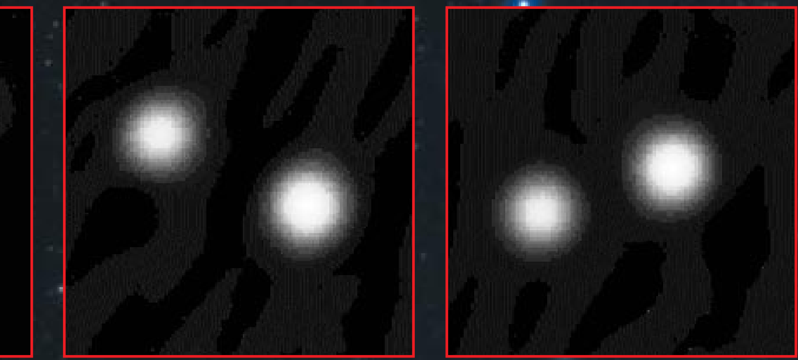
A Sharper

A new generation of optical interferometers is letting astronomers study stars in 100 times finer detail than is possible with the Hubble Space Telescope

View of the Stars



CHRISTIAN A. HUMMEL *USNO/NRL Optical Interferometer Project*

FIRST BINARY-STAR SYSTEM imaged with a conventional telescope was Mizar, the middle star in the handle of the Big Dipper. Although Mizar's two components (Mizar A and Mizar B) are less than 0.004 degree apart on the sky, they are themselves each binary stars. In 1996 the Navy Prototype Optical Interferometer (NPOI) resolved the two stars that make up Mizar A, producing the highest-resolution image then made in optical astronomy. These four images show Mizar Aa and Mizar Ab as they execute half an orbit around their common center of gravity.

by Arsen R. Hajian and J. Thomas Armstrong

About 20 years ago one of the authors of this article took his father's binoculars and tiptoed out of the house at night. The budding astronomer decided that he would look for playmates on other planets going around stars in the sky. To his chagrin, the binoculars made no difference whatsoever. The stars appeared as twinkling points of light to his naked eye, and they were pointlike through binoculars as well. Although the largest stars could engulf our entire solar system within their luminous diameters, every star (aside from the sun) is simply too distant to be resolved with binoculars.

Two decades later the same kid can see not just a point of light but a circular disk—at least for some of the brightest stars. This stellar resolution takes advantage of a technique that was suggested more than 130 years ago: interferometry [*see box on page 60 for the history of the technique*]. Instead of looking through binoculars or even a conventional telescope, he must use a computer display connected to a device called an optical interferometer. For more than half a century, interferometry at radio wavelengths has succeeded brilliantly, mapping the structures of distant galaxies and quasars by their radio emissions. Only in the past 15 years, however, has technology allowed interferometry at infrared and visual wavelengths to take off—and the results have been well worth the wait. The Hubble Space Telescope reigns supreme for taking crisp photographs of faint objects, but ground-based optical interferometers can see, for the brightest stars, details 100 times finer than Hubble can.

Optical interferometry is evolving from a difficult laboratory experiment to a mainstream observational technique. Interferometers now coming into operation will

ROGER RESSMEYER *Corbis*

image stellar surfaces, multiple-star systems, clouds or disks of material orbiting stars, and shadows of planets passing in front of stars. Before long, astronomers will have a vast portfolio of new images, including spectacular movies of stars rotating and showing "starspots," the equivalent of sunspots. We will learn more about the birth, structure, activity, evolution and death of stars.

The essence of interferometry is to combine two nearly identical signals to produce interference and thus obtain information that is not available from either signal alone. For example, overlapping the light from two separate telescopes can produce a pattern of light and dark bands. The spacing of those bands and how they vary as the telescopes are moved tell astronomers about the structure of the light source at a much finer resolution than that of the individual telescope images. This method of mapping the spatial structure of the object is called spatial interferometry. (Other types of interferometry can determine properties such as the spectrum of the object's light.)

Spatial interferometry at optical wavelengths is a tricky business, requiring state-of-the-art hardware. In this article we describe how these interferometers work, why it has taken so long for the technique to mature, what we want to look at and what the future holds.

Engineering and the Atmosphere

An astronomer who wants to make a detailed image of a star faces two problems: the limits to telescope size and the turbulence of Earth's atmosphere. Consider one of the most basic questions we can ask: What is the apparent size of a star (that is, the size of the disk that it forms on the sky)?

At closest approach to Earth, the crescent Venus subtends about one arc-

Contributions to Astronomy

Optical interferometry has already become more than a technical curiosity. Almost two dozen interferometers have produced substantial research results in astronomy, including the following:

Single Stars: Stellar Diameters

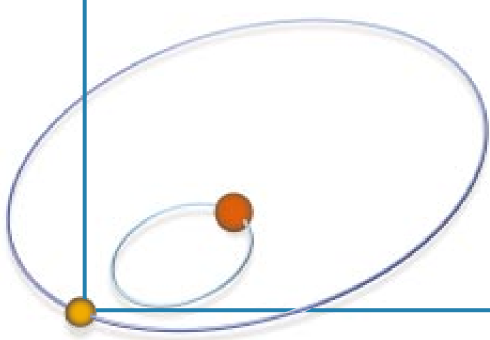
The first measurements of stellar diameters were made in 1920 by Albert A. Michelson and Francis G. Pease, who measured the diameter of Betelgeuse and five other supergiant stars with diameters of 20 to 50 milliarcseconds. If human eyes had this resolving power, you would be able to see the individual atoms composing your hand at arm's length. Roughly half a century later, Robert Hanbury Brown's team at the Intensity Interferometer in Australia measured 32 bright stars ranging from 0.4 to 5.5 milliarcseconds in diameter. Astronomers have now measured the diameters of well over 100 stars, sometimes with about 1 percent precision. Only a few stars have been measured by other techniques, such as studying them as the moon passes in front of them.

A recent image of Betelgeuse

Multiple Stars: Orbits

At least half the stars in the sky in fact consist of two or more stars orbiting around their common center of gravity. Observing the orbits of such double or multiple stars is the only practical way to measure the masses of stars.

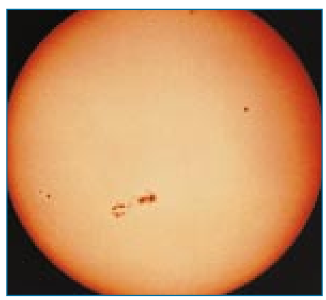
In 1920 John A. Anderson of the Mount Wilson Observatory in California observed the binary star Capella with Michelson's six-meter interferometer and measured the apparent separation of the two component stars at six points around their orbit. Even in 1920 Capella was a well-known spectroscopic binary, meaning that the speed of the two stars in their mutual orbit had been measured by the Doppler shifts of their spectra. Anderson combined his results with those spectroscopic data to deduce the inclination of the orbit (relative to our line of sight) and thereby determined the masses of both stars and the distance to the system.



Modern interferometers have continued to measure binary orbits, with improved precision and higher resolution. The smallest separation between components of a binary star yet measured is about two milliarcseconds for the star TZ Trianguli by Christopher D. Koresko and his colleagues using the Palomar Testbed Interferometer. Today optical interferometry is so precise that it is often the spectroscopic data that limit our knowledge of the stellar masses.

Stellar Surface Structure

Even more difficult than measuring a star's diameter is detecting surface features on its image. This task requires not only better resolution but also greater sensitivity, because surface structure involves relatively small variations of intensity. A simple example of such structure is limb darkening—that is, when the edge of a star's disk, its limb, is not as bright as its center. When one looks at the center of a star, one sees deeper into the stellar atmosphere, where the gas is hotter and brighter. Light from the limb, in contrast, comes from cooler and dimmer gas. Astronomers have observed limb darkening of the sun, and some limb darkening should occur for all stars, depending on their spectral type. Modern optical interferometry can distinguish between a uniform disk and one that is limb-darkened. Studies of limb darkening are needed to test our theories of stellar atmospheres. *—A.R.H. and J.T.A.*



The sun

COURTESY OF JOHN YOUNG CAVENDISH ASTROPHYSICS GROUP (*Betelgeuse*); SLIM FILMS (*illustration*); DENNIS DI CICCO *Corbis* (*sun*) minute, or 1⁄60 of a degree. The best unaided eyes are just capable of resolving a disk that is one arcminute across, that is, of seeing it as a disk and not a point. A telescope with a 15-centimeter mirror can do 60 times better than the finest naked eye, mostly because its aperture is about that much larger than a pupil. In such a telescope, a star appears as a fuzzy disk about one arcsecond in diameter, regardless of the star's size, because the telescope cannot form a smaller image. The fuzziness is caused by diffraction of light passing through the aperture; the smaller the aperture, the larger the image produced.

One arcsecond is the size of a gnat in the centerfield bleachers as seen from home plate or about the size of the largest moons of Jupiter as seen from Earth. But Betelgeuse, the star that forms the largest disk in Earth's sky (aside from the sun), is 1⁄15 that size, about 0.06 arcsecond (60 milliarcseconds) in diameter. The great majority of stars visible to the unaided eye are only a few milliarcseconds or less across.

The resolving power of a telescope—its ability to discriminate small images—improves in proportion to the telescope aperture, so obviously we should use a larger telescope. If a 15-centimeter telescope can resolve a one-arcsecond disk, then a 2.5-meter telescope might resolve Betelgeuse, and one of the 10-meter Keck telescopes on Mauna Kea, Hawaii, might show us details on its surface and resolve many other bright stars. Unfortunately, in practice, increasing the size of the telescope beyond 15 centimeters does no good until we deal with the effects of the turbulent atmosphere.

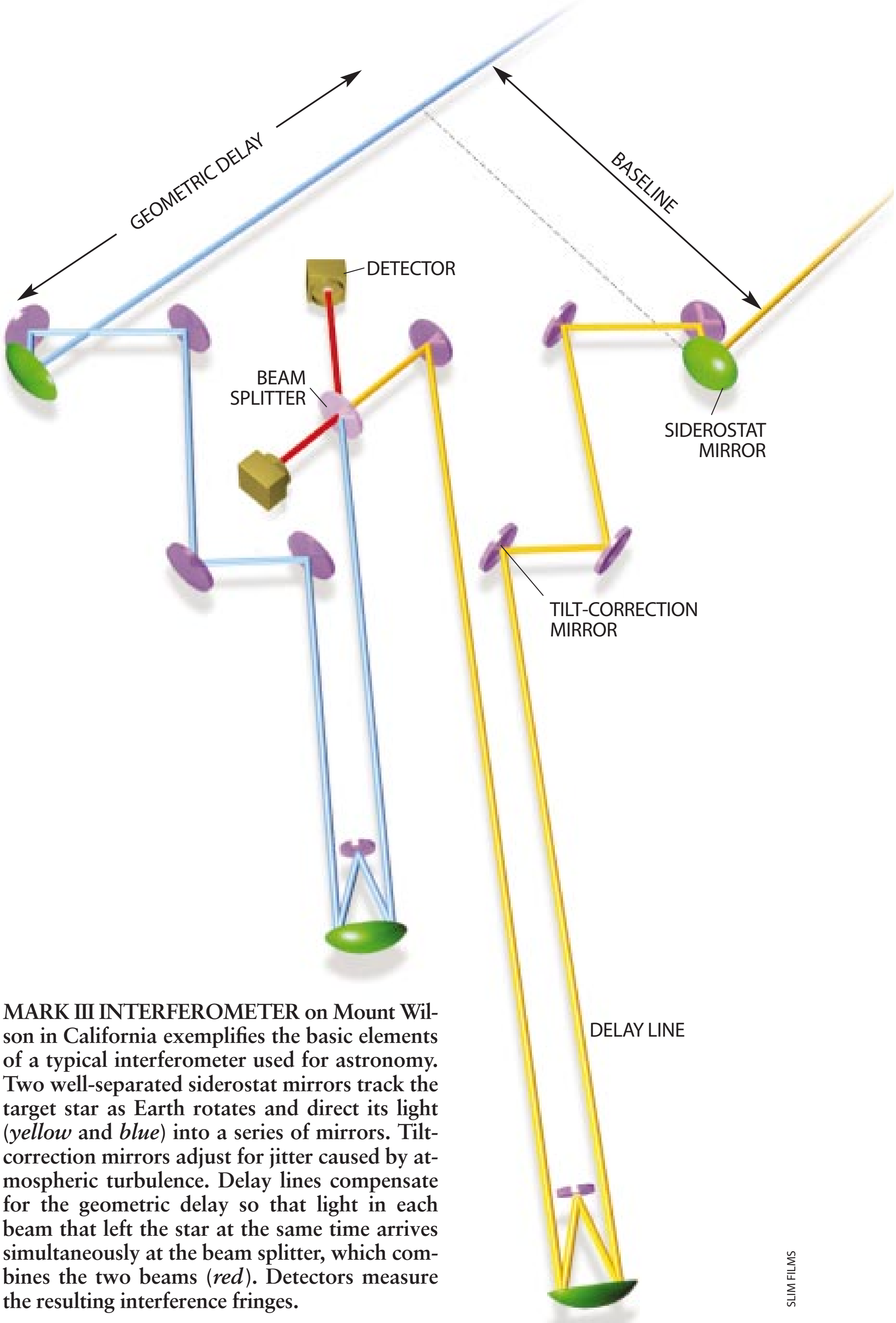
The situation is similar to that of trying to read writing on the bottom of a swimming pool when a strong wind is kicking up waves: the turbulent ripples on the surface distort the light waves coming from the bottom of the pool. Observing the light from stars through Earth's atmosphere is a similar exercise.

Light propagates as a wave. In space above the atmosphere, the light waves from a star arrive as a series of flat planes, like pristine sheets of paper. The turbulent irregularities in the atmosphere distort each wave as it travels to the telescope, making it more like a sheet of paper that someone has wadded up and then tried to smooth out.

The effect of all those wrinkles on the final image turns out to be essentially the same as if the distorted wave were made up of planar sections, each tilted in one direction or another. For light at visible wavelengths, these sections are typically five to 20 centimeters across, depending on the wind and weather, so the segment of the wave arriving at a 10-meter telescope is made up of thousands of such sections. Sections having the same tilt combine to produce an image of the star—a "speckle"—offset according to their tilt. The result is a swarm of speckles moving around rapidly as the atmosphere continually changes. Unless the exposure time is substantially less than one second, the star's image becomes a fuzzy disk that, even in good conditions, is not much smaller than the one produced by a 15-centimeter telescope.

Speckle interferometry deals with atmospheric turbulence by using a conventional telescope and exposure times of about 0.01 second, freezing the speckles' motions. The technique has proved useful for measuring orbits of binary stars, but producing images has turned out to be much harder than practitioners of the technique originally hoped.

In another method, adaptive optics, sensors measure the distortion of the arriving wave, and a computer deforms a mirror to undo as much of the distortion



MARK III INTERFEROMETER on Mount Wilson in California exemplifies the basic elements of a typical interferometer used for astronomy. Two well-separated siderostat mirrors track the target star as Earth rotates and direct its light (*yellow* and *blue*) into a series of mirrors. Tilt-correction mirrors adjust for jitter caused by atmospheric turbulence. Delay lines compensate for the geometric delay so that light in each beam that left the star at the same time arrives simultaneously at the beam splitter, which combines the two beams (*red*). Detectors measure the resulting interference fringes.

as possible. The deformable mirror must be continually adjusted on a timescale of milliseconds. This technique is proving revolutionary in large telescopes, resulting in sharp images with angular resolutions close to the theoretical limit defined by the telescope's aperture [see "Adaptive Optics," by John W. Hardy; Scientific American, June 1994].

But that is still not good enough to discern the size of most stars. Even with the effects of the atmosphere completely removed, a 10-meter telescope could resolve the disks of only a few dozen stars, those that are larger than about 10 milliarcseconds. To measure the diameters of just the stars visible to the unaided eye, for instance, we would need a telescope 500 meters in diameter. Such a large mirror—built to the required precision (a fraction of a micron), supported without distortion and directed to point at specific stars—is far beyond the realms of near-future engineering and economic possibility.

But it turns out we don't need the entire disk of the 500-meter mirror. The trick of interferometry is to place two much smaller telescopes 500 meters apart, correcting for the image motion caused by the atmosphere and combining their light at a central location.

How Interferometry Works

Picture three instruments: a conventional reflecting telescope; the same telescope with all but two small segments of its primary mirror masked off (making it into a so-called sparse-aperture telescope); and an interferometer, consisting of two small primary mirrors and a means of conveying the light that they gather to a detector. Each instrument collects light and delivers it in synchrony to its detector in a different manner.

In the conventional telescope the curvature of its single large mirror assures that all parts of a light wave from a star arrive at the focus at the same time. (In fact, that simultaneous arrival defines the location of the focus.) The sparse-aperture telescope works the same way: its two mirror segments gather light, and each segment simultaneously delivers its part of a wave to the focus. Both telescopes produce an image on a detector (usually a charge-coupled device, or CCD) positioned at the focus, although the image from the sparse-aperture telescope is degraded because of the incompleteness of its primary mirror.

The interferometer resembles the sparse-aperture telescope in having two small mirrors that collect light, but it has several key differences. First, the two mirrors can be on independent mounts instead of being part of a single, large, rigid framework that gets pointed in its entirety at a star. This autonomy is possible because the light-gathering function of each mirror has been separated from

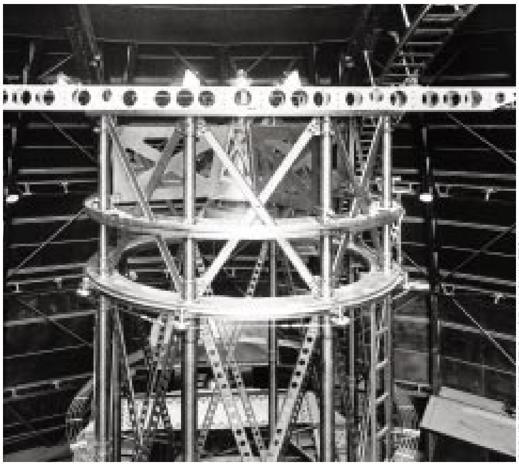
Interferometers for Astronomy across the Ages

1868: French physicist Armand-Hippolyte-Louis Fizeau suggests masking a telescope aperture to perform interferometry. He proposes measuring the sizes of stars by placing a two-hole mask over a telescope and observing the resulting interference pattern.

1876: Édouard Stephan tries Fizeau's technique with the 80-centimeter telescope at Marseilles. But the 65-centimeter separation between the holes that he uses is not enough to measure the stars' sizes. When Stephan looks through his eyepieces at a star, he sees an image of the star from each aperture in the mask. These images are large and usually overlap. The region of overlap is crossed by dark stripes (interference fringes). To measure a star's diameter, one increases the separation between the apertures until the fringes disappear. The larger the separation required, the smaller the star. But Stephan runs out of telescope before the separation becomes large enough. He concludes only that the stars he observes are all smaller than 0.16 arcsecond.

1891: Albert A. Michelson, apparently without knowing of the work of Fizeau and Stephan, tries the same technique, but he looks at the Galilean moons of Jupiter. He succeeds in measuring their sizes because, at diameters between one and two arcseconds, they are considerably larger than stars.

1920: Michelson measures stars by installing a six-meter metal beam with mirrors at each end across the aperture of the 100-inch (2.5-meter) Hooker telescope at Mount Wilson in California, then the biggest in the world (*right*). In the 1930s Michelson's collaborator Francis G. Pease attempts interferometry with mirrors on a 15-meter mount, but he fails, probably because the mount is not mechanically stiff enough.

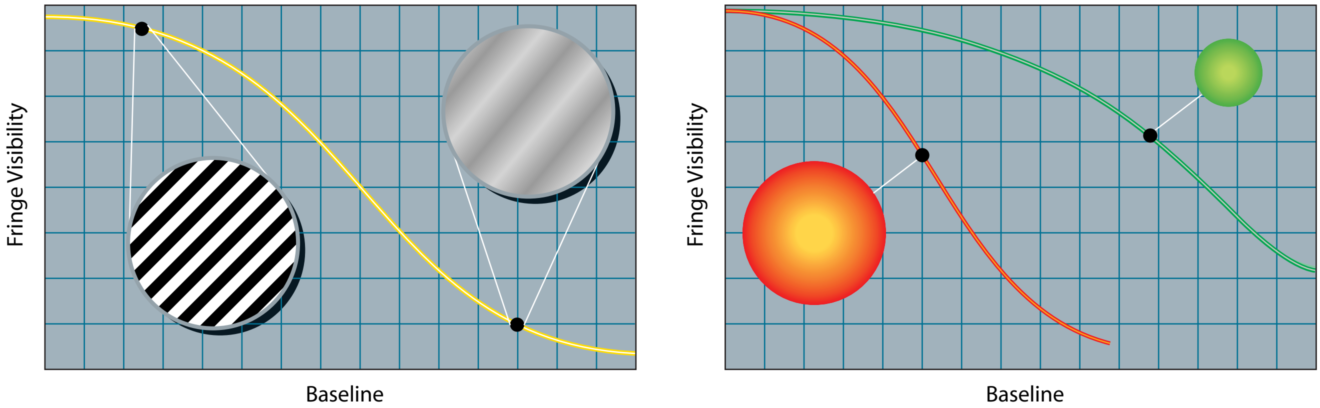

CARNEGIE INSTITUTION OF WASHINGTON

Michelson's 1920 interferometer

1950s–1960s: Tremendous advances are made in the use of interferometry for astronomical observations using radio wavelengths. Radio interferometry is much easier than optical interferometry because the wavelengths are several thousandfold longer, which reduces the atmosphere's relative effects and eases the engineering precision needed to achieve interference. Further substantial advantages include being able to amplify the radio signals and to record the data at each telescope for combining later.

1958–1976: Robert Hanbury Brown, Richard Q. Twiss and their colleagues take two important steps when they build the Intensity Interferometer near Narrabri, Australia. First, they break the aperture barrier by using two separate telescopes instead of putting a contraption of mirrors across one central telescope. The interferometer's two 6.5-meter telescopes are separated by 10 to 188 meters, a record that has yet to be surpassed. Second, they use electronic detection and data recording, whereas previous researchers observed by eye.

Brown and Twiss also take the novel approach of detecting individual photons at the separate telescopes and correlating their arrival times. This technique has the virtue of simplicity (the light beams from the telescopes are never brought together) but has low sensitivity: even with 100 hours of observation time, the scientists can study



SLIM FILMS

INTERFERENCE FRINGES for a single star (*left*) have higher visibility, or contrast, for short baselines and lower visibility for long baselines. The diameter of a star (its angular size on the sky) can be deduced from its fringes (*right*). As the baseline is increased, the fringe visibility of a large star falls faster than that of a small star. Measurements of small stars therefore need larger baselines.

the process that combines their light.

The second difference is how the light is combined in synchrony. In general, one of the primary mirrors is closer than the other to the star under observation [*see illustration on page 59*]. Think of a specific wave of light from the star as a pulse that it has emitted. Unless the star and the mirrors happen to be positioned symmetrically, this pulse will hit one mirror before the other. To compensate for this difference in timing, the light path from each mirror to the common detector includes an adjustable detour, called a delay line, consisting of mirrors on a slide that can be positioned with very high precision.

The third difference is that the light is

stars no dimmer than those of Orion's belt, about magnitude 2.5 in technical terms.

1974: Two groups use the separate-telescope approach with more sensitive detection techniques. Antoine Labeyrie and his colleagues, working at visual wavelengths and using Michelson's technique of combining the two beams before detection, observe the star Vega with a 12-meter baseline. At Kitt Peak, Ariz., a group under Charles H. Townes, working in the midinfrared, borrow a technique from radio astronomy to observe Mercury on a 5.5-meter baseline. Known as heterodyning, the method involves converting the detected high-frequency signal down to lower frequencies in much the same way as a radio receiver converts 100-megahertz FM radio signals down to the frequencies of sound in the human hearing range.

1980: The Very Large Array (a radio interferometer) is commissioned in Socorro, N.M. It goes on to produce thousands of significant results. [For more on radio interferometry, see "The Very-Long-Baseline Array," by Kenneth I. Kellermann and A. Richard Thompson; SCIENTIFIC AMERICAN, January 1988.]

Recent optical work: Following the work of Labeyrie and Townes, activity in optical interferometry picked up speed. Townes has continued the midinfrared development begun in the early 1970s. His group is now operating a two-element heterodyne interferometer with 1.6-meter telescopes on a 32-meter maximum baseline and has studied dust around stars far along in their life cycle. A third telescope and a 75-meter maximum baseline are soon to come.

MICHAEL COLLIER AND NATHANIEL WHITE *NPOI*

Navy Prototype Optical Interferometer on Anderson Mesa in Arizona

Since 1974 astronomers have built over a dozen visual and near-infrared interferometers, of which eight are in operation and five are under development. All of these have extended the architecture used by Labeyrie in various ways: baseline length (the current maximum is 80 meters at the Sydney University Stellar Interferometer, Australia); aperture size (1.5 meters, GI2T, France); number of telescopes used at once (four, Cambridge Optical Aperture Synthesis Array, England); and wavelength range (450 to 850 nanometers, Navy Prototype Optical Interferometer, U.S.). The box on page 58 discusses the types of results obtained by these groups.

—A.R.H. and J.T.A.

combined not to produce an image of the star but to detect how the two beams of light interfere. When the peaks and troughs of the two light waves coincide (the waves are "in phase"), constructive interference occurs, producing a high intensity. Light that combines out of phase interferes destructively, producing a low intensity. These oscillations of bright and dark are called fringes.

Astronomers measure the fringes' contrast, or visibility, which varies according to the characteristics of the light source (for example, the size of a star or the separation between two stars in a binary system) and according to the length and orientation of the interferometer's baseline, the line connecting the two mirrors. Astronomers can take measurements from many different baselines, most easily by waiting while Earth rotates. In addition, most of the new interferometers have more than two mirrors in the array and can move the mirrors along tracks.

The researchers analyze the signals by computer, using Fourier transform algorithms to convert the measured fringes into a map of the object under study. That map is actually the same as the imperfect image that would be seen by a sparse-aperture telescope with a diameter equal to the interferometer's baseline. So although the results can have very high resolution, the information they convey is incomplete, somewhat like a view of a house partially hidden behind a tall picket fence. As data from more baselines are combined, the image becomes more complete, as if one saw the house through the fence's blurred pickets while gliding by on a bicycle.

Costs and Complications

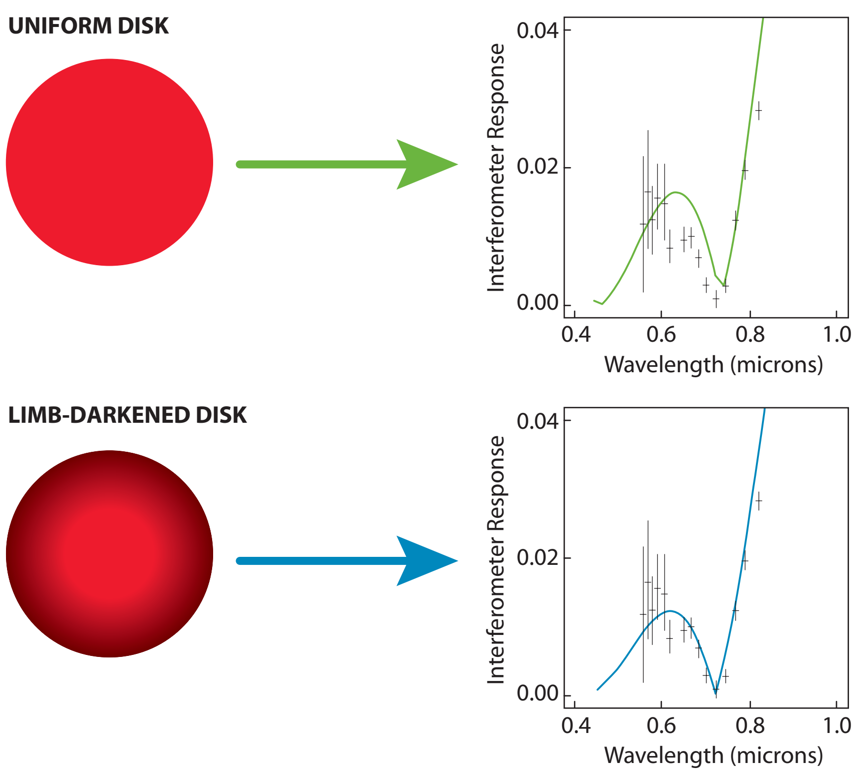
Optical interferometry avoids the costs and difficulties of building a single mammoth telescope but exacts its own price in ways that designers must consider carefully. The light beams from each telescope must be transported dozens or hundreds of meters to the central facility where they are combined. Different wavelengths of light travel at different speeds through air, so the beams must be transported in a vacuum. The expense of the infrastructure grows quickly as the baseline size and number of elements are increased.

An interferometer with more than two telescopes can produce more complete images of objects by simultaneously obtaining fringes for many different baselines. But there are limits to how far this can be pushed. With a 10-telescope interferometer, for instance, one would want to split each light beam into nine beamlets for combining with beamlets from the other telescopes. This dilution lowers the instrument's sensitivity because each set of fringes must be produced with fewer photons. The practical limit is in the range of five to 20 telescopes. In addition, the complexity of the combining optics increases very rapidly because the number of baselines increases roughly as the square of the number of telescopes. For example, two telescopes have a single baseline; 10 would have 45 baselines. Each mirror along a light path saps a percent or so of the beam's photons.

Atmospheric turbulence, the nemesis of large telescopes, also creates problems for an interferometer. Turbulence makes the apparent position of a star on the sky jitter around irregularly. This jitter often causes the beams in two arms of the interferometer to overlap imperfectly or not at all at any given moment. Including sensors and a rapidly responding tilting mirror in each optical path—technology that can be borrowed from adaptive optics—can partially correct the jitter problem.

But turbulence also causes a second problem: it adds a random and very rapidly changing delay to each beam because each telescope looks through a different patch of turbulent atmosphere. This effect degrades the interference needed to produce visible fringes, and it must be removed as much as possible to measure fainter stars and to improve precision.

The need for these corrections imposes severe constraints on the interferometer's sensitivity. One cannot get around these constraints by increasing the telescope sizes or using longer data collection times: the information needed to make the corrections—embodied in light from the object under study or another nearby bright star—must be gathered from apertures no bigger than about 20 centimeters (so that the angle tracker has only one speckle to follow) and must be gathered within about 10 milliseconds (so neither the speckles nor the fringes move appreciably). The interference signal itself must also be detected in a gathering time of a few milliseconds to avoid its smearing by the atmospheric fluctuations.



LIMB DARKENING of stars can be detected by interferometers. Data from Alpha Cassiopeiae (*cross shapes*) agree poorly with the theoretical curve for a uniform disk (*top*) but match that expected for a slightly larger but limb-darkened disk (*bottom*). Such results provide information about the atmospheres of stars but require large baselines to achieve resolution finer than the star diameter.

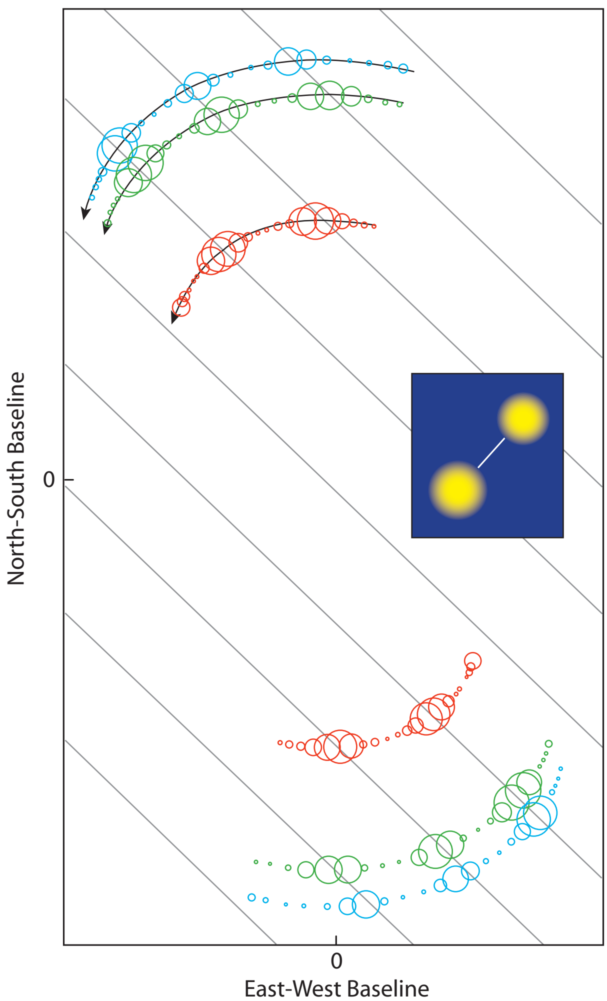
JOHNNY JOHNSON; SOURCE: NPOI

The amalgam of technology needed for all these functions ranges from high-speed photodetectors to computers capable of recording at least several gigabytes of data per night to frequency-stabilized lasers, which precisely monitor delay-line lengths that are changing on millisecond timescales. These tools have become available and mature only in the past 20 to 30 years, and the learning curve to use them effectively has been steep.

What's Coming

All these problems produce the single largest disadvantage of current optical interferometers: they are barely more sensitive than the naked eye, albeit with much higher resolution. Nevertheless, even limited to the few thousand brightest stars in the sky, interferometers are already amassing a tremendous observational database and producing unique results that justify the effort required [*see box on page 58*]. And these limitations will be overcome in the near future when sophisticated adaptive optics systems are installed on groups of large telescopes.

In recent years, astronomers have been constructing numerous optical and infrared interferometers of ever increasing sophistication. Optical interferometers with several telescopes will soon be online. For example, the Navy Prototype Optical Interferometer (NPOI) on Anderson Mesa in Arizona expects to deploy six apertures within the year, with 15 baselines. In principle, with enough data, astronomers can make a map of a star using methods similar to those used in radio interferometry. In practice, those traditional methods are straightforward in optical interferometry for only the simplest of source structures: binary stars. Custom algorithms are being developed to produce optical maps of sources whose appearance may take any form, such as elliptical stars, stars with spots, and stars with outflowing or flaring material. Optical interferometers have a lot of catching up to do to reach their cousins operating at the longer wavelengths of radio waves.



BINARY STAR CAPELLA produced this distinctive pattern of fringes at the Mark III Interferometer. As Earth rotates, the interferometer's baseline follows an elliptical arc. The size of each circle indicates the visibility of fringes seen using that baseline, at one of three wavelengths (*colors*). Equally spaced lines pass through the positions of maximum visibility. The two stars in Capella must be oriented at right angles to these lines (*inset*), separated by a distance that depends on the reciprocal of the lines' spacing.

Interferometers that have advanced adaptive optics, such as the Keck Interferometer (two 10-meter telescopes 85 meters apart) and the Very Large Telescope Interferometer (an array of four eight-meter telescopes in Chile), will image faint astronomical phenomena with superb angular resolution. Both of these facilities will be enhanced with smaller, more widely spaced outrigger telescopes. Proposed space-borne platforms such as the Space Interferometer Mission, the Terrestrial Planet Finder and the MicroArcsecond X-ray Imaging Mission will push astrometry (the science of measuring stellar positions) into the *micro*arcsecond range and will be able to detect planets. Even with optical interferometry, our children still won't be spotting playmates on other planets anytime soon, but nonetheless a profusion of technology and scientific results lies ahead. SA

The Authors

ARSEN R. HAJIAN and J. THOMAS ARMSTRONG share a long-standing interest in optical interferometric techniques. Hajian has been interested in optical interferometry since his early days as a binocular kleptomaniac, and he joined in the NPOI collaboration in 1995. In addition to his work on NPOI, he is building an interferometric spectrometer at the U.S. Naval Observatory, where he is an astronomer. Armstrong, an astronomer at the Naval Research Laboratory in Washington, D.C., has worked in optical interferometry since joining the Mark III collaboration in 1989. He initiated the Mark III binary-star observation program, which has continued with NPOI, and devised the layout of NPOI.

Further Information

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Links to home pages of current and planned stellar optical interferometry projects and many other resources are at http://huey.jpl.nasa.gov/olbin/links/links.html

JOHNNY JOHNSON; SOURCE: MARK III INTERFEROMETER