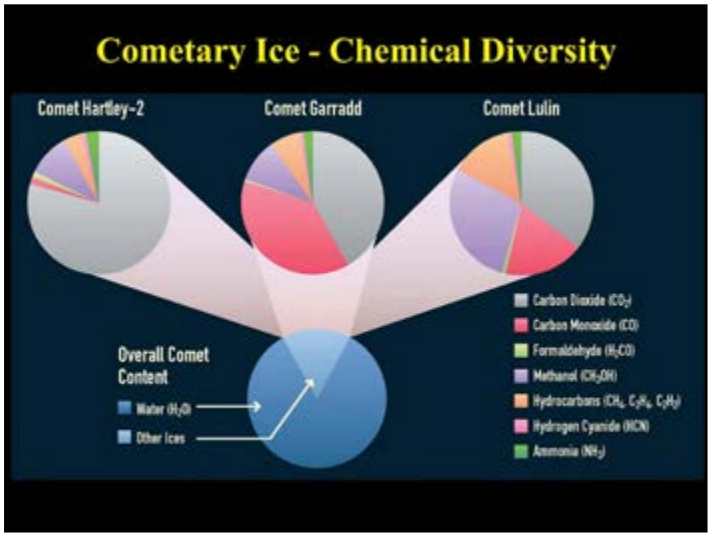
Facing Page: The technology of the Keck Observatory, represented here by this glimpse of astro-architecture of the Keck II telescope secondary, has made remarkable contributions to our understanding of the Universe.

Below: A single 1-ton mirror segment is lifted by specialized crane out of the Keck I telescope; the secondary mirror and support structure witness the operation silently from nearly 60 feet above.



In the Neighborhood

From a cosmic perspective, our solar system contains our celestial next-door neighbors. Many of us are familiar with the major planets and moons, but the scientists presenting at Keck Week talked about more esoteric objects, including comets from the outermost part of our solar system, trans-Neptunian "dwarf planets," and formation of the solar system.



Oort Cloud Comet

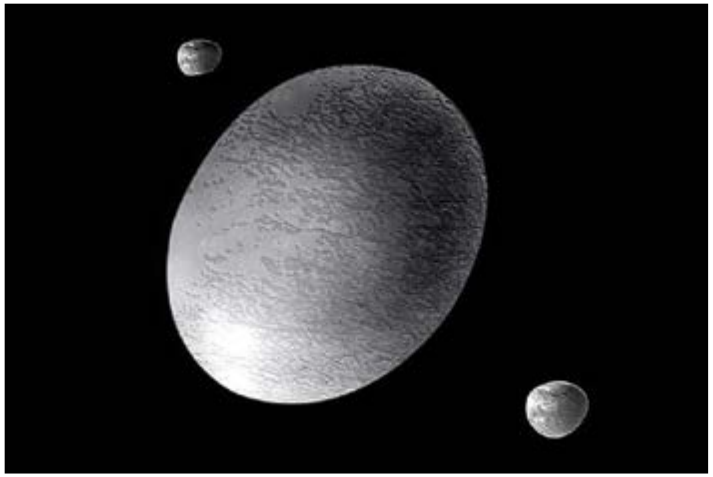
Our solar system is populated with comets: icy bodies that are occasionally viewed from Earth as bright objects with long tails of gas and dust. Detecting volatile organic compounds in comets – methane, acetylene and carbon monoxide, for example – helps astronomers understand the chemical formation histories of these objects.

Michael Mumma from the NASA Goddard Space Flight Center and his team have studied comet Tempel 1, a periodic comet that orbits the Sun every 5.5 years. It was also the target of NASA's Deep Impact mission in 2005, which released a 370-kg impactor to collide with Tempel 1 and dig up debris from the surface layers of the comet.

Mumma and his collaborators used Keck Observatory's near-infrared spectroscopy to quantify volatile substances in Tempel 1. They found that the abundance ratios of these substances were similar to the abundance ratios of comets deriving from the Oort Cloud, a reservoir of icy bodies in the outer solar system. This strongly suggested that Tempel 1 formed in this same remote region as other Oort Cloud comets and was captured by one of the planets during a rare plunge into the inner solar system.

Top: This image of comet Tempel 1 was taken 67 seconds after the Deep Impact impactor crashed into it. The bright splash was created from scattered light from the collision saturating the camera's detector. Credit: NASA

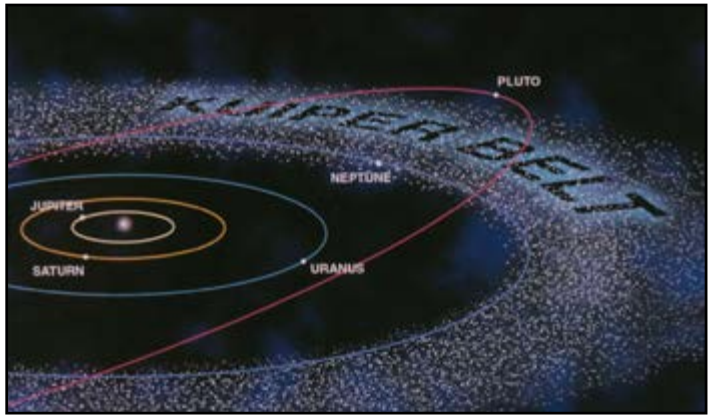
Bottom: This slide from Keck Week shows that while the overall content of comets is frozen water, they also contain a mixture of other ices that reveal a lot about their makeup. Credit: Michael Mumma/NASA



Trans-Neptunian Objects

Michael Brown from the California Institute of Technology presented some of his research about our solar system. Known as "plutokiller" on Twitter for his instrumental role in demoting Pluto from planet status, Brown and his team used Keck Observatory to characterize Haumea, an icy comet-like body confined in orbit near Neptune.

While most trans-Neptunian objects are single bodies, a few have been found with satellites.



Haumea is an ellipsoidal object with an average radius of about 700 km and two small moons named Hiiaka and Namaka. Brown used the orbital period of one of Haumea's moons to determine the mass of Haumea, which, along with measurements of Haumea's size, yielded an estimate of its density. Brown and his collaborators found that Haumea had a density approaching that of rock, but its surface revealed spectral signatures of crystalline water ice.

"The object must [be] rocky on the inside and icy on the outside," Brown said. "Like an M&M you really don't want to eat."

Solar System Formation

Geoff Blake, a cosmochemist at Caltech, followed Brown's talk with how he and his collaborators have been using Keck Observatory to study solar systems undergoing gravitational collapse to investigate how disks made of gas and dust condense into solar systems.

Solar systems are created from swirling clouds of gas and dust that eventually coalesce gravitationally into a star and its planets. "The study of current star-forming environments can tell us much about how we came to be," Blake said.

Blake's team used high-resolution images of these protoplanetary disks to search for characteristic gaps in the disks caused by planets sweeping out lanes in the gas and dust. Each protoplanetary disk has its own configuration of forming planets and Blake and his collaborators relied on

Left Top: Mike Brown's team discovered Haumea in 2004. It is one-third the mass of Pluto and is located beyond Neptune's orbit. The International Astronomical Union (IAU) recognized Haumea as a dwarf planet in 2008. Credit: NASA

Left Bottom: The Kuiper Belt belt is home to at least three dwarf planets: Pluto, Haumea, and Makemake. Some of the Solar System's moons, such as Neptune's Triton and Saturn's Phoebe, are also believed to have originated in the region. Credit: NASA

Below: This artist's concept illustrates a solar system that is a much younger version of our own. Dusty disks, like the one shown here circling the star, are thought to be the breeding grounds of planets, including rocky ones like Earth. Credit: NASA

simulations of planet formation to estimate how nascent solar systems may look millions of years in the future.

From this work, Blake reported that using Keck Observatory has allowed scientists to not only be able to find nearby stars with disks, but also to measure the chemical compounds making up the disk, including water and other chemical compounds needed for life. Perhaps most exciting, scientists can now detect planets being born and Keck Observatory's next generation of infrared instruments, working with the giant radio array in Chile, will be able to directly image the birth of solar systems.

The Milky Way

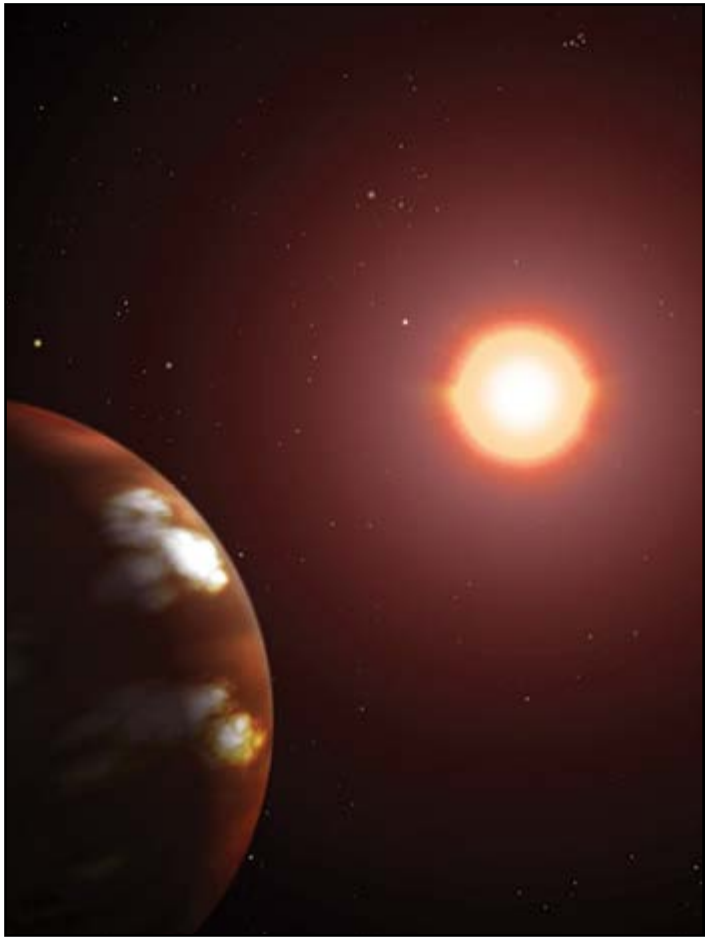
Within our own galaxy, planets are much more numerous than the eight known to orbit our star, the Sun. Also discussed at the Keck Week Science Meeting was current research being done to distinguish the boundaries between planets and stars.

More than Eight

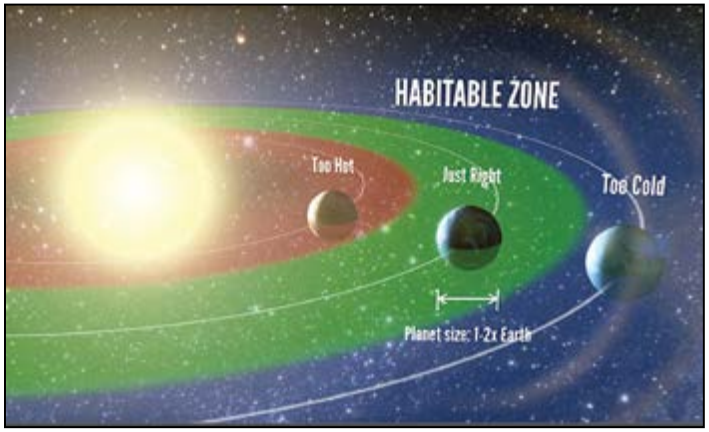
Geoff Marcy and his team of planet hunters rely on Keck Observatory to gather spectra of stars so they can look for periodically shifted spectral lines – telltale evidence that an unseen planet is gravitationally tugging on its host star. Planets pull feebly on massive stars: the effects correspond to spectral shifts as small as a few meters per second. "We can tell whether the star is 'walking' toward or away from us from a thousand light years away," Marcy said.

At Keck Week, Marcy reported identifying more than 100 extrasolar planets, the vast majority of which are Jupiter-mass planets closer to their parent stars than Mercury is to our Sun.

According to NASA, the purpose of the Kepler space telescope's mission was to discover how many of the 200 billion stars in the Milky Way harbor Earth-like planets. At Keck Week, Marcy answered that question, stating his team has determined 23 percent of Sun-like stars have a planet the size of one to three Earths within Mercury's orbit.



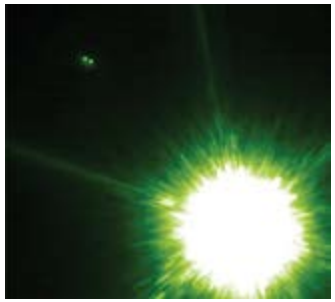
This artist's concept shows the newly discovered, Neptune-sized extrasolar planet circling the star Gliese 436. The planet was discovered using data from the W. M. Keck Observatory on Mauna Kea, Hawaii.
Credit: NASA



This is an artist's representation of the "habitable zone," the range of orbits where liquid water is possible on the surface of a planet. The authors find that about 1 in 5 Sun-like stars harbor a planet between 1 and 2 times the size of Earth that falls in the habitable zone.
Credit: Petigura/UC Berkeley, Howard/UH Manoa, Marcy/UC Berkeley

Finding Missing Links

Typically, planets are thousands of times smaller than stars, both in size and mass. But not always. High-resolution astronomy from Keck is challenging the borders between these objects.



This is an infrared image of the dusty brown dwarf binary HD 130948BC in the upper left in orbit around a young sun-like star, seen to the lower right.
Credit: Trent Dupuy and Michael Liu/UH Manoa.

"For a long time, people wondered if there was some missing link that connects the lowest mass stars and the highest mass planets," said Michael Liu, an astronomer at the University of Hawaii. In 1988, astronomers discovered the first brown dwarfs: objects intermediately between planets and stars with surface temperatures in the range of 480–1900 C (comparable to the melting point of copper). While stars burn normal hydrogen into helium, brown dwarfs do not get hot enough in their interiors to start this reaction. They, unlike planets, burn the rarer hydrogen isotope deuterium in a similar but far less energetic reaction.

Liu's research focused on determining the masses of brown dwarfs, a key parameter that dictates its evolution. The light-collecting ability and spatial resolution of Keck Observatory telescopes proved critical to weighing brown dwarfs, enabling Liu and his team to determine the masses of more than a dozen of them.

"In the last two decades, we have figured out these much lower mass, failed stars called brown dwarfs come in a wide range of varieties," he said. "We understand their temperatures, we are diagnosing their atmospheres and measuring their masses directly through the power of the Keck Observatory telescopes and particularly with the advances made possible through their Laser Guide Star Adaptive Optics systems."

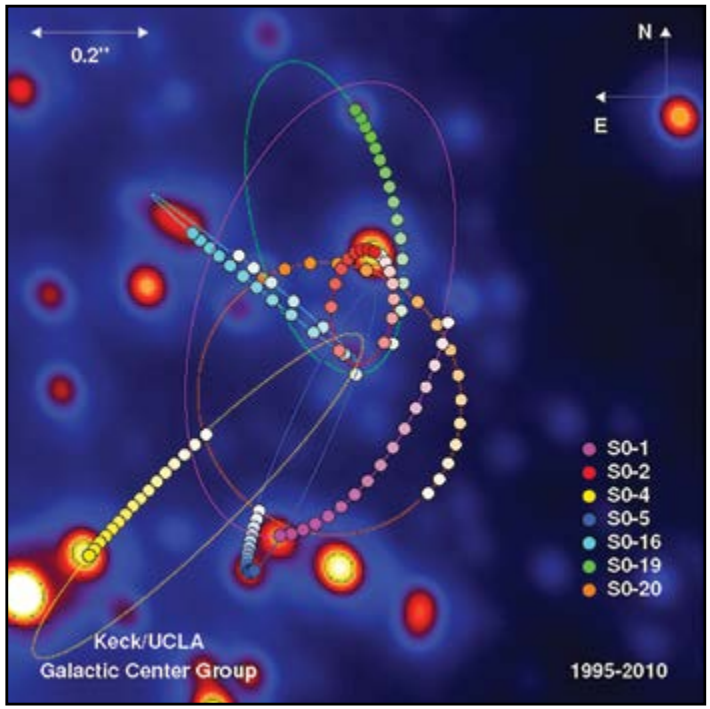
Astonishing Orbits

While most of the presenters at Keck Week talked about revolutionary discoveries that involved the spectra of starlight, Andrea Ghez, an astronomer at the University of California, Los Angeles, reported studying the orbits of stars at the center of the Milky Way to investigate a much stranger object that does not emit any light: a supermassive black hole. The black hole reveals itself by its gravitational effect on nearby stars.

"The orbits of stars provide us with the most direct proof of a black hole in the center of our galaxy," Ghez said.

Ghez and her team obtained high-resolution images of the Galactic Center using both of Keck Observatory's world-class Laser Guide Star Adaptive Optics systems to trace the movements of stars. They used their observations spanning two decades to deduce the orbits of the stars, employing orbital mechanics to constrain the mass of the unseen object to which the stars are gravitationally bound. Based on the sizes of the stellar orbits and the astonishingly high velocities of the stars – up to 12,000 kilometers per second – they found conclusive evidence that the Milky Way hosts a supermassive black hole with a mass more than four million times the mass of the Sun.

"Keck has transformed our understanding of the center of our galaxy," Ghez said. It may continue to transform our understanding of basic physics. With future improvements in Keck's adaptive optics systems, fundamental predictions of Einstein's theory of general relativity can be tested.



Left: The orbits of stars within the central 1x1 arcseconds of our Galaxy. While every star in this image has been seen to move over the past 15 years, estimates of orbital parameters are only possible for the seven stars that have had significant curvature detected. The annual average positions for these seven stars are plotted as colored dots, which have increasing color saturation with time. These orbits provide the best evidence yet for a supermassive black hole, which has a mass of 4.1 million times the mass of the Sun.
Credit: Keck/UCLA Galactic Center Group

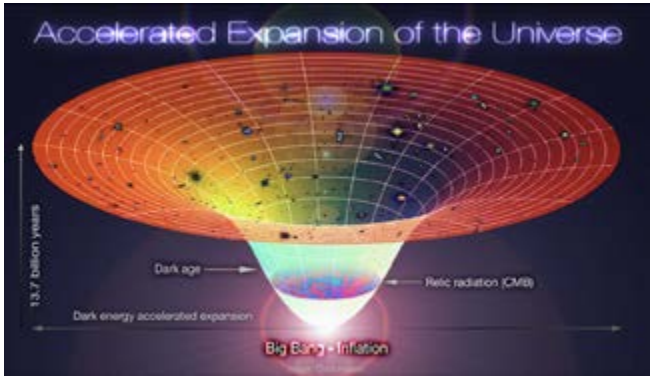
Extragalactic

Outside our Milky Way, Keck Observatory's powerful set of instruments have helped astronomers redefine our understanding of galaxies large and small, near and far, as well as the intergalactic medium that connects them all.

Time Travel

Analogous to the leap in our understanding of stars in the 1920s and 1930s (the "golden age" of stellar astronomy), the last two decades has witnessed enormous leaps in our understanding of galaxies. Much of this work has been done at Keck Observatory, reported astronomer Sandra Faber of the University of California, Santa Cruz.

Using Keck Observatory data, scientists have learned galaxies have a typical size and mass (approximately one billion solar masses); that there are two types of morphologies (spheroid and rotating disks); and that galaxies are distributed in filaments, groups and clusters.



Right: Lambda-CDM, Accelerated Expansion of the Universe. The time-line in this schematic diagram extends from the big bang/inflation era 13.7 billion years ago to the present cosmological time.
Credit: Coldcreation

Around the time the Keck Observatory was being built, the λ CDM model was being formulated, leading to predictions about the large-scale structure in the distribution of galaxies, as well as the expansion of the Universe.

With two decades of data gathered at Keck Observatory, Faber reported the λ CDM model has held up and is a reliable tool to make predictions about the evolution of our Universe.

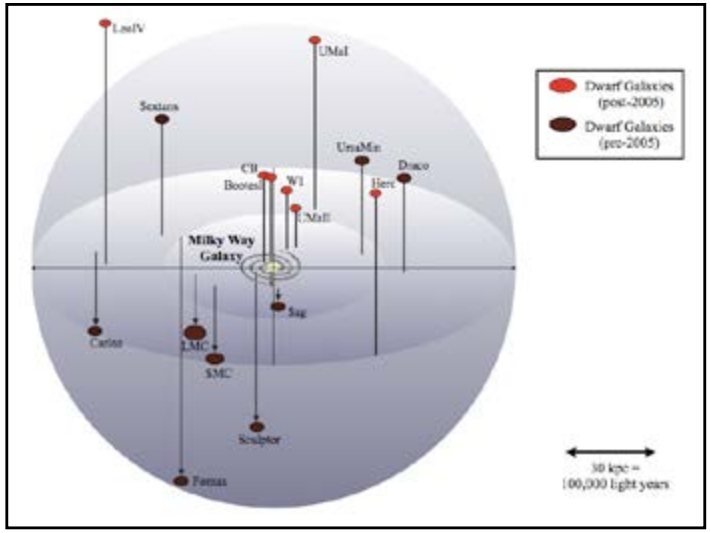
"By sitting here on planet Earth, looking at galaxies around us and back in time with giant telescopes like Keck, we have actually managed to probe the evolution of the Universe back to 10^{-35} seconds," Faber said. (10^{-35} is 0.0000...001, where there are 34 zeroes before the "1".) "And we have discovered that our Milky Way, which is 100,000 light years across today, is the child of a quantum fluctuation which was once 10^{-33} centimeters in size that got captured by the expansion of the Universe. It wasn't allowed to die. It got seized by the throat; it got frozen in and its gravity produced the galaxy we see today. We are all children of quantum mechanics."

Dwarf Galaxies are Huge in Dark Matter

While the Milky Way is a decidedly average galaxy in terms of size, it is gigantic compared to the wispy galaxies that Yale University astronomer Marla Geha studies. Geha and her team are investigating dwarf galaxies about 1/100,000 as bright as the Milky Way. These diminutive galaxies, thought to be the building blocks of more massive galaxies, allow Geha and her collaborators to determine how large galaxies form and assemble from smaller galaxies.

Relying on high-resolution images and spectra from Keck Observatory to study the dwarf galaxies clustered around the Milky Way, Geha's team measured how quickly the stars are moving within the galaxies and used this to infer the masses of the galaxies.

Revealed by the potent combination of two powerful astronomy tools: the Sloan Digital Sky Survey and the Keck II telescope's DEIMOS instrument, these faint, ghost-like galaxies are amazing laboratories for simultaneously advancing science and raising new questions about the cosmos.
Credit: Marla Geha/Yale University



Geha then demonstrated that dwarf galaxies contain a significant amount of dark matter, a mysterious substance that exerts gravity but does not emit or reflect light. She showed that the masses inferred from the stellar velocities are far in excess of masses estimated based on the galaxy's starlight alone.

The Andromeda is the nearest major galaxy to our own Milky Way Galaxy. Hundres of billions of stars that compose it cause the diffuse light we see from Andromeda. The several distinct stars that surround Andromeda's image are actually stars in our Galaxy that are well in front of the background object. This image of M31 was taken with an amateur telescope.
Credit: Lorenzo Comolli

M31, the Galaxy Next Door

Raja Guhathakurta at the University of California, Santa Cruz, studies the chemical properties of dwarf galaxies that orbit around the Andromeda galaxy, or M31, focusing on elements other than hydrogen or helium.

Massive stars create metals in their hot interiors and when they explode as supernovae they scatter these metals into space. The expelled metals are then incorporated into later generations of stars, so finding a dwarf galaxy with a low level of metals in its stars is a hint that we are seeing one of its first generations of stars.

Using Keck Observatory's high spectral resolution observations of absorption lines from different elements, Guhathakurta reported how his groundbreaking research into the nature and evolution of M31 offers many keys to knowing our own Milky Way.

"Our group has discovered, thanks entirely to Keck Observatory, a vast halo around Andromeda calling into question whether galaxies are really island universes," he said.

Intergalactic

Galaxies populate the Universe and contain the vast majority of stars and planets. However, astronomers have shown that the space between galaxies is far from empty – gas and dust exist in the so-called intergalactic medium.

Xavier Prochaska, an astronomer at the University of California, Santa Cruz, has focused on

understanding how this material came to be located beyond galaxies, and how we can determine its properties. This material is too tenuous to be seen directly, so Prochaska uses Keck Observatory with a novel technique, which he referred to as "science in silhouette." The method relies on observing a bright source behind the gas and dust of interest. Atoms in the intervening intergalactic medium absorb some of the light from the background object. This absence of light (the "silhouette") can be used to determine the motion and chemical composition of the intergalactic medium.

It was expected that this intergalactic gas, isolated from the stars filling galaxies, might be primordial, with very few metals from contaminating supernovae. But Prochaska found that a surprisingly large percentage of his samples show metal enrichment. Prochaska commented, "Oddly enough, it's taken great effort to find pockets of gas that are not enriched."

In this image, a stream of primordial inflowing gas is illuminated from behind by a distant background quasar (lower left; quasar added by an artist, along with the starry background). Using data collected from Keck Observatory, researchers led by Neil Crighton (MPIA and Swinburne University of Technology) have now made the first unambiguous detection of this accretion of pristine gas onto a star-forming galaxy, that was previously theorized to exist based on cosmological simulations of galaxy formation. This simulation shown here was run by the Making Galaxies in a Cosmological Context (MaGICC) project in the theory group at MPIA. Credit: G. Stinson and A. V. Macciò/ MPIA

The High Redshift Universe

Richard Ellis, an astronomer at the California Institute of Technology, has studied how galaxies evolve with time by pushing the capabilities of large telescopes like those at Keck Observatory. Ellis and his team have observed more than 100 galaxies at a redshift of z=6, an epoch when the Universe was less than one-tenth of its current age. Their conclusion: galaxies across the Universe are fundamentally different from more local galaxies in terms of appearance, chemistry and star formation.

The young galaxies that Ellis and his collaborators study are extremely faint and typically require two nights of observations with the Keck telescopes in order to yield useful data. Ellis and his team found that more than half of the z=6 galaxies showed a strong hydrogen emission line, indicative of hydrogen gas heated by young stars. These observations show that energetic star formation occurred in galaxies when the Universe was young, only 1 billion years after the Big Bang.

The Hubble Ultra Deep Field reveals seven newly discovered distant galaxies, which are seen as they appeared in a period 350 million to 600 million years after the Big Bang. The most distant galaxy of these, at redshift 11.9, means we view it only 380 million years after the Big Bang, when the Universe was less than 3% of its present age. Credit: NASA, ESA, R. Ellis/Caltech, J. Dunlop and Ross McLure/ University of Edinburgh, B. Robertson/University of Arizona, A. Koekemoer/Space Telescope Science Institute.

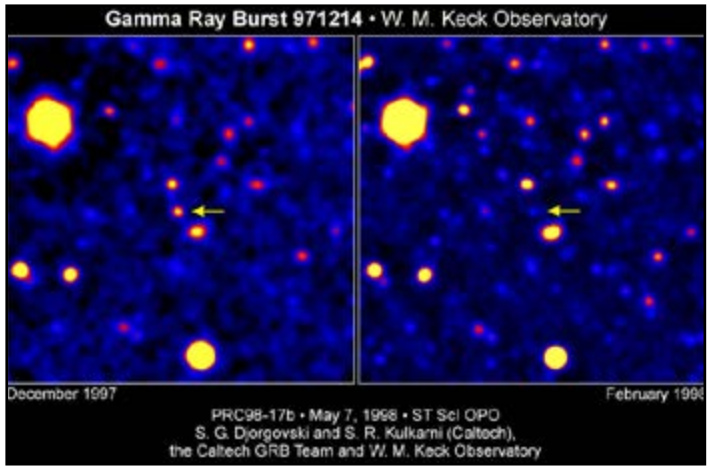
Across the Universe

Some of the talks at Keck Week described new insights into exotic phenomena including gamma ray bursts, and the mysterious "dark energy."

Shrinivas Kulkarni, an astronomer at the California Institute of Technology, reported on his investigations into the connections between gamma ray bursts and supernovae. Gamma ray bursts, which emit powerfully at the shortest wavelengths of the electromagnetic spectrum, have a history rich in politics and mystery.

In the 1960s, the United States launched a satellite to look for flashes of high-energy gamma rays coming from nuclear weapons tests. They inadvertently found that gamma rays were not coming from the Earth's surface, but from the sky. The uniform distribution of gamma flashes indicated that they came from a great distance, beyond our own galaxy and beyond even the nearest large clusters of galaxies.

Unfortunately, gamma ray telescopes only gave rough positions on the sky. Astronomers spent decades trying to pin down the precise location on the sky of a gamma ray burst in hope of discovering whether they were associated with a nearby star, a distant galaxy, or something else. Only in 1997 were scientists finally able to identify the optical counterpart to a gamma ray burst and show that it came from a faint galaxy. Spectra from Keck Observatory on a subsequent gamma ray burst led to a distance from the burst and its host galaxy, and the realization that gamma ray bursts are among the very brightest objects in the sky. Kulkarni and his students and collaborators showed that these bursts are associated with the deaths of massive stars.



The image on the left shows the visible-light afterglow of the burst (marked with an arrow), obtained about two days after the burst, while it was still relatively bright.

The image on the right shows the same field as seen about two months later, after the burst afterglow has faded away, revealing a faint galaxy at its position (also marked with an arrow). The measurement of its distance shows it to be some 12 billion light years away.

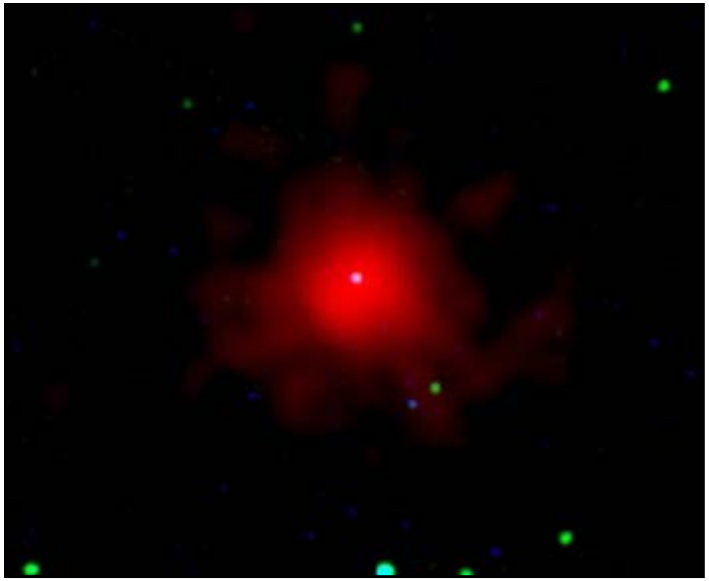
Credit: S. G. Djorgovski and S. R. Kulkarni/ Caltech, the Caltech GRB Team, WMKO

Dark Energy

One of the most fundamental questions in astronomy is, "How will the Universe end?"

The Universe's expansion was discovered by astronomers in the 1920s, but the history of that expansion is necessary to predict the ultimate fate of space and time. This depends on what is contained in space: a universe populated with only regular matter, which is susceptible to the attractive force of gravity, is predicted to eventually slow down its expansion as indeed was observed in the relatively nearby Universe.

Astronomers, including University of California, Berkeley's Alex Filippenko, used Keck Observatory in the 1990s to determine the rate of expansion of the Universe by observing supernovae of a certain type at different distances. This type of supernova was known to be of uniform intrinsic brightness, a so-called "standard candle." The observed brightness combined with the redshift gave two



This image shows the Swift telescope's optical (blue and green) and X-ray views of GRB 080607, which the astronomers used to study the star-forming environment of a distant galaxy. The white spot at center is the burst's optical afterglow. Credit: NASA, Swift, Stefan Immler

different measures of the distance, which provided a measure of the rate of expansion.

The results were shocking. The supernovae were dimmer than expected, suggesting that the Universe's expansion was in fact accelerating. This was the discovery of dark energy – a mysterious force that repels matter. Subsequent measurements show that about 75 percent of the Universe is in the form of dark energy. What exactly dark energy is remains a topic of hot debate in physics.

Two separate research teams confirmed these unexpected results and the 2011 Nobel Prize in physics was awarded to Saul Perlmutter, Brian Schmidt and Adam Riess, key members of the research groups. Filippenko holds the distinction of being a member of both of these research teams.

The Best of the Best

Pioneering science requires pioneering thinkers. Keck Observatory's astronomers have pushed the mighty telescopes to create a legacy of cutting-edge science that has changed our understanding of the Universe. The legacy continues, night after night from the quiet on Mauna Kea's summit, with Keck Observatory and its pioneers continuing to advance the frontiers of knowledge from this extraordinary wheelhouse on Planet Earth.

Observing Assistant Heather Hershey operating the Keck II telescope in the control room at the summit, while the observing team directs their research from remote operations in Waimea, seen here in the background video link.

Cosmic Visionaries

The governing Board of Directors of the W. M. Keck Observatory consists of three esteemed officials appointed from each of our founding partners: the California Institute of Technology and the University of California. In addition, NASA, the W. M. Keck Foundation, and the University of Hawaii each have liaisons to the Board of Directors. The W. M. Keck Observatory Directorate and the board are advised by a Science Steering Committee whose membership consists of astronomers representing our partner communities. The Advancement Advisory Council is a group of major donors; its charter is to champion the need to generate diverse philanthropic revenue necessary for Keck Observatory to reach its full potential and lead humanity into a new era of understanding of the Universe and our place in it.

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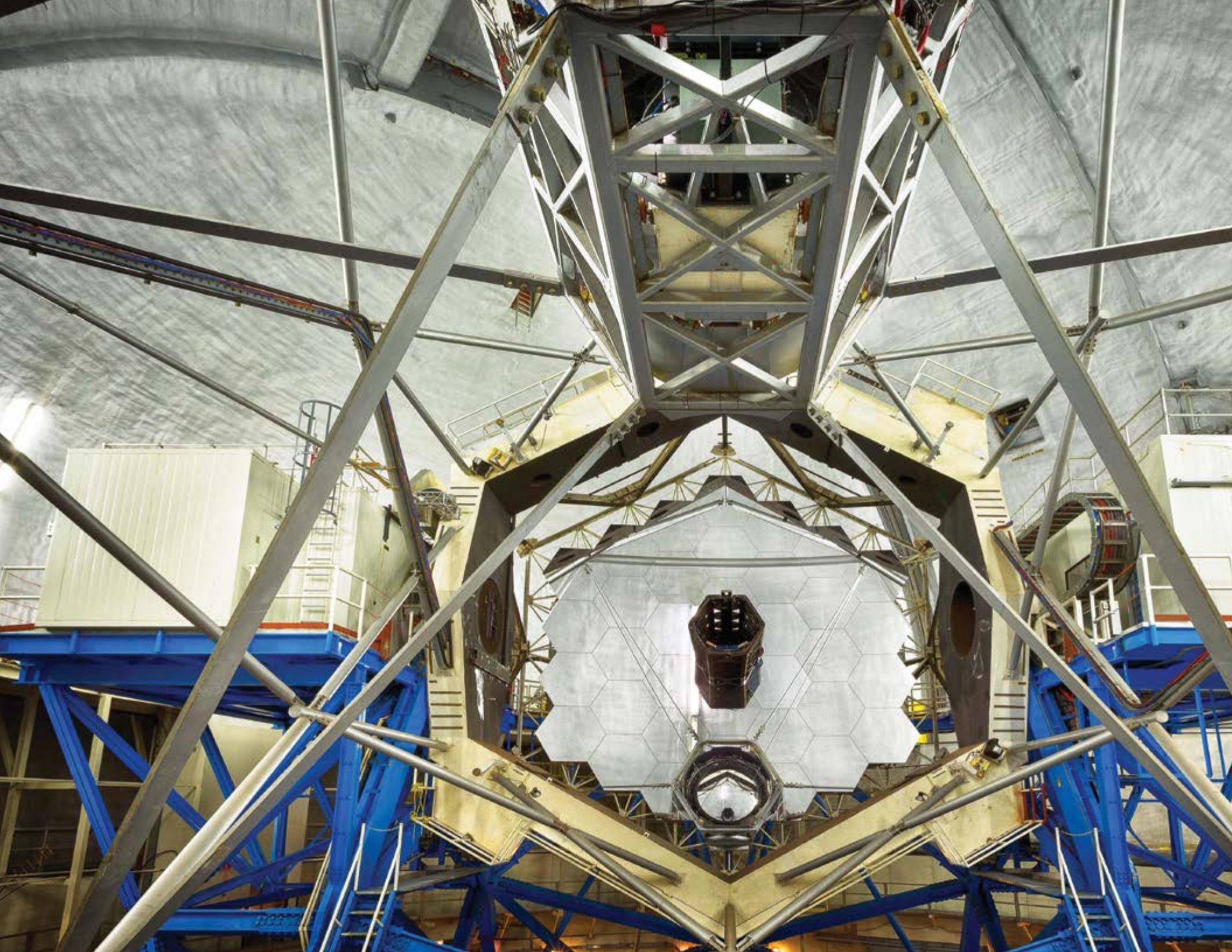
To sustain its lead in ground based astronomy, Keck Observatory ambitiously pursues both public funding and private philanthropy. Featured in this photograph at right are Friends of Keck Observatory, from left to right, Carol Davies, Richard Bader and Harold Cogger.

Facing Page: (TOP) In the photograph taken at Keck Observatory headquarters are standing left to right: Guenther Hasinger, University of Hawaii liaison; Shrinivas Kulkarni, Board member; Sandra Faber, Board member; Taft Armandroff, Keck Observatory Executive Director; George Blumenthal, Board Vice-Chair; Thomas Soifer, Board member; Hashima Hasan, NASA liaison, and Elaine Stamman, Board secretary. (BOTTOM) Members of the Keck Observatory Science Steering Committee meet regularly to help develop future scientific priorities. Here, standing left to right: Hilton Lewis, Deputy Director; Taft Armandroff, Observatory Director; Crystal Martin; James Graham; Judith Cohen; Chris Martin; Sandra Faber; Andrea Ghez; Guenther Hasinger; Shrinivas Kulkarni; Michael Liu, Anne Kinney; and Charles Beichman.



Keck Observatory: Innovation from Day One

Hilton Lewis

Your Mission

Take the world's largest telescope, 350 tons of steel and glass on top of an almost 3-mile-high dormant volcano in freezing nighttime temperatures, and point it precisely at a galaxy whose light has been traveling toward us for the last 13 billion years.

It's huge, this galaxy, but from our vantage point it occupies a miniscule piece of the night sky — the full moon appears almost 10 million times its area — and the galaxy only appears that "big" because it has been magnified by a gravitational lens, a remarkable property of space-time predicted by Einstein's general theory of relativity.

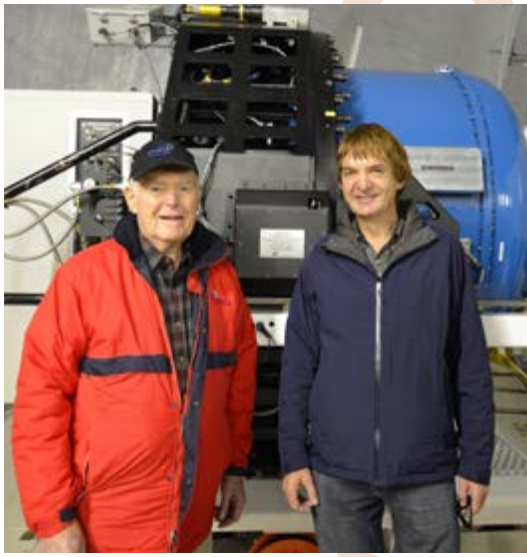
Now track this galaxy precisely for the next four hours as it wheels slowly across the night sky, while the steel and glass behemoth flexes and bends under its own weight and as the cooling night air causes the steel superstructure to contract.

Don't forget to maintain the shape of the primary mirror — it's made up of 36 1-ton tiles, each needing to be controlled to within 1/4000th the diameter of a human hair — while precisely positioning a 1-ton secondary mirror suspended nearly 60 feet above, at the very top of the telescope.

Welcome to modern astronomy!

Upper Right: Hilton Lewis, Deputy Director (right), seen here introducing astronomy benefactor Gordon Moore to MOSFIRE, the newest and most advanced astronomical instrument at Keck. MOSFIRE was made possible through funding provided by NSF and Gordon and Betty Moore.

The Challenge



For more than 20 years, carrying out this complex mission has been central to the success of the W. M. Keck Observatory. In many ways, the effective nightly functioning of the two 10-meter telescopes is the easy part. Underpinning this success is a detailed understanding of the properties of materials and structures, exactly how much the telescope is tilted or how its precision-bearing surfaces differ from perfection, how the earth wobbles in its rotation around its own axis, how light bends as it passes through our atmosphere — and a multitude of other effects. Our understanding of all this, gleaned over hundreds of years of scientific and technical progress, is translated into compensating actions by advanced computers running the most sophisticated numerical recipes.

To ensure these giant structures are rigid and lightweight yet able to move almost without friction requires exquisite design, the hallmark of modern telescopes. The trick is to get the design right, build the underlying structures and seamlessly incorporate the many components that make up a full telescope. Geometry on this scale is a far cry from what you learn in high school: centers

of rotation of supposedly rigid bodies move around, circles deform into ellipses, and right angles aren't, well, right. Then there's the glass that makes up the mirrors that isn't glass after all, but rather a remarkable amalgam, part amorphous, part crystalline, which expands or contracts only about 1/2000th as much as steel does as it warms or cools. A modern telescope is nothing like the machines we encounter in our daily lives.

Although most of what makes up the Keck Observatory telescopes is familiar, there are three aspects we don't routinely consider in our day-to-day interaction with machines: *precision*, *scale* and *complexity*. Let's first consider ***precision***: the most detailed control operates at the level of one-thirtieth of the wavelength of visible light — this is the level to which the edges of the individual segments that make up the primary mirror are aligned. Now add in ***scale***: we must integrate components that range from elements that bend tiny mirrors, up through the ultra-precise setting of mirror segments that weigh 1 ton each, all the way to positioning a 700-ton steel dome.

But in many ways, the most interesting aspect of all is ***complexity***: ensuring that the multitude of systems that make up the telescope are all functioning perfectly at the same time — the bearings, motors, pumps, controls, cryogenics, cameras, spectrographs, deformable mirrors and lasers, along with the computers, networks and software that control them. Add in the requirement to maintain this perfect synchronous functioning all night, every single night of the year, and you start to get a good appreciation of the challenge.

More with Less

The Keck telescopes were born of a small number of crucial and pioneering concepts and have benefited from the rapid-fire evolution of technology ever since. Novel techniques of stress-mirror polishing and ion figuring of the individual segments (each of which is a piece of the hyperbolic surface of a much larger mirror) were critical to being able to manufacture the segments precisely and cost-effectively. Real-time computer control of the segments to maintain the overall shape of the primary mirror and full computer control of the entire telescope is commonplace now but was in its infancy when the observatory was first built.

Technical innovations in instrument building are the basis of the rapid improvement in telescope performance, from devices that compensate for flexure to the most sensitive optical and infrared detectors ever made to ultra-precise mechanisms operating just a few degrees above absolute zero.

And we have made enormous advances in adaptive optics, in the components, controls and algorithms that change the shape of deformable mirrors thousands of times per second. The associated high-powered lasers have evolved from finicky room-size devices requiring 60 kW of input power and using organic dyes dissolved in alcohol alongside 20,000-volt power supplies to ultra-modern cabinet-size fiber lasers that use about 1 kW of power while generating more laser light.

Left: Summit operations team members Justin Pitts and Marvin Nakata ascending the exterior ladder of the Keck I dome to ensure the telescope is operational.

Right: The summit crew of the Keck Observatory show a moment of exhilaration as the best astronomy operations team in the world

Driving Progress

While technical virtuosity has been the backbone of Keck Observatory's success, a less appreciated but crucial issue for any modern observatory is that of staying competitive. How does one upgrade intricate devices that are in use every single day of the year without breaking them or taking them out of service for more than the briefest period? It's a challenge mastered by Formula 1 race car teams in the heat of the race. And it's one Keck Observatory faces continually. It demands a sophisticated approach in both technical design as well as in how staff is selected, trained, organized and motivated.

It is a truism to say the steady march of technology drives progress. However, the crowning achievement of Keck Observatory, its creative engineers and scientists and its partners in academia and industry, is the way in which new technologies are first translated into lab prototypes, then developed into rugged and reliable systems and eventually into a machine consistently delivering cutting-edge science by the world's best astronomers every night of the year. We owe our gratitude to the dedicated and talented men and women who continue to develop, operate and maintain these technological marvels, making possible the stunning celestial discoveries that extend our perspective and ennoble our spirit.

Keck's Powerful Astronomical Instruments

Ian McLean

Even a first visit to the W. M. Keck Observatory leaves one convinced that astronomy is an amazingly high-tech enterprise. Beyond the magnificent structure of the massive telescopes themselves, the intricate panoply of complex scientific equipment used to make cosmic discoveries is impressive.

The Keck Observatory telescopes are optical-infrared telescopes, and instrumentation attached to the telescopes is designed to measure light all the way from the ultraviolet to the infrared. Some infrared light is partially blocked by greenhouse gases in Earth's atmosphere, which is why high, dry sites like Mauna Kea are excellent locations for the world's best telescopes.

While images of the sky in visible light and infrared light are a prerequisite for most studies, the primary advantage of a giant telescope is its huge collecting area and therefore, its ability to record both the image of a very faint object as well as its spectrum. The spectrum of starlight is rich in information that astronomers translate into knowledge about the Universe.

To stay at the forefront of science, Keck Observatory's technology is updated on a regular basis, and new instruments are developed and commissioned. Today, the telescopes are equipped with an impressive suite of eight instruments: two for infrared light and two for visible light on each telescope. On Keck I the instruments are called LRIS, HIRES, OSIRIS and MOSFIRE. On Keck II the instruments are NIRSPEC, NIRC2, ESI and DEIMOS. Moreover, both telescopes are equipped with adaptive optics (AO) systems that reduce the blurring effects of atmospheric turbulence. AO enables astronomers to capitalize on the other big advantage of a large telescope: its potential for better angular resolution. Three of the infrared instruments (OSIRIS, NIRC2 and NIRSPEC) use the AO systems.

All of Keck's scientific instruments perform spectroscopic measurements. The HIRES instrument, for example, provides the highest spectral resolution, and this spectrograph is well-known for its role in the discovery of planets orbiting nearby stars. NIRSPEC is an infrared analog of HIRES. ESI is a spectrometer designed to cover most of the optical spectrum in a single exposure, while LRIS and DEIMOS are multi-object spectrographs designed to enable many faint-object spectra to be recorded simultaneously. MOSFIRE provides the equivalent

capability at infrared wavelengths and is particularly important for studying the formation of galaxies in the early Universe. NIRC2 and OSIRIS are infrared instruments designed specifically for the adaptive optics systems, and therefore provide the finest detail in ultra-high-resolution images.

Over its 20-year lifetime, Keck Observatory has continuously invested in improvements to its instrumentation in order to deliver pioneering science results. Today, our giant telescopes have the best digital imaging devices: spectrographs with exquisite optical performance, and even a means of compensating for turbulence in the air above the observatory.

Since joining the faculty at UCLA in 1989, I have witnessed a remarkable evolution in instrumentation. For example, one of the first instruments to be used routinely for science on Keck I was called NIRC, Near Infrared Camera. In 1994, its state-of-the-art infrared camera had 256 x 256 pixels, which provided a field of view of 38 x 38 seconds of arc on the sky. NIRC was the longest serving instrument at the observatory until its retirement a few years ago. NIRC contributed to numerous scientific discoveries ranging from dwarf planets in the Kuiper Belt, to the black hole at the center of the Milky Way galaxy. Delivered in 2012, the current infrared camera and multi-object spectrometer (MOSFIRE) has a modern infrared detector with 2048 x 2048 pixels, and its field of view spans more than 360 seconds of arc on the sky. New digital imaging devices have also been installed in LRIS and HIRES since the delivery of those workhorse instruments in the 1990s, and a project already is under way to upgrade the OSIRIS detectors.

Meanwhile, novel instruments, like the Cosmic Web Imager, and new adaptive optics systems are in development. New instrumentation will inevitably lead to new discoveries, and those discoveries will drive us to make even better tools. I wonder, what might the next 20 years bring?

Above: Mike Aina attaches a mount for the antenna to the secondary mirror structure of Keck I, integral to automating aircraft detection for laser guide star adaptive optics.

Top right: Optics technician George Wall in the Mirror Barn which stores Keck Observatory's distinctive primary mirror segment spares.

Middle right: Operations staff Steve Milner, Grant Hill, Mark Devenot and Andrew Cooper in the main hallway that connects the twin Keck telescopes at the summit facility.

Bottom right: Summit crew Allen Agliam, Joe Gargiulo, Sky Hudek and Eric Appleby transferring a mirror segment onto a handling cart in preparation for recoating in the mirror lab.

Funding Exploration: A Legacy of Scientific Excellence

A common bond that unites all humanity now and through the ages is our fascination and awe of the night sky. Polynesian navigators looked to the stars for direction as they sailed the vast expanse of the Pacific Ocean in search of new lands. Galileo sparked the tradition of creating tools like telescopes to observe and understand the mechanisms of the cosmos beyond what we could discern with our naked eyes. Today's astronomers continue this tradition of exploration with strategic applications of the most powerful technologies added to giant telescopes like those at the W. M. Keck Observatory.

Made possible by capital grants totaling more than $138 million from the W. M. Keck Foundation, Keck Observatory is managed by the California Association for Research in Astronomy (CARA) established by its founding partners, the California Institute of Technology and the University of California. CARA was organized as a 501(c)(3) corporation in 1985 exclusively for educational and charitable purposes. The Keck I telescope began science operations in 1993, followed by Keck II in 1996. The National Aeronautics and Space Administration joined as a partner in the Keck Observatory in 1996.

Today, Keck Observatory is recognized throughout the world as a premier research facility: its technology and astronomical discoveries are showcased in textbooks, the media and educational programs. The commitment of the founding partners and NASA to sustain Keck Observatory's preeminence in astronomy is strong, and the engagement of new collaborators has increased both funding opportunities and astronomers' access, deepening the facility's importance to the national astronomy system.

Through the years, our research organization has successfully competed to earn significant support from the major grant programs of the National Science Foundation (NSF) to develop and implement new science capabilities. In addition, CARA's commitment to establishing an Advancement program has been successful in both enhancing Keck Observatory's contact with the public and increasing private support. The Advancement Team offers distinctive ways for Friends of Keck Observatory to meaningfully participate with their philanthropy, including a supernovae legacy society, naming opportunities and numerous campaigns to fund instrument upgrades and new capabilities. Since the advancement program began in 2005, Keck Observatory has attracted 794 donors and more than $13 million in philanthropic contributions.

In the original partnership agreement between Caltech and the University of California, Keck Observatory is guaranteed an annual base of operating support. This support was $13.4 million in fiscal year 2013 and covered basic operations and modest maintenance costs for the summit and headquarters facilities. NASA contributed an additional $4.1 million for operations. During the past year, Advancement contributed an additional $1 million from individual gifts and private grants. The balance of the observatory's funding support came from multiyear grants and new awards from the NSF.

The budget for the Keck Observatory for FY2014 is $27.4 million. Audited financial statements are available upon request or directly from the observatory's website at www.keckobservatory.org.


Visitor Center Open Mon-Fri 10am-2pm
W. M. KECK OBSERVATORY

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"Having the Keck telescopes on the Big Island means that I can retire in paradise and still be involved in new scientific discoveries. We have the world's premier telescopes on our doorstep and the world's foremost scientists to teach us all about their work: stars, galaxies, exoplanets, black holes, dark matter, dark energy – it's so exciting. Keck Observatory not only enriches my own life, it makes Hawaii a leading astronomical center and opens the Universe for all here to explore." —Elaine Dobinson

Elaine, seen here with Keck Observatory controller Gavin Sebastian at Keck Week, was formerly with the Jet Propulsion Laboratory in Pasadena, California. She is a member of Keck Observatory's Guidestars, a volunteer corps that educates and informs guests to the Keck headquarters visitor center in Waimea.

Team Advancement (from left to right Joan Campbell, Ron Laub, Bill Healy, Steve Jefferson and Debbie Goodwin) on the slope of Mauna Loa, seeking perspective.

Inspiring Imagination

From the beginning, the mission of the W. M. Keck Observatory has been elegantly simple: *"To advance the frontiers of astronomy and share our discoveries, inspiring the imagination of all."*

As evidenced by the Director's Letter and the science and technology feature articles published in this report, Keck Observatory's discoveries about our Universe alongside our unsurpassed technical innovations continue to make this the premier observatory on Earth.

On March 16, 1993, Keck I gathered the first scientific data from the summit of Mauna Kea. To acknowledge 20 years of revolutionary science since that first moment, Friends of Keck Observatory conceived and hosted a unique experience called Keck Week. It was a series of programs to commemorate all that has been accomplished. Attendees celebrated not only the science from Keck Observatory, but also the brightest minds in astronomy alongside our country's most significant scientific philanthropists.

To encourage supporters of the Keck Observatory to attend Keck Week 2013, an integrated marketing approach was strategically enacted, heavily involving social media. This translated into over 2000 guests participating in Keck Week 2013 and nearly $1 million raised in private support to further Keck Observatory's technology. One of the many benefits of this anniversary event was that Keck Observatory won the Best Social Media Campaign award in Hawaii for 2013 from Pacific Edge Magazine.

News stories and articles were published worldwide including in Time Magazine and the New York Times as well as an incredible, 8-page spread in the Honolulu Star-Advertiser. Building on this worldwide attention, we hosted several film and news teams to document the work from our facility, including CNN, the BBC, National Public Radio, Public Broadcasting System and Time.

Throughout 2013 the well-attended Astronomy Talks program continued, hosting five public events at the Kahilu Theatre and Gates Performing Arts Center. Subjects ranged from our newest instrument, MOSFIRE, to black holes and the fate of the Universe; all of these are archived on the Keck website.

These Astronomy Talks were given by Drs. Benjamin Zuckerman, Guenther Hasinger, Ian McLean, Charles Beichman, and closing the season with a special presentation on Polynesian wayfinding by Master Navigator Kalepa Babyan.

Patrons of Keck Observatory, in addition to participating in the 20th Anniversary Keck Week presentations, received invitations to Evenings with Astronomers, a by-invitation-only lecture series sponsored by the Rob and Terry Ryan Foundation to build community and philanthropic support for Keck

Facing page, far right, from top to bottom: Astronomers Mike Brown, Andrea Ghez and Geoff Marcy, Raja GuhaThakurta, Alex Filippenko, and Richard Ellis were some of the world-renowned scientists who participated in Keck Week 2013.

Observatory. Evenings with Astronomers in 2013 featured presentations by astronomers Evan Kirby, Shrinivas Kulkarni and Imke de Pater.

In the digital realm, we launched a completely redesigned website that hosted 225,000 unique visitors in FY13, increased our fan base on Facebook by more than half, and more than doubled the number of people we communicate with on Twitter.

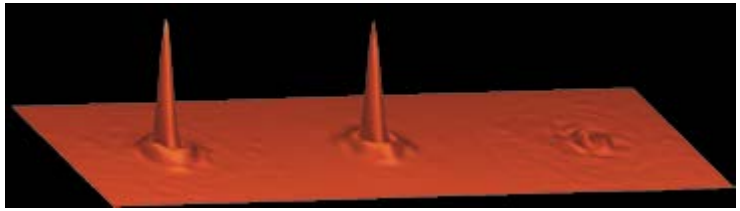
Local outreach was active as well, with Keck Observatorystaff providing education programs to children from several schools including Ka Umeke Kaeo PCS, Kona Christian Academy, Kanu O Ka Aina, West Hawaii Explorations Academy and the Upward Bound Program.

Finally, one of the most important features of our commitment to share and inspire is our Visitor Center volunteer program at our headquarters facility in Kamuela. Keck Observatory's Guidestars are composed of outstanding and highly qualified docents who introduce visitors of all ages and backgrounds to the wonderment that is Keck Observatory.

Welcome To Our Universe
Keck Week 2013

The diverse sites and people that participated at our Open House in March remind us how extraordinary Keck Observatory is.

INSPIRATION



Science Bibliography

Refereed publications FY2013

Key to Publications:

A&A: Astronomy & Astrophysics

AJ: The Astronomical Journal

ApJ: The Astrophysical Journal

ApJS: The Astrophysical Journal Supplement

Astonomy Letters: Astronomy Letters

Astrophysics and Space Science: Astrophysics and Space Science

Icarus: Icarus

MNRAS: Monthly Notices of the Royal Astronomical Society

Nature: Nature

PASJ: Publications of the Astronomical Society of Japan

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