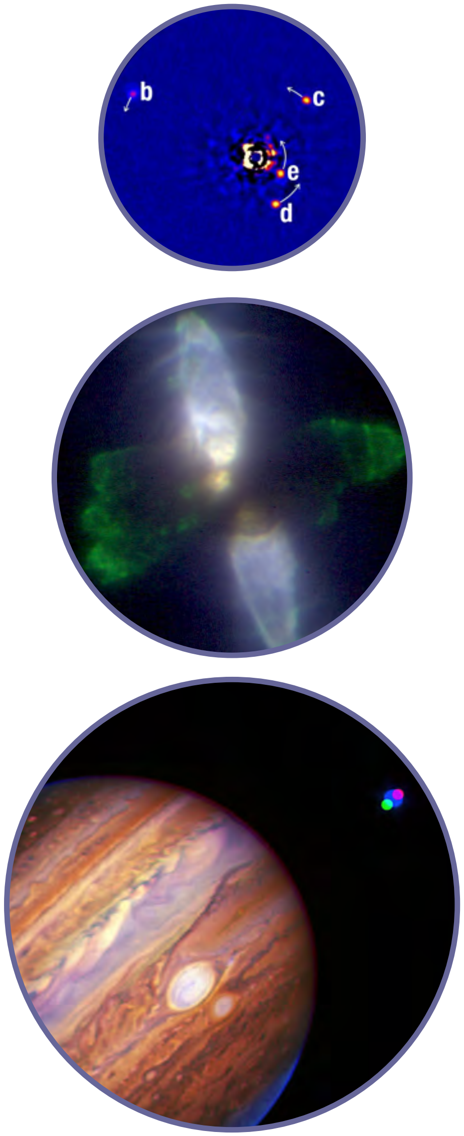
The Keck Observatory
Portal to the Universe

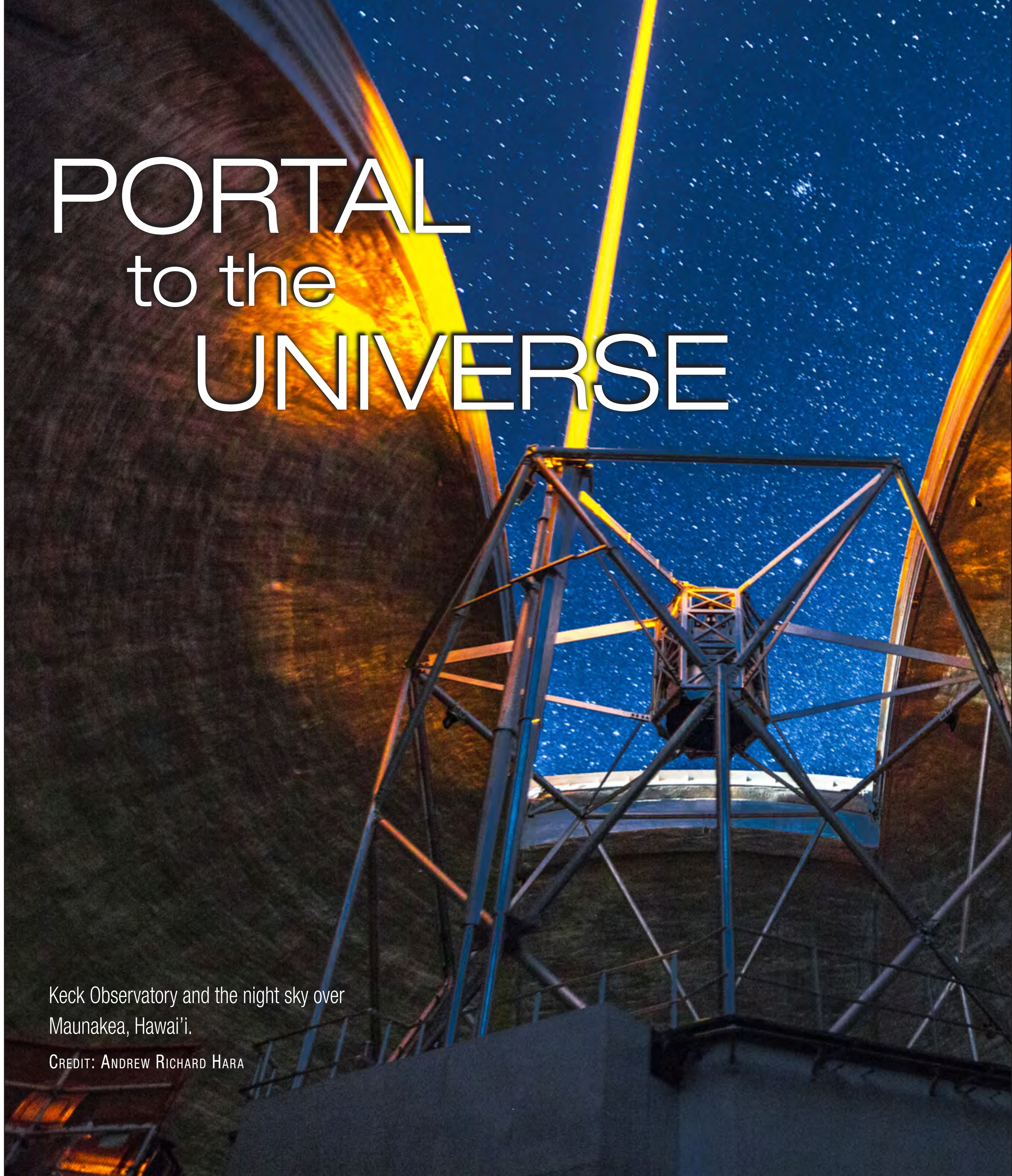
Keck Observatory at sunrise on Maunakea, Hawai'i.
CREDIT: ANDREW RICHARD HARA

W. M. KECK OBSERVATORY
Maunakea, Island of Hawai'i



Keck brings us views of our solar system, our galaxy, and beyond. From bottom to top: The Great Red Spot of Jupiter, the Egg Nebula, and a picture of four planets around HR 8799 taken December 8, 2010 (Credit: NRC-HIA, C. Marois/W. M. Keck Observatory).

PORTAL to the UNIVERSE



Keck Observatory and the night sky over Maunakea, Hawai'i.

Credit: Andrew Richard Hara

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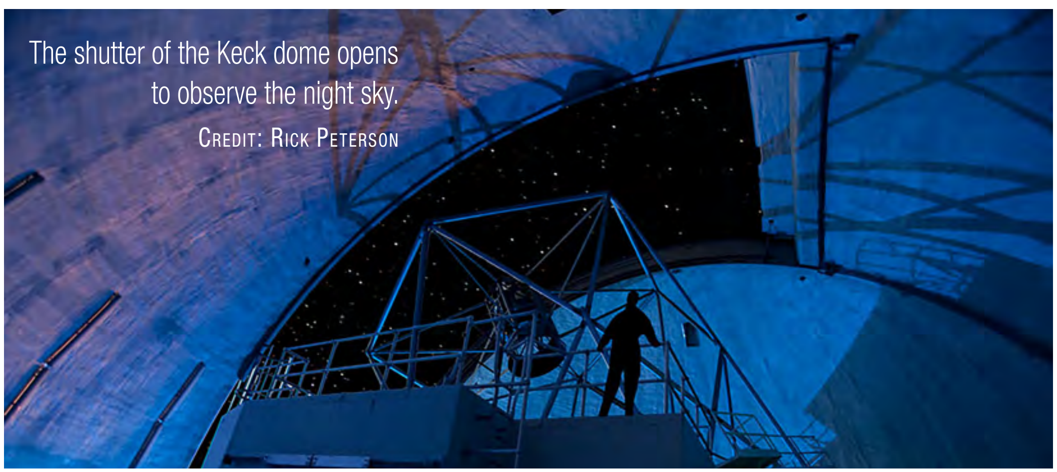


The shutter of the Keck dome opens to observe the night sky.
Credit: Rick Peterson

QUICK FACTS
about the
Keck Observatory

OBSERVATORY STATS

- **Location:** Maunakea, Hawai'i
- **Altitude:** 4,145 meters (13,599 ft)
- **Mirror diameters:** 10 meters (33 ft) each
- **Collecting area:** 72 m^2 (820 ft^2) each
- **Angular resolution:** 0.04 to 0.4 arcseconds
- **Instrument wavelength:** Optical to near-infrared
- **First light:** 1990 (Keck I), 1996 (Keck II)

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.

MISSION

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

Credit: Andrew Richard Hara

The W. M. KECK OBSERVATORY Portal to the Universe

THE SUMMIT OF MAUNAKEA on the island of Hawai'i is a place where earth and sky become one and the boundless expanse of the universe consumes you. Clouds, appearing like white sea foam, roil far beneath your feet. A trade wind blows soft yet reassuringly, a near-perfect calm. And, as the night approaches, the setting sun turns the thin, ice blue atmosphere into a panoramic layering of reds and violets before ceding to the darkness that's in waiting. In this stillness, time and direction begin to shed their meaning, as the infinite sky unfolds an entire history of both past and future, a storybook of all that has happened and all that will come.

This summit has become an international destination for astronomy, where meteorological conditions and distance from human-made light provide viewing of planets, stars, and galaxies that is without parallel. And nestled here, on this the world's tallest island mountain, is the W. M. Keck Observatory, the largest and most versatile and productive astronomical observatory ever constructed. With its twin 10-meter telescopes, Keck drinks up the night. Its targets could be as varied as the volcanic eruptions on Jupiter's moon Io, the frenzied motion

Our overarching goal is to maximize the scientific impact of the twin Keck telescopes, and to continue on this great trajectory of discoveries.

of stars around the supermassive black hole at the center of our galaxy, or the whispers of light from the first galaxies to form after the Big Bang. Its versatility and accessibility have enabled long-term, collaborative efforts resulting in profound reimaginings of our physical world, such as the measurements of supernovae in distant galaxies that showed how the expansion of the universe was not slowing down as expected but, inexplicably, speeding up. That Keck-fueled discovery pointed to a mysterious anti-gravitational force called "dark energy" and led to the 2011 Nobel Prize in Physics.

Now in its third decade of operation, the Keck Observatory has never been more primed for paradigm-shifting discoveries. Carefully planned upgrades — relatively simple for earthbound scopes compared to satellites — have ensured that Keck utilizes the latest technologies…if not pioneering the technology itself. Keck, for example, was the first large observatory to install laser-guide-star

View of part of the Maunakea summit, Hawai'i. Visible are the Subaru Telescope (left), the two telescopes of the W. M. Keck Observatory, and the NASA Infrared Telescope Facility (far right, opposite page). Credit: Vadim Kurland adaptive optics, improving its already stellar resolution by nearly an order of magnitude. Other instrument and software installations keep Keck woven into the mission design of NASA observatories, such as the Hubble Space Telescope and, soon, the James Webb Space Telescope. Such continuous versatility has made the Keck Observatory one of America's best investments in science and technology.

Productive, flexible, dependable, economical, the W. M. Keck Observatory on Maunakea, Hawai'i, is — both metaphorically and physically — central to the international astronomy community and humankind's pursuit to understand more fully the workings of the universe. This booklet describes how Keck's clear strategic direction, extraordinary operations staff, and state-of-the-art instrumentation have combined to offer an indispensable tool to study all regions of space, both near and very, very far.

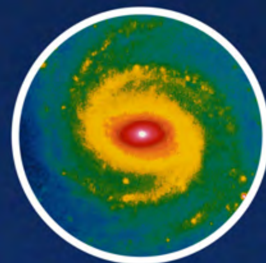
Continuous versatility has made the Keck Observatory one of America's best investments in science and technology.

The Nobel Prize in Physics 2011 was awarded to Saul Perlmutter and, jointly, to Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae." The team included Keck observations in their ground-breaking research.

Keck: A Chronology

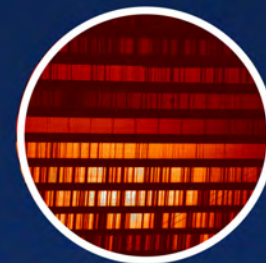
1977
Concept proposed

1985
Howard B. Keck gives $70M to fund construction of Keck I



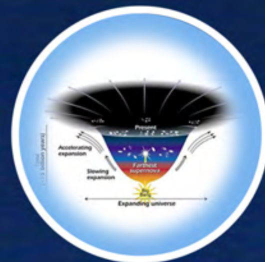
1990
Keck I observes first light with 9 of the eventual 36 segmented mirrors; science observations would begin in 1993

1991
Keck II breaks ground upon additional donations from the Keck Foundation



1995
Astronomers use Keck to reveal how galaxies were common even in the early universe; would later lead to Gruber Prize for Cosmology for Charles Steidel of Caltech

1996
Keck II is completed; joins Keck I as the world's largest optical telescopes



1998
Astronomers discover an "accelerating" universe; would later earn a Nobel Prize

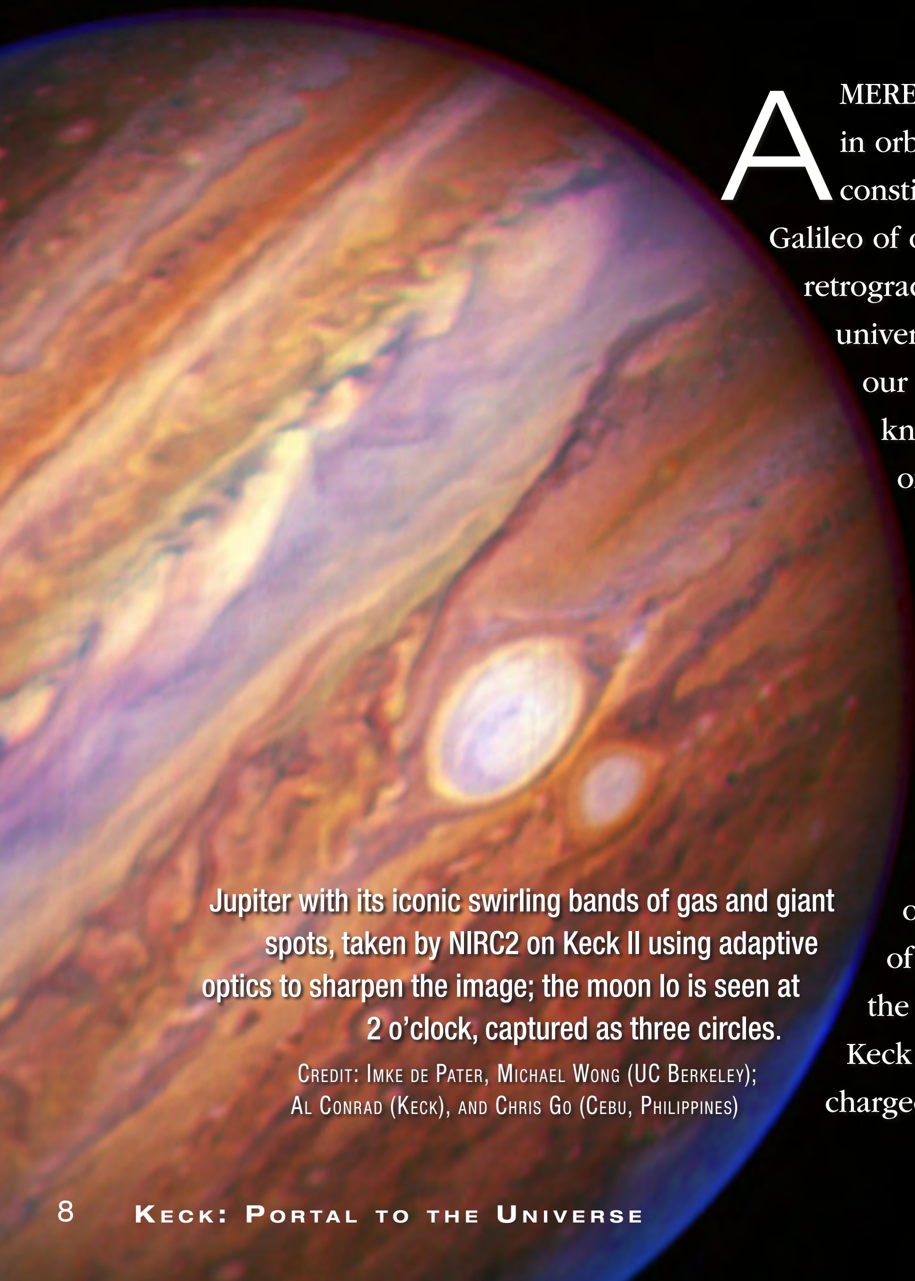
1999–2004
Adaptive optics installed, then augmented with laser-guide-star technology

2012
Instrument upgrades enter third generation with MOSFIRE

2017
Cosmic Web Imager installed; maps large-scale structure of the Universe

CLOSE TO HOME

Keck and Our Solar System



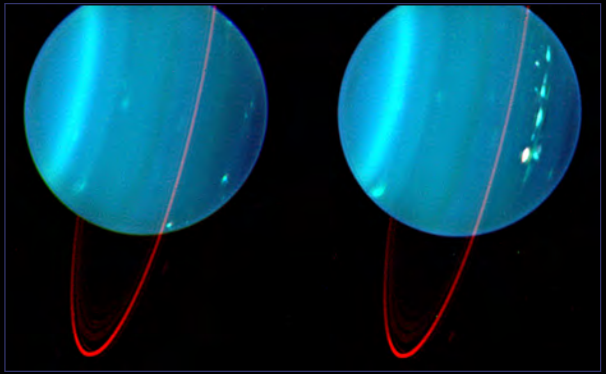
Jupiter with its iconic swirling bands of gas and giant spots, taken by NIRC2 on Keck II using adaptive optics to sharpen the image; the moon Io is seen at 2 o'clock, captured as three circles.

Credit: Imke de Pater, Michael Wong (UC Berkeley); Al Conrad (Keck), and Chris Go (Cebu, Philippines)

A MERE 400 YEARS HAVE PASSED since Galileo discovered four moons in orbit around Jupiter. This was a revolution of planetary objects constituting a revolution in science. These and other observations by Galileo of our solar system, such as the phases of Venus and the apparent retrograde motion of planets, pointed to a heliocentric model of the universe. Moreover, what Galileo's simple telescope hinted at was that our solar system was alive…not with biological forms (that we yet know of!) but rather with sheer wonder — fanciful worlds with rings of ice, methane lakes, or anti-cyclonic storms.

Instruments on the Keck Observatory provide modern scientists with "remote access" to the planets and moons of our solar system, something Galileo could only dream of. Keck instruments virtually take us there, providing what could best be described as collecting samples of these nearby worlds. This is done with the use of spectrometers, such as the Near Infrared Spectrometer (NIRSPEC), which reveal planetary chemistry. For example, scientists using Keck instruments along with images obtained from NASA's Cassini satellite have revealed the process of methane storms on Saturn's moon Titan, a phenomenon akin to the water cycle on earth but with liquid and vapor methane. Similarly, Keck scientists have discovered that the rings of Saturn can "rain" charged ice particles towards Saturn's upper atmosphere.

On Jupiter's moon Europa, scientists using another of Keck's spectrometers, the OH-Suppressing Infrared Imaging Spectrograph (OSIRIS), found the strongest evidence yet that salty water from the vast liquid ocean beneath Europa's frozen exterior may make its way to the surface — an exchange of matter and energy between the subsurface and surface that may allow us to remotely find evidence of life that could exist below the ice. On Jupiter's moon Io, scientists using Keck cameras and spectrographs discovered massive volcanic eruptions spewing lava into space over a period of about five days, revealing active geological forces seen elsewhere only on Earth, Saturn's Enceladus, and Neptune's Triton.



Keck sees Uranus in a new light: a composite of infrared images showing the eastern and western hemispheres. (The north pole is at 4 o'clock.) The Keck image from July 2004 revealed new features of the planet's atmosphere and rings.
CREDIT: HEIDI B. HAMMEL, SPACE SCIENCE INSTITUTE; LAWRENCE SROMOVSKY, UNIVERSITY OF WISCONSIN-MADISON/ W. M. KECK OBSERVATORY

The Keck Observatory also has demonstrated that the planet Uranus is anything but bland. Scientists spotted unexpected, massive storms driven by a process not known, for this planet is too far from the sun for the storms to be caused by solar effects. Previous Keck observations had revealed that Uranus' rings have colors, with the outer most being a distinctive blue. Further out in our solar system, with the exceptional resolution provided by Keck's laser-guide-star adaptive optics, scientists could discern a moon orbiting Eris, the most massive of the dwarf planets, yet another breakthrough discovery…a discovery said to have ended the debate about whether Pluto should be classified as a planet or just one of many dwarf planets.

Taken together, such observations illustrate the Keck Observatory's power when combined with observations from orbiting spacecraft while also providing unprecedented views of planets not yet visited by NASA probes.

One of two surviving Galileo-style telescopes, late 1609 – early 1610.
CREDIT: MUSEO GALILEO, FLORENCE, ITALY

Looking forward: In the coming years, Keck scientists, working with NASA and other partners, will utilize next-generation instruments to explore locations where life could have existed or could exist today, using techniques such as remote sensing of methane on Mars (a possible signal of active organics) and atmospheric and ground water on Mars or the moons of Jupiter and Saturn. Keck scientists also will study how the solar system formed and evolved, search for hazards such as near-earth asteroids, and gather complementary data to support numerous planned NASA and European Space Agency missions to the planets — providing valuable contextual observations to significantly enhance the rather temporally and spatially sparse coverage afforded by these missions.

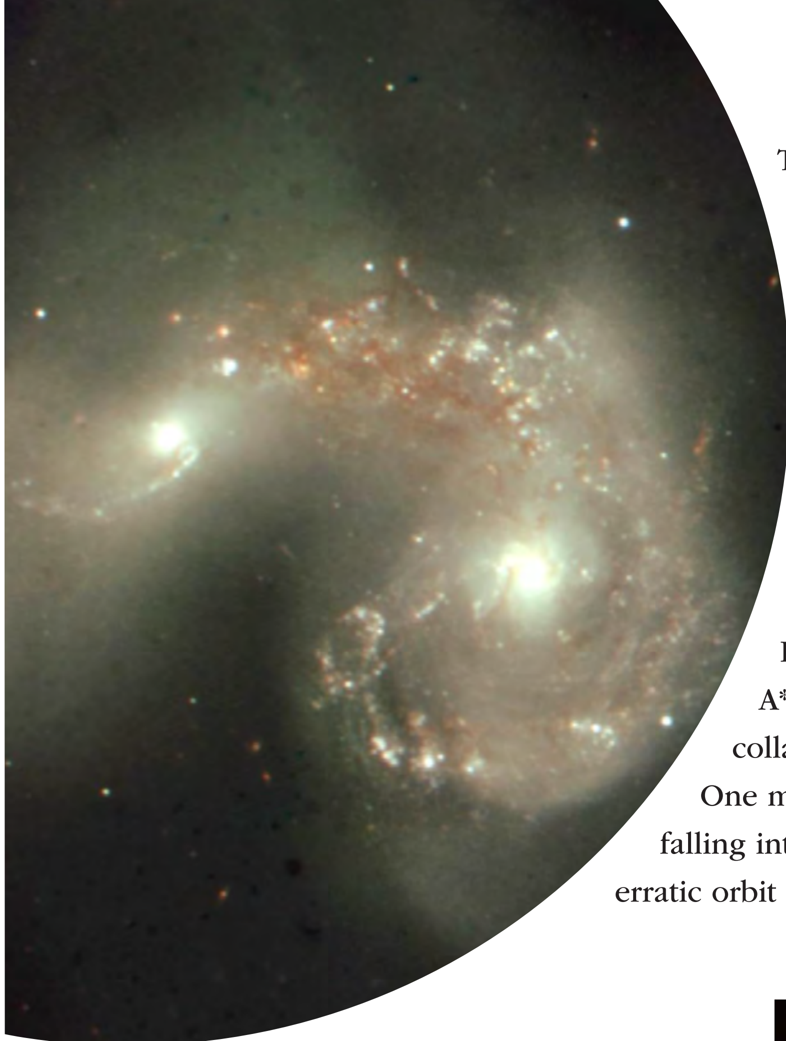
GALACTIC NEIGHBORHOOD

Keck and the Milky Way

Black holes, supernovae, pulsars, stellar nurseries, proto-planetary disks of solar systems in the making… Our Milky Way galaxy is filled with wonder and mystery. And Keck's suite of instruments can capture these phenomena in unique ways.

Our local galactic region is abundant with brown dwarfs, relatively cool spheres of gas that haven't enough mass to ignite hydrogen fusion in their cores and thus shine more brightly. As a result, brown dwarfs are nearly invisible to most telescopes and have been poorly studied. These objects, however, do shine brightly in the infrared waveband. The Keck MOSFIRE instrument, short for Multi-Object Spectrometer For Infra-Red Exploration, is arguably the world's best brown dwarf hunter. The instrument combines unsurpassed sensitivity in the near-infrared wavelengths with an ability to scan a huge swath of the sky and survey up to 46 objects at once.

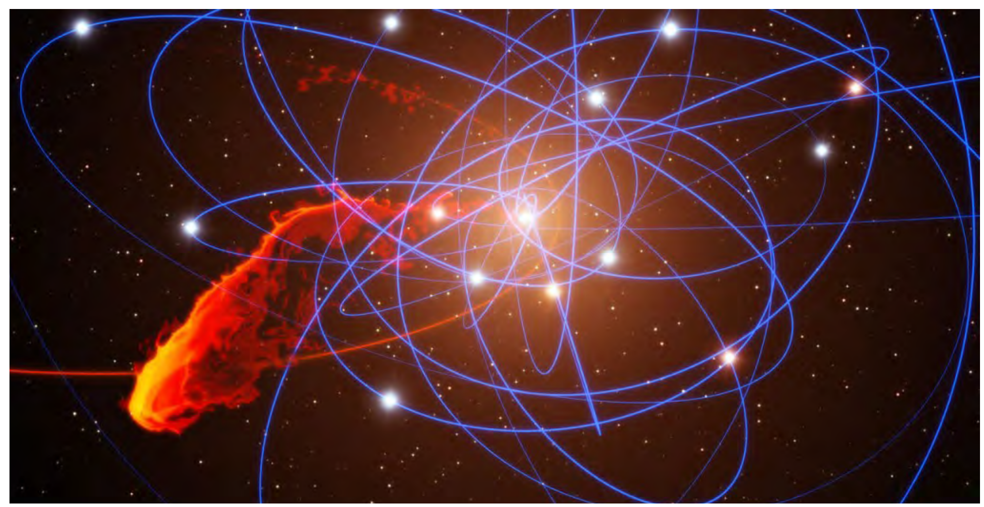
Credit: Ethan Tweedie Photography



This unprecedented infrared sensitivity also makes Keck MOSFIRE ideal for studying young stars and stellar nurseries, as well. Here, cool infrared — compared to "hotter" optical, ultraviolet, and X-ray light — is a dominant wave band; moreover, regions of new stellar activity are often enshrouded in dust, which infrared light can penetrate more easily than optical light can.

Similarly, the suite of Keck infrared instruments explores the dusty plane of our galaxy clear through to the chaotic galactic core, home to Sagittarius A*, a supermassive black hole at the center of our galaxy. High-angular–resolution infrared images from Keck have been able to resolve clusters of stars around Sagittarius A*, and infrared spectra have determined the nature of stars there, a collage of blue super giants, red giants, and strange dust-obscured stars. One mysterious object there is a star-cloud hybrid called G2, which may be falling into the black hole. UCLA astronomers are using Keck to monitor G2's erratic orbit around Sagittarius A* to see exactly when it takes that final plunge.

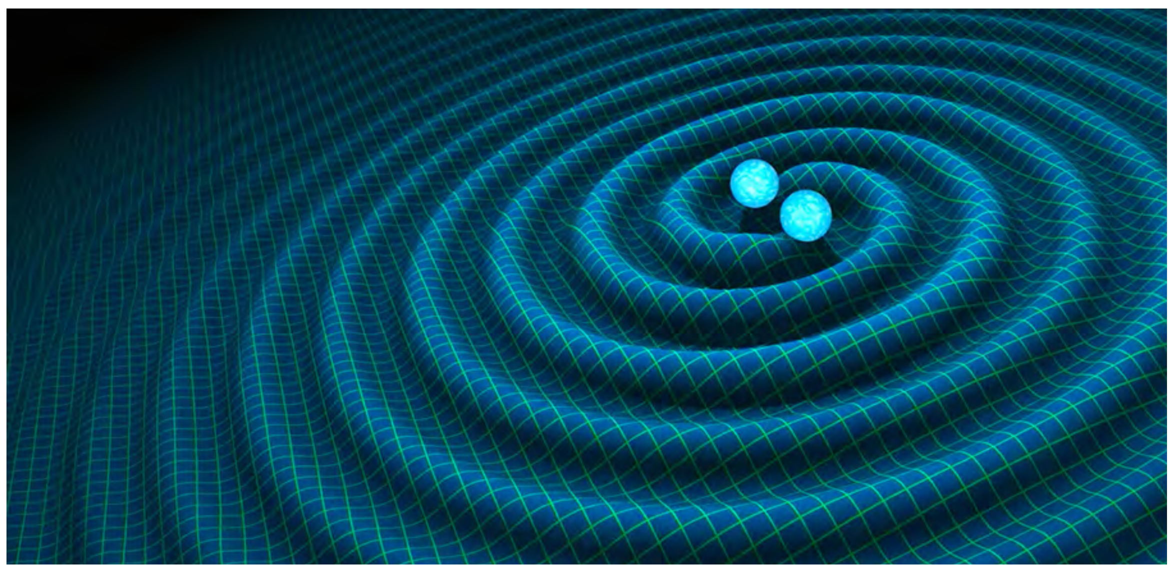
Above, left:
The MOSFIRE instrument's "first light" image of the Antennae galaxies, acquired on April 4, 2012. At right: Artist's concept of the G2 gas cloud/star during its close approach to the black hole at the center of the Milky Way.
Credit: ESO/MPE/Marc Schartmann



Keck may complement LIGO by providing observations at the moment of a neutron star merger.

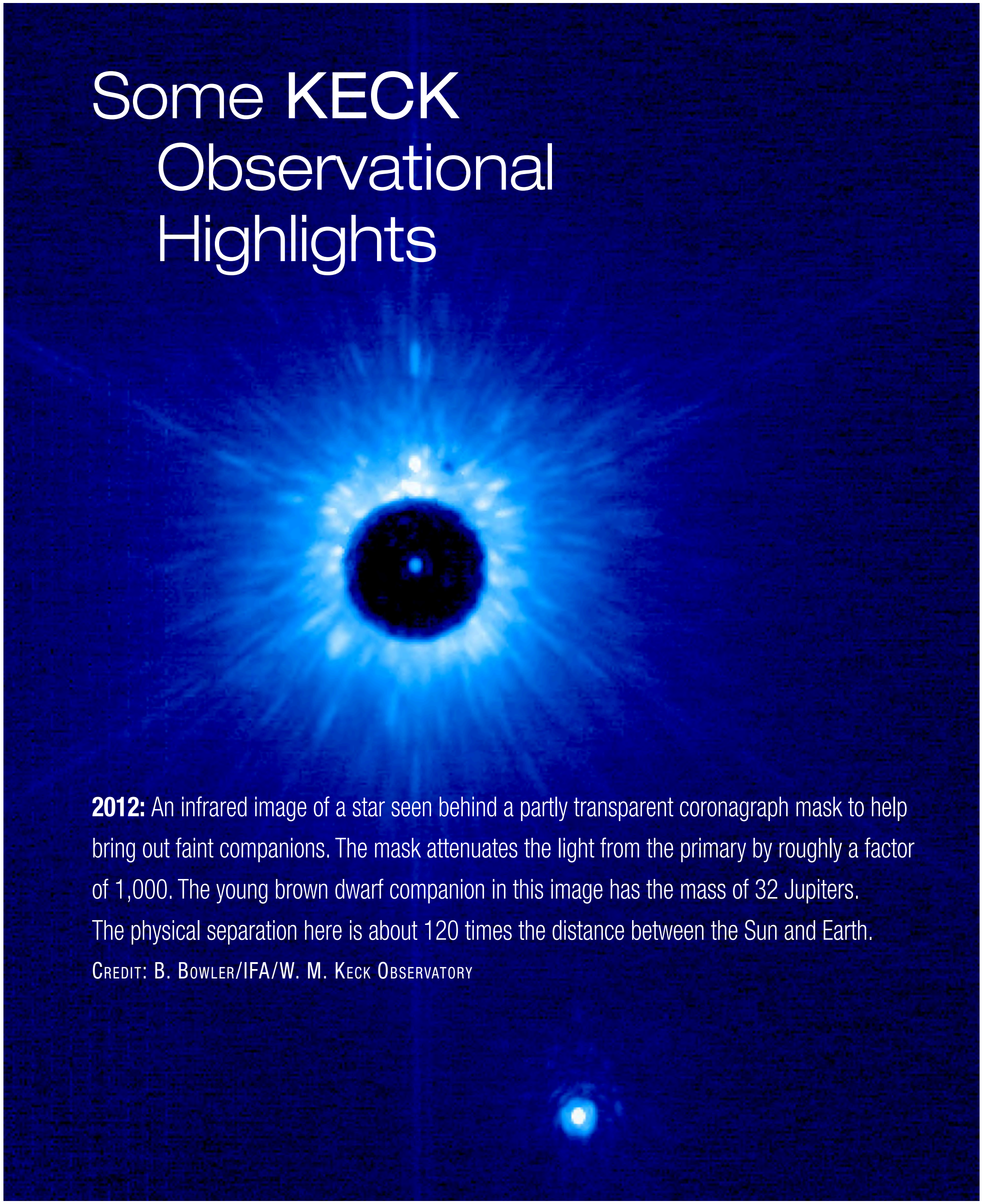
Keck is also primed to enter into an entirely new field, gravitational wave astronomy. In 2016, scientists using the ground-based Laser Interferometer Gravitational-Wave Observatory (LIGO) directly detected gravitational waves — ripples in spacetime predicted by Einstein, who himself thought they would be far too subtle to measure. This landmark first observation was of gravitational waves produced by the merger of two massive black holes, which likely do not generate much electromagnetic radiation. Yet future LIGO detections could be of merging neutron stars, and these are expected to be visible at optical and near-IR wavelengths. Thus, Keck may complement LIGO by providing observations at the moment of a neutron star merger.

Looking forward: Considering the fascinating possibilities offered by LIGO and what has been learned from star-cloud G2, which we may soon catch falling into a black hole, the Keck Observatory team is enhancing its ability to conduct time-domain astronomy, essentially zooming to a region of the sky at the moment some great activity is occurring. The Keck team is enabling one of its telescopes, Keck I, to more quickly slew to the action; and in the coming years, the team hopes to do the same for Keck II.



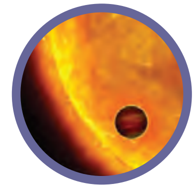
Two neutron stars swirl into each other, their gravitational forces beginning to churn the fabric of space. The gravitational wave signal is a warning of the collision to come.
Credit: R. Hurt/Caltech-JPL

Some **KECK** Observational Highlights



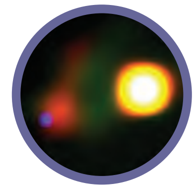
2012: An infrared image of a star seen behind a partly transparent coronagraph mask to help bring out faint companions. The mask attenuates the light from the primary by roughly a factor of 1,000. The young brown dwarf companion in this image has the mass of 32 Jupiters. The physical separation here is about 120 times the distance between the Sun and Earth.

Credit: B. Bowler/IFA/W. M. Keck Observatory

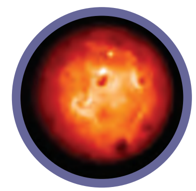


1999: First exoplanetary transit prediction (star HD 209458)

2005: Tripling what was understood to be Andromeda's size by plotting the motion of stars along the galaxy's edge

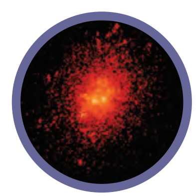


2007: First planetary disk detected, seen around Mira, a dying star system



2010: Quiescent volcanic activity discovered on Io, the innermost moon of Jupiter

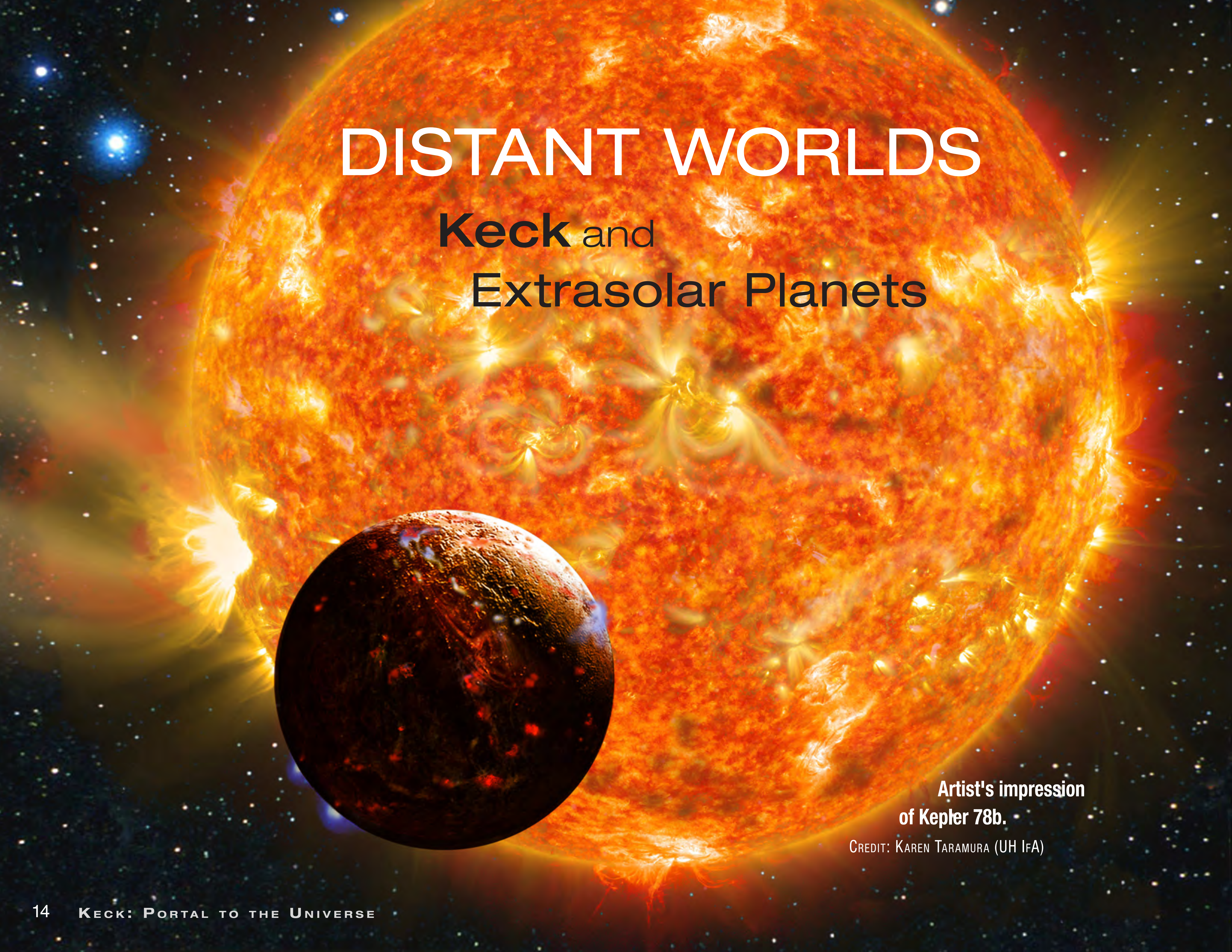
2014: Keck observes merging galaxies in unprecedented detail



2016: Keck spots the most distant galaxy to date

DISTANT WORLDS

Keck and Extrasolar Planets



Artist's impression of Kepler 78b.

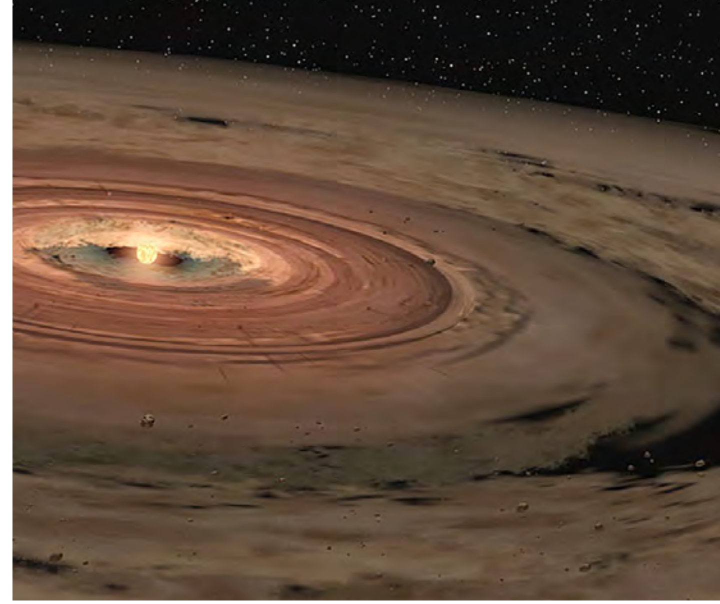
Credit: Karen Taramura (UH IfA)

THE GALAXY IS TEEMING WITH STARS, and the majority possess planets in their orbit. Until the early 1990s, the existence of extrasolar planets, or exoplanets — worlds beyond our solar system — was assumed solely on the basis of odds. With a billion stars out there, surely one of them must have planets like our Sun does. But advances in technology and dedicated observations soon began to reveal their presence. The first confirmed sighting of an exoplanet orbiting a main-sequence star came in 1995, a Jupiter-size planet found in a four-day orbit around the nearby star 51 Pegasi. Astronomers detected the planet indirectly, by virtue of watching the radial velocity of 51 Pegasi wobble back and forth due to the gravitational tug of this massive planet in a close-in orbit around its parent star.

As the decade unfolded, dozens more exoplanets were found; indeed, the Keck Observatory's High Resolution Echelle Spectrometer (HIRES) has detected more extrasolar planets than any other instruments, ground-based or in orbit. Another key Keck instrument for this task has been the second-generation Near Infrared Camera (NIRC-2). In a landmark observation in 2008, Keck captured the first direct image of a multi-planet system around a Sun-like star.

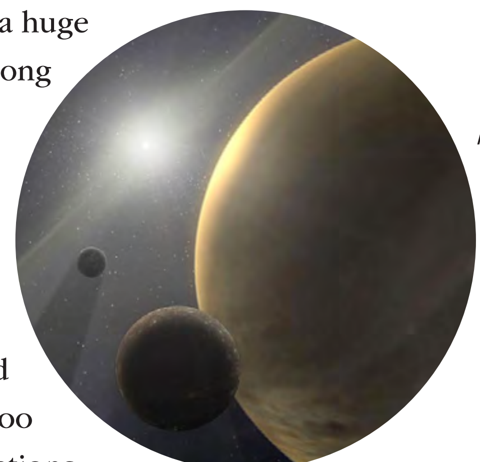
In 2009, NASA launched the Kepler space observatory, a mission dedicated to discovering exoplanets. Now the game was heating up. The mission has been a huge success, discovering more than 1,000 exoplanets in nearly 450 star systems, along with thousands more yet-confirmed planetary candidates.

Hand-in-glove with the Kepler mission has been the Keck Observatory, providing detailed information concerning the chemical properties, velocity, radius and mass of many of Kepler's discoveries. In 2013, scientists using Kepler and Keck data identified the first known Earth-size rocky exoplanet. Other discoveries by these two planet hunters include several worlds situated in the so-called Goldilocks zone, at a distance from their star that's not too close, not too far, but just right to support life as we know it. Keck observations suggest that 20 percent of Sun-like stars in our galaxy have Earth-like planets in a habitable zone.



This artist's rendition of 51 Ophiuchi's inner and outer dust disks illustrates the size difference of their constituent grains.

CREDIT: NASA/JPL-CALTECH/T. PYLE (SSC)

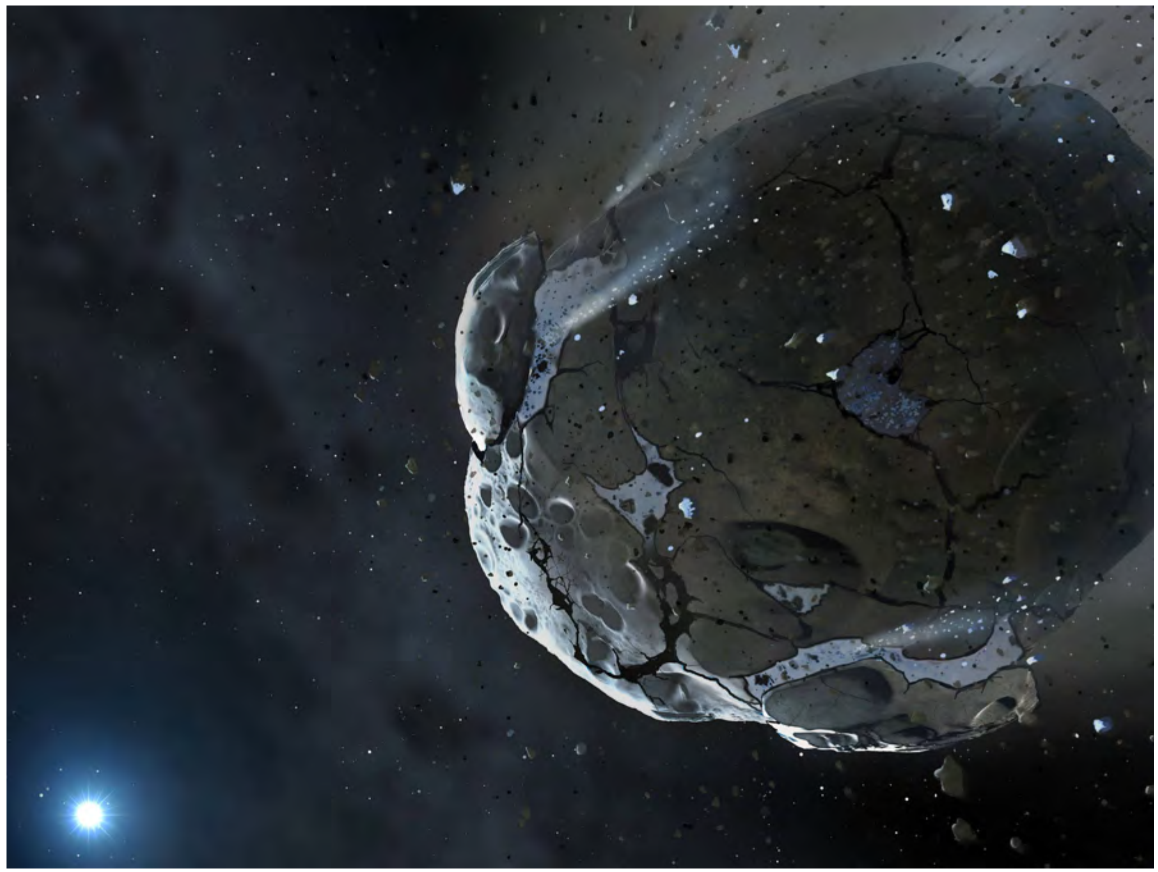


Artist's concept of an exoplanet and its satellites.

CREDIT: NASA/JPL

The planned Keck Planet Finder will bring planet hunting to new heights.

Looking forward: The planned Keck Planet Finder (KPF) will bring planet hunting to new heights, characterizing hundreds of planets identified by Kepler as well as the upcoming Transiting Exoplanet Survey Satellite (TESS), undoubtedly uncovering habitable worlds in the decade to come. In typical collaborative spirit, the Keck Observatory uploads all its data to the Keck Observatory Archive (KOA), a NASA-funded collaboration that makes all data free to the public. These are exciting times for planet hunters, professional and amateur alike.



Artist's impression of a rocky, water-rich asteroid being torn apart by the strong gravity of the white dwarf star GD 61. Keck is searching our Solar System for such objects, which likely delivered the bulk of water on Earth and represent the building blocks of the terrestrial planets.

Credit: ©Mark A. Garlick, space-art.co.uk, University of Warwick and University of Cambridge

An artist's impression of a view from a rocky moon around a giant gaseous planet, with at least two other moons and a host star in the distance.
CREDIT: NASA

DEEP VOYAGE

Keck and Extragalactic Space

Keck offers extraordinary views beyond our galaxy for the same reason it excels in observing nearby dim brown dwarfs and dusty stellar nurseries: infrared sensitivity. Extremely distant stars and galaxies may radiate ultraviolet and optical light; but these objects are receding from our view in an expanding universe at such a rapid pace that their light has redshifted towards lower energies and into the infrared band by the time it reaches us. Long-term and large-scale Keck surveys of the distant universe have produced an infrared map of the brightest galaxies. This, in turn, has enabled scientists to map the structure and evolution of the universe.

Redshift is a fundamental physical property of light from a source that's moving away from us, akin to a train whistle shifting to a lower pitch as it races past us; the faster the movement, the greater the shifting towards lower energies of light. And because scientists have a good estimate of how fast the universe is expanding — 65 kilometers per second for every 3 million light-years in distance, a rate known as Hubble's constant — the degree of shifting towards lower energies can be used to determine the distance of the object emitting the light. Because of its superior sensitivity, Keck is often the go-to observatory to measure the precise redshift and thus distance to objects that were discovered by other observatories. This is one of the reasons why Keck is among the world's most cited observatories in the scientific literature, because so many astronomical observations of the early universe rely on Keck.

So powerful is Keck that it has detected what is currently known as the darkest galaxy, among the first galaxies to form about 13 billion years ago when the structure we see today — that cosmic web of stars and galaxies — was just starting to emerge. Using the Keck Deep Extragalactic Imaging Multi-Object Spectrograph (DEIMOS), scientists spotted this early galaxy far beyond a galaxy cluster. The gravity of the intervening cluster acted as a lens, magnifying the more distant object, a phenomenon called gravitational lensing. The galaxy was tiny, only 0.01% the mass of our Milky Way galaxy. This observation provides important details about when, where, and how the first galaxies formed; it also highlights Keck's ability to complement NASA's James Webb Space Telescope with its goal of finding the first stars and galaxies.

Keck instruments also have helped scientists study supermassive black holes, strange beasts that contain the mass of millions and sometimes billions of suns compressed into a central region no larger than our solar system. Most galaxies have these, including our own, and Keck is helping to categorize them. Quasars are well-known examples. These are exceedingly distant galaxies in which the central core outshines all the stars in that galaxy. Supermassive black holes are central and often dust-enshrouded, making them an ideal target for Keck. Keck's infrared observations complement radio and X-ray observations, helping develop a complete picture of how these objects form and evolve.

Because supermassive black holes represent such extreme gravitational force, Keck observations provide an opportunity to test how matter behaves in such an environment — a test of Einstein's theory of gravity, called general relativity. Keck observations, in collaboration with radio and X-ray data, already have confirmed how time slows down near the edge of a black hole.

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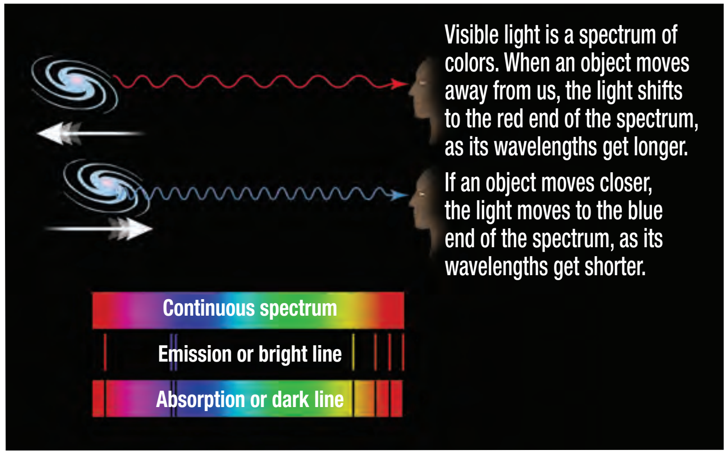
So powerful is Keck that it has detected what is currently known as the darkest galaxy.

Looking forward: Faint-object spectroscopy, used to characterize and explore the astrophysics of distant or low-luminosity sources, is an area historically dominated by the Keck Observatory telescopes. Instruments such as LRIS, DEIMOS, MOSFIRE, and OSIRIS have been true workhorses. The Keck Observatory team hopes to enhance these instruments with the addition of Ground-Layer Adaptive Optics (GLAO), which would improve image quality over a wide wavelength band and also result in a major increase in spectroscopic sensitivity.

WHY INFRARED?

Infrared is an invisible part of the electromagnetic spectrum comprising longer wavelengths, or lower frequencies, than those of visible light. These wavelengths extend from the red edge of the visible spectrum (about 1-micron wavelength) down to what we call microwaves (about 10,000 microns). The infrared band itself is divided into near-, mid-, and far-infrared sections — with "far" being the farthest away from visible light and closest to microwaves.

About half of the Keck Observatory instruments analyze near-infrared light. Why not stay entirely in the optical band? Infrared is an important energy range in astronomy for three primary reasons, all crucial to Keck's mission.



- **Infrared is a thermal energy.** Although humans don't radiate visible light, we do "glow" in infrared. Similarly, cooler objects in the universe that don't shine brightly in visible light, such as dim stars, brown dwarfs, and planets, radiate in infrared energies, which Keck instruments can detect.
- **Infrared is a "stealth" energy.** Whereas visible light is blocked by clouds, dust, or window shades, infrared wavelengths can penetrate such obstruction. So, with infrared detectors, astronomers can peer into dust-enshrouded cores of star-forming regions, see clear across the dusty plane of the Milky Way galaxy in which we reside, and discern objects in the galactic core that are not otherwise visible to us in optical wavelengths.
- **Infrared is a "well-traveled" energy.** In the expanding universe, all distant galaxies are moving away from us. This means that any light that they emit is redshifted — shifted to lower energies. So, the light from distant galaxies and quasars may leave these objects in the visible or ultraviolet part of the electromagnetic spectrum, but by the time the light reaches us, it may be shifted all the way into the infrared band. Thus, Keck astronomers rely on infrared detectors to observe the most distant objects in the Universe.

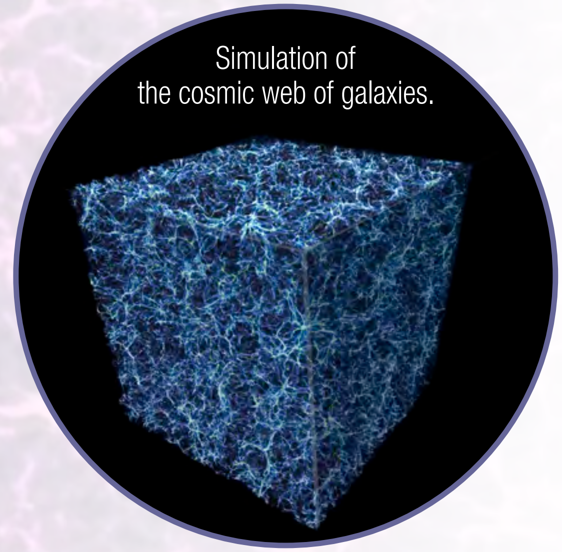
Given the properties of infrared radiation, it is perhaps ironic that water vapor in the Earth's atmosphere blocks some of the light from reaching the Earth's surface. For this reason, NASA has placed many infrared detectors in space, above the atmosphere. Fortunately for Keck, the observatory is at a such a great altitude and situated in such an exceptionally cool and dry region (nearly cloud-free, with more than 300 clear nights per year) that the infrared detectors are hardly affected by atmospheric water vapor.

DISCOVERING THE PAST AND FUTURE

Keck and Cosmology

KECK IS HELPING to piece together how the universe evolved from a hazy ball of matter and energy after the Big Bang about 13.8 billion years ago to the fine-scale structure we see today. Keck's observations of a galaxy cluster called MACS J0717 provides an instructive example. Theories of cosmic evolution suggest that stars and galaxies form along filaments of unseen matter, like pearls on a string. These filaments are made of ordinary matter plus a theorized form called dark matter. It's the gravity from the underlying dark matter that attracts ordinary matter, which coalesces into stars and galaxies.

MACS J0717 is a unique cluster in that it is itself of smash-up of four galaxy clusters, representing a massive early-universe collision and a tremendous conglomeration of matter. So massive is MACS J0717 that it creates a gravitational lens, as described in the previous section, magnifying the faint galaxies far beyond it. Scientists used the Hubble Space Telescope in conjunction with the Subaru Telescope and Canada-France-Hawai'i Telescope (both of which are on Maunakea) to capture high-resolution images of the region. This created a two-dimensional map. Scientists then turned to Keck for spectrographic measurements of the objects' distance and speed. Keck's DEIMOS can gather spectra from more than

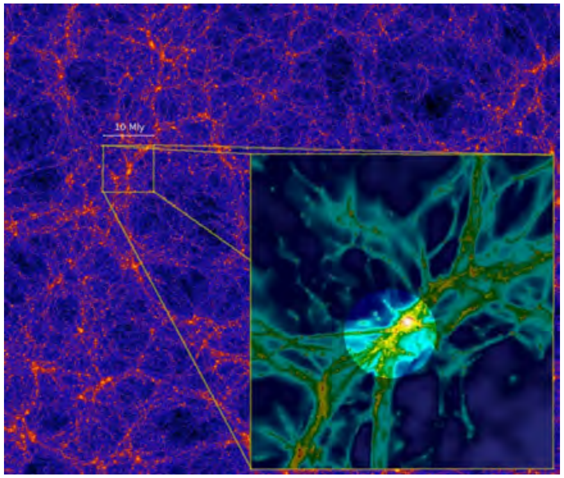


Simulation of the cosmic web of galaxies.

Imagine the universe as a cosmic web with bright chains and cluster of galaxies interspersed with dark voids. Simulations show that, after the Big Bang, tiny fluctuations of matter and energy gave way to the structure we see today. As a result of gravity, those places with a little more matter attracted yet more matter and grew denser, while places with less matter lost the gravitational tug of war and grew sparse.

CREDIT: NASA/ESA/E. HALLMAN (UNIVERSITY OF COLORADO, BOULDER)

130 galaxies in a single exposure; in "mega-mask" mode, DEIMOS can take the spectra of more than 1,200 objects at once. Measurements such as this produced the first 3D map of the early universe, revealing the cosmic web of galaxies strung along the yet-to-be-seen dark matter filaments.



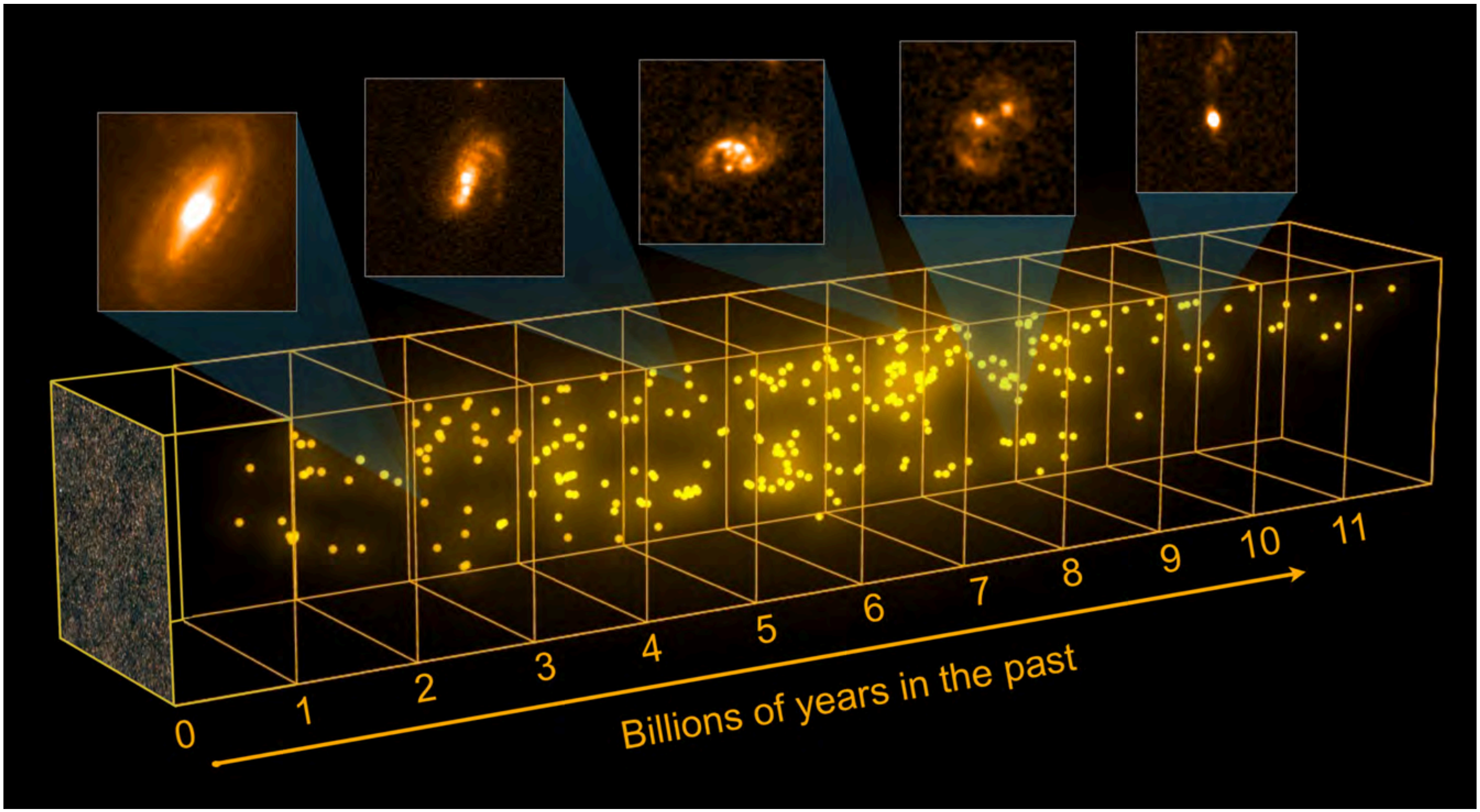
The Universe resembles a cosmic web in which bright galaxy clusters are strung along endless filaments of unseen dark matter. Theorists predict that this dark matter comprises upwards of 84 percent the mass of the cosmic web and serves as a gravitational "glue" holding the galaxies in place.

Credit: S. Cantalupo (UCSC); Joel Primack (UCSC); Anatoly Klypin (NMSU). Inset: S. Cantalupo

With an eye to the future collaborations, Keck's newest instrument, the Cosmic Web Imager, will have the power to study the faint filaments between clusters of galaxies. This will provide further insight into the evolution of structure and will work hand-in-glove with NASA's James Webb Space Telescope.

Can Keck help predict the future? In a way, yes. In the 1990s, most astronomers thought that the attractive force of gravity would eventually slow the expansion of the universe and, in trillions of years, slowly pull back all matter into a "big crunch". Keck observations during the 1990s of distant supernovae — designed to confirm this theory! — instead led to a startling discovery: the expansion of the universe was not slowing down but, rather, speeding up. This pointed to a theorized anti-gravitational force called dark energy that was over-powering gravity. The finding earned the 2011 Nobel Prize in Physics for Saul Perlmutter of the Lawrence Berkeley National Laboratory, who, using Keck data, shared the prize with Brian Schmidt of the Australian National Laboratory and Adam Riess of Johns Hopkins University for their complementary observations.

Looking forward: Dark energy paints an entirely different picture of the future, one in which every star and, indeed, every tiny bit of matter will be infinitely distant from each other. What could this force be? The Keck Observatory team hopes to stay on the dark energy trail with a technology upgrade called the Keck All sky Precision Adaptive optics, or KAPA. This technology would further enhance Keck's ability to use gravitational lensing to map the very earliest structure, leading to a better measurement of Hubble's constant and place stronger constraints on dark energy — that is, when dark energy ramped up and how fast it is accelerating the universe. Also, the Cosmic Web Imager, a highly flexible instrument designed to support a cornucopia of science investigations, will focus on complex extended objects in the night sky, including mapping the architecture of large-scale structure in the universe. Paired with the most superb telescope and site on Earth, the Keck Cosmic Web Imager will ensure profound new discoveries about the cosmos for decades to come.



A 3D projection of ~300 galaxies in a census of the same part of the sky. The 3rd dimension shows how many billions of years back in time we are seeing each galaxy, determined by observations from the Keck Observatory. At top are images from the Hubble Space Telescope of five galaxies in the census. Credit: C. Carreau, ESA

Credit: Ethan Tweedie Photography

COLLABORATIVE AND COMPLEMENTARY

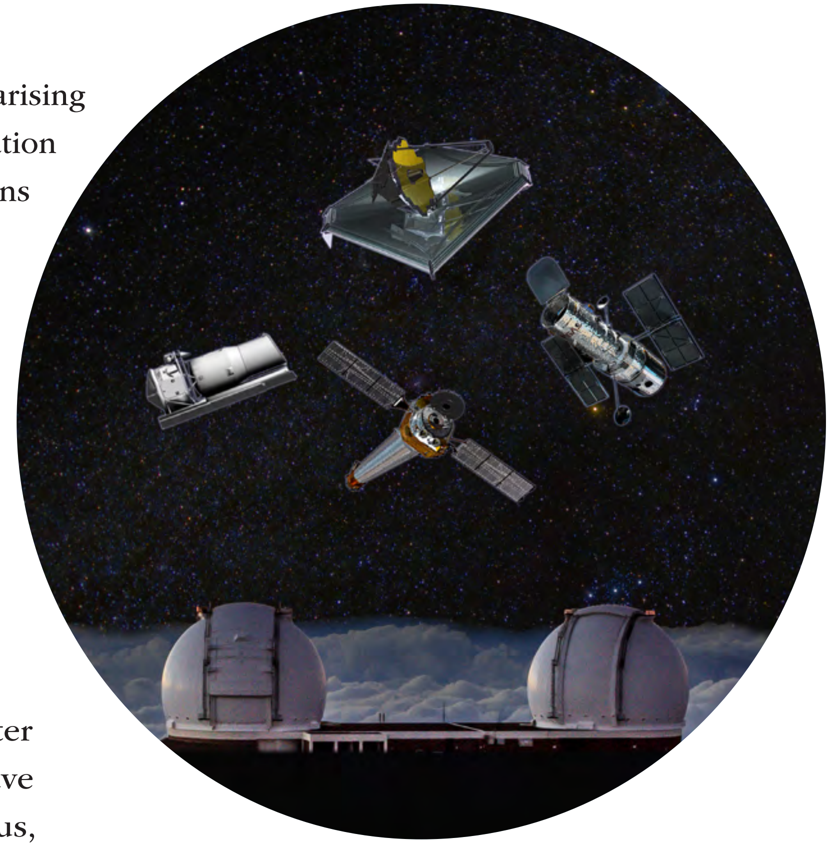
Keck's Place in the Astronomical Community

Keck is privately owned yet publicly and internationally focused. In this regard, Keck is arguably the most successful private observatory in terms of opening its doors to a broad community of astronomers from around the world, tapping into this international brain trust. Telescope time is allocated by partner institutions: Caltech, University of California, and the University of Hawai'i System accept proposals from their own researchers; and NASA accepts proposals from U.S.-based researchers. Principal investigators are awarded "classical" time to do what they want to do, uninterrupted, on the night allotted to them — which is the sort of old-school astronomy rarely seen these days.

The Keck Observatory mission is *to advance the frontiers of astronomy and share our discoveries, inspiring the imagination of all*. Every element of the Keck Observatory, from its technology development to allotted observation time, is planned with the broader astronomical community in mind. For example, Keck has "flown" with the Hubble Space Telescope since its first light in 1993, coincidentally the year of the Hubble servicing mission that corrected that telescope's misshaped optics. Together, these complementary instruments have mapped out the early universe. Exemplary observations include those arising from the Hubble deep sky surveys, in which Hubble pinpoints the location of exceedingly distant objects and then Keck — with longer observations of these objects — collects enough photons from these dim sources to determine distance and velocity, extracting meaningful cosmological data to produce a map.

As such, Keck scientists and engineers have been working studiously over the past decade preparing for the launch of NASA's James Webb Space Telescope (JWST), colloquially known as Hubble's successor. In fact, JWST and Keck have been mutually informing each other's technology in a way that will maximize compatibility once the former is launched. For example, Keck observations have been prototyping expected JWST observations, essentially targeting objects that JWST will want to observe in greater details. Because Keck's mirrors are larger than JWST's, Keck will have superior angular resolution at certain key infrared wavelengths. Thus, to fully complement JWST, Keck scientists are planning to enhance the observatory's adaptive optics and to improve its sensitivity in the near-infrared band (closer to optical wavelengths), as JWST will be most powerful observing the far-infrared.

As mentioned, Keck has supported and continues to support many other NASA missions. These include the Kepler planet finder as well as Swift and Fermi (gamma-ray), Chandra and NuSTAR (X-ray), and Spitzer (infrared). Keck provides important optical and infrared data to complement data from these observatories, providing a more complete understanding of any given celestial object or event. Similarly, Keck is primed to study in greater detail Jupiter-size exoplanets and brown dwarfs found during ESA's GAIA surveying and astrometry mission, launched in 2013.



Keck works closely with several of NASA's observatories. Pictured here (not to scale) from the top, going clockwise, are the James Webb Space Telescope (not yet launched), Hubble Space Telescope, Chandra X-ray Observatory, and Spitzer Space Telescope.

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Pushing the limits in faint-object spectroscopy

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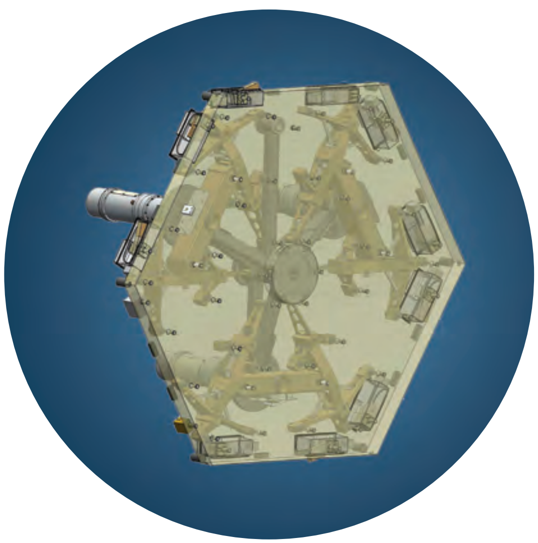
Leading AO imaging and spectroscopy with new capabilities



A schematic of a Keck mirror segment.

CREDIT: W. M. KECK OBSERVATORY

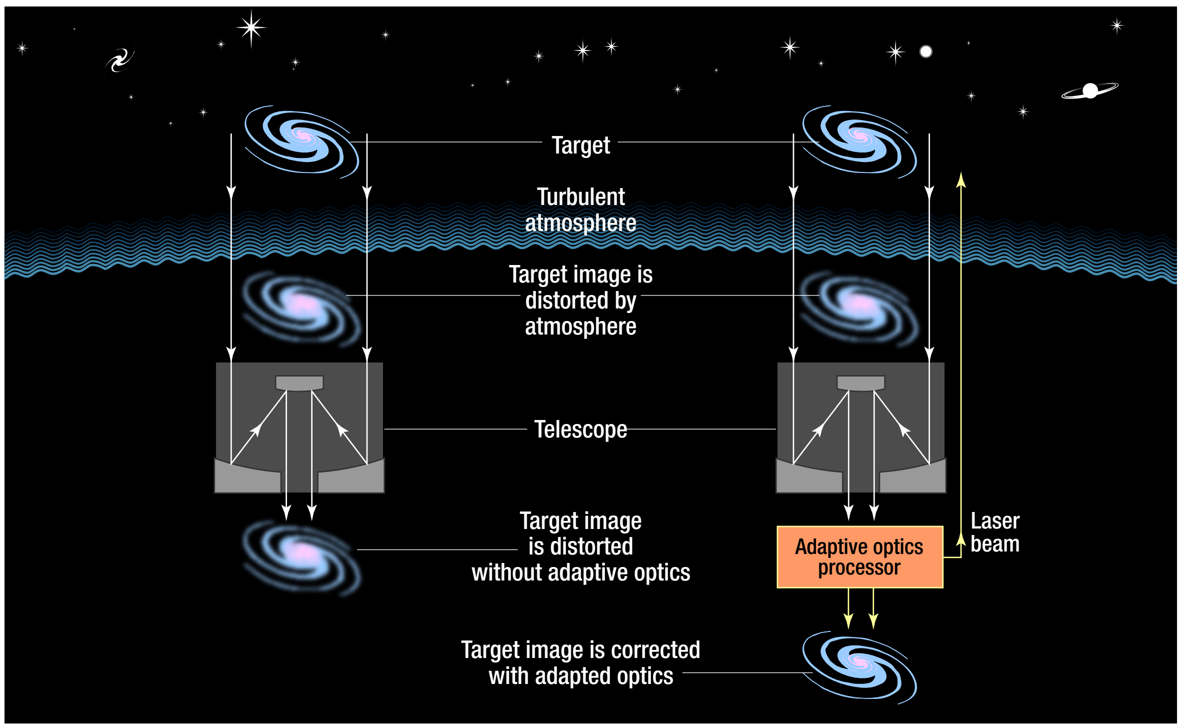
Keck shares the summit of Maunakea with several other ground-based observatories, all of which Keck partners with for complementary observations to maximize precious nighttime viewing hours. Keck and Subaru have enjoyed a particularly fruitful partnership for many years. Subaru is the 8.2-meter flagship telescope of the National Astronomical Observatory of Japan, literally Keck's next-door neighbor on the summit. An impressive observatory in its own right, Subaru enables Keck to be even more flexible. For example, when a "target of opportunity" (ToO) arises, such as a supernova or gamma-ray burst, Keck management can arrange for one or the other observatory to chase it in exchange for time on the telescope not on the ToO at some later date. Also, the basic synergy between Subaru and Keck has been for Subaru to identify interesting targets in survey mode and for Keck to follow them up with targeted observations. In general, Keck and Subaru plan instrument upgrades that are complementary, not duplicative, in true partnership spirit.

Combining adaptive optics capabilities for Keck and Subaru will set the stage for the next-generation of massive telescopes, such as the Thirty Meter Telescope (TMT), by identifying targets. The first- and second-generation instruments for TMT do not emphasize high-resolution spectroscopy, and thus Keck likely will be in even greater demand in the coming decades providing complementary data to TMT and other more massive yet initially instrument-limited observatories.

The Keck Observatory has led in this spirit of cooperation, avoiding counter-productive competition among countries, agencies, and the astronomy community itself, and this has resulted in Keck maintaining its vitality even as it enters into an era of even more massive telescopes.

ADAPTIVE OPTICS: Novel Laser Guide Star

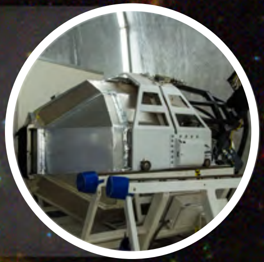
Stars "twinkle" when we see them from the ground because their light is being distorted as it passes through the Earth's atmosphere. Adaptive optics senses and compensates for the atmospheric distortions of incoming starlight by calibrating the light with a known, nearby star. This results in an improvement in image quality on fairly bright astronomical targets by a factor 10 to 20. Yet sometimes there is no suitable nearby star to calibrate incoming light. So, both Keck Observatory telescopes are equipped with laser-guide-star adaptive optics, essentially sodium lasers aimed at the sky to excite sodium atoms that naturally exist in the atmosphere 90 km (55 miles) above the Earth's surface. The laser creates an "artificial star" that allows the Keck adaptive optics system to sense the atmospheric conditions and compensate for them, opening a window to up to 80 percent of the targets in the sky compared with the 1 percent accessible without the laser.



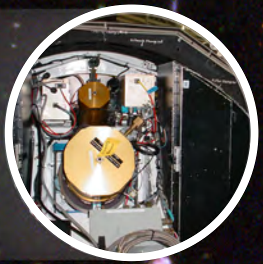
Adaptive optics (AO) is a technology used to improve the performance of optical systems by reducing the effect of wavefront distortions: it aims at correcting the deformations of an incoming wavefront by deforming a mirror in order to compensate for the distortion.

MEET THE INSTRUMENTS


DEIMOS


ESI


HIRES


LRIS

Integral to Keck's remarkable observations is its ability to discern an object's position in the sky (acute resolution) combined with collecting as many photons as possible (acute sensitivity). Twin telescopes — Keck I and Keck II, denoting when they came online, not technical superiority — each have 10-meter mirrors comprising 36 hexagonal segments working as a single unit. Sensors and actuators adjust each segment's position in relation to its neighbor to an accuracy of 25 nanometers, about 1/4000th the width of human hair. Carefully planned upgrades maximize the observatory's functionality. The current instruments suite includes:

VISIBLE WAVELENGTHS

DEIMOS — The Deep Extragalactic Imaging Multi-Object Spectrograph is the most advanced optical spectrograph in the world, capable of gathering spectra from 130 galaxies or more in a single exposure.

ESI — The Echellette Spectrograph and Imager captures high-resolution spectra of very faint galaxies and quasars ranging from the blue to the red in a single exposure.

HIRES — The largest, most precise of Keck's instruments, the High Resolution Echelle Spectrometer breaks up incoming starlight into its component colors to measure the precise intensity, revealing distance, velocity, and chemical composition.

LRIS — The Low-Resolution Imaging Spectrograph is a faint-light instrument capable of taking spectra and images of the most distant known objects in the universe, exploring stellar populations of distant galaxies, active galactic nuclei, galactic clusters, and quasars.

NEAR-INFRARED WAVELENGTHS

MOSFIRE — The Multi-Object Spectrograph for Infrared Exploration gathers dozens of spectra from objects spanning a variety of distances, environments and physical conditions, from the discovery of ultra-cool, nearby substellar mass objects, to the detection of oxygen in young galaxies only 2 billion years after the Big Bang.

NIRC-2 — The second-generation Near Infrared Camera works with the Keck Adaptive Optics system to produce the highest-resolution ground-based images and spectroscopy in the 1- to 5-micron range, revealing surface features on solar system bodies, characteristics of exoplanets, and the morphology of remote galaxies.

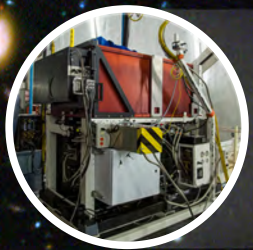
NIRSPEC — The Near Infrared Spectrometer studies very high redshift radio galaxies, the motions and types of stars located near the Galactic Center, the nature of brown dwarfs, the nuclear regions of dusty starburst galaxies, active galactic nuclei, interstellar chemistry, stellar physics, and solar-system science.

OSIRIS — The OH-Suppressing Infrared Imaging Spectrograph allows astronomers to suppress wavelengths where the Earth's atmosphere shines brightly due to emission from OH (hydroxyl) molecules, thus allowing the detection of objects 10 times fainter than previously available.

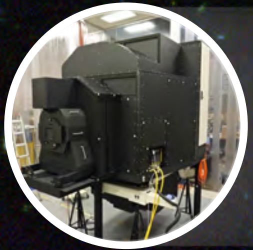
CWI — The Cosmic Web Imager is a highly flexible instrument supporting a cornucopia of investigations that focus on complex extended objects in the sky, including mapping the large-scale structure in the Universe. CWI's versatility, paired with the most superb telescope and site on Earth, ensures that it will make profound new discoveries about the cosmos for decades to come.


MOSFIRE


NIRC-2


NIRSPEC


OSIRIS


CWI

MEET THE PARTNERS

The Keck Observatory represents a significant fraction of U.S. peer-reviewed public access to large telescopes.

KECK OBSERVATORY IS RECOGNIZED as one of the most prolific and sought-after tools in astronomy. Made possible by a grant of $138 million from the W. M. Keck Foundation, the Keck I telescope began science observations in 1993; observations with Keck II began in 1996. Today, the Keck Observatory is supported by public funding sources and private philanthropy. As a 501(c)3, the organization is managed by the California Association for Research in Astronomy (CARA), whose Board of Directors includes representatives from the California Institute of Technology and the University of California, with liaisons to the board from NASA and the Keck Foundation. The Keck Observatory headquarters is an architecture-award-winning facility located on a 7-acre campus in the town of Waimea on the Island of Hawai'i.

CREDIT: RICK PETERSON

The partners in the operation of Keck Observatory are Caltech, the University of California, and NASA. The allocation of observing time is divided as follows: Caltech (36.5%), University of California (36.5%), NASA (14.5%), and University of Hawai'i (12.5%). The University of Hawai'i participates in Keck observing by providing access to Maunakea; Yale University and the Swinburne Institute of Technology participate in Keck observing via a partnership with Caltech.

NASA allocates its one-sixth share of the observing time on Keck I and Keck II to both strategic projects and investigations competitively selected by a time allocation committee. Usage of NASA's time on the Keck telescopes is open to the entire U.S. astronomical community, and nearly 200 principal investigators from more than 100 institutions have earned time on Keck this way. Thus, Keck Observatory represents a significant fraction of U.S. peer-reviewed public access to large telescopes.

The W. M. Keck Observatory is very grateful for the generosity of individuals, corporations and foundations that recognize the value of our science and leadership in this golden age of astronomical exploration. With this crucial support, Keck Observatory astronomers will continue to push the frontiers of exploration, discovering new worlds, probing the mysteries of the Milky Way, and measuring distant galaxies and other cosmic phenomenon to further understand the nature of the Universe and our place in it.

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S. Wright, AO TG, UCSD
R. Campbell, Keck Observatory, Observing Support and AO Operations Lead
Christopher Wanjek, Science Writer

Keck's Headquarters in Waimea is open to the public, and school visits can be arranged. Visitors can explore hands-on exhibits and hear from knowledgeable docents and staff.

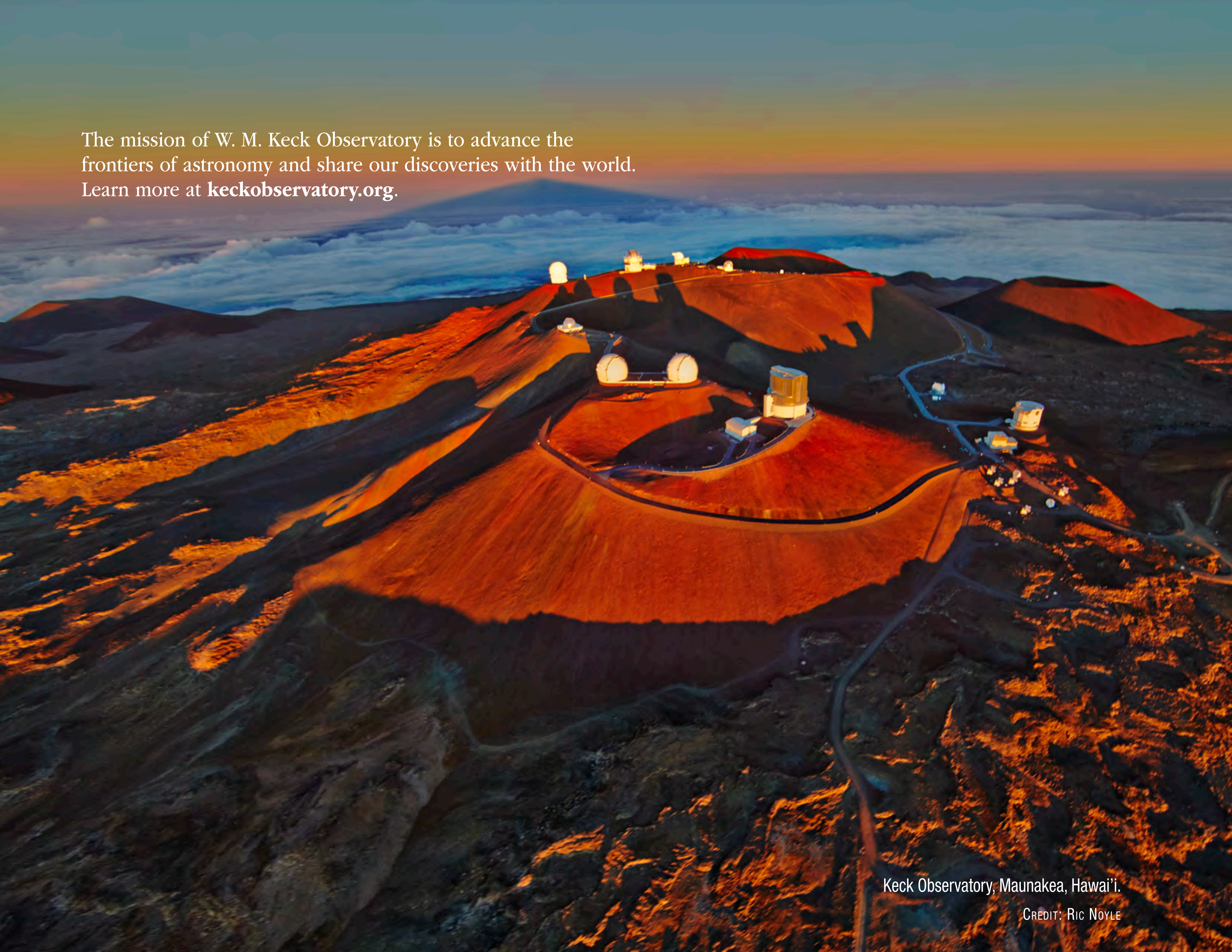
KECK OUTREACH

EACH YEAR, the W. M. Keck Observatory participates in and sponsors educational events for Hawai'i Island families, educators, students, and hobbyists, as well as visitors to the Big Island, to foster a greater appreciation of science and its influence in society.

A false-color image of UGC 2847, a spiral galaxy in the constellation Camelopardalis.

Credit: Keck Observatory

The mission of W. M. Keck Observatory is to advance the frontiers of astronomy and share our discoveries with the world. Learn more at **keckobservatory.org**.



Keck Observatory, Maunakea, Hawai'i.

Credit: Ric Noyle