bate, photochromic materials can take minutes to store data. But Zilker notes that "this reorientation is extremely stable." His team roasted a material containing stored data at 160°C for 4 weeks, and the stored information did not degrade. "For permanent long-term storage, these are my materials of choice," says Zilker. He adds that they might also be viable for read-write memories. They can be erased with circularly polarized light, which scrambles the side-chain orientations. And he sees a way around the slow recording times: Because the refractive index changes that these materials undergo as the side chains align are so large, he says, systems could be designed to work with the smaller changes that result from a writing time of a few milliseconds.

Another class of materials that promises durable holographic storage is photopolymers. In these materials, the laser light triggers molecules to link up in chains, or polymerize. The polymerization is most extensive at the bright spots in the hologram, and it also changes the refractive index locally. Photopolymers are the equivalent of fast film, says Hesselink. "If you absorb a photon, a chemical reaction takes place and maybe 100 events could take place, and this makes the materials two to three orders more sensitive than the photochromic materials or photorefractive materials." The transformation, however, is permanent, making photopolymers a promising basis for read-only memories but not for read-write systems.

Another drawback of these materials is that they shrink during the writing process, as the molecules polymerize. The shrinkage shifts the angle of each hologram and alters the distance between its features. This makes it hard for the system to find stored holograms when it reads data. But researchers at Lucent are addressing the problem with a so-called "two chemistry" system, which is still under wraps. By separating the chemical events that record the hologram from the chemistry of the material as a whole, they say, it reduces shrinkage drastically.

In spite of these hurdles, companies are pushing ahead. "The most crucial aspect now is to find the right niche, the right market," says Psaltis. And several companies are betting that read-only systems for archiving and quickly retrieving large amounts of data will turn out to be the right niche. Because holographic systems handle information as entire "data pages," they can search stored information rapidly by looking for telltale patterns, rather than examining it bit by bit. "Holographic storage stands to be a real winner as a search engine for associative retrieval of information," says Sincerbox.

Optostor AG, a company near Düsseldorf, Germany, expects to have a holographic read-only memory system for long-term archiving on the market in about 2 years. Its heart will be a photorefractive crystal measuring 50 millimeters by 50 millimeters by 4 millimeters, containing a terabyte of data stored in holograms that have been "fixed" by heating. "You can put it in a normal PC, and the dimensions are only a little bigger than a typical disk," says Theo Woike of the University of Cologne in Germany, whose research group has a contract with the company.

Others are also at work on read-only holographic storage based on photorefractive crystals and photopolymers, although some researchers speak coyly of having read-write systems in the works, while refusing to divulge proprietary information. One is Hesselink, who was a founder of Siros Technologies, formerly Optitek. "We have spent a lot of effort on [storage in] photopolymers—a read-only material. But in the Siros implementation, there is also a possibility of making that a read-write system," he says.

The wait has been longer than he and others expected 5 years ago. But their optimism hasn't dimmed. When will the first commercial holographic storage system appear on the market? "Within a year, I think," says Sincerbox.

–ALEXANDER HELLEMANS

Alexander Hellemans is a science writer in Naples, Italy.

NEWS

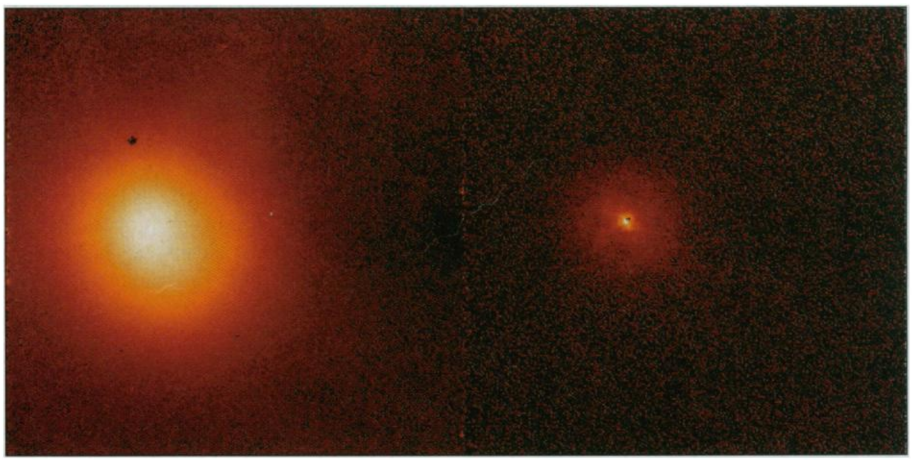
Technique for Unblurring The Stars Comes of Age

Adaptive optics technology, which can undo the effects of atmospheric turbulence, is expanding its reach to fainter stars and larger swaths of sky

For millions or billions of years, the light from distant stars rushes toward Earth relatively undisturbed, but in the last few microseconds it gets scrambled. Turbulence in Earth's atmosphere distorts wavefronts and blurs details, placing what once looked like an ironclad limit on the resolution of even the largest ground-based telescopes. Although the 10-meter Keck telescopes on Mauna Kea, Hawaii, can detect light from vanishingly faint objects in the distant universe, they can't see these objects—or anything else—in much more detail than a large amateur backyard instrument can capture.

For the past few years, however, technologically minded astronomers have been working on a solution, called adaptive optics (AO). The concept is daring: Measure the changing distortions in the light waves and compensate for them hundreds of times per second by flexing a deformable mirror in the light path, using tens or even hundreds of tiny piezoelectric actuators. But what at first looked like technological hubris gradually became a working technology, albeit limited to a few telescopes and able to make observations only near bright stars, used as probes of atmospheric distortion. "We had the concepts available back in the 1980s," says Laird Close of the European Southern Observatory (ESO), "but it took longer than expected" to make AO a practical tool for astronomers.

Now astronomers are fitting AO systems to many more telescopes; soon, most of the



Look sharp. A star comes into focus in images made this year at the Keck II telescope, one of the world's largest, before (left) and after the adaptive optics system was activated.

CREDIT: KECK OBSERVATORY

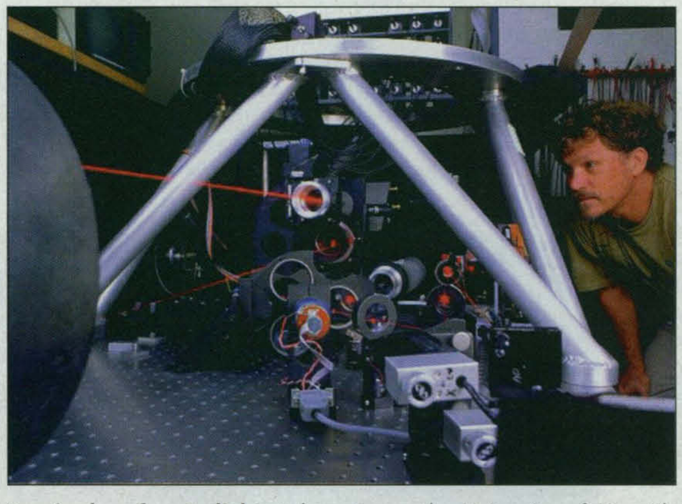
giant, 4- to 10-meter telescopes that have been sprouting on dry mountaintops from Chile to Hawaii to the Canary Islands will have working AO systems. The results are already starting to make headlines in the scientific literature. And there's more to come, says telescope designer Roger Angel of the University of Arizona, Tucson: "The scientific importance of such corrections will be greatly enhanced when the current restriction to bright objects is removed." Indeed, new technologies are beginning to free AO from dependence on bright "guide stars"; ultimately, AO may allow any celestial object, even the faintest, to be unscrambled.

The field could get an injection of new ideas from a research outfit opened just this month: the Center for Adaptive Optics (CfAO), funded by the National Science Foundation, at the University of California, Santa Cruz. Directed by UCSC astronomer Jerry Nelson, the CfAO will receive $20 million over 5 years to bring AO to maturity, not just for astronomy but also for studying and treating the eye, because the same tactics that can sharpen an image of a star can also deliver a clear picture of the retina through the imperfections of the eye's lens.

Until AO came along, the only way astronomers could escape atmospheric distortion was to put a telescope into space. Unhampered by the atmosphere, the Hubble Space Telescope can deliver images showing details much smaller than ground-based telescopes can resolve, even when blessed with superlative optics and ideal seeing conditions. But Hubble's main mirror measures a mere 2.4 meters in diameter. A 10-meter ground-based telescope collects 17 times as much light, and if a scope of that size could eliminate atmospheric distortion, it would be able to see details four times finer than Hubble can.

Adaptive optics may ultimately allow ground-based telescopes to disregard the atmosphere. Developed largely by the U.S. military to sharpen laser beams and get better images of satellites and missiles, the technology was declassified in the early 1990s. Astronomers quickly began refining it for their own uses, although they had already developed some AO systems of their own. In 1990, for example, ESO installed an astronomical AO system on its 3.6-meter telescope at La Silla, Chile.

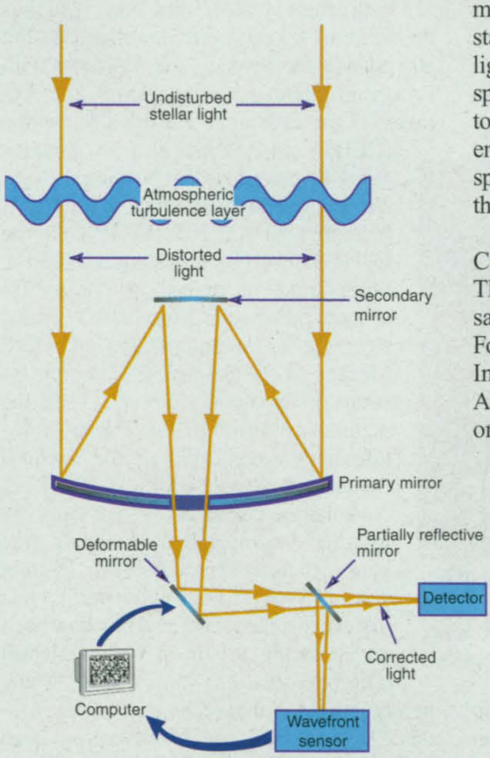
It and many other AO systems, including one on the 10-meter Keck II telescope, in operation since last August, detect atmospheric distortion with a costly technology known as a Shack-Hartmann wavefront sensor. "Basically, it's a bunch of small lenses and a CCD [charge-coupled device] detector," says ESO's Close. The lenses are arranged in a matrix. Each lens creates a tiny image of the observed star. Small displacements of these images, caused by atmospheric turbulence, are registered by the CCD detector, and a fast computer calculates the necessary distortions of the deformable mirror to compensate for the atmospheric blur.



Repair shop for starlight. A laser traces the University of Hawaii's Hokupa'a adaptive optics system as project manager Buzz Graves watches.

CREDIT: (TOP) RICHARD WAINSCOAT

Under the best conditions, the system can sharpen the vision of a telescope the size of Keck by a factor of about 10. But Close says the technique has disadvantages. "Each lens collects just a tiny portion of the incoming light, and you have to collect an image every 2 milliseconds, so you run out of photons very quickly." As a result, the Shack-Hartmann technique can only be used with relatively bright guide stars, which are used to sharpen all the objects in the immediate vicinity. That puts objects that are not close to a suitable guide star off limits to the system. And then there's cost: The Keck system has a price tag of $7.5 million, mainly because of the large number of lens elements and actuators and the enormous computer power needed to manage them.



Calming the wavefronts. An adaptive optics system undoes the effects of atmospheric turbulence by sampling starlight, calculating corrections, and reshaping a deformable mirror in the light path.

Fire on the mountain

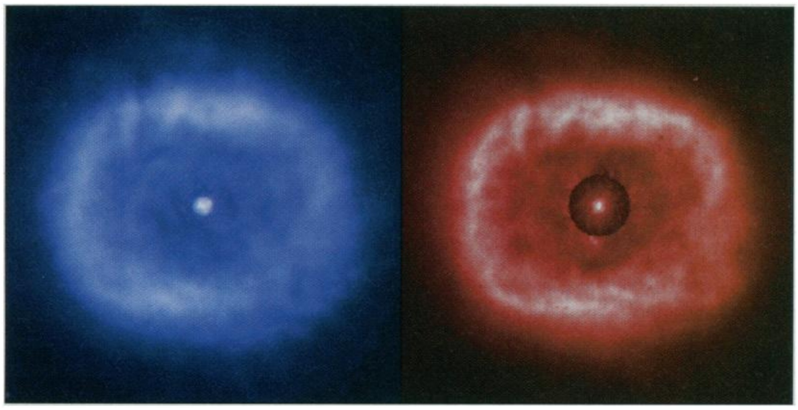
To increase their sky coverage—at even greater expense—astronomers working with Shack-Hartmann systems are now trying to create their own bright guide stars at places in the sky where none is naturally present. They use a powerful laser to kindle a spot of fluorescence in the thin haze of sodium atoms—the debris of meteors—found 90 kilometers up in the atmosphere. A 20-kilowatt laser beam, for instance, excites a glow equivalent to a 20-watt light bulb switched on in the upper atmosphere. This orange artificial "star" is too faint to be seen by the unaided eye, but it is bright enough for the system to measure the atmospheric blur and calculate corrections that can then be applied to fainter objects nearby.

"It's just amazing technology," says Close, "but it's really complicated stuff." The only laser system in routine use, he says, is ALFA (Adaptive optics with a Laser For Astronomy), built by the Max Planck Institute at the 3.5-meter telescope of Calar Alto Observatory in southern Spain. A second system, based on technology developed at Lawrence Livermore National Laboratory in California, has been set up at the 3-meter Shane reflector of Lick Observatory at Mount Hamilton, California, but it is still being refined, says Close. Nevertheless, laser experiments are under way at the Keck Observatory, and ESO also plans to install a laser system on one of the four 8-meter components of the Very Large Telescope (VLT) in Chile.

According to François Roddier of the University of Hawaii, the main problem with laser guide stars is that the two-way trip of the light—from the laser up to the sodium layer and back—cancels out some effects of atmospheric turbulence that an ordinary guide star would betray, in particular the tiny image displacements called jitter. As a result, although the laser guide star provides a probe of the wavefront distortions that blur an image, "you still need a natural guide star to correct for these tiny image motions," says Roddier. Fortunately, he adds, "this star can be rather faint," because jitter requires less frequent corrections than wavefront distortions. Powerful lasers also produce a lot of excess heat, causing microturbulence in the telescope dome, which further degrades the image quality. At the Keck Observatory, the experimental laser system is housed in a huge refrigerated box to minimize the problem.

Roddier has developed a technique that he says works just as well as Shack-Hartmann systems with laser guide stars and is much cheaper. Called curvature AO, it relies on just two images of the guide star, one captured just in front of the telescope's focus and one just behind it. Both images are blurred, but in the absence of atmospheric turbulence, every part of the image would have the same brightness. The wavefront distortions, however, create tiny brightness gradients across the images. By comparing the brightness distributions, Roddier's system can pick up the distortions and pass this information on to the deformable mirror a few hundred times per second, so that it can repair the wavefront. Whereas a Shack-Hartmann system makes separate corrections for each small patch of turbulence above the telescope, which requires dozens of actuators to bend and dimple the deformable mirror, a curvature system calculates more global corrections and thus can work with fewer actuators. "It's simpler," says Roddier, "and it can be built for half a million dollars."

Moreover, because the system divides the incoming light among fewer lens elements than a comparable Shack-Hartmann system, its guide stars can be only 2% as bright, increasing the sky coverage of the system without a laser. Arizona's Angel notes, however, that for the very faintest objects, "laser guide stars are [still] the only way to measure AO corrections."



Space comes down to Earth. Images of the same nebula-shrouded star from the Hubble Space Telescope (left) and the 8.1-meter Gemini telescope, with adaptive optics (right).

A curvature system called Pueo (which is the name of a keen-eyed Hawaiian owl but also stands for Probing the Universe with Enhanced Optics) was installed at the 3.6-meter Canada-France-Hawaii Telescope (CFHT) on Mauna Kea in January 1996. Roddier says that because the system can operate over much of the sky, it is turned on for 20% to 40% of the CFHT's observing time. Indeed, CFHT observations accounted for some 80% of last year's publications on AO results. Recently, for example, a team led by Bill Merline of the Southwest Research Institute in Boulder, Colorado, used the razor-sharp vision of Pueo to spy a 15-kilometer moon orbiting the asteroid Eugenia (*Science*, 14 May, p. 1099).

Summoning a star. A laser creates a faint streak of fluorescence—invisible to the naked eye—in the upper atmosphere over an observatory in southern Spain, where it can serve as a guide star for adaptive optics.

A larger curvature system built by Roddier's team, called Hokupa'a (the Hawaiian name for the Pole star, literally translated as "immovable star"), was first used at the CFHT and has now been set up at the 8.1-meter Gemini North telescope, also on Mauna Kea. "Many people now use this technique," says Roddier. "Very soon a Japanese curvature system will be installed at the [8.2-meter] Subaru telescope," also on Mauna Kea. And ESO is planning five large curvature systems for the VLT—one for each of the four telescopes and one for the ultralarge, virtual telescope that will result when all four are combined through a technique called interferometry.

Exponential challenges

In spite of this progress, plenty of problems remain for the new CfAO to tackle. Astronomers, never ones to think small, are now envisioning a new generation of ground-based telescopes with mirrors between 25 and 100 meters in diameter (*Science*, 18 June, p. 1913). There's little point in building telescopes of that size without AO systems to take advantage of their potential for seeing extraordinarily fine detail in faint objects. But according to UCSC's Nelson, who discussed the topic at a workshop on Extremely Large Telescopes last spring in Bäckaskog, Sweden, the challenge of correcting atmospheric distortion rises exponentially as mirrors grow larger. The number of actuators needed for the deformable mirror scales with the square of the telescope diameter, and the necessary computer power scales with the fourth power of the telescope size, to take into account all possible combinations of actuator movements. At present, even the fastest supercomputer couldn't do the job.

The new center will develop small and cheap actuators, faster computer code, and other technologies that might make AO practical for these optical giants. It will also apply the technology to the inner world of the eye. Using AO to correct for lens distortions should yield sharper images of receptors and blood vessels in the retina and turn lasers into more precise scalpels for treating retinal disorders.

The center, which has enlisted nearly 30 university and industry partners, will also look for ways to open the entire sky to adaptive optics. It will pursue a concept called atmospheric tomography, in which measurements of five or more guide stars are combined in a computer to create a full three-dimensional view of the major turbulence layers in the atmosphere right above the telescope. That way the system could calculate the corrections needed for every point in the field of view, not just for the neighborhood of a single guide star. If AO experts succeed again in turning an ambitious concept into a working technology, even the biggest Earth-bound telescope could take a quick step into space wherever it was pointed.

—GOVERT SCHILLING

Govert Schilling is an astronomy writer in Utrecht, the Netherlands.

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