ASTRONOMY

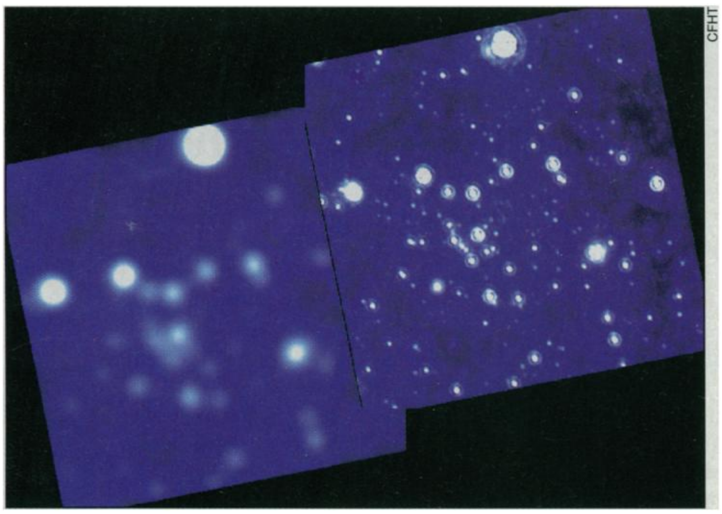
Rethinking the Telescope for A Sharper View of the Stars

Twinkling specks in the firmament might be good enough for poets and children's nursery rhymes, but astronomers need to do better. For decades, they have tried to transform these featureless points of light into distinct images—of galaxies, nebulae, binary stars, even features on single stars—by building larger and larger versions of the basic reflecting telescope pioneered by Isaac Newton. But they have run into limits set by the turbulent atmosphere, the effects of gravity and temperature on giant mirrors, and practical constraints on telescope size. Simply making bigger instruments is no longer enough: Astronomers have had to get smarter and rethink the telescope.

Inside the domes that are sprouting like high-tech mushrooms on mountaintops in Hawaii, Chile, and the American Southwest are telescopes that embody this new thinking. They combat the warping effects of gravity on their giant mirrors with computer-controlled "active optics" systems. They reclaim images from the ravages of the atmosphere with adaptive optics—what Masanori Iye of the National Astronomical Observatory in Japan calls "a miracle instrument" that precisely undoes the atmospheric distortions. And a few systems now transcend the limits on telescope size by combining light from three or more separate telescopes.

The goal of all this, says Roger Davies of the University of Durham in the United Kingdom, is "a sharper and deeper view of the universe." Uncorrected images of, say, the core of our galaxy from the largest ground-based telescopes show mainly haze. But images made with the adaptive optics–equipped Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii, show distinct stars swarming around a source of intense gravity, probably a black hole. And by combining light from three small, widely spaced telescopes, Ken Johnston and his team at the U.S. Naval Observatory recently made the highest resolution picture ever created in optical astronomy, showing two stars that are such close companions no single optical telescope has ever been able to separate them.

The appeal of larger mirrors is as strong as ever: They gather more light, revealing fainter objects, and in principle they also allow a telescope to see finer detail. The biggest mirrors now scanning the heavens are those of the twin 10-meter Keck telescopes on Mauna Kea, each with a light-gathering area as large as a suburban backyard. Close behind are several others under construction. These include the Very Large Telescope (VLT) on the Paranal mountain in Chile—actually four separate telescopes, each with an 8.2-meter mirror—the Japanese Subaru 8.2-meter instrument on Mauna Kea, and the twin telescopes of the Gemini Project, one in Hawaii and one in Chile.



Stripping away the shimmer. An adaptive optics system on the Canada-France-Hawaii Telescope sharpens a view of the galactic center *(right)* by eliminating the atmospheric blurring seen in a normal image *(left)*.

But the force of gravity can make building such large mirrors a self-defeating exercise, says master mirrormaker Roger Angel of the Steward Observatory in Arizona. "As mirrors get bigger, in the traditional ways of making them the only way to hold their shape was to make them thicker and heavier"—with the result that the telescope structure becomes overly massive, he notes. Angel cites the example of a Russian 6-meter telescope mirror, 60 centimeters thick, that weighed 50 tons. "You cannot build very large telescopes using that philosophy," adds Davies, a member of the Gemini team.

Instead of relying on stiff mirrors, designers of the Gemini, VLT, and Subaru telescopes opted for mirrors about 20 centimeters thick, too thin to fight gravity on their own. These mirrors rely on active optics to compensate. As gravity distorts the mirror, a couple of hundred tiny pistons attached to the back push it to within a few tens of nanometers of a perfect shape. The system calculates the necessary adjustments by monitoring the image of a selected star, reshaping the mirror perhaps once an hour to remove distortion from the image. The Keck telescopes, the second of which became operational only a few months ago, rely on a variant of the idea. Each 10-meter mirror has 36 separate, individually controlled, hexagonal mirror segments.

Gravity is not the only enemy of large mirrors; temperature changes are another. Large mirrors cool slowly at night, and if a mirror is much warmer than the air layer above, it will drive convection—the process responsible for the shimmer seen over hot pavement—thus blurring the image. Most telescopes are equipped with coolers to help minimize the temperature difference, but Angel and his team at the Steward Observatory Mirror Laboratory, the world's largest research facility for optical fabrication, have an additional stratagem.

Their mirrors are molded with a honeycomb structure on the back, which supports the glass front face and allows it to be just a couple of centimeters thick. That speeds the response of these mirrors to changes in temperature, says Angel. These "hollow mirrors" are also rigid enough to need less active control than the thin mirrors of the VLT, Gemini, and Subaru. Currently, Angel and his team are casting their largest hollow mirror yet, 8.4 meters across, destined for the Large Binocular Telescope on Mount Graham in Arizona.

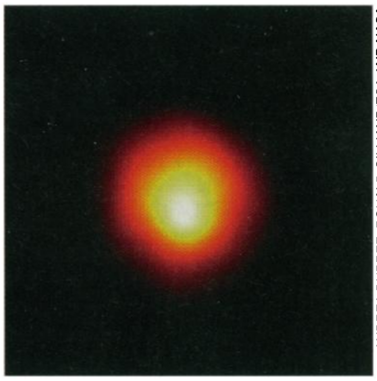
Undoing the atmosphere. Active optics and temperature control can mean that the last few meters of the starlight's journey are untrammeled. But what about the few kilometers before it gets to that point: the trip through the turbulent, convective atmosphere? The answer, adaptive optics, "has been a gleam in the eye for 40 years," says Angel. Now, thanks in part to the U.S. "Star Wars" (SDI) program of the 1980s, that gleam is becoming sharper. Adaptive optics relies on monitoring the image of a bright star next to the object being observed to measure the atmosphere's blurring effects. The system measures the "wrinkles" in what should be a flat wave front coming from the guide star and manipulates a small deformable mirror off which the image bounces. By taking readings and reshaping the deformable mirror a thousand times a second, the system precisely undoes atmospheric distortion. In principle, this allows the telescope to produce images as sharp as the theoretical "diffraction limit" of its mirror permits, surpassing the clarity of even the Hubble Space Telescope.

The first adaptive optics systems, developed for military purposes, were declassified and offered to the astronomy community in 1991 (*Science*, 28 June 1991, p. 1786). "Over the past 1 to 2 years, the first scientific results have now started to come out," says Ray Sharples, a colleague of Davies's at Durham who helped build an adaptive optics system for the William Herschel 4.2-meter telescope in the Canary Islands. With it, Durham astronomers have been able to resolve stars in the core of the globular cluster M15 and spot the otherwise invisible dwarf companion of the star Gliese 105a. Another pioneering system is sharpening the vision of the CFHT. Called PUEO, after a sharp-eyed Hawaiian owl, it produces "very clean images" approaching the diffraction limit of the telescope, says François Roddier of the Institute for Astronomy in Hawaii, a leader in developing the system.

Adaptive optics is not a perfect solution, however, because it has a kind of tunnel vision, correcting only along a single line of sight. "Basically, a compensated image consists of a diffraction-limited core surrounded with a halo of uncompensated light," says Roddier. This means that adaptive optics systems will never render crisp panoramic pictures; those will remain the preserve of the 2.4-meter Hubble Space Telescope in its privileged roost high above the distortions of the atmosphere. What's more, the object of interest has to lie close to a sufficiently bright guide star, and sometimes there's nothing suitable nearby.

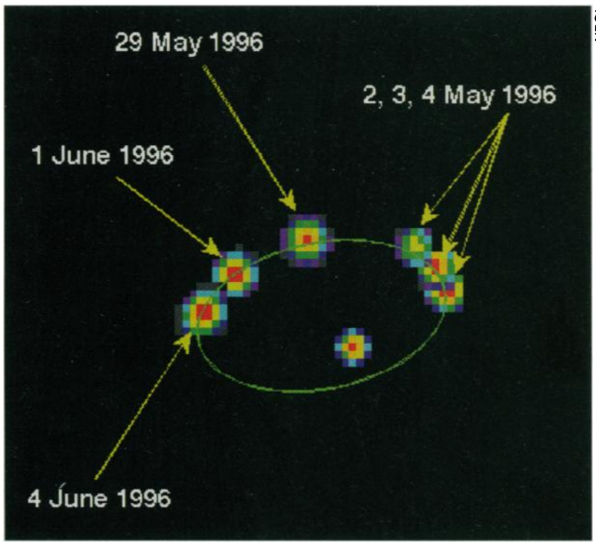
Here astronomers have a technical fix, which will see the light in adaptive optics systems that will be added to the Keck and Gemini telescopes: creating their own guide stars. In the upper atmosphere, some 90 kilometers up, is a layer of sodium atoms. A powerful laser beam reaching the sodium layer can make a tiny spot glow yellow, providing an artificial guide star that can be set aglow next to any object of interest. "Laser guide stars can increase the type of scientific observation you can do," says Sharples.

Telescopes in tandem. With active and adaptive optics now firmly established, bringing ground-based telescopes to the peak of their performance, one last obstacle remains: the diffraction limit itself, which is set by the mirror's size. Mirrors are not likely to grow much larger than 8 meters, says Angel, because of the practical difficulties of getting larger mirrors down freeways, into boats, and up mountain tracks. But astronomers have figured out a way to trick any telescope into behaving as if it were bigger: Link it up with others by interferometry, using techniques masterminded by radio astronomers decades ago. The result matches the resolution of a single telescope having a mirror equal in size to the spacing of the separate telescopes.



Sizing up a giant. A view of Betelgeuse from the Hubble Space Telescope is the first direct image showing a star as more than a point.

Last year, a team at the University of Cambridge, U.K., led by John Baldwin, pooled signals from three small telescopes to make the first optical image ever to reveal the two components of the binary star Capella (*Science*, 16 February 1996, p. 907). Now Johnston and his group have used their Navy Prototype Optical Interferometer (NPOI) near Flagstaff, Arizona, to tease apart another binary star, Mizar A.



So close, so far. The sharpest optical images ever made, from the Navy Prototype Optical Interferometer, distinguish the two stars in the binary system Mizar A. Separated by just a quarter of the Earth-sun distance, they lie 80 light-years off.

The NPOI consists of three telescopes, each with a mirror effectively just 10 centimeters in diameter, set as far as 38 meters apart in a Y configuration. Yet the image it delivered has a resolution of 3 milli–arc seconds, more than 10 times sharper than any existing single-mirror telescope image. The two stars it distinguished lie 80 light-years off but are separated by just a quarter of the distance from Earth to the sun. "It seems to me it's absolutely clear now that one can do this sort of stuff," comments Baldwin.

It's not easy, however; interferometry requires that the light from each telescope travel precisely the same distance, to within a wavelength of light, from mirror surface to combination point. That's a punishing requirement, given light's short wavelengths. What's more, Johnston points out, the small mirrors of these first optical interferometers don't gather much light, limiting them to bright sources. Although interferometry cancels out atmospheric distortions across the entire array, making the mirrors larger than about 10 centimeters or so reintroduces the atmospheric demon for each individual mirror. But astronomers have yet another ploy in their quest for sharper images of the faintest objects: fitting each of the telescopes in an interferometer with adaptive optics. "That will allow the use of mirrors larger than 10 centimeters as interferometer apertures, so that fainter objects can be detected," says Johnston.

All three innovations should one day find themselves mountaintop neighbors. Plans are afoot to turn the Kecks into an interferometer by combining the two big telescopes with four smaller new ones. And, if all goes well, sometime early in the next century astronomers will link the four big mirrors of the VLT, each one equipped with active and adaptive optics systems, into an interferometer capable of producing images 50 times sharper than those of Hubble.

Beyond the mountaintops, the logical next step in the search for the sharpest images is putting interferometers in space. "It will happen in space, but it will take a long time," says Baldwin. Angel and his colleague Neville Woolf have already made a proposal for a space-based interferometer, one of several now in play. Theirs, featuring four 4-meter dishes made of glass just 2 millimeters thick, spaced along an 80-meter beam, should be sharp-eyed and sensitive enough to separate the faint glow of an Earth-like planet from its parent star. After their successes at seeing detail in the stars, telescope builders think that goal is in reach. "The technology to build this thing is unquestionably with us," says Angel.

–Andrew Watson

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