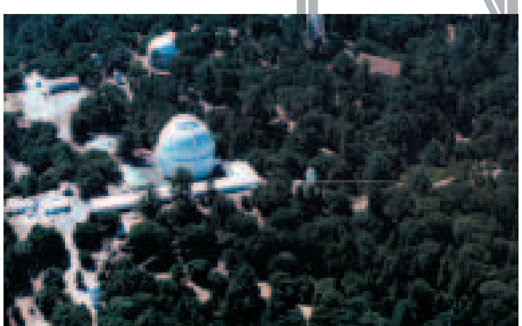
Resolving the Faces of Stars

Nestled among the venerable telescope domes on Mount Wilson, a mile-high peak overlooking Los Angeles, is the highest-resolution optical instrument in the world.



ERIC SIMISON / SEA WEST ENTERPRISES

The CHARA Array is one of several facilities on Mount Wilson, a 1,740-meter (5,710-foot) peak that overlooks Los Angeles, California. The array's telescopes are located in several of the smaller domes around the large dome for the Hooker telescope. The CHARA domes are connected by pipes, seen in the photo as thin white lines.

By David H. Berger, Jason P. Aufdenberg, and Nils H. Turner

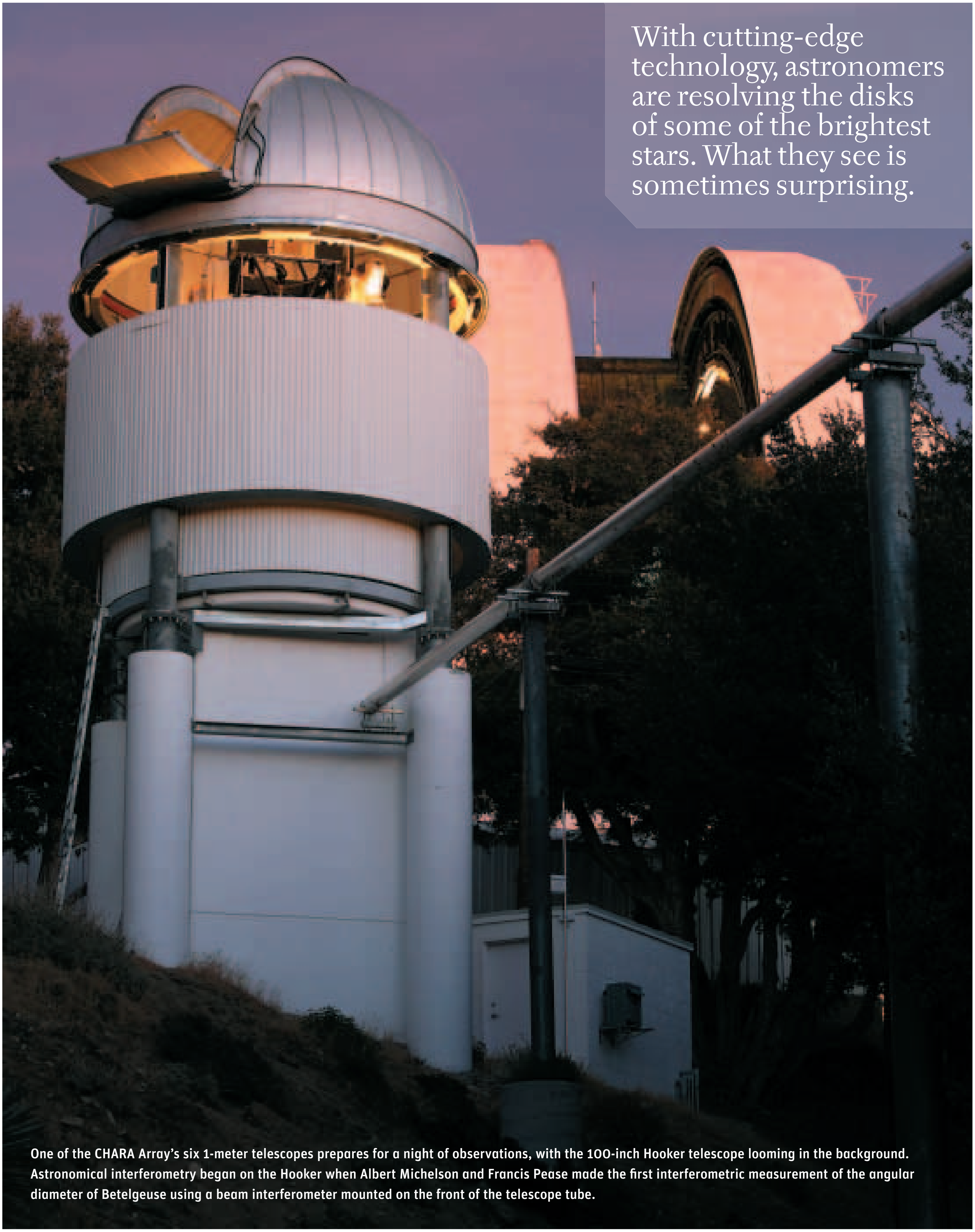
Inside several hundred meters of evacuated pipe, beams of starlight from six 1-meter (39-inch) telescopes converge on a central facility to be matched up light wave for light wave. The result allows measurements of details as small as a thousandth of an arcsecond wide — the apparent size of a penny in Los Angeles seen from Atlanta. Georgia State University's Center for High Angular Resolution Astronomy (CHARA) built and runs the instrument under the directorship of Harold McAlister. The CHARA Array is currently the largest of several new installations around the world applying 21st-century technology to an old idea: optical interferometry.

The concept of interferometry predates photographic film, but astronomers didn't really put it into practice until the early 1920s (see "Milestones in Optical Interferometry," page 44). Now, nearly a century later, technology is catching up with theory. Astronomers are using a new breed of giant interferometers to measure some of the most difficult fundamental parameters in stellar astrophysics, in particular the sizes and shapes of stars (*S&T:* May 2003, page 30).

These parameters are most easily studied for the nearest and brightest stars, those dear to skygazers' hearts. The CHARA Array has resolved the disks of familiar stars such as Vega and Regulus, revealing new aspects of their structures. It is now in its third year of scientific operations. Its capabilities will be enhanced over the next two years, with up to six telescopes operating simultaneously and its working wavelength moving from the near-infrared into the visual. These improvements will sharpen the array's power to image stars and their environments.

THE QUEST FOR HIGH RESOLUTION

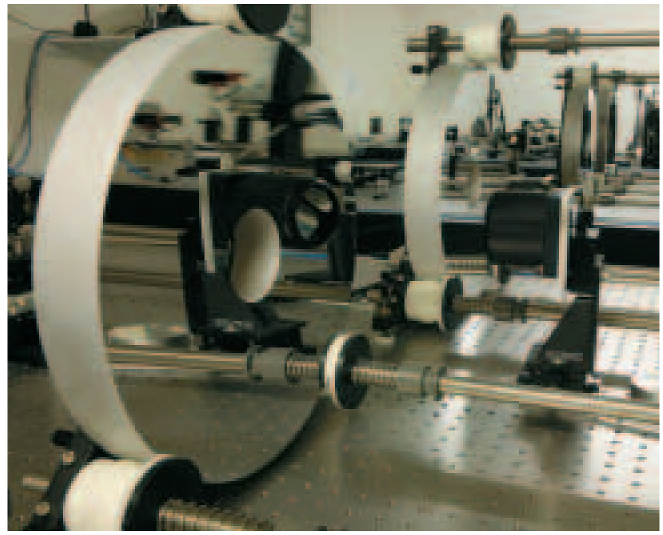
Astronomers often define resolution as how close together two points can be seen as separate objects. For telescopes with just one primary mirror or lens, the resolving power is set by the size of the primary optic and the observed wavelength of light. In theory, either using a larger mirror or observing at shorter (bluer) wavelengths will yield higher resolution. But Earth's atmosphere usu-



With cutting-edge technology, astronomers are resolving the disks of some of the brightest stars. What they see is sometimes surprising.

One of the CHARA Array's six 1-meter telescopes prepares for a night of observations, with the 100-inch Hooker telescope looming in the background. Astronomical interferometry began on the Hooker when Albert Michelson and Francis Pease made the first interferometric measurement of the angular diameter of Betelgeuse using a beam interferometer mounted on the front of the telescope tube.

MIKE SIMMONS



MIKE SIMMONS (2)

Light signals from the array's telescopes are fed into the Optical Path Length Equalization (OPLE) facility. Mirrors on "carts" (wheeled sleds) adjust path-length differences between the telescopes with a positioning precision of 10 nanometers. This capability allows astronomers to merge the same wave peaks from a star to produce fringes. Adjustments must be made continuously to compensate for Earth's rotation. *Left:* Coauthor Nils Turner examines one of the sleds. *Right:* After light passes through the OPLE carts, it goes through auxiliary optics that reduce the beam widths from 12.5 centimeters (5 inches) to 2 cm, the size used in the rest of the optical chain.

ally blurs our view and limits resolution to that of a modest backyard telescope. Large telescopes require *adaptive optics,* which compensate for atmospheric distortion, to achieve anything like their theoretical resolving power (*S&T:* October 2001, page 30).

This is where interferometry enters the picture. The basic idea is for two or more telescopes to collect starlight. If the light from each telescope can be aligned wave for wave, the resolution is determined not by the size of an individual telescope's mirror, but by the separation between them. The CHARA Array has telescopes separated by up to 331 meters, making it the longest-baseline optical interferometer in the world. This gives it the resolving power of a hypothetical 331-meter mirror! Its light-gathering power remains that of several 1-meter mirrors, and interferometry demands a lot of light, so the array can be used to examine only bright objects.

Astronomers using long-baseline interferometry can measure angular sizes of single stars to very high precision. With more complex analysis, the data can tell us about a star's atmosphere, surface features, and the nature of any circumstellar disk or shell. For a multiple system, we can watch two or more stars wheel around each other over the course of a single night and determine fundamental parameters such as their masses, surface brightnesses, and temperatures.

FINDING FRINGES

To understand how a stellar interferometer works, imagine a wave of light coming from a star. Each of the interferometer's telescopes intercepts a different part of the same flat wavefront and sends it to a central facility, where the parts are optically merged together. We not only measure the sum of their intensities, but due to the wave nature of light, we get an interference signal — usually expressed as alternating light and dark intensity patterns known as *fringes* — that provides information on the distribution of light across the star or its surroundings on a tiny angular scale.

Fringes occur only where each wave has traveled an equal distance from the star to the telescopes, through each, and to the central facility. Some of an array's telescopes will be slightly closer to the star than others, so the wave of starlight will encounter the telescopes in sequence. Long-baseline interferometers compensate for this by lengthening or shortening the light paths behind the telescopes using mirrors to create "delay lines." At the CHARA Array and similar instruments, mirrored carts on long rails equalize the travel distances of the light.

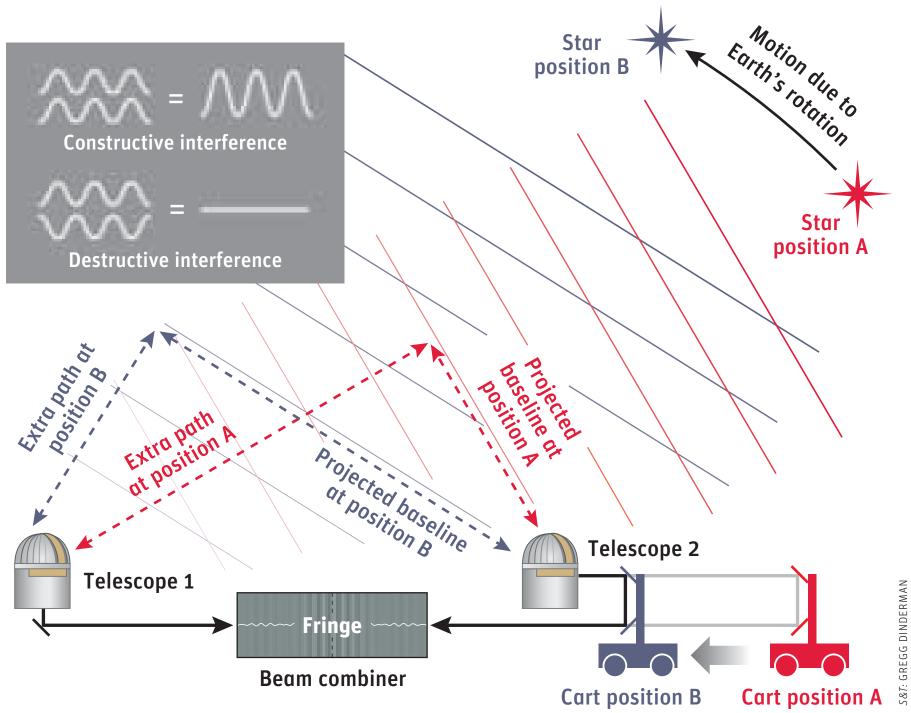
To complicate matters, Earth's rotation moves the fringe position at a rate of a few centimeters per second and up to hundreds of meters throughout the night. A separate laser metrology system measures the position of the mirror carts to less than the width of a human hair over the entire range of travel. To accommodate such a long travel distance, the delay-line building on Mount Wilson is the length of a football field!

Next, the collimated beams are sent to a room where the light can be combined in several ways. The CHARA "Classic" system superimposes the beams from two telescopes using a beamsplitter and detects fringes in the near infrared. The Fiber Linked Unit for Optical Recombination (FLUOR) instrument, designed by collaborators from Paris Observatory, merges the light inside small fiber optics. Lastly, a University of Michigan team has created a system to combine the light from all six telescopes, which will enable direct detection of hot Jupiters — massive planets in very tight orbits around other stars.

WHIRLING DERVISHES

Of the dozens of nearby stars resolved by the CHARA Array, perhaps the most provocative are rapid rotators. Regulus, Vega, and Alderamin (Alpha Cephei) rotate about their axes roughly twice a day. By comparison, our Sun turns roughly once a month. Rapid spin causes a body's equator to bulge.

Interferometry is a technique that exploits the wave nature of light. When astronomers combine two beams of light that are in phase (that is, their crests and troughs line up), the beams constructively interfere with each other, and the resulting variation in amplitude is the sum of the two beams. When two beams arrive out of phase, they cancel each other out. A light wave from an individual star reaches one telescope of an interferometer slightly before another, so astronomers use movable carts to add a delay line to one of the telescope's beams to synchronize the arrival of the signals at a detector, known as a beam combiner. The resulting interference pattern is known as a fringe. As Earth rotates, the star's position in the sky changes. The carts constantly move in order to equalize the path lengths of the two telescopes, so the fringe pattern stays on the detector. From the star's perspective, the effective separation between the two telescopes (the baseline) changes during the night.



For example, Saturn's equatorial diameter is 10% larger than its polar diameter due to its fast, 10.8-hour rotation. Spin distorts Regulus and Alderamin so much that they are 30% wider across the equator than from pole to pole. We know this because the CHARA Array resolves Regulus and Alderamin as ellipses rather than as circular disks.

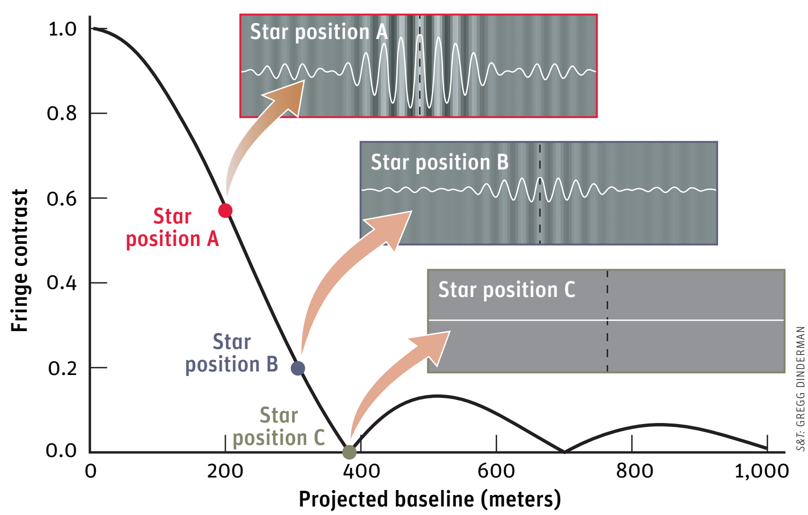
Vega, on the other hand, points its pole almost directly toward Earth, and thus it shows us a circular cross section. But fast spin also *dims* a star's equator, because the surface there is more distant from the energy-producing core. Vega revealed its fast rotation by the fact that the edges of its resolved disk are cooler and dimmer than the center. Swedish astronomer Edvard Hugo von Zeipel first predicted this "gravity darkening" in 1924, and Henry Norris Russell obtained the first observational evidence for it in 1939 from the light curves of eclipsing binary stars with rapidly rotating components. Last summer, one of us (Aufdenberg) led a team using the CHARA Array to resolve a 2,200°C (3,960°F) temperature drop between Vega's center and limb, confirming the star's pole-on orientation (*S&T:* April 2006, page 16). In contrast, we see both Regulus and Alderamin nearly equator-on.

Vega's comparatively large angular size, 3.3 milliarcseconds, is more than twice that of Regulus or Alderamin, allowing us to make a more direct measurement of Vega's gravity darkening. Detailed studies of these nearby rapid rotators help us to better understand the evolution of entire stellar populations and how stars affect their environments. They also give us insights into the first stars in the universe, which were both massive and rapidly spinning.

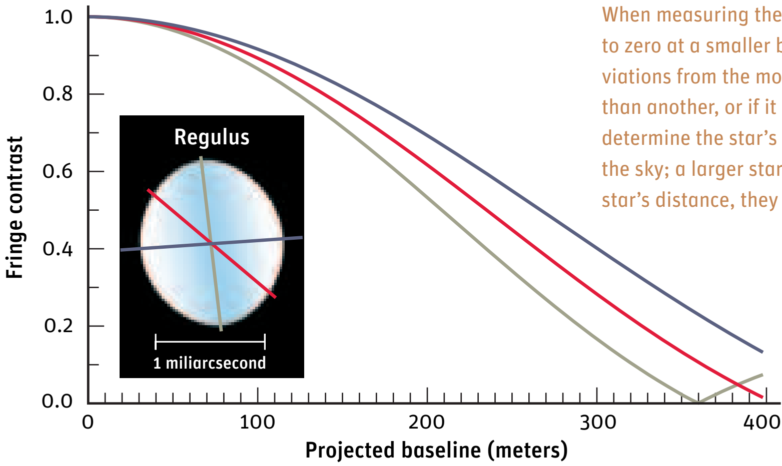
STARS AND THEIR SURROUNDINGS

Astronomers recently used the CHARA Array to detect faint gas and dust very close to several stars. For example, 1% of Vega's near-infrared emission comes from the hot, inner region of its rubbly debris disk, first revealed by the Infrared Astronomical Satellite (IRAS) in 1983. This disk helps us understand planetary systems around other stars. The CHARA observations confirm the presence of warm dust within 1 astronomical unit of the star, suggesting a recent major debris-producing event, such as an asteroid collision.

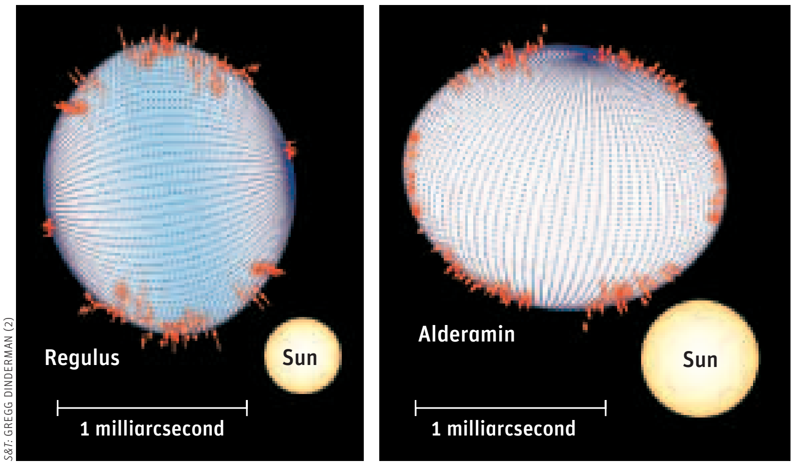
Extended cocoons of gas resolved around the Cepheid variables Polaris and Delta Cephei suggest a connection between these stars' pulsations and the shedding of mass, with far-reaching implications. The relation between a Cepheid's pulsation period and its luminosity provides astronomers with accurate distances to nearby galaxies. It is therefore crucial for astronomers to fully understand the physics of these so-called standard candles to firm up the cosmic distance scale.



The variation in amplitude of the combined beam, known as the fringe contrast, changes as the baseline changes. Multiple measurements of the fringe contrast during the night would trace the black curve if the star were a uniformly illuminated disk. The angular size of the star determines the shape of the curve.



When measuring the longest axis of an aspherical star such as Regulus, the fringe contrast drops to zero at a smaller baseline, because the larger size is easier to resolve. In other words, slight deviations from the model tell astronomers if a star's angular diameter is larger along one direction than another, or if it has limb darkening. By measuring different cross sections, astronomers can determine the star's shape. The same method can be applied to stars of different angular sizes on the sky; a larger star would reach the zero point sooner than a smaller star. If astronomers know a star's distance, they can quickly convert the angular diameter to a physical diameter.



S&T: GREGG DINDERMAN (2)

The CHARA Array has resolved the disks of Regulus and Alderamin (Alpha Cephei), allowing astronomers to measure their angular diameters across their equatorial and polar axes. Both stars rotate so rapidly — about 317 and 280 km per second at the equator — that they are within 20% of breakup speed. If the Sun were located at Regulus's 77 light-year distance, it would present a disk just 0.4 milliarcsecond across. At Alderamin's 49 light-year distance, it would be 0.6 milliarcsecond across.

Interferometry also yields precious information about the most common stars in the universe, red (*M*-type) dwarfs. These stars are so small and faint that it's hard to determine accurate diameters. Yet interferometry provides the only means to measure the diameters of single stars, and it provides a sanity check on sizes derived from eclipsing binaries. A team led by one of us (Berger) used the CHARA Array to resolve the angular diameters of six red dwarfs, which together with parallax measurements yield physical diameters accurate to better than 5%. Intriguingly, these sizes exceed theoretical predictions by 15 to 20%. This discrepancy may stem from stellar activity driven by the dwarfs' magnetic fields — something not generally included in current models. The CHARA Array and other interferometers are thus starting to paint a very different picture of cool stars.

Binary stars are extremely important tools for understanding stellar evolution in detail. Astronomers recently used the CHARA Array to follow the components of the bright spectroscopic binary 12 Persei around their orbit to yield precise masses for both stars. Each appears to have a diameter 30% larger than expected for its mass and spectral type. We don't know why.

A key parameter for calculating the masses of stars in a binary is the system's orbital inclination to our line of sight. In the past, this angle could be found only in visual binaries, where we can resolve the individual stars and plot their movements. But stars far enough apart to resolve by conventional means generally take decades or centuries to complete one orbit. Now, with interferometry's resolving

Milestones in Optical Interferometry

THOMAS YOUNG

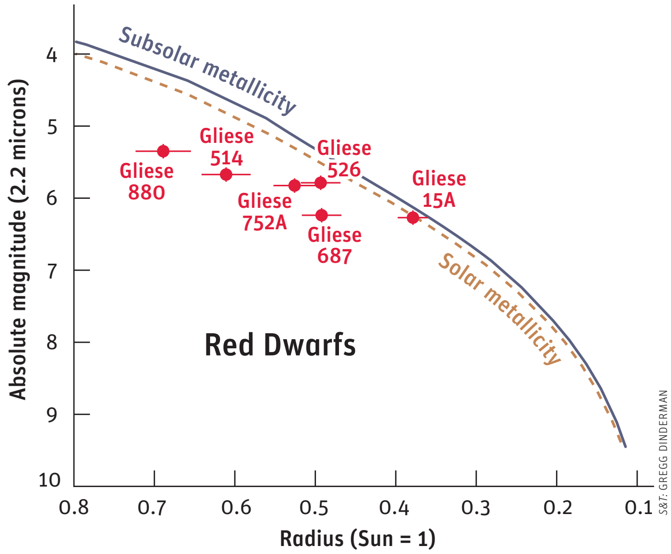
If you throw two stones into a still pond you'll see ripples that intermingle, creating striking patterns due to wave interference. Interferometry with light waves began in the early 1800s, several decades before scientists understood the wave nature of light. Here are some important milestones leading to modern stellar interferometry.

1805
English scientist Thomas Young first performs the famous double-slit experiment. He lets sunlight shine through a pinhole, then through two slits a few centimeters apart and onto a screen. Contrary to expectations, the screen shows alternating light and dark bands like ripples on a pond, hinting at the wave nature of light.

1862
Scottish physicist James Clerk Maxwell publishes his landmark work linking electricity, magnetism, and light as manifestations of a single force called electromagnetism. The equations describing this new force predict that electromagnetic energy propagates as waves, and that these emanations are the light we see and heat radiation we feel.

1868
French physicist Armand Fizeau first suggests using interference phenomena as a measurement technique in astronomy. He correctly surmises that a carefully planned double-slit experiment at a telescope's objective could lead to angular-diameter measurements of stars.

1874
Édouard Stephan, working at the Marseille Observatory in France, reports the results of a year-long survey of bright stars using a double-slit mask with a 65-cm (26-inch) separation. He reports that all of the observed stars exhibit fringes (alternating light and dark bands) indicating that his targets are much smaller than 0.16 arcsecond in angular diameter.



CHARA Array measurements of several red dwarfs have revealed a significant discrepancy between their predicted and actual diameters. Since red dwarfs are the universe's most common type of star, this is a mystery in need of a solution. The curved lines show models for stellar diameters depending on their heavy-element content (metallicity). Other interferometers have obtained similar results.

power, astronomers are effectively turning fast-revolving spectroscopic binaries into visual binaries, measuring inclinations and masses of a much greater diversity of systems.

LOOKING AHEAD

The CHARA Array originally combined light from only two telescopes, but we recently expanded to four. Within a year we will use all six telescopes. This will allow us to make two-dimensional maps, not just one-dimensional width measurements, of stellar surfaces, circumstellar disks, and binary stars, using techniques similar to those pioneered by radio astronomers with the Very Large Array in New Mexico.

In the coming years our observations will extend to shorter wavelengths, improving angular resolution by roughly a factor of four. We will also increase the array's sensitivity by using a fringe tracker, an instrument that practically removes fringe-position fluctuations caused by our atmosphere — adaptive optics for an interferometer. This will allow us to observe for longer times and hence to image much fainter targets, such as exoplanets. Interferometry will provide both the star-to-planet brightness ratio and the inclination of the planet's orbit.

Beyond the CHARA Array, the New Mexico Institute of Mining and Technology and its partners are developing the Magdalena Ridge Observatory in the mountains of central New Mexico. This interferometer will have baselines of up to 400 meters. Astronomers with the Optical Hawaiian Array for Nanoradian Astronomy (OHANA) project are using optical fibers to combine the light from some of world's largest telescopes atop Mauna Kea for a maximum baseline of 800 meters. Still longer baselines may appear in Antarctica.

Proposed space-based projects play a key role in the future of interferometry. If funded, these missions will measure the three-dimensional motions of galaxies in our Local Group, probe the atmospheric compositions of possible Earth-like exoplanets, and monitor starspot cycles on nearby solar analogs to help us understand our Sun's variability. Astronomers even plan to build a space-based X-ray interferometer to image the inner accretion disks around black holes.

Recent NASA budget cuts have stranded some missions in the pipeline, notably the Space Interferometry Mission and the Terrestrial Planet Finder. Surely, however, many exciting observations will eventually lie ahead in which interferometry plays an increasingly important role. ✴

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1918
German-American physicist Albert Michelson and American astronomer Francis Pease begin constructing a stellar interferometer with a 6-meter (20-foot) beam to be mounted to the front of the Mount Wilson 100-inch telescope. It uses a periscope arrangement to send the light from the outer mirrors (stand-ins for the slits in Young's double-slit experiment) into the telescope.

1920
Michelson and Pease make headlines by measuring the first stellar angular diameter. They find that Betelgeuse is 47 ± 5 milliarcseconds across, very close to the modern measurement of 43.33 ± 0.04.

1930s
Pease works on the next-generation stellar interferometer but meets with only limited success; the available technology, specifically the optical-path-length control system, is not up to the task.

ARMAND FIZEAU

1960s
British astronomer Robert Hanbury Brown and his colleagues exploit the quantum (particle) nature of light to develop the stellar-intensity interferometer. With this instrument, the light beams from each telescope don't interfere. Rather, the instrument measures the correlation of photons received separately at each telescope. Hanbury Brown's team measures the angular diameters of several dozen of the brightest stars.

1974
French astronomer Antoine Labeyrie uses two separate telescopes to feed a common beam combiner and detects fringes from Vega, thus realizing the modern optical interferometer.

ALBERT MICHELSON

JAMES CLERK MAXWELL