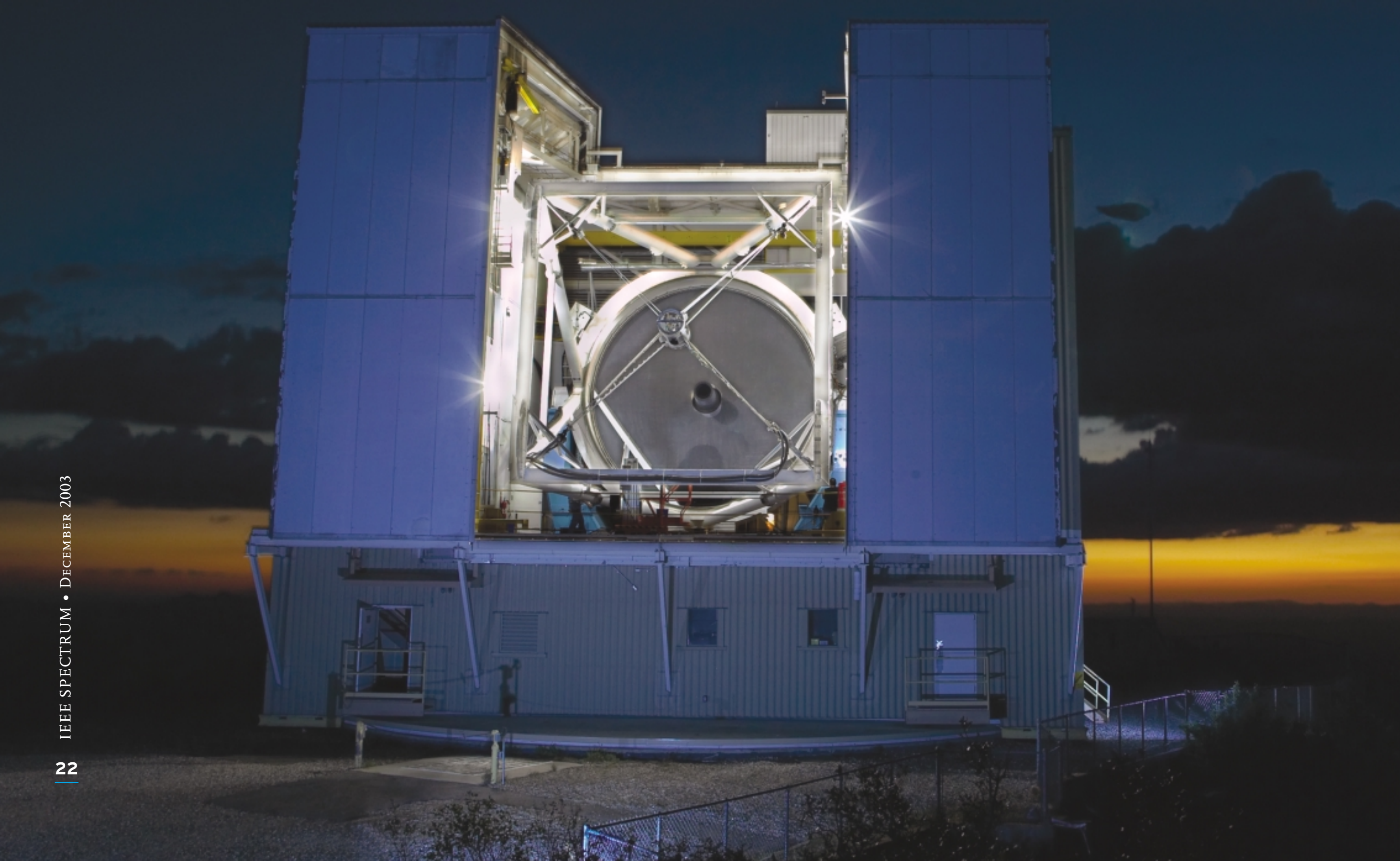
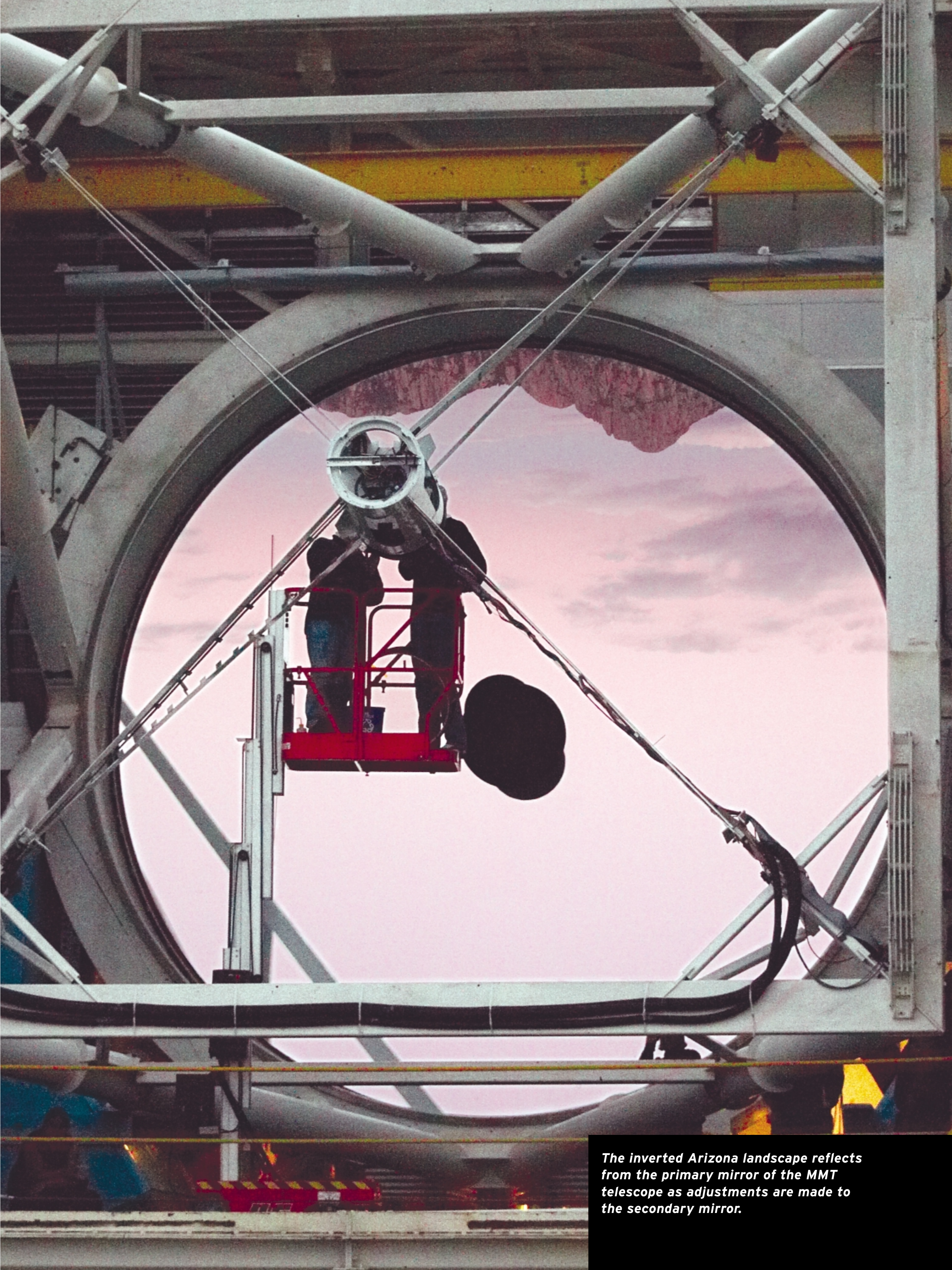
ASTRONOMY

TAKING THE TWINKLE OUT OF STARLIGHT

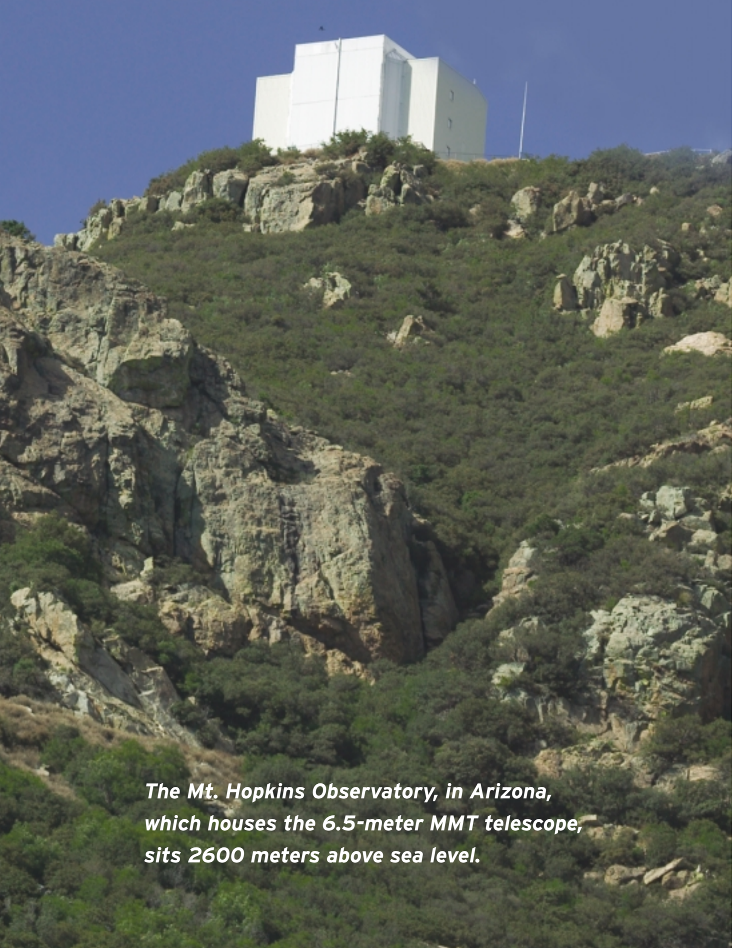
Shape-changing mirrors are giving astronomers their best views ever. They'll soon include the first sight of a planet in another solar system BY MICHAEL LLOYD-HART





The inverted Arizona landscape reflects from the primary mirror of the MMT telescope as adjustments are made to the secondary mirror.

You're camping out in the mountains on a clear summer night. The velvet-black sky sparkles with millions of flickering dots. The starry twinkle, though, which has driven generations of poets to rapture, is the bane of astronomers bent on capturing clear, sharp images of the galaxies, stars, and planets that populate the universe. Viewed through large Earth-based telescopes, that twinkle is seen as blur, which reduces astronomers' ability to see finely detailed structure.



The Mt. Hopkins Observatory, in Arizona, which houses the 6.5-meter MMT telescope, sits 2600 meters above sea level.

PRECEDING PAGES AND LEFT: EDWARD MCCAIN

Sir Isaac Newton identified the problem 300 years ago. Writing less than a century after the invention of the telescope, he declared: "If the theory of making Telescopes could at length be fully brought into Practice, yet there would be certain bounds beyond which Telescopes could not perform. For the air through which we look upon the stars is in perpetual Tremor." The "tremor" arises from turbulent mixing of air at different temperatures, which continually changes the speed and direction of starlight as it passes through the atmosphere. The same effect distorts the view of distant objects seen through the shimmer above a hot parking lot.

Today, a new technology called adaptive optics is, in effect, removing the atmospheric tremor. And the improvements that it brings to today's telescopes represent an advance at least as great as the invention of the telescope itself. The technique brings together the latest in computers, material science, electronic detectors, and digital control in a system that warps and bends a mirror in the telescope to counteract, in real time, the atmospheric distortion.

The advance promises to let ground-based telescopes reach their fundamental limits of resolution and sensitivity, outperforming space-based telescopes and ushering in a new era in optical astronomy. Most alluringly, using this technology, it will finally be possible to see gas-giant type planets in nearby solar systems in our Milky Way galaxy. Although about 100 such planets have been found in recent years, all were detected through indirect means, such as their gravitational effects on their parent stars; none has actually been seen directly.

An adaptive optics system recently installed on the 6.5-meter-diameter telescope, called the MMT telescope, on Mt. Hopkins, just south of Tucson, Ariz., takes the technology a step further [see photos, pp. 23 and left]. It reduces the thermal background "noise" that comes from the telescope itself to below that of any other conventional telescope using an adaptive optics system. With less "noise" astronomers can see fainter objects than they would be able to see otherwise.

Reaching for the limits

In theory, a telescope's resolving power is directly proportional to the diameter of its primary light-gathering mirror or lens. But in practice, images from large telescopes are blurred to a resolution no better than would be seen through a 20-cm aperture with no atmospheric blurring. At scientifically important infrared wavelengths, atmospheric turbulence degrades astronomers' ability to resolve fine detail by at least a factor of 10.

Space telescopes avoid problems with the atmosphere, but they're enormously expensive and the limit on aperture size of telescopes that are currently launchable is quite restrictive. The Hubble Space Telescope, the world's largest unclassified telescope in orbit, has an aperture of 2.4 meters; terrestrial telescopes can have a diameter four times that size.

One can turn instead to larger telescopes on the ground, equipped with adaptive optics systems to compensate in real time for the atmospheric aberration. With this setup, the image quality that can be recovered is close to what that same telescope would deliver if it were in space.

Images obtained from the adaptive optics system on the MMT illustrate the impact. We recorded two images of a small region in the vicinity of the middle "star" in Orion's sword—actually a cluster of many very young stars in an association that is still creating new members [see illustration, below]. The two images, obtained from light with a wavelength of 1.5 µm, show a close grouping of four of these stars. In the conventional blurred image, it's not really possible to make out more than two stars. With the adaptive optics, on the other hand, sharpness improves by a factor of about 13, making it clear that the fainter star is, in fact, a binary—two stars close together—and a fourth fainter member of the group appears that was previously undetected.

How is it that adaptive optics can provide such detail? As light from a distant star approaches Earth, it is made up of plane waves that, in the last microseconds of their journey to the telescope, become badly distorted by atmospheric turbulence. An adaptive optics system reflattens the wave fronts by reflecting the light off a deformable mirror whose shape is changed in real time to introduce an equal but opposite distortion [see figure, p. 26].

The information on how to distort the mirror comes from a wave front sensor, an instrument that measures the optical aberration imposed by the atmosphere on light from a star in the same field of view as the objects of interest to the astronomers. A fast computer converts the signals coming from the wave front sensor into drive signals for the deformable mirror. The whole system operates with a never-ending cycle of measurement and correction, at typical speeds of 1000 updates per second.

After the light reflects off the deformable mirror, a beam splitter sends part of the light to the wave front sensor and the rest to the camera that will capture the high-resolution image produced by the adaptive optics [see photo, p. 29]

In the early 1970s, the U.S. Department of Defense began supporting an effort to develop a real-time image correction system to obtain sharp pictures of Soviet satellites. The first high-resolution images from the sky were obtained in 1982 by a 1.6-meter telescope at the Air Force Maui Optical Station on the rim of the 3000-meter-high dormant Haleakala volcano in Hawaii.

Over the next 10 years, both the military and astronomical communities vigorously advanced the state of the art. A group at the National Optical Astronomy Observatory in Tucson, led by François Roddier, devised a new type of wave front sensor and a new deformable mirror that were successfully tested on the Canada-France-Hawaii Telescope on Mauna Kea on Hawaii's Big Island. Full-blown prototype adaptive optics systems were fielded at telescopes in Chile, the Canary Islands, Arizona, and California.

In the late 1980s, pioneering work by a U.S. Air Force team under Robert Q. Fugate, using a telescope at Kirtland Air Force Base in Albuquerque, N.M., showed that an adaptive optics system could operate very effectively using a laser to create an artificial "star" in the sky as the wave front reference. The work was classified and unavailable to the worldwide astronomical community, which meanwhile forged ahead on its own. By 1992, although no adaptive optics systems were yet operating as routine scientific tools at astronomical telescopes, the defense community realized that the astronomers were catching up and declassified much of its research.

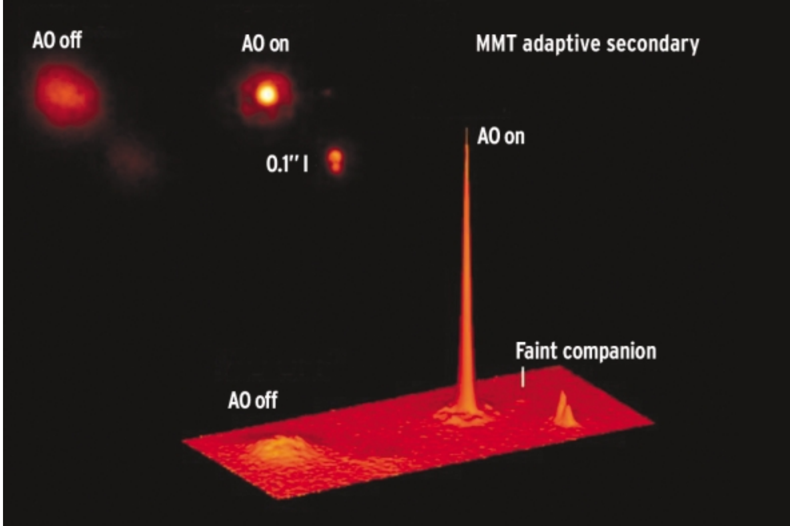
Large telescopes adapt

The information was a bonanza for the astronomers, and adaptive optics are now in regular use at large telescopes all over the world. On the summit of Mauna Kea, the two 10-meter telescopes of the W. M. Keck Observatory, the 8-meter telescopes of the Gemini international consortium and the National Astronomical Observatory of Japan, and the 3.6-meter Canada-France-Hawaii telescope are equipped with adaptive optics systems supporting astronomical observation programs.

The European Southern Observatory, based in Garching bei Muenchen, Germany, operates the Very Large Telescope on Cerro Paranal in Chile's Atacama desert. The telescope consists of four separate 8-meter telescopes that can be optically linked together to form one giant telescope. At present, just one of the four is equipped with adaptive optics, feeding a near-infrared camera and low-resolution spectrograph (an instrument that measures light intensity as a function of frequency), but plans call for the eventual addition of adaptive optics to all four.

One other telescope bears special mention: the 3-meter Shane telescope of the Lick Observatory, on Mt. Hamilton, near San Jose, Calif. It's the only astronomical telescope that doesn't need to rely on light from a star to provide the information on atmospheric distortion. Instead, it uses a laser beam projected into the sky, a technique similar to the one demonstrated by Fugate's team. Tuned to 589 nm, the same wavelength as sodium street lamps, the laser excites a layer of sodium atoms 95 km above Earth's surface left by meteorites as they burn up in the atmosphere.

These atoms scatter light back to the telescope, creating what looks like a glowing spot in the sky. Currently, the lasers needed



CLEARER THAN EVER Without adaptive optics, the image of a small star cluster in the constellation Orion appears blurred [top left]. It's much clearer with the adaptive optics turned on, and reveals a previously undetected star [top center]. Surface plots [right] show the dramatic increase in peak light intensity and sharpness.

LAIRD CLOSE

to do this job are expensive and difficult to maintain, but several efforts are under way to change that. The W. M. Keck Observatory will soon begin operation with a laser guide star, and, as the lasers become readily available, many other large telescope projects will adopt the laser guide star approach to adaptive optics.

Seeing (infra)red

The adaptive optics systems in these astronomical telescopes differ from military systems in their choice of wavelength. Defense applications typically call for correction of visible light, which is most important in imaging artificial satellites; astronomers, on the other hand, are mainly interested in the near and mid-infrared. In part, that's because of the enormous amount of science to be done there and in part, because the difficulty (and the cost) of adaptive optics rises very sharply with the shorter wavelengths of visible light.

In essence, a modern telescope consists of a large concave primary mirror, designed to capture a lot of light, and a smaller, secondary mirror that focuses the light onto a detector. In the infrared, the standard hardware implementation of adaptive optics starts with an existing telescope, complete with its primary and secondary mirrors, and adds a separate box of optics, including the deformable mirror, to perform the atmospheric compensation.

This approach has two disadvantages, particularly at wavelengths longer than 2.4 µm. One is that each additional optical surface added to the beam train absorbs some of the light from the target object in the sky, making the object appear fainter. On top of that, by virtue of its own warmth, it emits light in the thermal infrared (typically between 3 and 20 µm). This light forms a bright, diffuse background and introduces photon noise, further degrading astronomers' ability to detect faint objects.

Our team of adaptive opticians from the Steward Observatory at the University of Arizona in Tucson and the Osservatorio Astrofisico di Arcetri at the University of Florence, in Italy, has come up with a different solution. We do away with the additional optics and instead incorporate the adaptive optics directly into the telescope. At the MMT, we've built our own secondary mirror, which does double duty: it acts as a normal secondary by focusing starlight onto the high-resolution imaging system, but it is also deformable, to act as the adaptive optical wave front corrector.

Thus, starlight coming from the telescope is already fully corrected and focuses down to a high-resolution image, with greater intensity and thermal background an order of magnitude lower than what a telescope equipped with conventional adaptive optics could deliver.

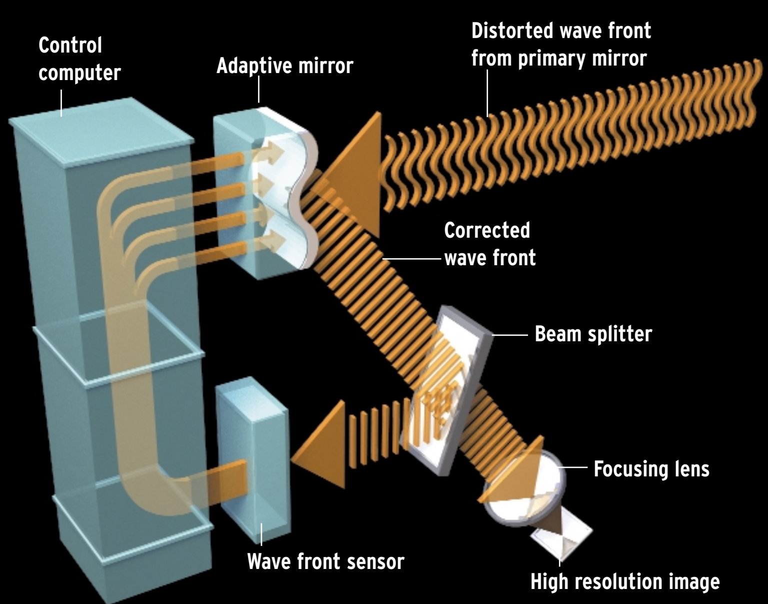
Although the scientific advantages of wave front correction at the telescope's secondary mirror have been recognized for 10 years or so, no one had actually attempted to do it that way because of the enormous technical challenges. At the top of the list, we needed to learn how to make a piece of glass whose surface could be precisely controlled and shaped to within a few nanometers a thousand times a second.

To address that challenge, we drew on the expertise of astronomers at the University of Arizona's Steward Observatory Mirror Lab, which made the two largest mirrors in the world, the 8.4-meter primary mirrors for the Large Binocular Telescope being constructed on Mt. Graham, in Arizona. The two mirrors were each made from a single piece of glass.

To make the adaptive secondary mirror, two pieces of glass with a very low coefficient of thermal expansion were first ground with matching spherical shapes. They were then bonded together with a 100-µm-thick layer of pitch, a liquid that is very viscous at room temperature.

This arrangement holds the two pieces of glass like a single rigid body as the convex surface is ground down to a membrane just 2 mm thick. The desired optical surface, a hyperboloid (a hyperbolic surface of revolution) with 80 µm of departure from the best-fit spherical surface, was then polished into the membrane with the same technique used for the large primary mirrors. To release the membrane, the whole assembly was baked to 120 °C, melting the pitch and allowing the membrane to slide off. The front convex surface of the membrane, coated with aluminum, becomes the deformable mirror.

The second difficulty, controlling the shape of the membrane at high speed and with extremely high precision, was solved by the

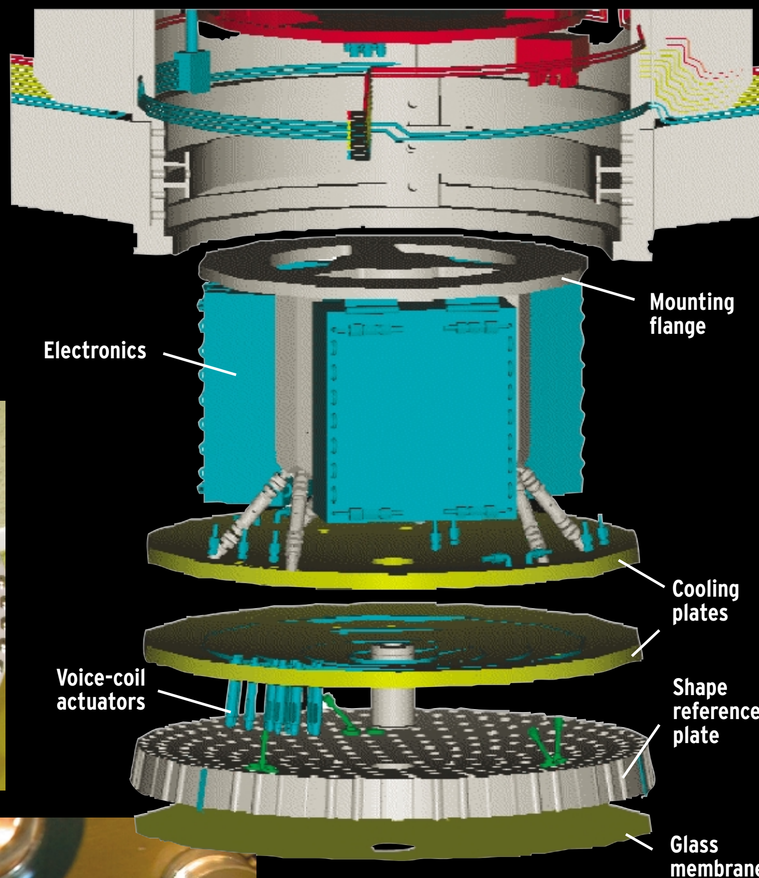


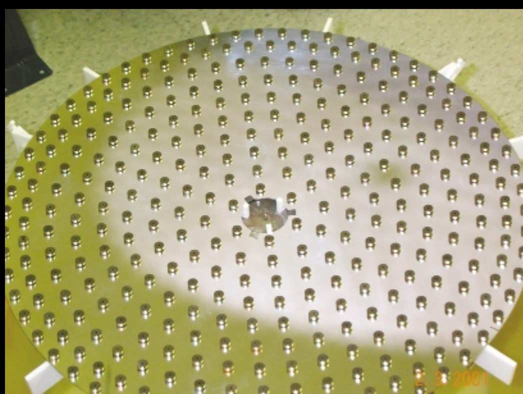
CANCELING DISTORTION In the MMT's adaptive optics system, light from the primary mirror, distorted by the atmosphere, reflects from the adaptive secondary mirror that is deformed to correct for the distortion. A beam splitter shunts some light from this mirror to a wave front sensor. The sensor's output goes to an array of digital signal processors in a control computer, which calculates how much and where to deform the mirror to compensate for the atmospheric distortion. The corrected light passes through a lens that focuses it into a high-resolution image.

BRYAN CHRISTIE

An Inside Look At Adaptive Optics

By changing its shape, a thin, deformable glass membrane [at the very bottom of the secondary mirror diagram, right], compensates for atmospheric distortion. The shape of the 2-mm-thick membrane is controlled by 336 radially polarized magnets attached to the back of the membrane [photo, below]. Each magnet is excited by its own matching coil [next photo, below]. The membrane is 642 mm in diameter.





AT THE CONTROLS In the telescope's control room [below, right], researchers monitor the behavior of the adaptive mirror. Color codes indicate the position of each magnet on the deformable mirror [far left] and the force exerted on each magnet by the coils [center].

LEFT: FRANCOIS WILDI TOP RIGHT: ADS
BOTTOM: EDWARD MCCAIN

Italian half of the consortium. The problem is that the membrane is very floppy, so that in trying to push it around to change its shape rapidly, it rings in hundreds of resonant modes. Unchecked, these resonances would make it impossible to control the rapid changes in the shape of the mirror. But by placing the membrane just 40 µm away from a second, rigid piece of glass called the shape reference plate, the Arcetri group discovered that the thin layer of air between them becomes so viscous that all the resonances are damped out. It's as though the glass were moving against a layer of molasses.

In the fully assembled mirror, the membrane's shape is controlled by 336 voice-coil actuators, like miniature loudspeakers [see left center photo, p. 27]. They couple to 336 rare-earth magnets glued to the back of the membrane [see top left photo, p. 27]. The separation between the copper coils and the magnets is 0.2 mm. A current through each coil generates a variable magnetic field, which exerts a force on the corresponding permanent magnet and moves the glass membrane.

Unique to this deformable mirror are capacitive position sensors that measure the mirror's local position. The capacitors are chromium rings deposited on the front surface of the reference plate around each of the 336 actuators. The capacitance between each chromium ring and an aluminum coating on the back of the deformable mirror across the 40-µm air gap is about 65 pF. A square-wave voltage applied across the capacitors allows them to be read at 40 kHz, giving a measure of the local position of the membrane with respect to the rigid reference plate accurate to 3 nm [see bottom photos, p. 27].

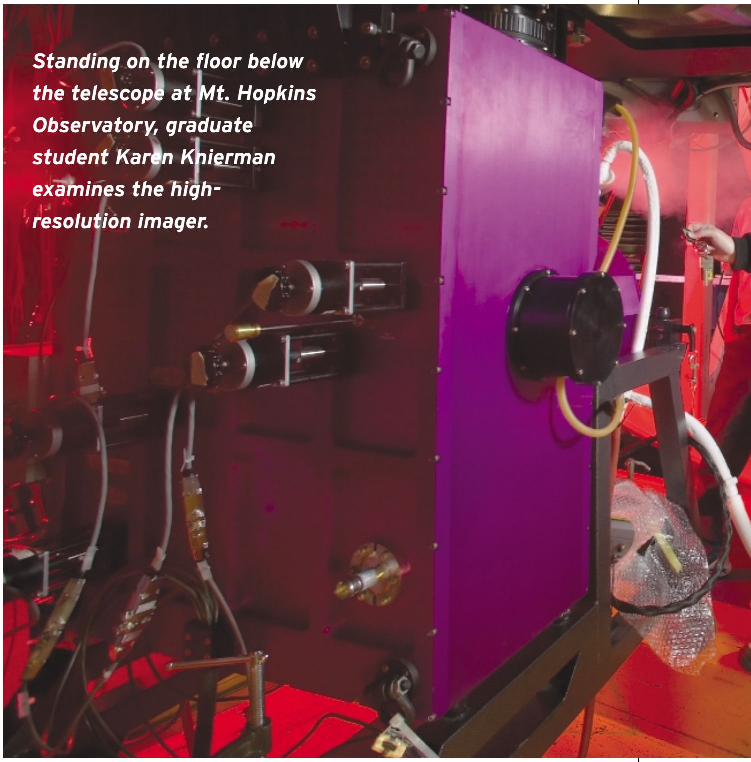
In the normal orientation when installed in the telescope, the flexible membrane is at the bottom [see top right illustration, p. 27]. Above that is the rigid reference plate, 50 mm thick, pierced by 336 holes through which poke the actuators. The coils of the actuators are mounted on the ends of 10-cm-long aluminum fingers that conduct heat to an aluminum cold plate, two machined pieces glued and bolted together.

Cooling fluid circulates through grooves milled into the lower plate. We use a 50/50 mixture of distilled water and methanol. This solution won't freeze at the chilly temperatures found on top of a high mountain at night in the middle of winter, even in the Arizona desert, and it will leave no residue in the unfortunate but unlikely event that any of it leaks onto the telescope's precious primary mirror.

Above the cold plate are three electronics units containing 168 digital signal processors (DSPs) from Analog Devices Inc. (Norwood, Mass.). Each DSP is responsible for controlling two actuators, reading the capacitive sensors at 40 kHz, and updating the drive currents in the coils to keep the mirror in the right shape. This feedback overcomes the mirror's natural floppiness, effectively making it very stiff in the face of disturbances from vibrations in the telescope, wind buffeting, and changes in the direction of gravity relative to the mirror's surface as the telescope tracks across the sky. Indeed, we've operated the MMT adaptive optics system in winds as high as 50 km/h, and the mirror holds its shape to an astonishing 10 nm.

With the difficulties in building an adaptive secondary mirror overcome, the scientific payoff is just beginning to roll in. One of the first results comes from the image on page 25. Combining measurements of the close binary pair in the lower right part of the image with similar observations from the Gemini North telescope on Mauna Kea a few years ago, we find that these two stars are orbiting each other, and we can detect the orbital motion. At a distance of 500 parsecs (about 1600 light-years), these stars are the farthest for which an orbit has been observed.

In addition, the faintest of the four stars seems to be a gravitationally bound member of the cluster. Since it has the lowest mass, it will almost certainly be ejected soon, transporting kinetic energy out of the cluster and leaving the others more tightly bound. With more observation, we will be able to predict how that will happen and, for the first time, see in detail a mechanism by which stars of varying masses are distributed through the galaxy.



Standing on the floor below the telescope at Mt. Hopkins Observatory, graduate student Karen Knierman examines the high-resolution imager.

Other stars, other Earths

Perhaps the most exciting scientific program to benefit from the new approach to adaptive optics will look at Jupiter-like planets orbiting other stars. We know of roughly 100 such gas giants through observations of their effects on the motion of their parent stars, but none has ever actually been seen by direct imaging. That's because, to start with, they're extraordinarily faint, and to compound the problem, they're right next to something that's enormously brighter. To within an order of magnitude, it's like looking for a firefly perched on the edge of a searchlight pointed straight into your eyes.

Nonetheless, the rewards of actually seeing these extrasolar planets are well worth the effort. Through observations of the dust left over from the planetary formation process, which is expected to be found in the plane of the stellar system, we will learn about the environment in which planets form.

Measurements of the planet's brightness at different wavelengths will tell us about the planet's temperature and chemical makeup and whether the system has the conditions to support life. Observations in the thermal infrared region of the spectrum from 3 to 10 µm will be particularly valuable, because many simple organic molecules like methane emit strongly there. Furthermore, we will exercise many of the observational techniques and new technologies required to eventually find and study Earth-like planets.

The big challenge here is to distinguish a planet's light from that of its parent star. In the visible range, where planets shine by reflecting starlight, contrast ratios between a planet

and its star can be extremely large. For example, the contrast ratio between Jupiter and the Sun is on the order of 10^{10}.

Younger giant planets, less than a billion years old or so, still retain much of the heat created by their coalescence out of the primeval matter from which their solar systems were formed, and radiate strongly in the thermal infrared. For such planets, the contrast ratio may be improved to a mere 10^6—still an enormous challenge. But most planetary systems, like our own, are thought to be much older. They will have cooled and will no longer glow in the thermal infrared as they once did.

A further complication occurs when trying to capture an image of the stellar system at the telescope. Regions of the image close to the star, where its planets might be found, are swamped by a halo of starlight scattered by Earth's atmosphere. The halo adds photon noise orders of magnitude greater than the tiny planetary signal. To have any hope of finding the elusive planet, we must rely on adaptive optics to suppress the halo as much as possible.

We will also do ourselves a favor by imaging at a wavelength of around 5 µm, where the contrast between planet and star is the lowest. That is where the very low thermal background radiation coming from the MMT adaptive optics system provides a crucial advantage, by reducing the photon noise against which the planet must be seen.

What's more, the stellar halo can be suppressed still further through destructive interference, using a technique called nulling interferometry. In this procedure, the images from two telescopes are overlapped exactly and in such a way that at the location of the star, the crests in the light waves from one telescope fall on the troughs of the waves from the other, canceling each other out. Thus, a very dark spot is created where, before, the bright stellar image was found.

The principle of conservation of energy requires that the starlight not be destroyed, and indeed it appears at a second output of the nulling interferometer. It is removed, though, in the crucial region closest to the star where we would expect to look for planets. The critical geometry needed to fulfill this nulling condition pertains only over a tiny slice of the image, corresponding to the fundamental resolution limit of the combined telescope pair. Planetary images in adjacent regions will remain, therefore—now with greatly improved contrast.

In a groundbreaking experiment, we have begun tests at the MMT of a prototype nulling interferometer in combination with the adaptive optics system. Instead of using two separate telescopes, the interferometer divides light from the 6.5-meter aperture into two parts. Additional optics then recombine them to satisfy the nulling criterion. In one of our first results, light from the primary star was suppressed so that it appeared no brighter than the secondary star. During the measurement, the adaptive optics maintained a stable high-resolution image well corrected for atmospheric turbulence.

As we continue to develop this program, further improvements in our instrumentation will allow us to see fainter objects. The next major step will be the completion in 2005 of the Large Binocular Telescope, combining two 8.4-meter primary mirrors on a single mount, each equipped with its own adaptive secondary mirror. The corrected light from the two halves of the telescope will then be brought together in the center in a new nulling interferometer now being built.

Predictions of the instrument's sensitivity show that we can expect direct detection of several planets already known to exist—for instance, those around ε Eridani, 47 Ursae Majoris, and υ Andromedae. Many others are likely to be discovered for the first time because of the instrument's ability to explore a much greater region of space around each star than is possible with today's indirect detection methods. ●

To Probe Further

The Center for Astronomical Adaptive Optics, Steward Observatory, University of Arizona, maintains a Web site with information on research projects planned and under way. Visit http://caao.as.arizona.edu/.

"Direct Detection of Terrestrial Exoplanets: Comparing the Potential for Space and Ground Telescopes," by Roger Angel, director of the Steward Observatory center, is available at the center's Web site.

A lecture series on adaptive optics by Claire Max, professor of astronomy and astrophysics at the University of California, Santa Cruz, explains the principles of adaptive optics. It is available at http://cfao.ucolick.org/~max/289C.old/.

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