feature article

Probing stars with optical and near-IR interferometry

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New high-resolution data and images, derived from the light gathered by separated telescopes, are revealing that stars are not always as they seem.

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Each time a piece of observational phase space is opened up, new discoveries are made and existing theories are challenged. In astronomy, therefore, there is a constant push to build instruments capable of greater sensitivity and higher spatial, temporal, and spectral resolution. The technique of interferometry has for many decades provided high angular resolution at radio wavelengths (see the article by Kenneth Kellermann and David Heeschen, PHYSICS TODAY, April 1991, page 40), and astronomers have been following a similar path at near-IR (1–11 μm) and visible (0.5–0.8 μm) wavelengths.

The application of interferometry to astronomy comes via the van Cittert–Zernike theorem, which states that the correlation of the radiation gathered by two widely spaced telescopes pointing at the same object is proportional to one spatial Fourier component of that object. Once enough Fourier components have been measured, one can perform an inverse transform and produce a picture. Each Fourier component's spatial frequency, in units of inverse radians, is the ratio of the baseline—the separation of the two apertures—to the observational wavelength. Longer baselines or shorter observational wavelengths yield higher-frequency spatial information and therefore better angular resolution. Similarly, adding more apertures makes it possible to collect more Fourier components in a shorter time, which yields better temporal resolution. Astronomers therefore want to create arrays of many telescopes, achieve longer baselines, and observe at shorter wavelengths. Unfortunately, unlike radio radiation, near-IR and visible waveforms cannot be digitized, so the photons must be brought together and physically mixed and the correlation measured directly. As a result, baselines have been limited to several hundred meters at visible wavelengths, whereas at radio wavelengths baselines can be as long as Earth's diameter. Nevertheless, to have the same resolution as a 100-m baseline at 0.5 μm, one would need a baseline of 42 000 km—more than three times Earth's diameter—in the 21-cm radio band.

Many interesting technical challenges stem from the fact that the physical tolerances in an interferometer are a function of the observational wavelength. In optical interferometry one must be able to control path lengths, or at least know them, at the 10- to 100-nm level. The past decade has seen most of those challenges solved (see the article by Thomas Armstrong, Donald Hutter, Kenneth Johnston, and David Mozurkewich, PHYSICS TODAY, May 1995, page 42), and creating images with resolutions in the submilliarcsecond range is now routine. For reference, a milliarcsecond is approximately the angular extent that a 1.8-m-tall man would have standing on the Moon, as seen from Earth.

Ground-based optical and IR interferometry is now shedding light on many areas of stellar astrophysics:[1] spots on stars other than the Sun; stars rotating so fast they become oblate and dark at the equator; systems of multiple stars caught in their mutual gravitation field and co-revolving around their center of mass, even exchanging matter; young stars in the process of creating planetary systems; giant stars close to the end of their lives; and the evolutionary differences between first-generation stars, consisting almost entirely of hydrogen and helium, and later-generation stars, which contain the heavier elements that are the origins of planets, asteroids, comets, and ourselves. Interferometry also shows great promise in extragalactic astrophysics.

Most of the cutting-edge topics discussed in this article were chosen because they are exemplified by bright, nearby systems on which it is easy to get detailed spatial information and good-quality images. That focus necessarily excludes some excellent interferometric techniques—such as high-resolution single-baseline spectroscopic measures, differential phase, astrometry, heterodyne, and nulling, to name a few—in use at facilities around the world.

Basic stellar properties

Interferometry has long been a valuable tool in the study of stellar evolution. Tests of stellar formation and evolutionary theory depend primarily on obtaining a broad sample of measurements of basic parameters of stars: temperature, luminosity (that is, absolute brightness), chemical composition, radius, and mass. Those data provide effective constraints on evolutionary models, particularly when combined with asteroseismology;[2] however, they are still not well known for a broad range of stellar types. Some properties can be measured by traditional astronomical means. For example, the chemical composition—at least of the star's surface, or photosphere—can be determined by studying spectral lines. A star's temperature can be determined from its luminosity and physical size. To determine the size and the mass, however, astronomers require extremely high-resolution data that are

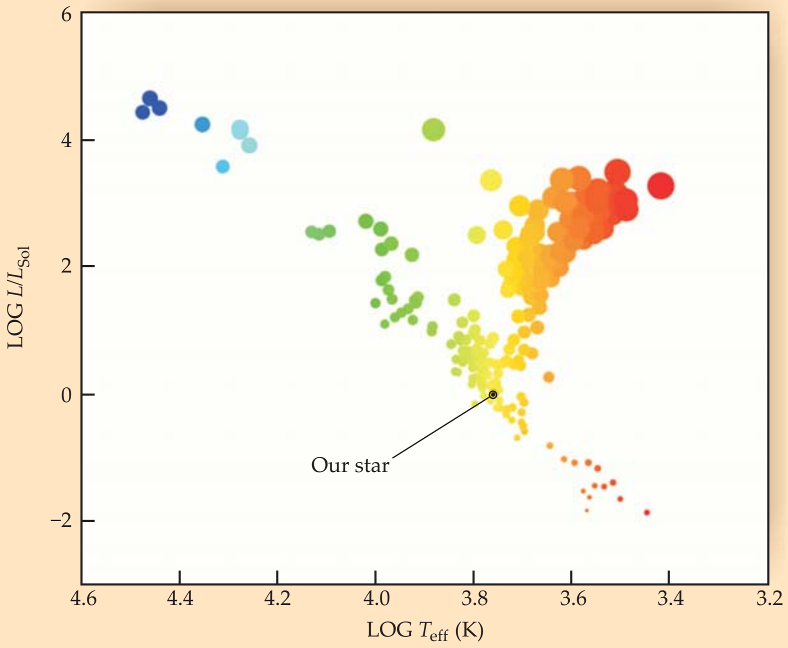

Figure 1. The Hertzsprung–Russell diagram, a plot of luminosity L (relative to the Sun's luminosity L_{Sol}) against temperature T_{eff}, has been used by astronomers for nearly a century to help categorize stars and to track their life cycles. In this HR diagram of more than 250 stars whose sizes have been measured by interferometry, the circles' sizes are proportional to the logarithms of the stars' radii, and color is a reflection of the photospheric temperature shown on the horizontal axis. Prior to the availability of interferometric measurements, some qualitative conclusions could be drawn about stars' sizes based on their positions on the plot: Cooler, faint stars at the bottom right are expected to be small, and more luminous cool stars at the top right must be giants. That understanding is now becoming quantitative with the direct diameter measurements provided by interferometry. The diagonal line from top left to bottom right is the main sequence, where stars spend the most stable, and frequently most lengthy, part of their lives. Our star, the Sun, is a main-sequence star. (Courtesy of Tabetha Boyajian, Georgia State University.)

not easily obtained except by interferometry.

The vast majority of stars, particularly those on the hydrogen-burning main sequence, have angular extents of tenths to tens of milliarcseconds, much smaller than the diffraction limit of even the largest existing telescopes. But long-baseline optical interferometers have the angular resolution needed to measure the sizes of a large number of stars and, consequently, to build the statistically valid data set required to test and advance stellar atmospheric and evolutionary models. As long ago as 1921, Albert Michelson showed that only a relatively small number of Fourier components are required to obtain a good measurement of a star's angular size.[3] By combining angular measurements with distances from the *Hipparcos* satellite,[4] astronomers can now determine stellar radii with less than 1% error, and often the precision of the distance determination is what limits the overall measurement of the stellar physical diameter. Figure 1 shows all stars within 150 parsecs whose diameters have been measured to within 10%. Interferometers have also measured the angular sizes of extragalactic objects.[5]

Binary stars

Once a star's chemical composition, physical size, and temperature are known, mass is the final parameter required to fully test models of stellar evolution. Mass is arguably the physical attribute most important to a star's evolution, so expanding the sample of known stellar masses affects all areas of astrophysics. One method for determining stellar masses is to measure the orbital parameters of a binary star system—two stars bound in their mutual gravitational field—and then use Newtonian mechanics and Kepler's laws of orbital motion to solve for the masses of the two stars. (Noninteracting binaries—systems in which the component stars are well separated and do not exchange mass—follow the same evolutionary path as single stars, so what is learned about binary stars can be applied to stars in general.) Finding the orbital parameters of a binary star system requires a complete three-dimensional knowledge of the orbital motions. Motion along the line of sight can be determined from the Doppler shifts of spectral lines, but motion in the other two, tangential directions is more difficult to observe. It must be measured from the small changes in relative position of the two stars, in a technique known as relative astrometry.

To solve for all orbital parameters of a binary star, it is typically necessary to observe the system through at least one full orbital period, which can range from hours to many decades. Because life is short, observers prefer to measure shorter-period systems, which have the advantage of high velocities that produce larger, more easily detected Doppler shifts. Unfortunately, they also have small angular separations between the stars—smaller than the resolution limit of any existing single-aperture telescope. The combination of relative astrometry, small field of view, and small angular sizes makes short-period binary stars ideal targets for ground-based interferometers. By combining high-resolution data from ground-based interferometers with data from other, traditional techniques, astrophysicists can now get a complete sample of fundamental astrophysical parameters for stars of widely varying stellar types.

Imaging

In measurements of angular diameters or orbital elements, interferometric data have usually been used to fit model parameters. But as the number of spatial frequencies that can be sampled has grown, interferometrists are now producing model-free images—such as the one shown in figure 2. Interferometric imaging, pioneered at radio wavelengths, was largely enabled by the use of a technique known as closure phase. To form an image, some knowledge of the phase of the correlation is essential. However, at the shorter radio wavelengths, and in the near-IR and optical bands, the phase difference of the radiation between two apertures is completely overwhelmed by atmospheric effects. Fortunately, in the sum of the phases of the coherence functions around a closed loop of three apertures, the atmospheric phase errors all cancel, which results in a measurable quantity called the closure phase. The first images of binary stars using ground-based separated-telescope optical interferometry and the closure-

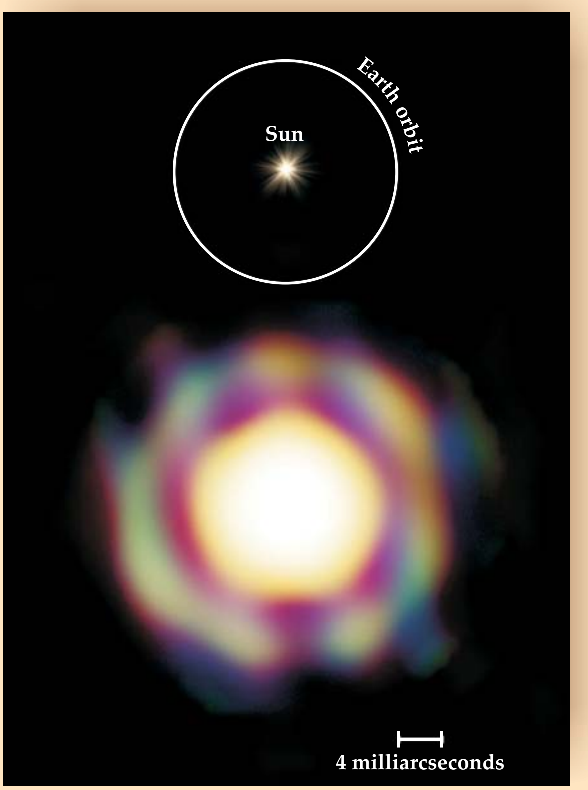

Figure 2. T Leporis, a giant variable star in the constellation Lepus, has a diameter roughly equal to the distance between Earth and the Sun and is surrounded by a sphere of molecular gas about three times as large. In this near-IR image, obtained using interferometry data from an array of four telescopes, the colors represent different frequency intervals between 1.4 μm and 1.9 μm. (Courtesy of Jean-Baptiste Le Bouquin, European Southern Observatory.)

phase technique were obtained more than a decade ago, and the method has been advancing ever since, as illustrated in figure 3.

Those first images, produced in 1996, used three telescopes and were comparable in quality to very long baseline images obtained using sparse radio arrays.[6] Later images, made using six telescopes, have much better spatial, temporal, and spectral resolution.[7,8] State-of-the-art beam combiners in the near-IR currently achieve precisions of 0.05° in closure phase and 0.2% in fringe amplitude, 10 to 50 times as precise as a decade ago. The precision of phase measurements is now close to what is required to directly detect a planet orbiting around another star system. (For more on the detection of exoplanets, see the article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale, PHYSICS TODAY, May 2009, page 46.) Visible-light beam combiners can now yield both amplitude and closure-phase measurements with spectral resolutions of 30 000 channels across the observed spectral band.

Improved angular resolution does more than enhance the precision of astrophysical measurements; it also reveals entirely new areas of study. Whereas the earliest interferometry efforts were able to resolve binary-star orbits and measure masses, the next generation improved resolution enough to resolve individual stars and directly measure their effective temperatures. Now, with submilliarcsecond resolution enabled by baselines of up to 330 m, arrays can resolve and image interacting binary stars for the first time.

Interacting binaries are stars that orbit one another so closely that tidal effects become important. Each star's gravitational field distorts the outer layers of the other, which can lead to mass transfer between them. Interacting binary stars are of great interest because strong binary interactions are thought to create both the standard-candle type Ia supernovae and the pulsar and black hole binaries seen throughout the galaxy. But their final end states are hard to predict due to difficulties in tracking angular momentum exchange, and the lack of direct observations has hampered theoretical progress.

The inset of figure 3 shows the first image of an interacting binary, the much studied system Beta Lyrae. The separation of the two stars is only about twice the diameter of the larger star. The system's orbit is viewed nearly edge-on, and the two stars eclipse each other every 13 days. With recent imaging advances, it is now possible to see the slight exten-

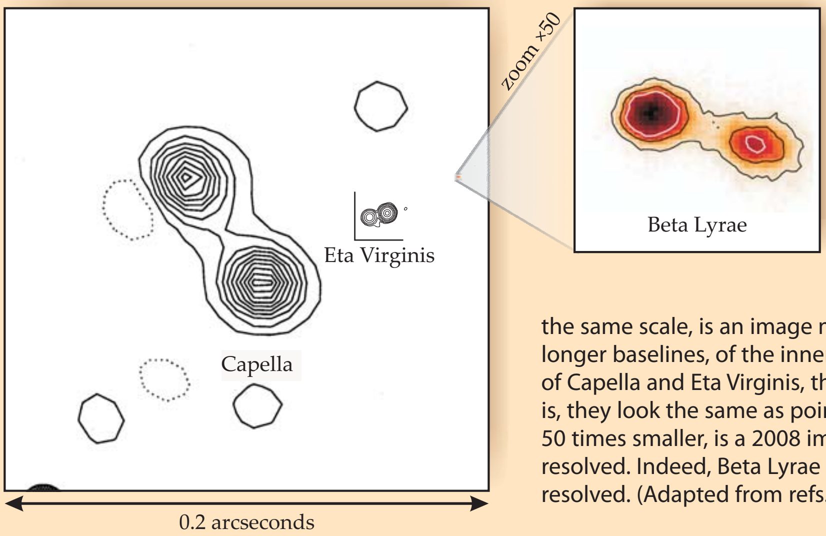

Figure 3. Three images of binary stars from different parts of the sky demonstrate the profound improvement over the years in the resolution of optical and near-IR interferometric imaging. On the left is a 1996 image of Capella, the first object to be imaged in that wavelength regime by a long-baseline interferometer. In the middle, shown on the same scale, is an image made in 2003, using more telescopes and longer baselines, of the inner component of Eta Virginis. In the images of Capella and Eta Virginis, the individual stars are not resolved—that is, they look the same as point sources of light. On the right, on a scale 50 times smaller, is a 2008 image of Beta Lyrae with both components resolved. Indeed, Beta Lyrae is the first interacting binary to be fully resolved. (Adapted from refs. 6, 7, and 8.)

sion of the brighter star due to gravitational distortion by its companion, and the thick, planar dust disk surrounding the stars can also be directly measured. The Beta Lyrae images are only the beginning—visible and IR interferometric imaging can be used to study many other interacting systems with high spectral resolution. All current theoretical models of how matter and angular momentum are exchanged in interacting star systems are based on indirect measurements. As more direct images become available, models will be challenged to an unprecedented degree in the coming years.

Oblate rotating stars

Current stellar evolutionary theory states that stars form out of collapsing fragments of molecular clouds. As the clumps shrink in size, they spin up due to conservation of angular momentum; they would reach rotational equilibrium well before achieving the critical density necessary for nucleosynthesis if some of their angular momentum were not somehow shed. Initially having rotation periods of a few days, most stars lose angular momentum through magnetic winds to their surrounding debris disks. The Sun, for instance, now rotates on its axis about once every 25 days, and a clear relation between age and rotation rate has been observed for Sun-like stars. But not all stars evolve like the Sun.

In a Sun-like star, the outer layer, called the photosphere, is radiative, while the layer just below it is convective. But stars more than 1.5 times as massive as the Sun, with surface temperatures above 8000 K, have fully radiative atmospheres, which stifle the generation of large-scale magnetic dynamos. Their weak magnetic fields cannot help shed angular momentum, so many of them have rotation periods of less than a day—within a factor of two of the speed required to break up the star. Like many other astrophysical phenomena, stellar rotation was initially detected via spectroscopy. One side of a rotating star is moving toward Earth, causing a blueward Doppler shift, while the other side is moving away, causing a shift toward the red. Each spectral line is therefore distorted and broadened in ways that can be modeled, so astronomers can measure the line-of-sight rotational velocity of the photosphere.

In the early part of the 20th century, the first theoretical model for rotating stars was created by Hugo von Zeipel, who assumed that stars rotate as solid bodies spun up into oblate spheroids. The von Zeipel model predicts that a star's equator, being farther away from the nuclear reaction at the center, is cooler than its poles. More recent theories predict that stars should rotate differentially rather than as solid bodies. However, understanding has remained purely theoretical until recently.

Direct imaging of rapid rotators can test the predictions of the von Zeipel model and other theories. Imaging can also determine the true orientation of a star's rotational axis, something practically impossible to do with spectral analysis alone. Knowing a star's orientation is critical because the observed luminosity and effective temperature deviate from the true stellar parameters due to viewing angle.

Since the first measurements of orientation and oblateness were made in 2001 using a single-baseline interferometer,[9] fast rotating stars have become a fruitful area for interferometric imaging. An example is shown in figure 4. Theory predicts—and the image confirms—about a 20% distortion of the star due to rotation. However, data show that the distended photosphere at the equator is much cooler than predicted. The discrepancy is thought to be due to differential rotation—a difference in angular velocity—between the pole and the equator.

Observations of rotating stars have serendipitously revealed a new way to measure the masses of single stars. From interferometric measurements of the oblateness and inclination of a rapidly rotating star, one can deduce the rotation rate as a fraction of the rate that would cause the star to break apart. From that quantity and the projected equatorial velocity obtained from Doppler spectroscopy, observers can calculate the gravitational field at the surface of the star and thus the mass of the star itself. That method is now being tested on rapidly rotating stars that are also in binary systems.

The new data raise many questions concerning both rotating stars themselves and astronomers' methods of categorizing and understanding stars in general. A star's stellar type, traced through mass, temperature, and intrinsic brightness, is one of the most fundamental ways astronomers have of understanding how a star fits into evolutionary models. One way of determining a star's stellar type is by measuring its temperature, but recent observations of rotating stars show pole-to-equator temperature differences much greater than the temperature variations among stars of different stellar types.

Furthermore, different physical processes

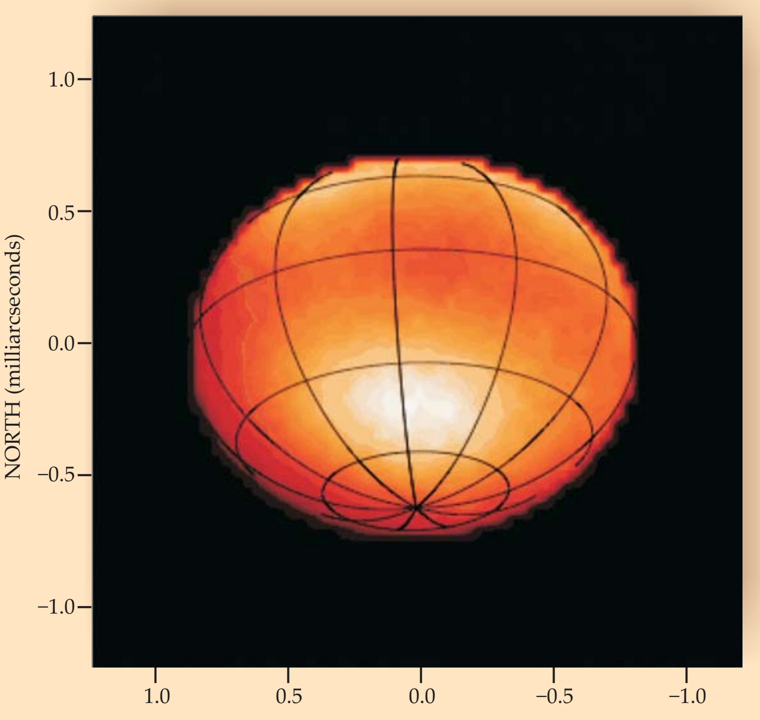

Figure 4. Alpha Cephei, a rapidly rotating star, imaged with IR interferometry. Centrifugal forces distort the photosphere into an oblate spheroid, with the cooler equator appearing darker than the hotter poles. (Adapted from M. Zhao et al., *Astrophys. J.*, in press.)

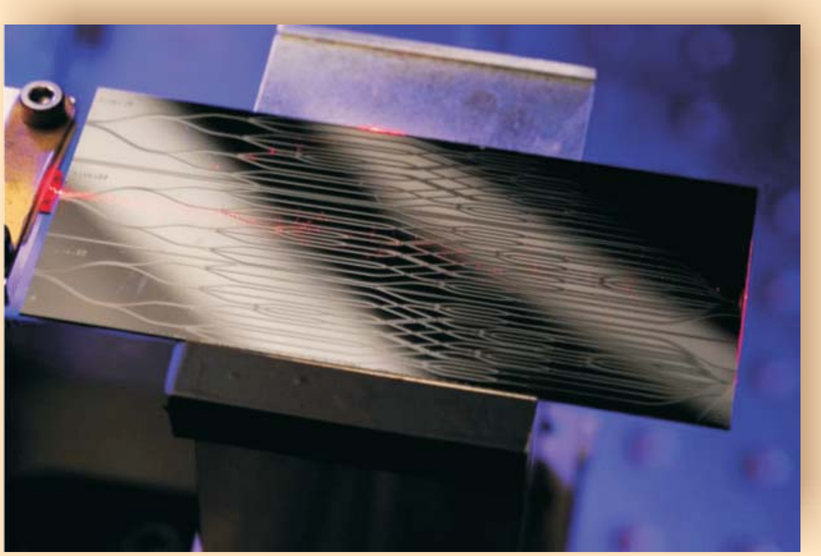

Figure 5. A beam combiner on a chip—an integrated-optics device manufactured using a silica-on-silicon process similar to the manufacture of integrated circuits—provides a large amount of optical processing power on a single small substrate. Integrated optics has been used in the communications industry for some time but is now being applied to interferometry. Optical components for splitting and combining beams are written into waveguides on the surface. The technology enables bulk optics that take up many square meters to be replaced by single chips smaller than a cell phone. (Courtesy of Laboratoire d'Astrophysique de l'Observatoire de Grenoble, CEA Leti, Université Joseph Fourier, and CNRS.)

are expected to be found in different parts of a rapidly rotating star. For example, the atmosphere could be convective near the equator and radiative near the poles. Stars are clearly not the simple and uniform objects they are often assumed to be. Other interferometric studies have shown that some stars previously thought to be perfectly normal, indeed so normal they are used as prototypes and standard candles, are in fact fast rotators seen pole-on. One such star is Vega, which has been used as a photometric standard for many years. Because there is no motion in such a star along the line of sight, there is no Doppler shift in the spectral lines, so the rotation cannot be detected spectroscopically. Only direct imaging can reveal Vega's rotation by mapping the temperature difference between the pole and the equator. Much of the theory of galaxy evolution is based on a foundation of understanding stellar evolution, so the impact of breakthroughs in stellar physics can ripple across all of astronomy.

Future directions

Optical interferometers are complex machines containing many optical elements. Instrumentalists are constantly looking for ways to reduce that complexity, increase the number of photons being collected, and examine fainter, more distant targets. Combining many beams using bulk optics requires dozens of optical components, each with a concomitant light loss, over large areas of optical table space. Integrated-optics devices, such as the one shown in figure 5, hold the promise of miniaturization and potential conservation of photons in interferometers' optical systems. Whole optical tables are anticipated to be replaced by single chips, with near-perfect beam combination and very small light losses. Other technological innovations aimed at increasing sensitivity include combining larger-aperture movable telescopes with full adaptive optics; designing more efficient beam-transport and delay-compensation schemes, perhaps by using fiber optics; and producing lower-noise, faster detectors for recording the fringes used to produce images.

Facilities employing new methods to improve sensitivity, possibly by a factor of 100, are now nearing completion and are expected to see first light within the next two years. One approach is to place several large telescopes on a common mount, which removes the need for complex beam-transport systems and delay lines and thereby reduces the number of times the light is reflected. Although a common mount restricts the maximum size of the baseline, it enables new beam-combination techniques that allow interferometric imaging of fainter sources. An alternate approach to increasing sensitivity, which allows for very large baselines, is to completely rethink the traditional designs for telescope mounts, beam transport, and delay lines in order to reduce the number of reflections involved in bringing the beams together.

In the coming decade, astronomers anticipate that a location will be chosen for an ambitious new interferometric facility. Antarctica is sure to offer some spectacular advantages but also some unique challenges. Because of the cold environment and downward, or katabatic, wind flow over parts of the continent, many Antarctic locations are similar in some ways to balloon or space platforms, described below. In particular, thermal background is low, and atmospheric clarity is much improved. An Antarctic facility would have the advantages of stability, large spaces to deploy many separated-aperture telescopes, and accessibility not available to balloon or space facilities. However, significant engineering challenges are associated with placing telescopes, perhaps on towers, on ice sheets in environments not easily accessible year-round.

The next major frontier is expected to be interferometry in space, where telescopes could be housed on free-floating spacecraft flying in formation with thousand-kilometer baselines. All wavelength regimes could be studied without atmospherically induced errors. If issues associated with spacecraft stability and orientation perturbations can be adequately addressed, space-based interferometry has the potential to allow full-sky absolute astrometry at the microarcsecond level. Launching an optical interferometer on a balloon could be considered a logical steppingstone to space-based facilities, and scientists in France have already flown a demonstrator mission. NASA astronomers are evaluating separated-aperture mid-IR systems using a Japanese gondola; the altitude advantages allow imaging through atmospheric windows and obtaining higher spatial resolutions than are currently possible. Many space-based interferometric missions are already under development by NASA and the European Space Agency, each with its own wavelength regime, number of apertures, and scientific goals, including detailed astrometric mapping of the galaxy; high-resolution imaging of stellar surfaces; and the detection, characterization, and imaging of Earth-like planets in neighboring stellar systems.

Although science is often driven toward a defined goal, progress frequently occurs almost incidentally following the deployment of new technology. That phenomenon has been studied and documented by Martin Harwit,[10] who said, “The most important observational discoveries result from substantial technological innovation in observational astronomy.” Ground-based interferometers now routinely create images of stellar surfaces, something not possible only a few years ago; every image yields new and interesting information about the stars around us and challenges current understanding of stellar astrophysics. As imaging capability, sensitivity, and angular and temporal resolution continue to improve, astronomers can anticipate that interferometry will challenge their view of the universe and open up new areas of observational astronomy.[11]

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