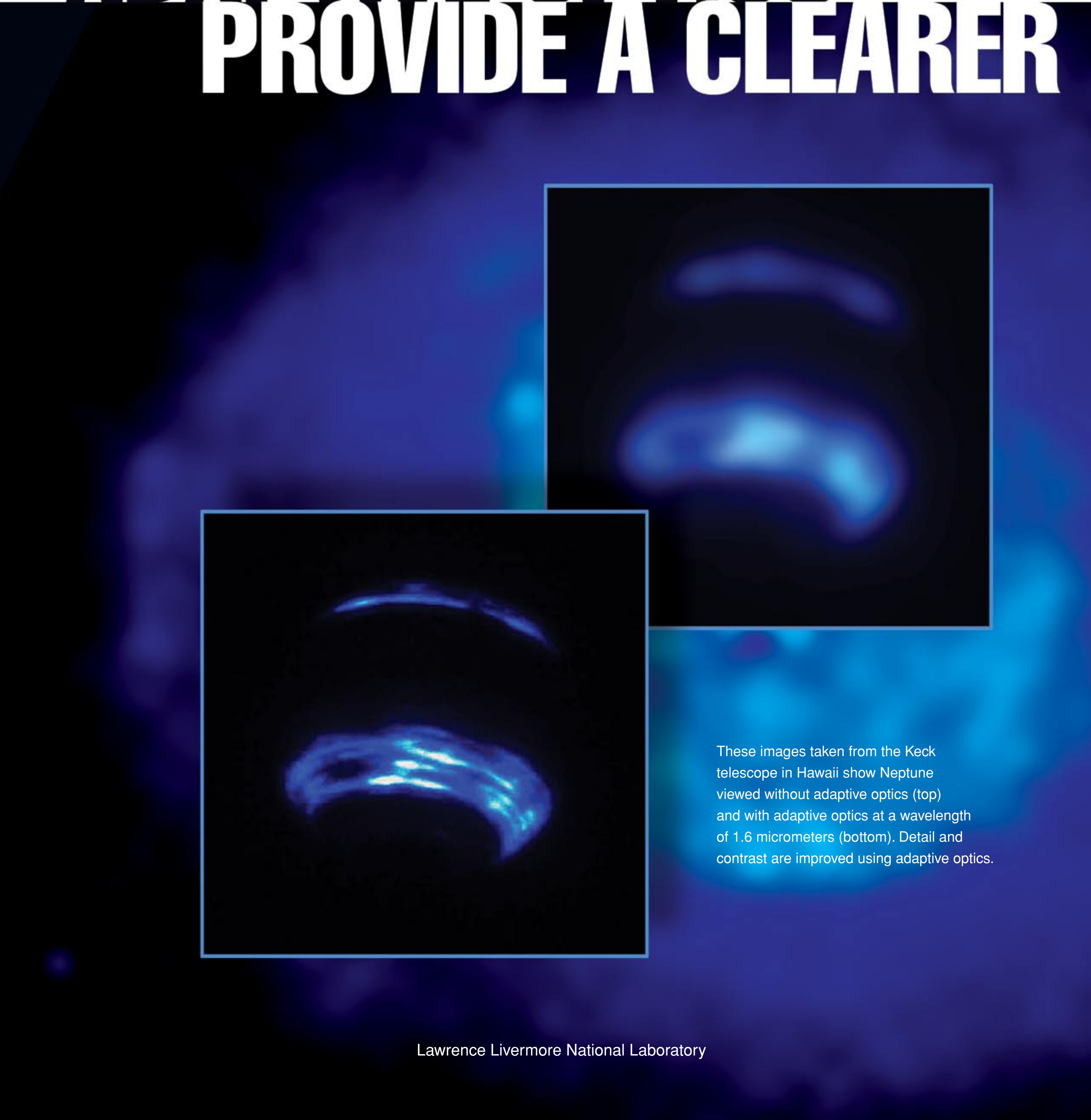
ADAPTIVE OPTICS PROVIDE A CLEARER



These images taken from the Keck telescope in Hawaii show Neptune viewed without adaptive optics (top) and with adaptive optics at a wavelength of 1.6 micrometers (bottom). Detail and contrast are improved using adaptive optics.

The Center for Adaptive Optics, with strong participation by Livermore researchers, advances a revolution in how we see.

FROM astronomers training their telescopes on the faintest pinpoints of light to newspaper readers straining to read small print, the demand persists for images that are clear and sharp. The Center for Adaptive Optics (CfAO), a National Science Foundation Science and Technology Center, is showing how to sharpen images with adaptive optics (AO) systems. Founded in 1999, the center researches AO in the fields of astronomy and vision science so that astronomers can more clearly visualize distant galaxies, stars, and planets and physicians can better diagnose eye diseases and more accurately prescribe corrective lenses. (See the box below.)

Adaptive Optics: A Short Primer

Whenever light from stars passes through the atmosphere, it becomes distorted by layers of air with different temperatures and densities. As a result, we see a shimmering or twinkling orb instead of the distinct and steady pinpoint of light seen from space.

Adaptive optics (AO) corrects the wavefronts of light, "straightening" them so that stars, galaxies, and other celestial objects gain resolution and contrast. AO systems work best with longer wavelength light, that is, light in the infrared region of the electromagnetic spectrum. Conceived in the 1950s by astronomers, AO was developed in the 1970s for laser beam propagation as part of the U.S. Strategic Defense Initiative.

Current AO systems use a wavefront sensor to sample the light that is being collected by the telescope's primary mirror. Only about 1 percent of the sky contains stars sufficiently bright to be of use as a reference beacon for an astronomical AO system. An alternative to a natural star is an artificial star made by a laser. Laser guide stars use a laser trained in the vicinity of the astronomical object of interest. The wavefront sensor takes hundreds or thousands of samples per second of the atmosphere-distorted light from the natural or artificial reference beacon, while sending the data to a computer that controls a deformable mirror. The mirror is adjusted by many tiny actuators, canceling the distortions of the atmosphere while it images the object of interest.

One way to escape the adverse effects of Earth's atmosphere is to place telescopes in space. However, spaced-based observatories, such the National Aeronautics and Space Administration's Hubble Space Telescope, are extremely costly to build and operate and must be compact for launching. Land-based telescopes equipped with the latest AO systems have the potential to provide several times greater resolution than Hubble in the infrared region.

The center is headquartered at the University of California at Santa Cruz (UCSC), one of the world's leading institutions for research in astronomy and astrophysics. UCSC is the home of UC Observatories, which operates the Lick Observatory on Mount Hamilton in California and is one of the partners in the Keck Observatory on the dormant volcano Mauna Kea in Hawaii.

The CfAO is one of the National Science Foundation's 13 Science and Technology Centers, the first of which was established in 1987 to fund fundamental research and create educational opportunities. The centers also encourage technology transfer, provide innovative approaches to interdisciplinary research, and emphasize partnerships.

The CfAO directly funds researchers nationwide and administers a growing network of partners that include universities, national laboratories, observatories, medical research centers, and private industry. Center partners develop AO systems that combine advanced technologies such as precision optics, wavefront sensors, deformable mirrors, lasers, and control systems. The center also helps transfer information about developments in AO from research laboratories to commercial entities and the broader scientific community.

Livermore physicist Scot Olivier, who is the center's associate director of knowledge transfer and partnerships, says, "Frequent interchanges occur between the center, universities, and private industry." Olivier also leads Livermore's 20-member Adaptive Optics Group. "Through its partnerships with industry," says Olivier, "the center is building an industrial base; researchers can now buy equipment that didn't exist just a few years ago, such as silicon-based MEMS [microelectromechanical systems] for deformable mirrors."

Other Livermore researchers also play a major role in the CfAO organization and participate in its activities. Claire Max, Livermore astrophysicist and UCSC professor of astronomy and astrophysics, is the center's director. Former Livermore engineer Don Gavel is the center's associate director of AO for extremely large telescopes. About 10 other Livermore employees, as well

Laboratory for Adaptive Optics

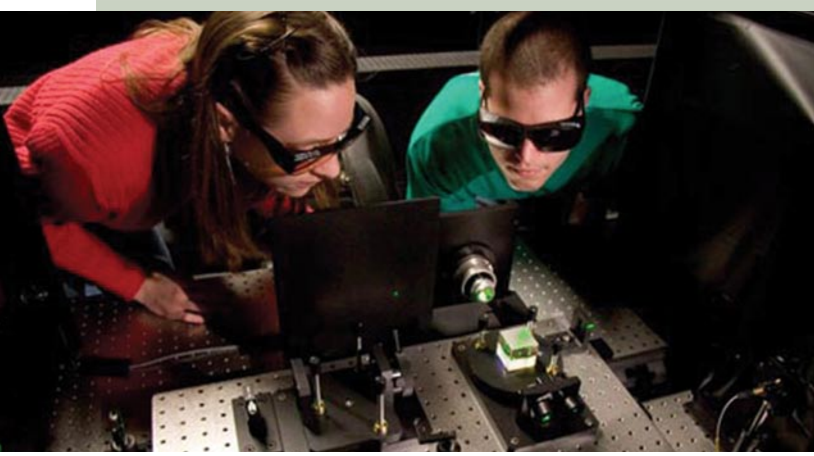
In August 2002, the Center for Adaptive Optics (CfAO) at the University of California at Santa Cruz received a six-year, $9.1-million grant from the Gordon and Betty Moore Foundation to establish a Laboratory for Adaptive Optics. This new facility, the first comprehensive university laboratory dedicated to adaptive optics (AO) in the U.S., supports the center's mission to advance and disseminate AO technology.

Researchers use the laboratory to develop prototypes of advanced AO equipment and concepts and test them in a controlled laboratory setting. The laboratory also serves as a training facility where researchers and students gain experience with AO equipment.

The laboratory currently focuses on developing equipment for extreme AO to directly image planets around nearby stars and on multiconjugate AO to account for the effects of turbulence at different levels in the atmosphere and over a much larger area of the sky. Livermore astrophysicist Bruce Macintosh will use the laboratory to integrate and test the Gemini Planet Imager, which is designed for the Gemini South Telescope to look for planets around other stars. Multiconjugate AO will be featured on the planned Thirty Meter Telescope.

Claire Max, director of the CfAO, notes that the center previously did not have laboratories or experimental facilities directly associated with it. "The Laboratory for Adaptive Optics gives us a capability that will be the foundation for many future projects and significant advances in AO systems," says Max.

"We test new components and new algorithms under controlled conditions and compare different ways of optimizing the performance of adaptive optics systems," says Max. "One of the problems with testing equipment on a telescope is that one never knows exactly what the atmosphere is doing during the test, whereas in the laboratory one can simulate what the atmosphere might do."



At the Laboratory for Adaptive Optics, researchers develop prototypes of advanced adaptive optics equipment and concepts and test them in a controlled laboratory setting. The laboratory also serves as a training facility for researchers and students. Pictured are graduate students Katie Morzinski (left) and Mark Ammons.

as a Student Employee Graduate Research Fellowship participant (see the article on p. 4), are involved in center-sponsored research. In addition, every year several college students complete internships at Livermore under center sponsorship. Livermore research on AO technology supports several of the Laboratory's national security projects such as long-range surveillance for homeland security and high-power lasers for stockpile stewardship.

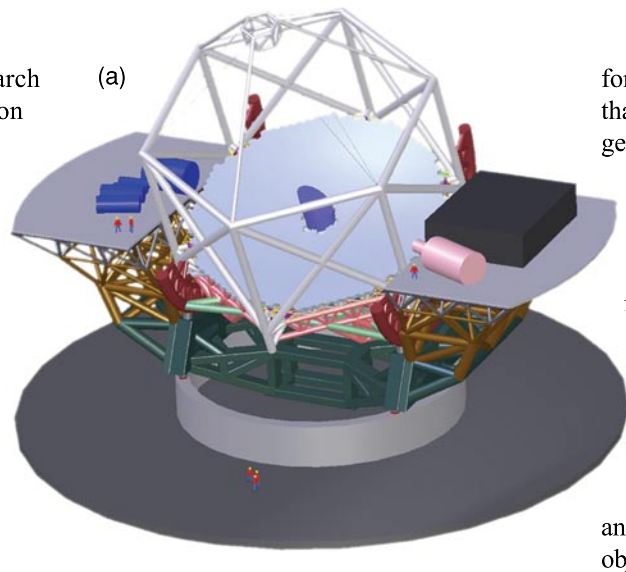
In the field of astronomy, CfAO researchers equip existing telescopes with innovative AO systems, and they design advanced AO systems for planned extremely large telescopes. In astronomical AO systems, light is first detected from either a bright star or a laser guide star, which serves as a reference beacon shining through the atmosphere. The system's wavefront sensors then analyze the distortions of the light caused by atmospheric aberrations. These distortions are removed by the adjustment of an "adaptive" component, usually a deformable mirror, allowing for a sharper view of the fainter, more distant celestial object of interest.

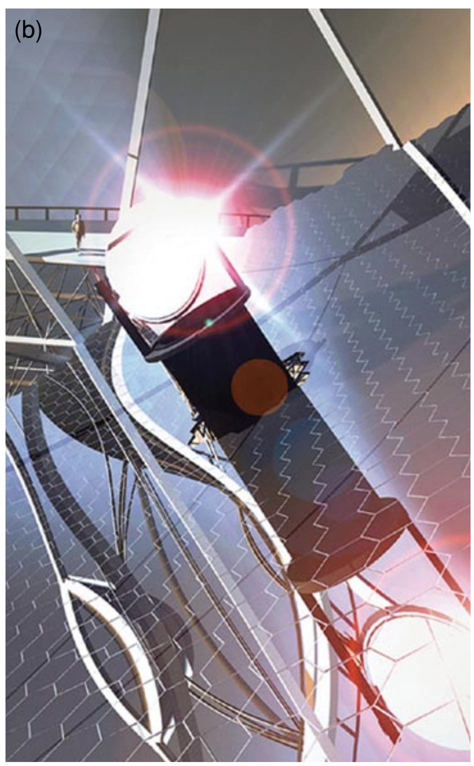
The vision-science instruments designed by center-affiliated researchers use AO in ways somewhat similar to telescopes. A laser is focused on a retina, and the reflected light is analyzed by a wavefront sensor. Actuators fed by data from the sensor continually change the surface of a deformable mirror to provide the necessary compensations for obtaining a clear image of the optical structures in the eye.

AO for Giant Telescopes

One of the CfAO's major efforts is to study the requirements for extremely large optical telescopes, whose primary mirrors range from 30 to 100 meters in diameter. AO for these giant telescopes will allow scientists to achieve major advances in their knowledge of the universe. The center is developing long-range partnerships for working on key AO technologies that will be required to operate this new generation of telescopes. The technologies include improved deformable mirrors, wavefront sensors, and artificial guide stars.

(a)





(a) The Center for Adaptive Optics is playing an important role in the Thirty Meter Telescope (TMT) Project, which will allow astronomers to detect the most distant objects in the universe. (Image courtesy of the TMT Project/Todd Mason, Mason Productions.) (b) The design of the 30-meter-diameter telescope is based on more than 700 hexagonal-shaped mirror segments. (Image courtesy of the TMT Project.)

The center is playing a key role in the Thirty Meter Telescope (TMT) Project, a collaboration between UC, the California Institute of Technology, anda number of Canadian universities. The optical–infrared telescope will allow astronomers to resolve detail in early galaxies and planetary systems and detect the faintest and most distant objects in the universe. The center's new Laboratory for Adaptive Optics is used for developing one of TMT's AO systems. (See the box on p. 16.)

The TMT design is based on more than 700 hexagonal-shaped mirror segments that stretch 30 meters in diameter. The design fulfills the conceptual goals of the Giant Segmented Mirror Telescope, which was identified by the National Academy of Sciences as the highest priority, ground-based facility for the first decade of the 21st century. Livermore astrophysicist Bruce Macintosh has completed a feasibility study for extrasolar planet detection using TMT. Full-science operations of the telescope are scheduled to begin as early as 2015 on a site to be chosen in 2007.

Laser Guide Stars

The CfAO is developing advanced technologies for laser guide stars that produce artificial reference beacons in the atmosphere. A new generation of laser guide stars, some of which are being developed by Livermore physicist Deanna Pennington, will be combined into multiconjugate AO systems. These systems will deploy multiple lasers and wavefront sensors that compensate for distortions at different altitudes over a wider area.

Pennington is working on fiber lasers that will replace the dye lasers used on the world's first two fully functional laser-guide-star AO systems. Both of those AO systems—one on the 3-meter Lick telescope and the other on the 10-meter Keck 2 telescope—were designed by Livermore scientists. The new lasers are similar to the laser used on the front end of the National Ignition Facility at Livermore and are an adaptation of lasers used in the telecommunications industry. Guide-star AO systems based on fiber lasers will be much more compact, robust, and cost-efficient. A prototype system is planned for deployment on a telescope within two years.

The center is also helping astronomers pursue astronomical science projects using laser guide stars. Max is using Lick and Keck observatories to study the formation of galaxies in the early universe. She is also developing methods and procedures for efficient use of the laser-guide-star AO systems, methods for data analysis, and ways to study nearby galaxies with active black holes in their cores.

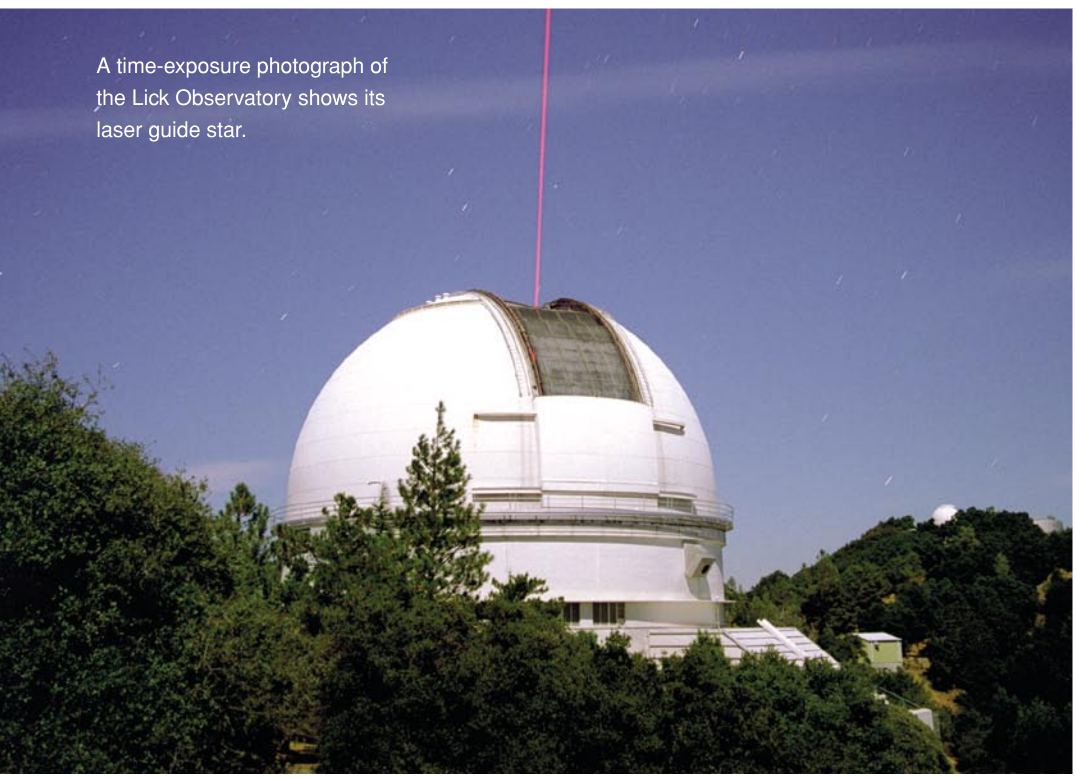
Looking for Planets

Effectively probing the environments of distant stars in a search for planets requires the development of next-generation, high-contrast AO systems. These systems are sometimes referred to as extreme AO. Macintosh says direct imaging of planets is challenging because planets such as Jupiter are a billion times fainter than their parent stars. "Detection of the youngest and brightest planets is barely within reach of today's AO systems," he says. "To see other solar systems, we would need new tools."

In 2005, Livermore was selected as the lead institution to build the Gemini Telescope Planet Imager for the Gemini South Telescope. The Gemini Observatory is a multinational institution that operates two 8-meter-diameter optical–infrared telescopes, one in Hawaii (north) and one in Chile (south).

Livermore will partner with seven universities and institutions in the U.S. and Canada to build the new instrument. "The Gemini Planet Imager will be the most advanced AO system in the world," says Macintosh. The system will have a 2-centimeter-square deformable mirror with 4,000 actuators. This deformable mirror will be made of etched silicon MEMS, similar to microchips, rather than the large reflective glass mirrors used on older AO systems. The new mirror will correct for atmospheric distortions by adjusting its shape 2,500 times per second with an accuracy of better than 1 nanometer. When the imager is operational in 2010, astronomers will be able to detect planets 30 to 150 light years from our solar system.

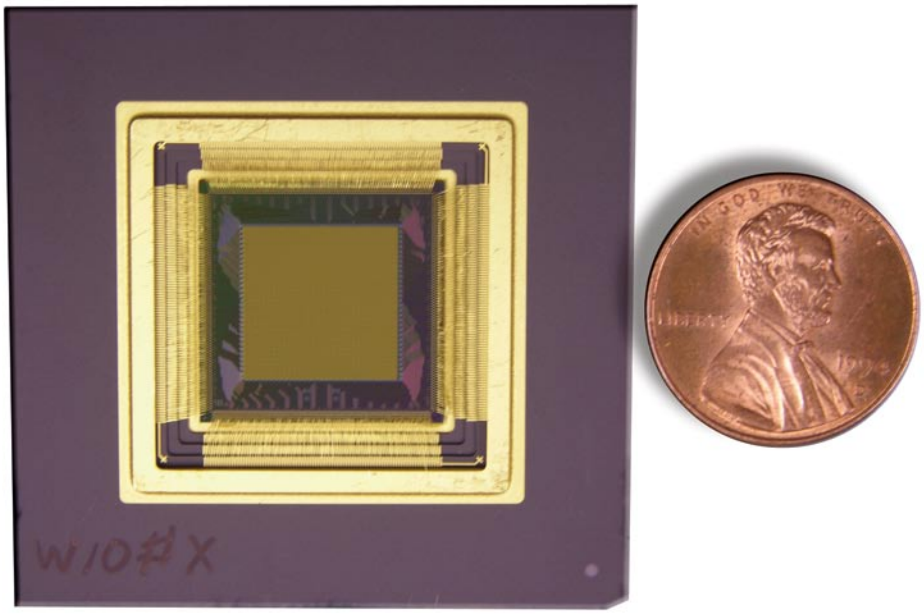
Macintosh, the lead developer of the Gemini Planet Imager, has been working with the center's Laboratory for Adaptive Optics, which features an extreme AO test bed. The Gemini Planet Imager will use an imaging infrared spectrograph to detect and characterize extrasolar planets. The goal is to find young, extrasolar planets orbiting nearby stars, using advanced infrared image-processing techniques to separate planets from other, much brighter celestial objects and system "noise." With funding from Livermore's Laboratory Directed Research and Development Program, Macintosh is currently using existing AO to probe dust and possible planets in nearby solar systems, and he is developing technology needed for Gemini.



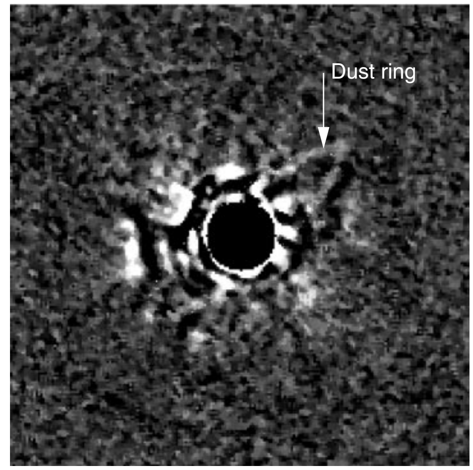
A time-exposure photograph of the Lick Observatory shows its laser guide star.

Revolutionizing Vision Science

Technology derived from AO research for astronomy is being adapted to measure aberrations in the eye. AO promises to revolutionize vision science by allowing physicians to measure the optical imperfections of the living eye with unprecedented thoroughness and accuracy. Physicians will also be able to diagnose tiny retinal defects before they become a threat to healthy vision. In all, the CfAO has spawned more than a dozen vision-science AO instruments.



This prototype deformable mirror made of an etched silicon microelectromechanical system has 1,024 actuators that adjust the shape of the mirror hundreds of times per second.



Livermore astrophysicist Bruce Macintosh used the Keck telescope and adaptive optics to obtain this image of the young star HR4796. The image shows a tilted dust ring. The star is masked out by an occulting spot. The image has been processed to highlight the ring, which results in white and black artifacts close to the star.

The vision instruments direct a weak laser beam into the retina, and the perturbed wavefront of the light reflected off the retina is then analyzed with a sensor. Data from the sensor is used to adjust the shape of an adaptive mirror so it compensates for the distortions. The resulting image can be used to provide prescriptions for eyeglasses and contact lenses as well as a more accurate diagnosis of retinal disease.

AO is poised to transform the phoropter, the standard binocular device used to test vision and calculate lense prescriptions. A team of Livermore physicists and engineers, with other collaborators, has developed an optical instrument called the MEMS-based adaptive optics phoropter (MAOP). The device received a 2003 R&D 100 Award from *R&D Magazine* for being one of the most significant high-technology inventions of the year. (See *S&TR*, October 2003, pp. 12–13.)

The instrument uses a wavefront sensor that measures the aberrations in a patient's eyes and then adjusts the surface of an adaptive mirror to correct the visual flaws. The MAOP can detect and correct for aberrations that conventional phoropters cannot. In this way, results from the MAOP can be used to design contact lenses that produce 20:10 eyesight or to guide laser surgery for vision correction. (These enhanced corrections cannot easily be incorporated into eyeglasses because different portions of the lenses are used for different gaze directions.) Bausch & Lomb, an industrial partner of the CfAO, is conducting clinical trials of the instrument.

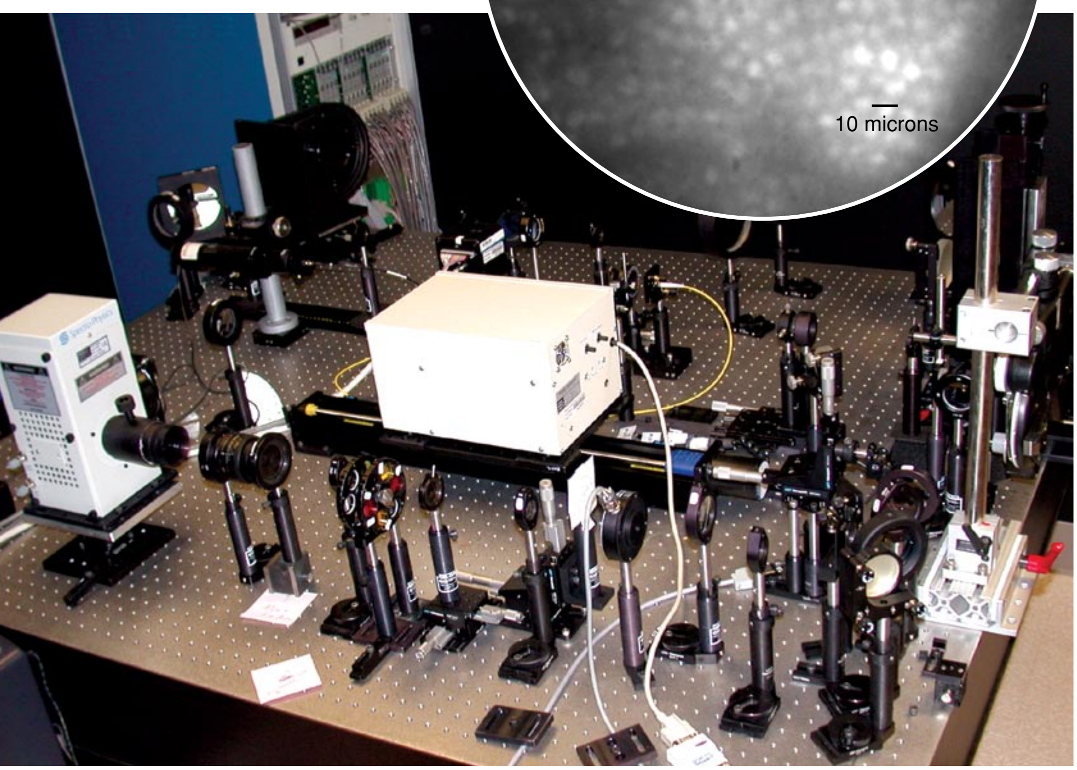
With support from the Department of Energy, the National Institutes of Health, and the National Science Foundation, researchers are incorporating AO technology into vision instruments so clinicians can more effectively diagnose such retinal diseases as glaucoma and macular degeneration. One such instrument is the scanning laser ophthalmoscope (SLO), which scans a low-power laser beam across the retina to build up an image. When confocal imaging is added to the SLO, image contrast increases as the focal length is adjusted and images are recorded at different depths within the retina. With the addition of an AO system, the instrument produces error-free images of the internal structures of retinal cells with improved resolution. In this way, ophthalmologists can watch individual blood cells moving through tiny blood vessels in the retina and, as a result, detect retinal diseases earlier.

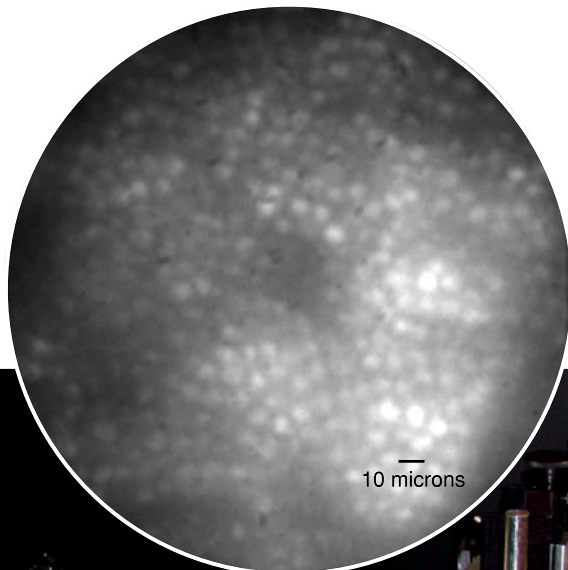
Another technique, optical coherence tomography (OCT), is used increasingly among ophthalmologists to diagnose and monitor retinal disease. OCT makes noninvasive measurements of the thickness of retinal layers, such as the nerve-fiber layer that thins in patients with glaucoma. Several groups nationwide have combined AO with OCT to make possible the first noninvasive three-dimensional (3D) visualization of the human retina at the cellular level.

"Adaptive optics is currently the only option for studying living retinal tissue at the cellular level," says Olivier. He notes that an AO system can compensate for tiny fluctuations in eye muscles, which means during an examination, the eye would not have to be temporarily paralyzed.

Livermore's AO Group is involved in two, five-year Bioengineering Research Partnerships (BRPs) funded by the National Institutes of Health. Both efforts are outgrowths of CfAO-funded research at Livermore and elsewhere to develop instruments for high-resolution retinal imaging. The goal is to develop and test clinical ophthalmic instruments using MEMS AO devices to revolutionize the diagnosis and treatment of the diseases that cause blindness and to develop techniques for vision correction in the general population.

The first BRP is led by the University of Rochester and includes UC Berkeley, Livermore, Indiana University, and the University of Southern California's Doheny Eye Institute. In this effort, Livermore's AO Group is developing a portable, MEMS-based, AO confocal scanning laser ophthalmoscope for use at the Doheny Eye Institute.





This adaptive optics ophthalmoscope is being used by medical researchers at the University of California at Davis to view individual retinal cells (inset), allowing for the early detection of retinal diseases such as glaucoma and macular degeneration.

The second BRP is led by UC Davis Medical Center and includes Indiana University, Duke University, and Livermore. In this effort, Livermore's AO Group is combining MEMS technology with OCT instruments developed at the partner universities to improve the ability to visualize the retina in 3D with cellular-level resolution.

Enhancing Scientific Literacy

One of the center's charters from the National Science Foundation is advancing education, especially among student groups that are underrepresented in science and engineering. Many of the CfAO's educational activities take place in Hawaii because a number of major observatories are located on Maui and the island of Hawaii.

A major educational thrust is aimed at the professional development of graduate students and postdoctoral researchers. The center runs an annual, weeklong professional development workshop on Maui. For example, in February 2006, graduate students, postdoctoral researchers, faculty members from Hawaiian community colleges, and staff from Hawaii-based observatories met to learn teaching skills. The group formed into small teams to prepare science curriculum for high-school and college students. "We want scientists to become more effective science communicators and educators," says Lisa Hunter, the center's associate director for education.

Center educators also work to motivate high-school and college students interested in science and engineering. Eight-week summer internships for college students are held on the islands of Maui and Hawaii and on the mainland. The Maui internship program is directed at helping students gain entry into the local high-technology workforce. The program on the island of Hawaii emphasizes working in technical positions on island observatories or gaining admission into graduate school in a technical field.

The mainland program is open to college students from underrepresented groups and begins with a one-week intensive short course at UCSC. Taught by CfAO graduate students and postdoctoral researchers, the course provides background in AO-related topics, such as spectroscopy, and prepares students for performing research. Students then begin internships at Lawrence Livermore, UC Berkeley, UC Los Angeles, UCSC, or the University of Rochester. "These students receive a lot of support from the center and a lot of encouragement from us," says Olivier. At the completion of their research project, the students make a presentation to their peers at UCSC. About 10 students have completed internships at Livermore, and many of them have gone on to graduate school.

The center also offers a four-week summer course for high-school students considering a technical degree. The course, which covers vision, astronomy, and optics, is taught by CfAO scientists. A weeklong AO summer course is offered for graduate students and professionals.

The Center for Adaptive Optics operates eight-week summer internship programs for college students on the islands of Maui and Hawaii and on the mainland. Students assigned to Livermore work under an Adaptive Optics Group researcher. John Ruiz from the University of Houston and Aftan Alameda from San Antonio College were two of the 2005 Livermore interns.

Accomplishments Are Gratifying

Olivier says it is gratifying that the center has encouraged collaboration between researchers, fostered interactions between astronomers and vision scientists, and advanced educational opportunities for students. "We have come a long way," says Max. "Our educational programs both in Hawaii and on the mainland are recognized for their quality and diversity of participants. In astronomy, adaptive optics is a feature of many more scientific papers. The challenge of lasers for guide stars is not as daunting as it was several years ago. The performance of MEMS deformable mirrors is approaching the specifications required by astronomers and vision scientists. And vision scientists have developed new AO instruments and received international recognition."

Olivier notes the importance of partnerships as AO technology becomes more firmly established in astronomy, vision science, and military applications. For example, under a Defense Advanced Research Projects Agency initiative, Livermore teamed with academic institutions and industry to develop extremely fast and secure long-range communication links and aberration-free, 3D imaging and targeting systems using MEMS devices.

For Livermore researchers, technologies developed in support of the center help advance a wide range of work in remote sensing and large optical systems for national security missions. Livermore-developed techniques that allow an optical system to adapt to changing atmospheric conditions can be used to control the wavefront in high-energy laser systems. For example, a wavefront sensor concept developed for extreme AO is being used in Livermore's Solid-State Heat Capacity Laser. (See *S&TR*, April 2006, pp. 10–17.)

The advancements may help scientists discover new planets and understand the origin, formation, and composition of stars, planets, and galaxies. They may also provide better vision for pilots, enhance military surveillance, and save the sight of thousands of people through early detection and treatment of retinal diseases. It seems that few things are as important as seeing clearly.

—Arnie Heller

Key Words: adaptive optics (AO), Center for Adaptive Optics (CfAO), fiber laser, Gemini Observatory, Keck Observatory, Laboratory for Adaptive Optics, laser guide star, Lick Observatory, MEMS-based adaptive optics phoropter (MAOP), microelectromechanical systems (MEMS), National Science Foundation, optical coherence tomography (OCT), scanning laser ophthalmoscope (SLO), Science Technology Center, Thirty Meter Telescope (TMT), vision science.

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