

STELLAR OPTICAL INTERFEROMETRY IN THE 1990s

The unaided eye has an angular resolution of about 1 arcminute. From the invention of the telescope in the 17th century to the middle of the 1970s, astronomers improved on this resolution by two orders of magnitude by building bigger telescopes and putting them at good sites. Even at good sites, however, atmospheric turbulence limits the resolution at visible and infrared wavelengths to 1 arcsec or a little better. In the past 20 years, a further factor-of-ten improvement has come with two developments that deal with the atmosphere: "speckle interferometry," in which the blurred image is frozen in a short exposure and the image is reconstructed from many exposures, and adaptive optics, in which the effects of the atmosphere are sensed, then corrected with a deformable mirror, before the image is recorded. (See Laird A. Thompson's article in *PHYSICS TODAY*, December 1994, page 24.)

A further improvement by two orders of magnitude, as much as was realized from 1600 to the 1970s, will soon become available as long-baseline stellar interferometers now coming into operation reach their potential.^{1,2} While these optical interferometers build on methods that have been maturing for more than a century, most recently in radio interferometry, their implementation in large, efficient instruments at visible and near-infrared wavelengths had to await modern technologies.

An astronomical interferometer combines the light gathered by two or more telescopes separated by up to several hundred meters. Such a configuration can achieve the resolution (but not the light-gathering power) of a telescope with an aperture of several hundred meters. The simplest arrangement, an intensity interferometer, detects the intensities separately at the telescopes and then correlates the fluctuations. But because the light is "combined" incoherently—that is, the phase relationship between

After a decades-long wait for the necessary technology to develop, optical interferometers will soon yield improved images of stars and precise measurements of stellar positions, motions and diameters.

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beams from different telescopes is not preserved—an intensity interferometer has low sensitivity and loses important information about the image structure.

An interferometer that preserves these phase relationships is more difficult to build. The optical train of the interferometer must be continually adjusted to equalize the optical path lengths from the star,

through the atmosphere and the telescopes, to the detector. If the path lengths are equal to within a few wavelengths, interference fringes appear. One extracts image information by measuring the amplitudes and phases of the fringes, which are related by a Fourier transform to the distribution of brightness on the sky.

As with conventional telescopes, the most troublesome problems are wavefront distortions produced by the atmosphere. For an interferometer, the result is that the fringes must be sampled on time scales of 5–10 milliseconds, and the apertures of the individual telescopes are limited to 10–30 cm. In addition, the fringe sensing must be done with unamplified light, since low-noise, phase-coherent optical amplifiers are not possible, even in principle. These constraints limit the interferometers discussed here to observing stars brighter than tenth magnitude. Adaptive optics systems can ease the aperture limit if they include a bright artificial guide star, but this application is still a few years in the future.

The first interferometers

The idea of applying interferometry to astronomy dates from 1868, when Armand-Hippolyte-Louis Fizeau³ suggested (in passing!) that stellar angular diameters could be measured interferometrically. Édouard Stephan made the first attempt, converting the Marseilles 80-cm telescope into an interferometer by covering the aperture with a mask penetrated by two openings. Stephan was unable to resolve any stellar disks, and concluded (correctly) that they were smaller than 0.15 arcsec. Using the same technique on the Lick Observatory 12-inch refractor in 1891, Albert Michelson succeeded in measuring the diameters of the Galilean moons of Jupiter.⁴ It is not known whether Michelson was aware of Fizeau's suggestion or of Stephan's observations.

Michelson also pointed out that it was possible to build an interferometer larger than the practical size of a single telescope. But it was not until 1920 that he and Francis Pease took advantage of the new 100-inch telescope on Mount Wilson, California, to build such a device. They placed a 20-foot support beam across the front of

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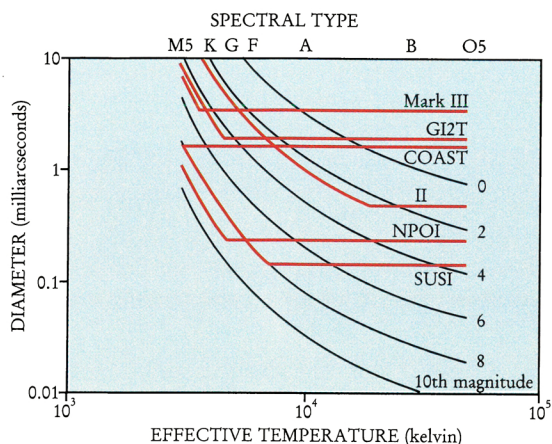


NAVY PROTOTYPE OPTICAL INTERFEROMETER at Lowell Observatory on Anderson Mesa, Arizona. The small white buildings seen in this aerial view house the elements of the astrometric array; the six imaging array elements will be moved among the concrete piers along the arms of the Y. The long building is the optics laboratory, housing the delay lines. Also visible are one of the Lowell Observatory domes and Lower Lake Mary, about 200 feet lower than the top of the mesa. **FIGURE 1**

the telescope, with mirrors to feed the light from the ends of the beam to the telescope's primary mirror, and succeeded in measuring the angular diameters of seven red giant stars.⁵ In spite of Pease's later attempts with a 50-foot baseline, large interferometers did not become an important tool in optical astronomy, because of the lack of adequate means to deal with the atmospherically induced fringe motions and the difficulty of maintaining sufficient mechanical stability in a large apparatus. Interferometers of the type used by Stephan and Michelson did,

however, remain in use for some binary-star observations.

The intensity interferometer built by Hanbury Brown and his colleagues in Australia in the 1960s—a prototype had been built at Jodrell Bank, England, in the 1950s—was the next to produce significant results.⁶ By correlating intensity fluctuations at the foci of two 6.7-m light collectors separated by 10–188 m, Brown and John Davis measured the diameters of 32 bright stars. Because of the inherent limitations of the technique, the interferometer could observe stars no fainter than second magnitude,



RESOLUTION LIMITS of several interferometers discussed in this article. Black curves, labeled with magnitude at $\lambda = 545$ nm, show stellar angular diameters as a function of effective temperature. Red curves show the observational limits of the interferometers due either to magnitude limits or resolution limits. The region above and to the right of a red curve is available to the corresponding interferometer. "II" indicates the intensity interferometer of Hanbury Brown. The stellar spectral types along the top correspond to the effective stellar temperatures along the bottom. **FIGURE 2**

in spite of its large collecting area. The intensity interferometer signaled a revival of interest in optical interferometry, which gained momentum in the mid-1960s from the example of radio interferometry, from the development of fast detectors able to record the fringe pattern and from the realization that laser metrology could substitute in part for mechanical rigidity.

The first interferometers of this second generation were the mid-infrared, CO₂ laser heterodyne interferometer of Charles Townes and his colleagues at the McMath Solar Telescope on Kitt Peak, Arizona, and the I2T (Interféromètre à Deux Télescopes) of Antoine Labeyrie.⁷ Several other optical and near-infrared interferometers followed in the late 1970s and the 1980s. (See table 1.) Of these, the Mark I interferometer on Mount Wilson, built by Michael Shao and his collaborators, is notable as the first to track fringe motions. The last of its successors, the Mark III (also located on Mount Wilson), was the most productive of this generation, although it was limited to stars brighter than fifth magnitude.⁸ The Mark III measured 11 star positions with 10-milliarcsec (mas) precision, diameters of about 70 stars larger than 2 mas and 26 binary-star orbits, several smaller than 10 mas.

Astronomical objectives

There is a wide variety of objects that astronomers would like to view with higher resolution. Some targets, such as solar system objects and the nuclei of active galaxies

and quasars, are currently out of the reach of optical interferometry. Solar system objects that are bright enough to be detected are too large in angular size to produce fringes with the current baseline lengths of a few meters and more (Michelson used a 10-cm "baseline" to measure Jupiter's moons), and there are no galactic nuclei that are bright and point-like enough to observe. These projects must await the installation of adaptive optics on interferometers. The new interferometers will, however, provide many new and improved observations of stars and their immediate environs.

Images of stars. The biggest qualitative advance will be the ability to make images of stars. With the current designs, images of ten or more pixels across the stellar disk can be made. (The Moon is about 30 pixels in diameter to the unaided eye.) Starspot and flare activity may be observable on the surfaces of cool giants and of interacting binary stars; the presence of these features has so far been inferred only from spectra and from intensity variations. Extended atmospheres and circumstellar shells due to a variety of mass-loss mechanisms can be studied. Circumstellar material ejected by rapidly rotating Be stars (stars of spectral type B with bright hydrogen emission lines) and mass exchange in close binary systems can be imaged both in line and continuum radiation.

Astrometry is the measurement of precise stellar positions and motions. Until recently, the best astrometric catalog was the FK5, with positions of about 1500 stars precise to about 50 mas. The forthcoming catalog from the Hipparcos satellite, in orbit from 1989 to 1993, is expected to have a precision of about 2 mas for some 100 000 stars. These positions degrade with time, however, as the peculiar

Table 1. Separate-element interferometers to 1990

Year	Interferometer	Baseline (m)	λ (μ m)	Technique
1965	Intensity interferometer	10-188	0.44	Correlation of intensity fluctuations
1974	I2T	12	0.5-0.75	Moving combiner table; dispersed fringes
1974	McMath auxiliaries	5.5	11	CO ₂ laser heterodyne; electronic delay
1979	Mark I	1.5	0.4-0.9	Delay line with delay modulation
1982	Mark II	3.1	0.4-0.9	Delay line with delay modulation
1985	SUSI prototype	11.4	0.44	Delay line
1986	Mark III	3-31.5	0.4-0.9	Delay line with delay modulation
1986	GI2T	12-65	0.5-0.75	Moving combiner table; dispersed fringes
1987	SOIRDETE	15	2-12	Delay line; drift fringe scanning
1988	ISI	4-34	11	CO ₂ laser heterodyne; electronic delay
1990	IRMA	2.5-19.5	2.2	Delay line; drift fringe scanning
1990	CHARON II	11-140	0.5-0.75	Delay line; dispersed fringes

LAYOUT OF THE MARK III INTERFEROMETER on Mount Wilson. Starlight (red and blue) is directed by the siderostats (S) and a sequence of intermediate mirrors into the laboratory. Piezoelectrically driven tilt-correction mirrors (T) driven by the star-tracker system (not shown) keep the two stellar images superimposed. Paraboloidal retroreflector delay lines (DL) add optical path length to compensate for the geometric delay. Piezoelectrically driven mirrors (P) at the reflectors' foci are used to introduce fine delay corrections and to impose a modulation in the delay to facilitate fringe detection. The beams interfere at a beam splitter (BS), and the two output beams (purple) are focused on detectors at D. **FIGURE 3**

motions of the stars through space result in so-called proper motions, that is, changes in their positions on the sky.

One of the new interferometers, the astrometric array of the Navy Prototype Optical Interferometer (shown in figure 1), is designed to measure positions with precision comparable to that of Hipparcos. By repeatedly measuring stellar positions over several decades, NPOI will maintain the accuracy of the positions of the brightest Hipparcos stars while improving the precision of their proper motions. NPOI will also measure the positions of some radio stars whose positions are tied to the reference frame defined by extragalactic radio sources.

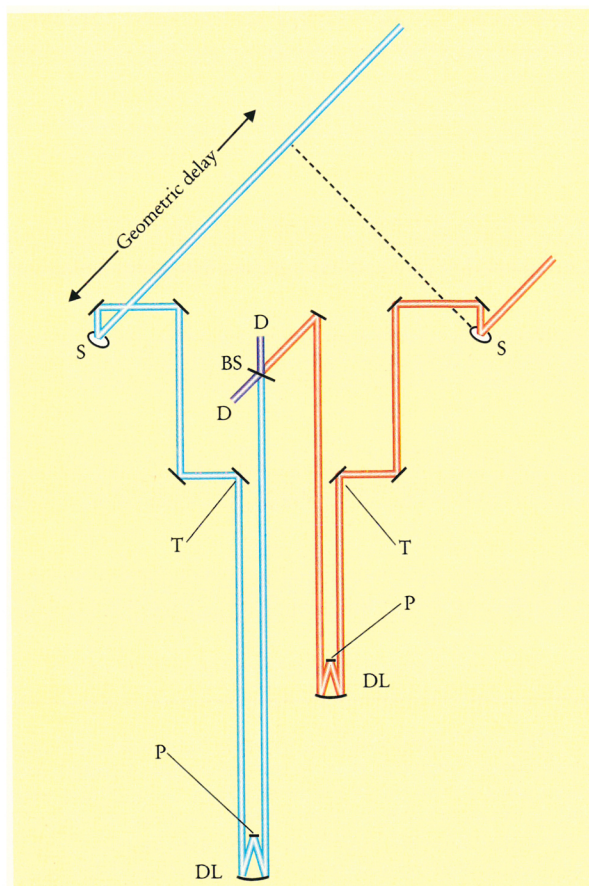
High-precision astrometry is important to astronomy for several reasons. Precise positions allow direct measurements of stellar parallaxes, the first step in establishing the cosmic distance scale. Proper-motion measurements can confirm stars as members of clusters whose distances are known and can help elucidate the dynamics of the Galaxy. Improving the link between the radio and optical reference frames will help match radio sources with their optical counterparts; for example, it is not yet known whether the bright radio source Sagittarius A* in the Galactic center corresponds to IRS 16, a nearby infrared object.

Stellar angular diameters. The measurement of stellar diameters was the first goal of astronomical interferometry. Even so, only about 100 diameters have been measured to a precision of a few percent. There are still fewer measurements of limb darkening, the difference in brightness between the center and the edge of a stellar disk. The new interferometers will measure the diameters of thousands of stars brighter than ninth magnitude and larger than 0.2 mas, and limb darkening for stars larger than about 0.4 mas. Figure 2 shows the range of stellar diameters that can be resolved with various current interferometers.

Having a large body of diameter measurements will directly affect our understanding of stars. Measurements of diameters and limb darkening will test stellar atmosphere models by directly calibrating the relationship between flux and effective temperature. Carbon-star diameters measured with the Mark III have already shown a need for improved modeling of the atmospheres of these stars.⁹

Another application of diameter measurements is finding distances to Cepheid variables, which form another foundation of the cosmic distance scale. One can determine the distance to the star from the observed change in angular diameter as the star pulsates combined with the change in physical size inferred from the radial motion measured by the Doppler shift in its spectral lines.

Binary-star orbits and stellar masses. Precise stellar mass measurements are as scant as precise diameter measurements; only about 100 are known to 1–2% precision.¹⁰ Masses can be found directly only for stars in binary systems, and then only if we can measure the



size, shape and period of the orbit. The period is easily measured, but to determine the size of the orbit we need both the line-of-sight velocities of the stars, measured from the Doppler shifts of spectral lines, and the inclination of the orbit to the plane of the sky, which is inferred if the stars eclipse one another or measured if the orbit can be observed directly. Perversely, binary components whose velocities are large enough that the lines from the two stars are clearly separated in the spectra usually have orbits that are too small to resolve with single telescopes. The new interferometers, which can observe stars three to five magnitudes fainter than were observable with past interferometers, with up to ten times higher resolution, will greatly increase the number of double-lined binaries (systems in which lines from both stars are observable) whose orbits can be resolved and masses can be measured.

Principles of stellar optical interferometry

An optical interferometer consists of separate light-collecting elements, each collecting a section of the wavefront from a star, and a means of bringing the sections of wavefront together. (See figure 3.) The separation of each pair of elements forms a baseline of given length and orientation. The two key elements of the interferometer are the system that equalizes the path lengths taken by the light waves collected by the separate telescopes and the system that correlates the waves once they have been brought together. The resulting data—the fringe amplitudes, phases and positions—are used to produce an image or a model of the celestial source and a measure of its position on the sky.

Table 2. Interferometers after 1990

Year	Interferometer	Apertures	Maximum baseline (m)	λ (μm)	Comment
1991	COAST (Cambridge University)	4×40 cm	100	0.4–0.95, 2.2	First phase closure; feed beam and delay lines in air
1992	SUSI (Sydney University)	2×14 cm	640	0.4–0.85	Only southern interferometer; delay lines in air
1994	IOTA (Center for Astrophysics)	3×45 cm	38	0.45–0.8, 2.2	Feed and delay lines in vacuum; multi- r_0
1994	NPOI astrometric array (USNO–NRL)	4×12.5 cm (35 cm in 1995)	38	0.45–0.9	Feed and delay lines in vacuum; laser metrology of array
1995	NPOI imaging array (USNO–NRL)	6×12.5 cm (35 cm planned)	437	0.45–0.9	Feed and delay lines in vacuum
1995 (anticipated)	ASEPS-0 test bed (JPL)	2×40 cm	100	2.2	Precise position differences over small angles
	CHARA (Georgia State University)	7×1 m	354	0.55–0.9, 2.1–2.5	NSF funding awarded, 1994
	Keck Observatory	2×10 m + 6×1.5 m	165	2.2–10	
	VLTI (European Southern Observatory)	4×8 m + 8×1.8 m	200	0.45–12	Implementation delayed

The path length followed by each light beam includes the distance from the star to one telescope, through the relay optics, to the point where the light is combined with light from the other telescopes. The difference in the path lengths through two different telescopes is the “delay.” Three terms contribute to the delay: geometric delay, from the star’s being closer to one telescope than the other; instrumental delay, from differences in path lengths from the telescopes to the beam combiner; and atmospheric delay, from differences in the index of refraction in the atmosphere over the two telescopes.

When the path lengths are equal, that is, when the delay $D = 0$, all the wavelengths interfere with the same phase, producing a white-light fringe. For nonzero delay, fringes at different wavelengths have different phases and tend to cancel one another. Thus if interference is to take place we require that $D/\lambda < \lambda/\Delta\lambda$, where λ and $\Delta\lambda$ are the observing wavelength and bandwidth.

The geometric delay changes slowly as the Earth rotates, but the atmospheric delay changes quickly. To understand the rapidity of the atmospheric-delay changes, it is convenient to introduce the transverse coherence length r_0 , defined by David Fried in 1966 to be the diameter of a patch of wavefront over which the rms phase variation is 1 radian. Typical values for r_0 are 5–15 cm. The turbulent atmosphere is well approximated by a frozen phase screen that is blown by the wind over the telescopes. The time for a $\lambda/2\pi$ change in atmospheric delay is $t_0 \approx 0.3r_0/v$, where v (typically about 10 m/s) is the wind speed. An exposure time of about $2t_0$, or only 5–20 ms, produces the best balance between maximizing the photon counts and minimizing fringe smearing.¹¹

Similarly, the optimum aperture size for one array element is about $3r_0$, even after the overall wavefront slope is corrected by centering the image. For larger apertures, the higher-order phase errors make the image break up into speckles, reducing the fringe contrast.

Optical interferometry is much more difficult than radio interferometry for two basic reasons. First, low-noise, phase-coherent amplifiers are available at radio frequencies, while a phase-coherent amplifier at optical

frequencies with a usefully wide bandwidth is at best very difficult to build. And even if such an optical amplifier existed, it would be unacceptably noisy for fundamental reasons arising from the uncertainty principle.

The second basic difference is that the effects of the atmosphere are much less troublesome at radio wavelengths. Even though the atmospheric distortions of a radio wavefront are ten times larger than those for a visible-light wave, the radio wavelength is about 10^5 times larger, so the phase errors are about 10^4 times smaller and r_0 is 0.5–10 km. This means there is much more time to detect the fringes, simply because an r_0 -sized patch takes much longer to be carried past an antenna by the wind. In addition, phase differences between radio interferometer elements remain small, so fringe contrast is easier to maintain than in the optical case.

To keep D near 0 in an optical interferometer, the instrumental delay is adjusted to compensate for the geometric- and atmospheric-delay changes. Almost all current interferometers accomplish delay adjustment and tracking with a “delay line,” a retroreflector or pair of mirrors on a cart that rolls on precision rails in one arm of the interferometer. Some systems also use the delay cart to modulate the delay by a few wavelengths, scanning a few cycles of the interference fringe over the detector and facilitating fringe detection. This technique requires controlling the delay to less than 10 nm at frequencies over 100 Hz, typically by moving a small, piezoelectrically driven mirror on the delay cart while measuring the delay with a laser interferometer.

Having traversed the delay lines, the beams are brought together at a beam combiner. The most common beam combination method is to illuminate a beam splitter—a glass plate that reflects 50% of the incident light—with one input beam from each side. The two output beams, each containing contributions from both inputs, are then focused onto detectors, possibly after being spectrally dispersed. The intensities of the output beams depend on the delay: For $D = 0$, the intensity will be at a maximum in one beam (strictly speaking, this is true only if the image being observed is symmetrical) and at a minimum in the other. There are

several variations on this method if more than two beams are to be combined.

With the fringes in view, two kinds of information are available. One is the fringe position, that is, the amount of instrumental delay that produces the white-light fringe. Astrometric interferometers use this information to find the position of the star being observed, assuming that the geometry of the array, including the baseline lengths and orientations, is well known. The atmospheric delay must also be taken into account. In practice, a set of stars is observed repeatedly and the resulting set of delay values is used to solve simultaneously for the baseline vectors and the positions of the stars.

The other type of information available consists of the fringe parameters: the fringe amplitude, or visibility, $V(\mathbf{B}, \lambda)$ and its phase $\phi(\mathbf{B}, \lambda)$ with respect to $D=0$, where $\mathbf{B}$ is the baseline vector between the two apertures. The fringe parameters are related to the image by a Fourier transform, as expressed by the fundamental equation of interferometric imaging,¹²

$$V(\mathbf{B}, \lambda) e^{-i\phi(\mathbf{B}, \lambda)} = \int I(\delta\mathbf{s}, \lambda) e^{-2\pi i(\mathbf{B}/\lambda) \cdot \delta\mathbf{s}} d\Omega$$

Here $I(\delta\mathbf{s}, \lambda)$ is the brightness distribution on the sky, and $\delta\mathbf{s}$ locates a point in the celestial source with respect to the point for which $D=0$. The integral is taken over the solid angle Ω subtended by the source. If $I(\delta\mathbf{s}, \lambda)$ is not symmetrical in $\delta\mathbf{s}$, the fringe phase will be nonzero. The effects of source structure on fringe amplitude are shown in figure 4 for a single star and in figure 5 for a binary.

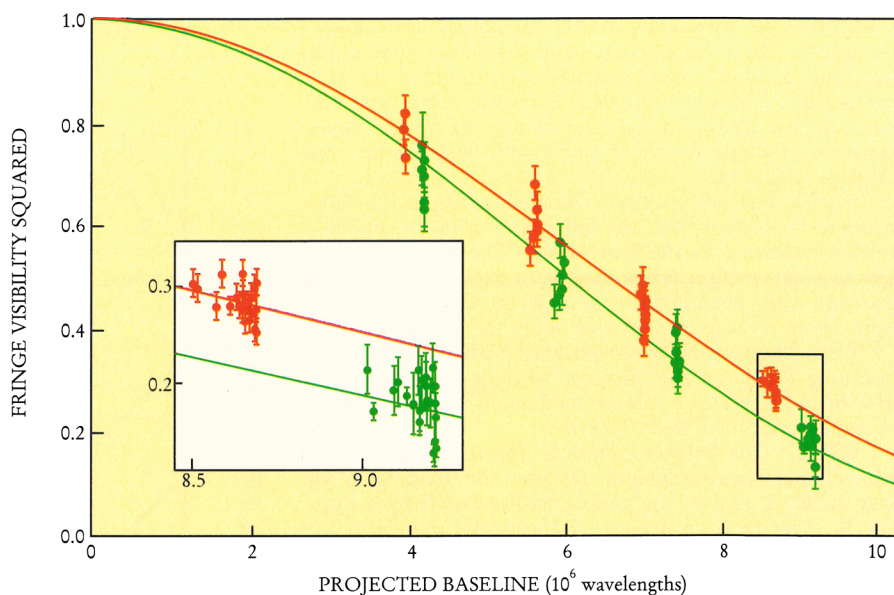
However, the atmosphere corrupts the fringe phase, often by many times 2π . Thus, with a two-element optical interferometer, only the fringe amplitude carries information about the source. With three or more array elements, some phase information can be recovered using methods developed in radio interferometry. If the atmosphere over array element i introduces a phase error α_i , and the source structure produces a phase ϕ_{ij} on baseline $i-j$, then the observed phase $\phi'_{ij} = \phi_{ij} + \alpha_i - \alpha_j$. If the ϕ'_{ij} are summed around a triangle of elements labeled $i=1,2,3$, then the closure phase contains no atmospheric contribution:

$$\phi_c = \phi'_{12} + \phi'_{23} + \phi'_{31} = \phi_{12} + \phi_{23} + \phi_{31}$$

As elements are added, the number of triangles and closure phases increases quickly, and the image becomes better constrained.

The third generation

Several of the second-generation interferometers are still active. In particular, Labeyrie's group plans to add a third 1.5-m telescope to their latest interferometer, the GI2T. Townes and his ISI group at Berkeley continue to extend the baseline lengths and are considering using direct fringe detection, rather than heterodyne techniques, to



DIAMETER MEASUREMENTS OF A SINGLE STAR, β Pegasi. The data were taken at wavelengths of 712 nm (green), which lies in a TiO absorption band, and of 754 nm (red), in the stellar continuum. The curves are for uniform disks of diameter 17.6 milliarcsecs (green) and 16.1 milliarcsecs (red). The star appears larger at the TiO wavelength because the stellar atmosphere becomes opaque at a larger stellar radius than in the continuum. (Adapted from A. Quirrenbach *et al.*, *Astrophys. J.* 406, 215, 1991.) **FIGURE 4**

increase their bandwidth.

Meanwhile five new, large interferometers are nearing completion, incorporating the advances made in the 1980s. (See table 2.) Most of them have already observed their first fringes, but they all are still in the commissioning phase. Despite some differences in detail, their major technical systems are similar: Siderostats (steerable flat mirrors) that feed beam-compressing telescopes are the interferometer elements; tilt-correcting mirrors correct for image motion; the delay lines are carts carrying mirrors on precision rails; and the beam combiners are similar to the one described above.

COAST. The Cambridge Optical Aperture Synthesis Telescope, intended for imaging at 0.8- and 2.2- μm wavelengths, is an array of four movable elements being built by John Baldwin and his colleagues at Cambridge University.¹³ The array is a Y whose arms, each with several siderostat stations, will ultimately be 60 m long, with a station at the array center, giving a maximum baseline of about 100 m. The 40-cm aperture is somewhat larger than $3r_0$ at 0.8- μm wavelength, but is about r_0 at 2.2 μm . Stellar light from the array elements is transported into the laboratory and through the delay lines in air. The laboratory is partially buried and is covered with a meter of earth for thermal stability.

COAST obtained its first fringes in 1991, and in late 1992 while observing the star Aldebaran was the first optical interferometer to measure closure phase. Currently, it can track fringes continuously for several hours. Astronomical observations of stellar diameters began recently with three elements on baselines up to 6 m, while the commissioning process continues.

SUSI. The Sydney University Stellar Interferometer, a project of Davis and his colleagues at Sydney University, consists of only two elements, but it has the longest baselines of any current or planned instrument, and it is the only one in the Southern Hemisphere.¹⁴ It is located at Narrabri, the site of the intensity interferometer, and

is intended for measuring stellar diameters and binary-star orbits. The array consists of eleven 20-cm siderostats, providing a 14-cm usable aperture, positioned along a north-south line; one siderostat from the north arm and one from the south can be used at a given time. Space has been provided for third and fourth feed beams from a future east arm.

SUSI's feed system from the siderostats to the laboratory is in vacuum, but the delay line is in air, inside a wooden enclosure in the laboratory. The delay line consists of a cart with a retroreflector at each end, riding on precision rails; moving the cart shortens the delay for one input beam as it lengthens the delay for the other.

First fringes were observed with SUSI in 1992 while observing Sirius on the shortest baselines. Baselines of up to 80 m have been commissioned, and the first diameter measurements have been reported.

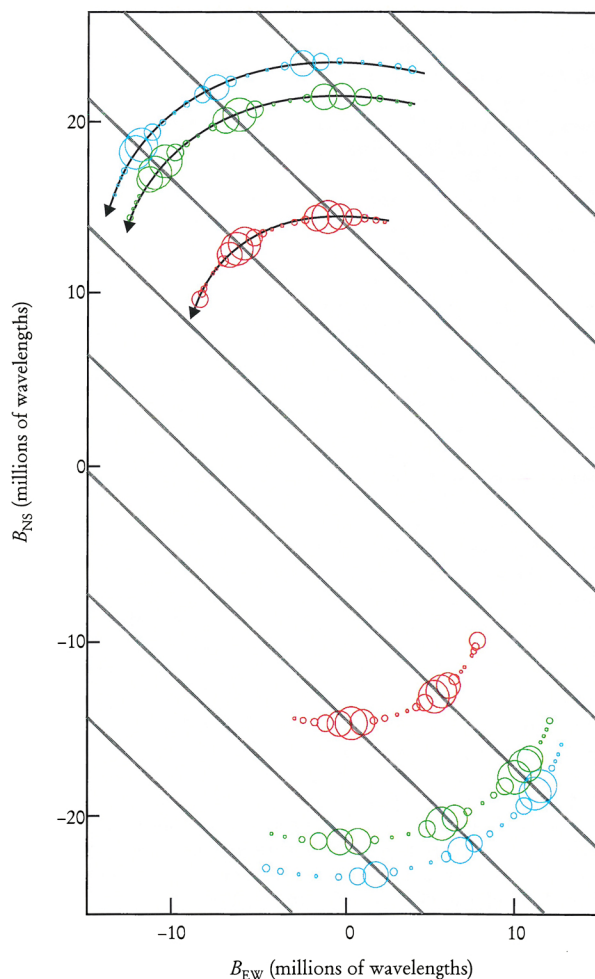
IOTA. The Infrared-Optical Telescope Array is a three-element interferometer designed for imaging in the near-infrared, and in the visible with a subdivided aperture.¹⁵ The array, a project of Harvard University, the University of Massachusetts, the Smithsonian Astrophysical Observatory, MIT and the University of Wyoming, is located on a knoll on Mount Hopkins, Arizona. The two arms, each with multiple siderostat stations, are 35 and 15 m long and are at right angles. The pupil plane will be divided into subapertures for optical observations, since the 45-cm aperture is somewhat larger than r_0 . The feed system and delay lines are in vacuum. First fringes were seen with IOTA in the 2.2- μ m band in 1994.

NPOI. The Navy Prototype Optical Interferometer, located at the Lowell Observatory outside Flagstaff, Arizona, is actually two arrays.¹⁶ The first, an array of four fixed elements in a Y with 20-m arms, is the only interferometer of this group designed for astrometry. The second array consists of six elements that can be moved along the arms of a 250-m Y. That array is intended for imaging stellar surfaces and close binary systems and for measuring stellar diameters and binary-star orbits. The astrometric array and the inner part of the imaging array were completed in 1994; first fringes were observed in late 1994 while observing α Andromedae. By 1996, the imaging array will be extended to its full size, and 35-cm beam-compressing telescopes will be installed on the astrometric array.

A distinguishing characteristic of the astrometric array is the metrology system for monitoring the array geometry. The siderostat mirrors shift because of thermal drifts and imperfections in the mirror mounts and bearings. The resulting changes in the baselines cause errors in the star positions unless those changes are measured independently. Each siderostat station includes laser interferometers to measure the motion of the siderostat with respect to a temperature-stabilized optical breadboard and to measure the motion of the breadboard with respect to bedrock. Another set of interferometers measures the horizontal motions of the breadboards with respect to one another.

The two arrays share all other subsystems, including vacuum feed pipes and delay lines, a temperature-stabilized beam combination area and a distributed real-time control and data acquisition system. Since there are only six delay lines for the ten siderostats, the two arrays cannot operate completely independently.

ASEPS-0. The Astronomical Studies of Extrasolar Planetary Systems test-bed interferometer will search for reflex motions of stars due to planets orbiting around them, working at 2.2- μ m wavelength with 20- to 100-m baselines.¹⁷ To do this, ASEPS-0 will use two elements, each of which will simultaneously observe two stars separated by up to a few arcminutes. The stars will thus be



FRINGE CONTRAST FOR A BINARY STAR, Capella (α Aurigae), as a function of the projections on the sky of the north-south and east-west baseline components of the Mark III interferometer. The elliptical arcs show how the baseline changes as the Earth rotates, while the circles indicate the magnitude of the squared fringe visibility measured along the arcs at wavelengths of 500 nm (blue), 550 nm (green) and 800 nm (red). Since the baseline length is measured in wavelengths, the three wavelengths used for these data effectively result in measurements on three baselines. The gray lines, running through the maximum fringe visibilities, are oriented perpendicular to the line separating the two stars. Their spacing is inversely proportional to the angular separation of the stars. **FIGURE 5**

observed using the same baseline and delay lines, with one star serving as a position reference for the second. Since fringes for both stars will be detected at the same time, the effects of the atmosphere will largely cancel, and extremely small changes in their relative positions will be detectable. Site construction of ASEPS-0, a project at the Jet Propulsion Laboratory under the direction of Michael Shao, started at Mount Palomar in late 1994; first fringes are expected in late 1995.

Future developments

Ambitious ground-based successors to COAST, SUSI, IOTA, NPOI and ASEPS-0 have already been proposed, some of which are listed in table 2. CHARA, a Georgia State

University project that received NSF funding in 1994, will comprise seven 1-m telescopes in a configuration similar to the NPOI imaging array. The Keck Observatory interferometer on Mauna Kea will consist of six 1.5-m telescopes separated by up to 100 m and will make occasional use of the two 10-m main telescopes. The VLTI (Very Large Telescope Interferometer) in Chile will be similar to the Keck interferometer, consisting of eight 1.8-m telescopes and sometimes including the four 8-m telescopes.

The trends exemplified by these instruments are longer wavelengths, more elements and larger telescope apertures. The movement to longer wavelengths is already under way, as a result of the recent availability of array detectors with high quantum efficiency in the 2- μ m band. The problems of optical interferometry are eased at longer wavelengths: In the optical and infrared $r_0 \propto \lambda^{6/5}$, so at 2.2 μ m, $r_0 \approx 30$ –60 cm, making the requirements for rapid delay and image-motion corrections less stringent.

In the optical regime, larger apertures will gather more light but will need adaptive optics to remove higher-order aberrations from the wavefront. For faint objects, this will require the use of a laser guide star to supply the photons needed to detect the aberrations.

Ultimately interferometers in space or on the Moon will provide solutions to the problems caused by the atmosphere, but not before the current crop of ground-based interferometers has brought optical interferometry into the mainstream of astronomy.

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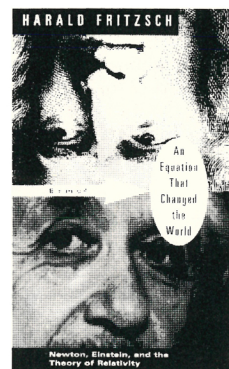
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