Intimate Views of the Stars

By teaming up small ground-based telescopes, astronomers can capture details of nearby stars that elude even the Hubble Space Telescope

If you want to see faint objects out to the edge of the visible universe, book time on the $2-billion-plus Hubble Space Telescope, the great eye soaring above the confusion of Earth's atmosphere. But if you want to examine nearby stars with a sharpness, or resolving power, tens of times better than the Hubble's, then sign on at one of the new optical interferometers. These ground-based arrays of small telescopes, costing as little as $1 million, can tease out such intimate details of the stars as their girth and close binary companions—details that no single telescope could image.

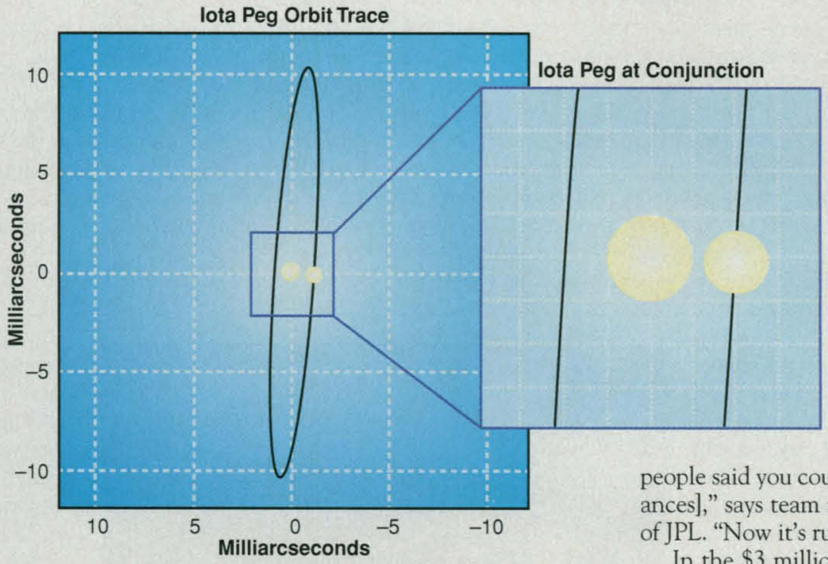
Now is a good time to get on board: At a meeting of the American Astronomical Society here in January, a rush of new results presented by one team suggested that these instruments are poised to fulfill their astounding promise. The instrument showcased at the meeting, called the Palomar Testbed Interferometer (PTI), "is producing just beautiful results that show this is all going to work," says Harold McAlister, director of the Center for High Angular Resolution Astronomy (CHARA) at Georgia State University in Atlanta. Led by Michael Shao of the Jet Propulsion Laboratory (JPL) in Pasadena, California, the PTI team has traced the orbits of binary stars separated by less than a fifth of the Earth-sun distance, enabling the team to "weigh" the stars with exquisite accuracy. The team has also measured the actual sizes of dozens of nearby giant stars, gaining new clues to how these stars grow old.

These results are just the beginning. Other interferometers are starting to yield results, and PTI is a test-bed for even more ambitious projects—"the groundwork for some truly phenomenal astronomy instruments," says Geoff Marcy of San Francisco State University, who predicts that future interferometers may even be able to photograph planets outside the solar system. But the Palomar instrument has also delivered a lesson in the pitfalls of interferometry, which reveals the secrets of stars not in crisp images or spectra but in subtle interference patterns. Early PTI measurements had hinted that the first planet discovered around another sunlike star was actually a second, dim star (*Science*, 30 May 1997, p. 1338). But most PTI team members now think they were misled by a calibration problem.

Interferometry, long a staple of radio astronomy, is a way around two stringent limits on an ordinary telescope's ability to see fine detail. One is related to mirror size: The bigger the telescope, the smaller the details it can resolve. The other is atmospheric turbulence, which smears out images and keeps large, ground-based telescopes from living up to their potential. By combining light from telescopes tens or hundreds of meters apart, an optical interferometer squirms out of both limits, mimicking a single telescope that has a mirror the size of the baseline (the distance between the telescopes) and is unaffected by turbulence. The result is a resolution of 1 milliarcsecond (mas)—1000th of a second of arc—or less. By contrast, the 2.4-meter Hubble is limited to 50 mas, and a ground-based telescope of the same size achieves only about 1 arc second.

The advantages come at a cost. Instead of the image that an ordinary large telescope would collect, an interferometer captures light and dark interference bands, generated when beams from the separate telescopes merge. If the light source is pointlike—a small or distant star, for example—the beams meet "coherently," with the crests and troughs of the light waves lining up to produce crisp bands. If the source is not a point—if it is, say, a binary or giant star—the coherence decreases by an amount that depends on the object's apparent size along the baseline. By making repeated observations while Earth's rotation reorients the baseline, an interferometer can capture the full dimensions of a star or a binary system.

To do so, however, it has to cancel atmospheric turbulence, which can also degrade the coherence of the beams by corrugating the wave fronts of the light before it enters the telescopes. Undoing the turbulence requires readjusting the light's path lengths within the device every few milliseconds, with an accuracy of a fraction of a wavelength. Because radio waves have much longer wavelengths, radio astronomers succeeded in coherently combining signals from separate radio telescopes decades ago. But the challenge of doing so with light waves looked forbidding until recently. "Ten years ago, people said you could never [meet such tolerances]," says team member Gerard van Belle of JPL. "Now it's run-of-the-mill."



Close shave. The Palomar Testbed Interferometer traced the orbit of one of the stars in the binary system, Iota Peg, around its companion. In this circular orbit, seen nearly edge-on, the stars are separated by about a tenth of the Earth-sun distance.

In the $3 million PTI on Mount Palomar near San Diego, something that JPL's Mark Colavita calls "a glorified trolley" keeps the beams in synch. Near-infrared light passes from the two 40-centimeter telescopes, set 110 meters apart, onto movable mirrors. Under the control of a laser-driven feedback system, these mirrors keep the beams as coherent as possible by trundling back and forth on rails, vibrating like a stereo speaker, and jiggling on mounts made of piezoelectric elements, which quickly swell or shrink in response to electric fields. The result is an effective resolution as fine as 1 mas—less than 10% of the Earth-sun distance seen from 150 light-years away.

The Palomar group isn't the only one to try to realize this promise. The Sydney University Stellar Interferometer, which is nearly ready to begin taking data with a 200-meter baseline, will ultimately have a baseline as

Boom and Bust at R Leonis

John Baldwin is hoping for some frosty nights in the next few weeks. They won't help his garden but could benefit his astronomy. At this time of year, frost goes hand in hand with clear night skies. And clear skies are a prerequisite for using an innovative telescope—set in a damp, low-lying field near Cambridge, England—to watch a star more than 300 light-years away puff up and shrink.

In a dramatic demonstration of the power of optical interferometry, a technique for linking separate telescopes into the equivalent of a much larger one (see main text), Baldwin and his colleagues at Cambridge University have made the first-ever observation of regular changes in a star's size. The star in question, a variable star called R Leonis, changes diameter by up to 35% over the course of nearly a year, an amount that one of Baldwin's Cambridge co-workers, Chris Haniff, calls "outrageous."

The result, to be published in the *Monthly Notices of the Royal Astronomical Society*, "is very exciting in itself," says Michael Feast, an astronomer at the University of Cape Town, South Africa. He notes that it promises insight into the behavior of these old, bloated stars, called Mira variables, and how they eventually throw off much of their mass and turn into white dwarfs. But he adds, "I also think it's exciting for what it shows [the Cambridge interferometer] can do, and what is now going to be done by them and by other groups too."

Ordinarily, picking out detail on something as distant as a star defeats even large telescopes. The Cambridge instrument, dubbed COAST, or Cambridge Optical Aperture Synthesis Telescope, does the job by capturing light with four small mirrors—each just 16 centimeters across—spaced as much as 6 meters apart (*Science*, 16 February 1996, p. 907). By adding light from the separate telescopes, COAST simulates a telescope with an aperture of 6 meters and—just as important—is able to see through the atmospheric distortion that turns R Leonis and every other star into a bright smudge with even the largest conventional telescope. And because COAST has four mirrors rather than the two of some other interferometers, it can produce complete images of objects, rather than just measuring them along a single dimension.

"We've followed the diameter of this star throughout its cycle," for a total of 2 years, says Baldwin, "and we've seen that throughout a large part of its cycle, the diameter changes from being very small when it's brightest to being much larger when it's at its faintest." The diameter varies from 450 times the diameter of the sun to 600 times, explains Baldwin, even though R Leonis is no more than twice the sun's mass. Its internal instability is thought to drive the cycle: When the star is most compact, its atmosphere dams up radiation, which forces the star to expand so the energy can dissipate.

R Leonis is not just pulsing; it's also losing mass. One day soon, judging from other Mira variables, it will be down to a tiny fraction of the sun's mass, and Baldwin and his colleagues hope their observations will help explain how these stars shed material. The COAST measurements show, for example, that R Leonis expands at the rate of up to 10 kilometers per second, and Haniff suggests that the star might throw off material as it reaches its maximum size, when gravity is less able to hold on to the rapidly expanding, tenuous atmosphere. Another possibility, says Baldwin, is that the surface of the star is churning, with "large convection cells 'boiling,' so that mass comes to the surface in some great sort of blob and then is thrown off."

If so, the surface of the star might look mottled. "There is some small evidence for variations on the surface of this particular star," says Baldwin. Checking out these hints is one goal for future observations, as is trying to capture images crisp enough to see signs of material floating away from the star's surface. **–Andrew Watson**

Andrew Watson is a writer in Norwich, U.K.

long as 640 meters, enabling it to make measurements as fine as 0.05 mas. And the Navy Prototype Optical Interferometer (NPOI) near Flagstaff, Arizona, will have as many as six telescopes spaced out along intersecting baselines as long as 437 meters. Like some other interferometers with multiple baselines, including one in Cambridge, U.K., and the CHARA array in California, NPOI is able to reconstruct actual images, rather than being limited to simple features such as the shape of an orbit or the radius of a star (see sidebar).

D. MOBLEY/NASA JET PROPULSION LABORATORY

Pipelines to the stars. Light pipes carry beams from the two outlying telescopes of the Palomar Testbed Interferometer to the beam-combining building.

Vital stats of the stars

So far, the lion's share of results on binary systems and giant stars has come from PTI. One effort, led by JPL's Andy Boden, fished out the orbits of the stars in close binary systems. Boden first determined the shape and apparent size of each orbit; then he added high-precision data from other astronomers on the Doppler shifts of the starlight. This "train-whistle" effect reveals each star's velocity toward and away from Earth, making it possible to compute how fast the stars are whirling around each other.

By using methods developed by other astronomers to analyze the orbital trajectories, Boden could then calculate the masses of both companions to within 1%. He was also able to measure the apparent diameters of the stars. Mass and diameter—along with temperature, which is derived from other observations—are stars' vital statistics, the numbers theorists need to test their understanding of how stars evolve. Such data are "few and far between," especially for stars with masses less than the sun's, says Daniel Popper, a veteran astronomer at the University of California, Los Angeles. "If you don't know the fundamental properties of stars," asks Popper, "what do you know about them?"

So far, says Boden, the sizes and masses "are landing right where we expected them to be." Likewise, the sizes of 70 older, bloated, and solitary stars measured for the first time by van Belle and others fall roughly in line with predictions based on computer models of how the stars burn successively heavier elements in fusion reactions.

But starting in the summer of 1996, it looked as if some of the first data out of PTI might undermine a different claim. A year earlier, Michel Mayor and Didier Queloz of the Geneva Observatory had discovered, from Doppler measurements on an ordinary telescope, that the star 51 Pegasi was wobbling toward and away from Earth with a period of 4.23 days (*Science*, 20 October 1995, p. 375).

An unseen companion is apparently pulling it to and fro. The observation gave only a minimum mass for the companion: 0.47 times the mass of Jupiter if we are viewing the orbit edge on, which would make the companion a clear-cut planet. But if we happen to be seeing the orbit face on, the companion's mass would have to be larger—perhaps as large as a star's—to explain the wobble. In work led by Xiaopei Pan of the California Institute of Technology (Caltech) in Pasadena, an initial look with PTI seemed to reveal just such a binary companion.

Since that first work, notes Caltech's Shri Kulkarni, "we acquired considerable experience in the proper usage of PTI." The team has now found, for example, that pointlike calibrator stars must be as close as possible in the sky to the targets so that variations in the atmosphere or the instrument don't mimic a moving companion. "The new data show no evidence that 51 Peg is any different from [a] single star," according to Kulkarni. Because Pan did not accept that verdict, an outside panel led by CHARA's McAlister has examined both claims. "It's not a completely open-and-shut case," says McAlister, but the panel agreed that 51 Peg's companion is most likely a planet and not a star.

The disagreement makes a larger point, says McAlister: Interpreting data from these devices is still "a very subtle business." But with new refinements in their observing technique, the PTI team now hopes to monitor stars for side-to-side wobbles caused by planets that are too small and have too long an orbital period to be detected with the Doppler technique—planets with, say, a tenth of Jupiter's mass and a period of 10 years. "I'm pretty confident," says Queloz, who has moved to JPL to help start up the program.

In the long run, PTI is merely a test-bed for more ambitious interferometers, including one that would link the Keck I and II telescopes, separated by 85 meters on Mauna Kea in Hawaii, together with as many as four smaller "outrigger" telescopes. The interferometers built so far can't see faint objects, because they consist of small telescopes that collect little light. The 10-meter Keck mirrors will change all that. The resulting interferometer might get a direct view of objects such as the 51 Peg planet.

Looking still further ahead, JPL's Shao leads the planning for NASA's Space Interferometry Mission (SIM), a spacecraft carrying an array of telescopes that could watch stars for planet-hinting wobbles as small as 0.001 mas. "SIM will map the 'hood for all its sizable planets," out to 100 light-years or so, says Marcy of San Francisco State. The Hubble has drawn eyes to the deepest reaches of space, but the new interferometers should pick up the hot gossip of our own neighborhood.

–James Glanz

NEUROBIOLOGY

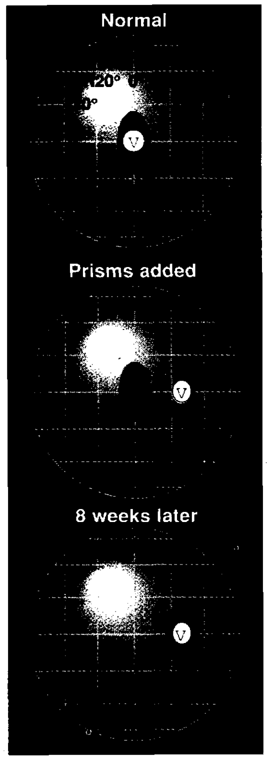
Owl Study Sheds Light on How Young Brains Learn

Consider how a child learns a second language. Whereas adults struggle to speak a new language even passably, a boy or girl can pick up a language on the street and speak it like a native for life. The young brain, it seems, is a sponge for knowledge, primed to soak up skills and information with an ease and depth it will never match again. It's a capacity that parents and teachers would do well to exploit, as cover articles in *Time* and *Newsweek* and a town meeting last year at the White House, led by Hillary Rodham Clinton, have stressed. New results now suggest an intriguing way in which the young brain may store what it learns for later use.


ANNE KNUDSEN

On page 1531, neuroscientist Eric Knudsen of the Stanford University School of Medicine reports that early experience imposes a "memory trace" on the brain that can lie dormant until adulthood and then be reactivated. Knudsen came to this conclusion from a study of barn owls that, when young, had learned to adapt to a visual field shifted by prisms fitted over their eyes. The trained birds, unlike controls, could relearn the task as adults—apparently because they had grown extra neural connections when they first adjusted to the prisms.

Beginning in the 1970s with the Nobel Prize–winning neuroscientists David Hubel and Torsten Wiesel, both then at Harvard, researchers have explored "sensitive periods" during an animal's youth, when normal neural connections are formed that produce binocular vision, depth perception, and other abilities needed throughout life. Knudsen's work goes further to show that unusual experiences can create extra links that may remain unused until much later. "This is very important, because it says there is a possibility of reactivating existing connections that were established [earlier]," says neurobiologist Carla Shatz of the University of California, Berkeley. "Even if those skills haven't been used for a long time, the learning is still there."



E. KNUDSEN AND M. BRAINARD

Wise young owl. Prisms on a young owl shift the location in visual space (V) to which optic tectum neurons respond. Over time, auditory neurons shift the locations to which they respond (A), to realign the auditory and visual maps.

Knudsen studied the ability of owls to localize sounds in space. In total darkness, an owl can pinpoint the source of a sound—such as the peep of a mouse it may be hunting—by using cues such as microsecond differences in when the sound reaches its two ears. The roots of this ability are in a brain area called the optic tectum, which contains a set of neurons that respond to both visual and auditory signals coming from particular locations, allowing the brain to merge its auditory and visual maps of space.

Owls' eyes are fixed in their sockets; the birds must move their heads to change their fields of vision. As a result, prisms placed over the birds' eyes displace the visual information sent to their optic tectum neurons. For example, if a prism shifts the visual image to the right, a neuron that originally responded to what was straight ahead is now tuned to a location to the left of center. This creates a problem for the owl: Its visual and auditory maps are out of register. "If you optically displace the visual map, you have to adjust the auditory map physiologically to bring the two maps back into alignment," says Knudsen.

In earlier work, Knudsen's team showed that preadolescent owls can do this: Within a month or so of wearing the prisms, the properties of the neurons shift so that they respond to sounds coming from the places to which the neurons are now visually tuned. Young birds can adjust to virtually any prism shift, an ability adult birds have lost.

What's more, Dan Feldman in Knudsen's lab found that the neurons form a new set of connections as they adjust. In birds wearing prisms that shift the visual image to the right