

Adaptive Optics Sharpen the View from Earth

Blur-free images reveal a wealth of astronomical detail.

FROM a remote outpost on the summit of Hawaii's dormant Mauna Kea volcano, the world's two most powerful telescopes, located at the W. M. Keck Observatory, are probing the deepest regions of the universe. Thanks to a Lawrence Livermore-Keck team of scientists and engineers, astronomers are obtaining images on the 10-meter Keck telescopes with resolution greater than that of other land-based telescopes or even the orbiting Hubble Space Telescope.

Many of the Keck images, together with those from the smaller Shane telescope at the University of California's Lick Observatory near San Jose, are being taken by Lawrence

Livermore astronomers working with colleagues from University of California (UC) campuses and the California Institute of Technology (Caltech). The images are shedding new light on the formation of stars and galaxies, revealing unexpected features on planets and moons in our solar system, and yielding new information on black holes in the centers of distant galaxies.

The key to the unsurpassed image clarity is adaptive optics that remove the blurring of starlight caused by turbulence in Earth's atmosphere, resulting in a tenfold improvement in resolution. Adaptive optics measure the distortions of light from a natural star

The W. M. Keck Observatory, located on Hawaii's dormant Mauna Kea volcano at an altitude of over 4 kilometers, houses the world's two most powerful telescopes. The Keck telescopes are seen with their domes open for observation.

or one manufactured by a powerful laser, and then remove the distortions by reflecting the light off a deformable mirror that adjusts several hundred times per second to sharpen the image.

A Livermore-designed adaptive optics system was installed on Lick's 3-meter Shane telescope in 1994, and Livermore's sodium-layer laser guide star system was added in 1996. In September 1996, Lick obtained the first significant image improvement using adaptive optics with a laser guide star. Routine astronomical observation with the laser guide star began in August 2001, and the guide star was turned over to the observatory for operation in spring 2002.

Keck's adaptive optics system, for which Livermore scientists and engineers working with their Keck colleagues provided the wavefront control system, made its first observations in 1998 and began general use in late 1999. Its laser guide star, a Livermore-Keck project, was installed in fall 2001 and achieved "first light" on December 23, 2001. "We asked for an early present this year, and just before Christmas, we were given a virtual star that will dramatically increase the research capabilities of the world's largest telescope," announced Frederic Chaffee, director of the Keck Observatory. The laser guide star should be fully integrated with the adaptive optics system by autumn 2002, with the first astronomical observation following shortly thereafter.

Exceptionally Clear Images

Astronomers are reporting exceptional results from the adaptive optics systems installed at the two observatories. At Lick, roughly 50 percent of images are taken using adaptive optics, and about half of those images are made with the laser guide star. At Keck, reports Livermore laser

scientist Deanna Pennington, "People are extremely pleased with the adaptive optics systems."

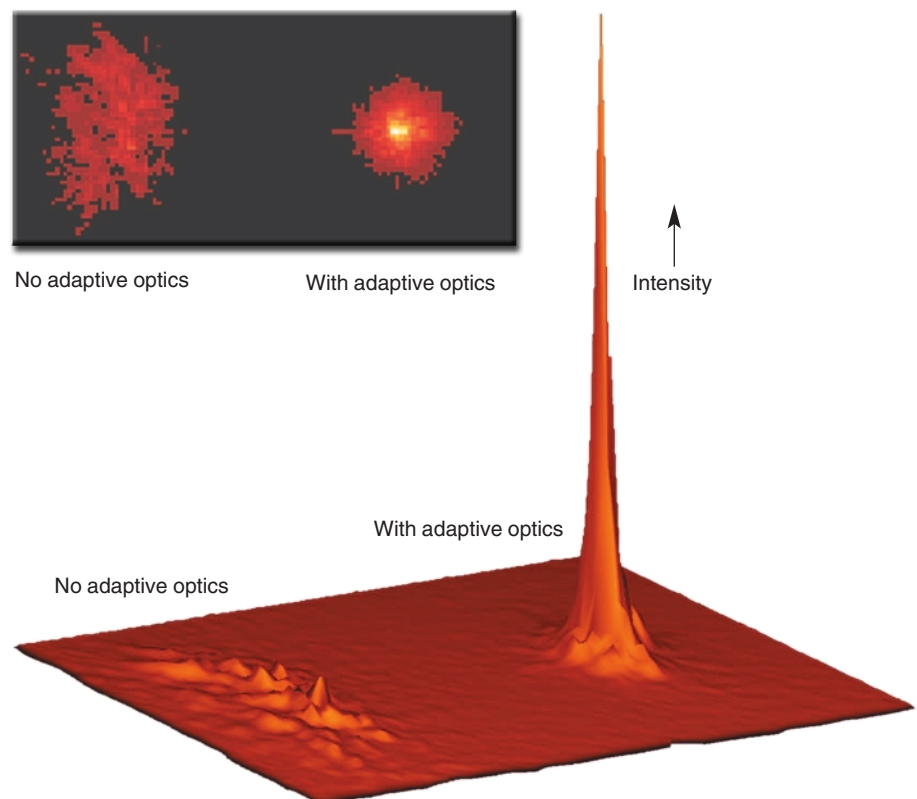
Pennington, who served as laser guide star project leader at both Lick and Keck, says astronomers are clamoring to use the Keck laser guide star because "It makes possible entirely new kinds of observations that astronomers simply couldn't access before."

Livermore astronomers have been among the first to use the adaptive optics systems. Most of them are part of the Livermore branch of the University of California's Institute of Geophysics and Planetary Physics. Since its establishment in 1983, the Livermore branch has been the focus of most astronomical activities at the Laboratory.

Livermore astrophysicists Claire Max, Bruce Macintosh, and Seran Gibbard have been observing objects within our solar system using both Lick and Keck adaptive optics. At Lick, they have been aided by Livermore's Don Gavel, lead engineer for the adaptive optics system. The Livermore efforts focused on observations of Io, Jupiter's largest moon; Titan, Saturn's largest moon; the planets Uranus and Neptune; and various asteroids.

Surprising Storms on Neptune

Astronomers using the Keck telescopes have obtained the best pictures yet of the planet Neptune, the eighth planet from the Sun. Thanks to adaptive optics, the images reveal a



Adaptive optics sharply increase the resolution of images taken at the Lick Observatory near San Jose, California.

wealth of small-scale features in Neptune's atmosphere, including narrow, bright bands encircling the planet, similar to those observed on Jupiter. There appear to be waves within the bands and regions where the bands move apart and come together as if they are separated by a vortex.

The images suggest violent methane storms with wind speeds reaching more

than 1,770 kilometers per hour. The imaging team, which has included astronomers from the UC campuses at Berkeley and Los Angeles (UCLA) and from Caltech, is working to understand what might be the source of the energy driving the extreme weather.

Working with UC Berkeley's Imke de Pater, the team has also captured near-infrared pictures of the planet Uranus, which mark the first ground-

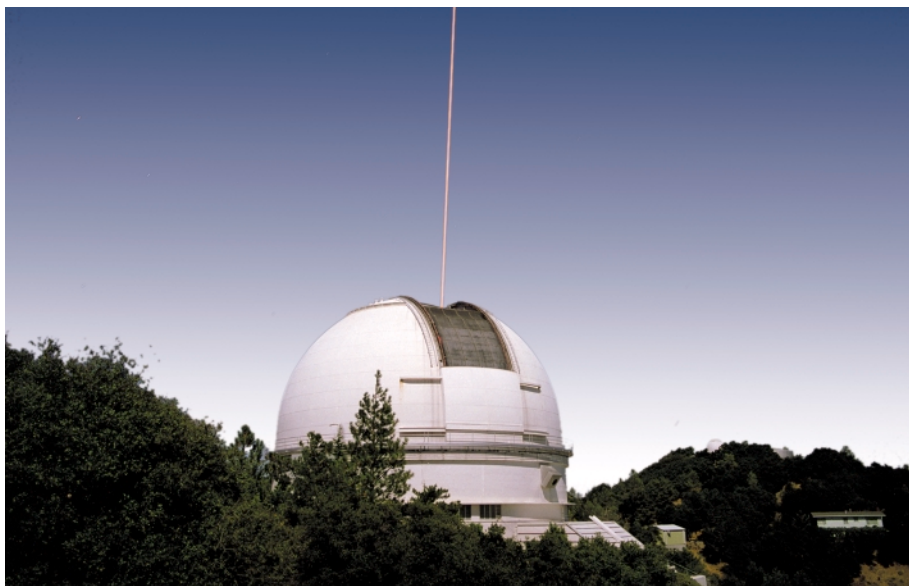
based detection of the faint rings around that planet. Also clearly visible is a layer of methane haze on Uranus's south polar cap, tiny cloud features at high northern latitudes, and, inside the planet's bright epsilon ring, three fainter rings.

Keck images of Io have revealed many glowing volcanoes. Macintosh took the images in the infrared band to detect sources of heat on the moon. Other striking images, taken by Gavel, are of the asteroid Kalliope with its own moon. Gibbard has been using Keck to obtain images of Titan, the only solid body in the solar system besides Earth to have a substantial atmosphere (mostly nitrogen, with about 3 percent methane). Some astronomers believe that Titan's atmosphere may be similar to that of Earth's during our planet's early development. Methane haze in the upper atmosphere obscures Titan's surface features at visible wavelengths. However, in some narrow "transparency windows" in the near-infrared band, surface features can be seen through the haze.

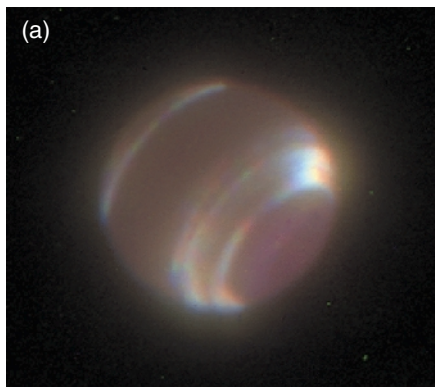
Without adaptive optics, says Gibbard, "Titan looks like a fuzzy star." She has been analyzing a large series of images to assemble the first map of Titan's surface. "By taking many images over time, we can see which features do not change, and these belong to the surface," she says. The use of adaptive optics has replaced a process called speckle imaging, which involved taking hundreds of very fast exposures and assembling them. "Adaptive optics is much simpler," Gibbard says.

Imaging Stellar Nurseries

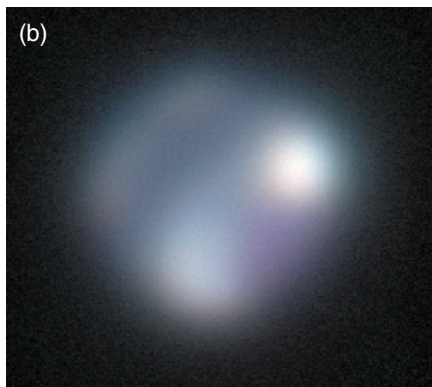
Macintosh and astronomers from UCLA are using adaptive optics on Lick and Keck to study the formation and evolution of planetary systems in the Trapezium (sword) region of the constellation of Orion. This region, the



Time-lapse photograph of the Lick Observatory and the laser guide star.



(a) Astronomers using Keck's adaptive optics have obtained the best pictures yet of the planet Neptune. The images show bands encircling the planet and what appear to be fast-moving storms of haze. (b) The same image without adaptive optics.



closest large-scale star formation to our Sun, serves as a stellar nursery.

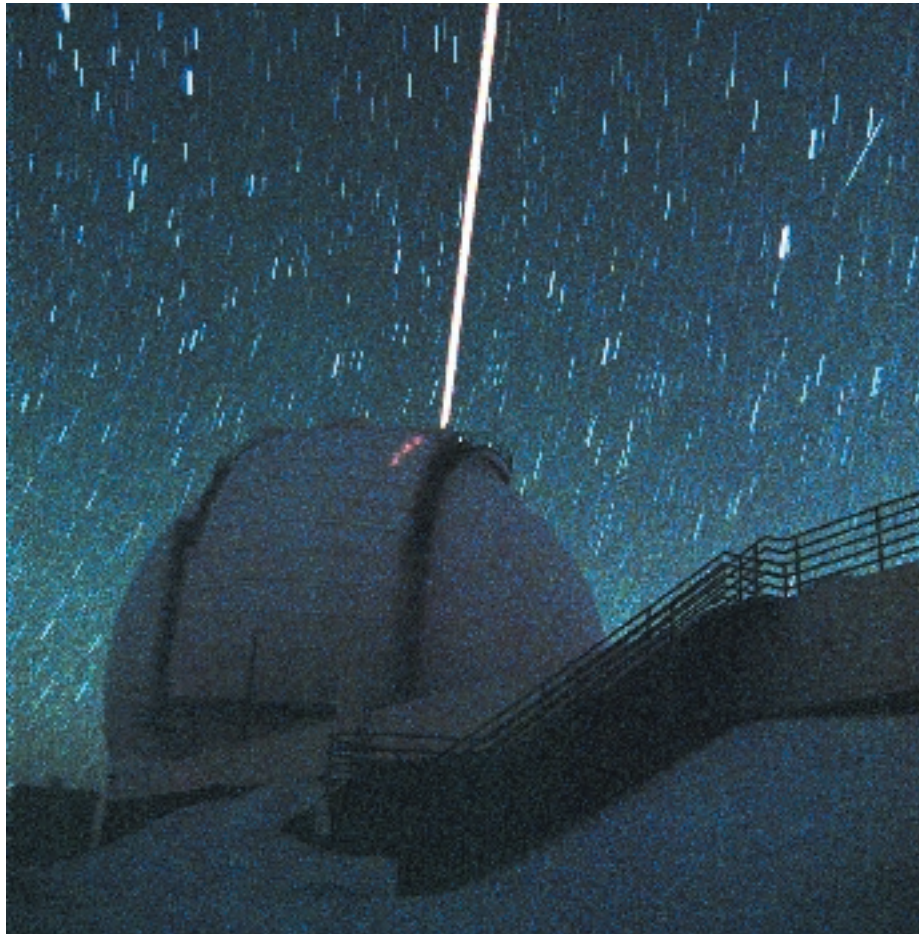
“One of the most fundamental questions in modern astronomy is the possibility of the existence of other solar systems like our own, those with potentially habitable planets,” Macintosh says. He notes that although planetary systems have been detected through indirect methods, all are different from our solar system because they have massive, Jupiter-like planets occupying the inner part where Earth is located in our system. “It is unclear which type of system is more common in the universe,” says Macintosh.

The astronomers first use Lick to scout for promising young stellar systems and then travel to Keck to obtain high-resolution images. Bright stars found in the constellation serve as handy natural guide stars for the adaptive optics system.

Macintosh says that large planets (about the size of Jupiter) that are 10 million years old or younger radiate significant near-infrared light. Keck’s adaptive optics system can detect these planets even though they are a million times dimmer than the star they orbit. Macintosh has also imaged several of the Orion proplyds—protoplanetary disk envelopes surrounding young stars—that are being disrupted by intense radiation from nearby supermassive stars.

“Keck could be the first telescope to image a planet orbiting a star outside of our solar system,” Macintosh says. He adds, “Keck’s adaptive optics system represents the most significant advance in astronomical capabilities since the launch of the Hubble Space Telescope.”

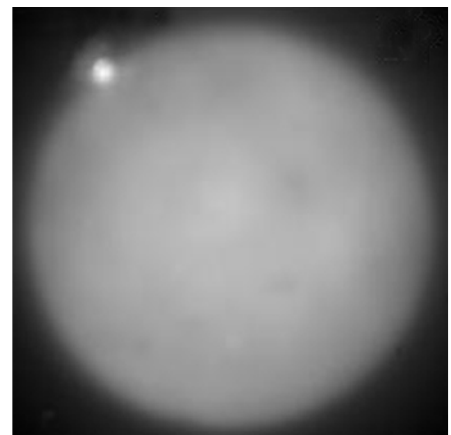
Jennifer Patience is studying the binary star systems that are found among the young stars in Orion’s Trapezium. “We want to know how common it is for planets to form in binary systems,” she says. Astronomers



“First light” from the laser guide star on the Keck II telescope, December 23, 2001.

believe that the presence of a nearby companion star may disrupt circumstellar disks surrounding young stars (circumstellar disks provide the raw materials for planet formation). Working with astronomers from UC Berkeley and UCLA, she uses Keck and Lick adaptive optics systems to look at star systems in the near-infrared spectrum and to see through clouds of galactic dust and gas that mask images in visible light.

The team has imaged 150 stars in Orion with resolution never before attained. Keck’s adaptive optics make it possible to resolve binaries with separations comparable to the distance



This image of Io, Jupiter’s largest moon, reveals volcanic activity. (Image courtesy of Keck Observatory.)

Astronomy Benefits from Laser Advances

Since their invention, ground-based telescopes have suffered from blurred images caused by Earth's fast-moving and turbulent atmosphere. However, advances in optics and computer technology have made it possible to sharply reduce this blurring by the use of adaptive optics that correct atmospheric distortions and allow ground-based telescopes to reach their theoretical maximum resolution.

Adaptive optics systems have traditionally required the astronomer to find a bright star as a reference point of light. However, less than 1 percent of the sky contains stars sufficiently bright to be of use as a reference light. To extend the usefulness of adaptive optics, Livermore scientists developed a laser system that creates a virtual reference star high above Earth's surface to guide the adaptive optics system. The laser guide star is created by projecting light from a dye laser on a layer of sodium atoms that are in the atmosphere 90 to 100 kilometers above Earth.

The main components of an adaptive optics system using a laser guide star are a wavefront sensor camera equipped with a charge-coupled device detector, a control computer, a deformable mirror, a pulsed dye laser that is tuned to the atomic sodium resonance line at a wavelength of 589 nanometers, and a set of solid-state lasers to pump, or energize, the dye laser. The dye laser, similar to that pioneered at Livermore for its Atomic Vapor Laser Isotope Separation program, creates a glowing star of sodium atoms measuring less than 1 meter in diameter at an altitude of about 100 kilometers above Earth's surface. This artificial reference can be created as close to the astronomical target as desired so that the light from the laser star and the observed object pass through the same small part of the atmosphere.

At the telescope, wavefront sensors measure distortions due to atmospheric turbulence, using light from the guide star as a reference. The sensors relay this information to a computer, which in turn controls the movements of tiny actuators attached to the back of a deformable mirror. The mirror changes its shape hundreds of times per second to cancel out atmospheric distortion.

Near-infrared images obtained with the adaptive optics systems on the telescopes at the W. H. Keck Observatory in Hawaii are superior to images obtained with the Hubble Space Telescope because Hubble's light-gathering mirror is much smaller. (Adaptive optics will not, however, replace space-based observatories, many of which are designed to sample certain bands of electromagnetic radiation such as ultraviolet light that are blocked by Earth's atmosphere.)

Lick's dye laser projects light into the sky through a 30-centimeter refractive telescope that is mounted on the side of the main telescope. The laser was designed and built by Livermore's Herbert Friedman. The deformable mirror has 127 actuators to raise or lower a tiny part of the front surface by up to 4 micrometers.

The laser guide star at the Keck II telescope uses a 20-watt dye laser, the most powerful laser in use at a telescope. The laser light is

projected onto the sky by a telescope with a 50-centimeter lens attached to the side of the 10-meter Keck II telescope. A 15-centimeter-diameter deformable mirror is adjusted continuously by 349 actuators.

Keck's laser guide star was built at Livermore and then reassembled at the observatory's headquarters in Waimea, Hawaii, which is slightly less than 1 kilometer above sea level. The observatory's telescopes are located at the summit of the Mauna Kea volcano, over 4 kilometers above sea level. Scientists observe on these telescopes remotely from the Waimea headquarters to avoid the risk of sickness from extended exposure to Mauna Kea's high altitude.

During the two-year temporary installation at headquarters, the Livermore team of Deanna Pennington, Curtis Brown, Pam Danforth, and Holger Jones made extensive improvements. "We installed a significant level of automation and diagnostics on the laser guide star system to make it more reliable and robust and permit it to be operated remotely from Waimea," says Pennington, laser scientist and systems engineer at both Lick and Keck. She notes that installing the adaptive optics system and laser guide star at Lick gave the Livermore team valuable experience in designing the larger system at Keck. The laser system was installed and activated on the telescope at the 122-kilometer summit over a 6-month period, culminating in the "first light" demonstration on December 23, 2001.

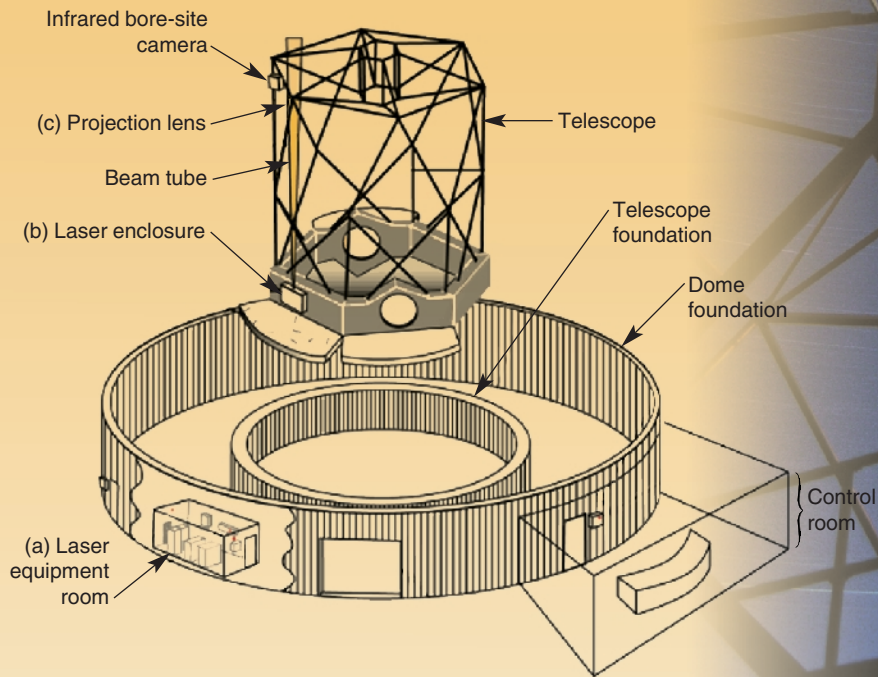
Keck's adaptive optics and laser guide star embody more than two decades of Livermore experience in adaptive optics technology. Adaptive optics systems with adjustable mirrors have been used on a succession of increasingly powerful lasers at Livermore, and they will be used on the National Nuclear Security Administration's National Ignition Facility (NIF), under construction at Livermore.

Claire Max and Friedman started Livermore's work on laser guide stars in the early 1990s. Feasibility tests conducted at Livermore in 1992 demonstrated the first laser guide star at usable power levels and determined the requirements for a telescope version.

Livermore scientists are working on the next generations of adaptive optics. About 20 Livermore employees belong to the Adaptive Optics program within the Physics and Advanced Technologies Directorate. One team is developing more reliable deformable mirrors based on microelectromechanical technology.

With funding from the Center for Adaptive Optics (see the box on p. 19) and the European Southern Observatory in Chile, Pennington will lead another group of Livermore scientists within the NIF Programs Directorate who are investigating fiber lasers to replace the current dye laser. Fiber lasers, widely used in the telecommunications industry, will be part of the NIF front end and will produce the laser beam before it is amplified. Pennington says that fiber lasers provide an "elegant solution" for generating 589-nanometer light because they are compact, efficient, and robust.

An overview of the layout within the dome of the Keck II telescope. (a) The laser equipment room on the dome floor houses the pulsed dye laser master oscillator, yttrium–aluminum–garnet pump lasers, and control systems. (b) The laser room on the elevation ring of the telescope houses an optics bench containing two stages of dye amplification, numerous diagnostics, and the bottom half of the projection telescope. (c) The 50-centimeter projection lens is located at the top end of the telescope.



between our Sun and Uranus, a distance that is less than the diameter of circumstellar disks. “We now have the capability of resolving most binary systems, including a range inaccessible to previous surveys,” Patience says. She notes that with the resolving power of Keck’s adaptive optics system, a person standing on Mauna Kea, located on the big island of Hawaii, could see objects as small as 1 centimeter tall on the island of Oahu, approximately 400 kilometers away.

Peering into Black Holes

Max, her colleague Gaby Canalizo, and astronomers from UC Santa Barbara, are using adaptive optics on Lick and Keck telescopes and Lick’s laser guide star to observe nearby active galactic nuclei, which are small, extremely

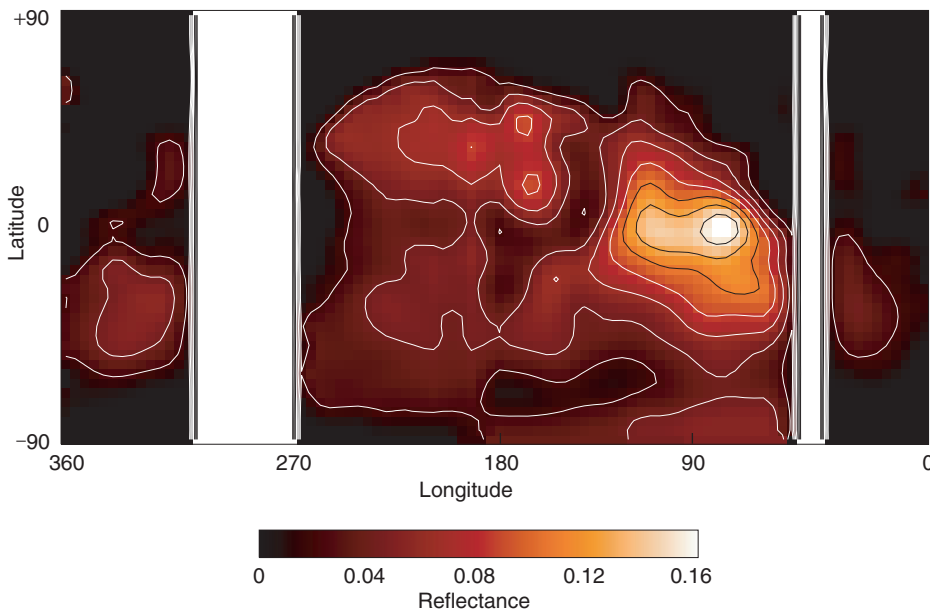
bright central regions in some galaxies. Very distant and bright active galactic nuclei are known as quasars. Active galactic nuclei are thought to contain black holes at their centers, which suck up stars, planets, and gas from the surrounding galaxy in a process called accretion. In some cases, the material is then shot out from the region surrounding the black hole at high speeds in outflows known as jets.

Max notes that for 30 years, Department of Energy laboratories have been doing pioneering work on the high-energy processes involved in black-hole formation and emission. However, only in the past few years has direct evidence for black holes begun to emerge—in the form of high-resolution observations that probe the active galactic nuclei close to the central black hole.

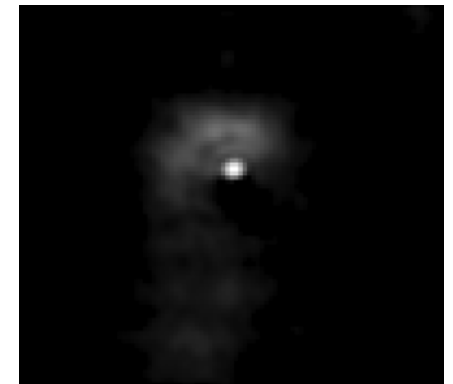
Max and Canalizo’s team is observing energy outflow from the process of accretion of matter into the most massive black holes in nearby galaxies. The images enable astronomers to explore the region nearby and the evolution of the central black holes. In the process, the astronomers have found double active galactic nuclei suggestive of galaxy mergers, which are believed to be a cause of black hole formation.

Looking to the Future

When the Keck laser guide star becomes available for viewing, Livermore scientists will be among the first to use it and thereby help to make laser guide stars a more accepted tool of astronomical research. Pennington notes that a National Academy of Sciences panel has identified laser guide stars as a key technology for advancing astronomy. Most experts say that the next generation of giant telescopes will not be feasible without adaptive optics systems equipped with laser guide stars.



The first map of the surface of Titan, Saturn’s largest moon, is being assembled with the help of adaptive optics. Colors denote reflectance, with 1.00 corresponding to the reflectance of a perfect mirror. Data from current observations are filling in the blank areas.



Keck adaptive optics image of a protoplanetary disk envelope surrounding a young star in the Trapezium region of the constellation Orion.

New Center Spreads the Word

Lawrence Livermore is a major partner in the Center for Adaptive Optics, which is headquartered at the University of California (UC) at Santa Cruz. The center, funded by the National Science Foundation, began operations in November 2001. The 27 partner institutions in the center also include several other UC campuses, the University of Chicago, the California Institute of Technology, the University of Rochester, the University of Houston, Indiana University, and 17 other partners.

The center's director is Jerry Nelson, professor of astronomy and astrophysics at UC Santa Cruz. Nelson designed the twin telescopes at the W. M. Keck Observatory in Hawaii. Livermore scientists Claire Max and Scot Olivier are associate directors, and Livermore scientists play important roles in center activities and sponsored research.

The center coordinates the efforts of researchers across the country involved in the growing field of adaptive optics for astronomical and vision science. The center also operates science education and outreach programs for scientists and college students.

"Our goal is to provide the sustained effort needed to bring adaptive optics from promise to widespread use by astronomers and vision researchers," says Max. She predicts that most large ground-based telescopes will have adaptive optics systems within the next few years. Relatively few astronomers, however, have experience with adaptive optics, let alone laser guide stars. "We

want to inform the broader astronomical community about adaptive optics through conferences and workshops," she says.

Max points out that adaptive optics are also used in vision science to compensate for aberrations in the eye that affect vision and impede efforts to study the living retina. Adaptive optics has made it possible to obtain images of the living human retina with unprecedented resolution, enabling researchers to see individual light receptors. Adaptive optics may also provide normal eyes with supernormal vision. A team of Livermore researchers led by Olivier is developing a high-resolution liquid-crystal adaptive optics system for human vision correction that will be used at UC Davis to study the limits of human visual acuity.



However, as a telescope gets larger, the requirements for an adaptive optics system become increasingly rigorous. The proposed California Extremely Large Telescope (CELT), a collaboration between UC and Caltech, is designed to have a 30-meter-diameter mirror, three times the size of Keck's. CELT's adaptive optics system will probably require multiple laser guide stars with several mirrors working together to correct for different layers of atmospheric turbulence. Each mirror may require about 5,000 actuators.

Thanks to increasingly powerful telescopes, more capable adaptive optics systems, and advanced guide-star lasers, the heavens are sure to be revealing more of their secrets in the new millennium.

—Arnie Heller

Key Words: active galactic nuclei, adaptive optics, atomic vapor laser isotope separation, binary star, black hole, California Extremely Large Telescope (CELT), deformable mirror, dye laser, Hubble Space Telescope, laser guide star, Lick Observatory, W. M. Keck Observatory.

For further information contact
Deanna Pennington (925) 423-9234
(pennington1@llnl.gov).

For online information on the
W. M. Keck Observatory:
www2.keck.hawaii.edu:3636

For online information on the
Lick Observatory:
www.ucolick.org/

For online information on the
Center for Adaptive Optics:
cfao.ucolick.org/