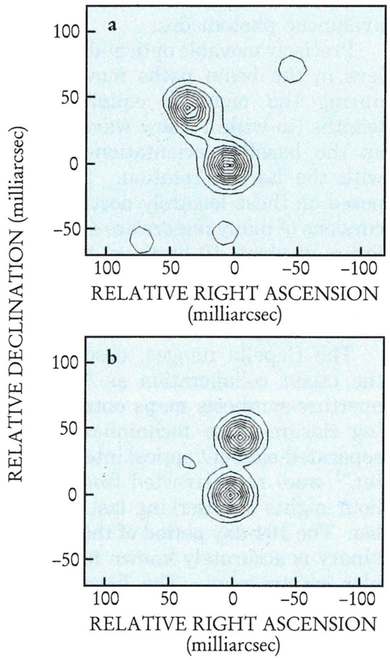
Telescope Array Begins Interferometric Imaging of Stars at Optical Wavelengths

Optical telescope arrays are breaking into the milliarcsecond imaging business, long a monopoly of very-long-baseline radio telescope arrays.

The extraordinary images of the binary star Capella published in the February issue of *Astronomy and Astrophysics*,[1] and reproduced on this page, herald the arrival of an important new astronomical technique: interferometric imaging with separated optical telescopes. The images were produced by John Baldwin and coworkers at the Cambridge Optical Aperture Synthesis Telescope (COAST), a Y-shaped interferometric array of four modest, movable telescopes, with a maximum separation of 100 meters. COAST sits alongside the much larger radio telescopes of Cambridge University's Mullard Radio Astronomy Observatory.

Capella, a familiar bright star in the northern winter sky, is really a binary—a very tightly bound pair of giant stars orbiting each other with a period of 104 days. Each one has about ten times the diameter of the Sun, but they are only as far apart as the Sun and Venus. Viewed from here, a distance of 40 light-years, their angular separation is only 55 milliarcseconds, much too small to be resolved by any conventional ground-based optical telescope or, for that matter, by the orbiting Hubble telescope.

Albert Michelson, more than a century ago, was the first to succeed in measuring the dimensions of unresolved celestial objects by optical interferometry. But until now, optical stellar interferometers have only measured angular diameters and separations. Real two-dimensional imaging requires the merging of optical phase information from at least three interferometric baselines. (See the article by Thomas Armstrong, Donald Hutter, Kenneth Johnston and David Mozurkewich in PHYSICS TODAY, May 1995, page 42.) That's much easier to do at radio wavelengths.



FIRST IMAGES ever made with an interferometric array of optical telescopes show the binary star Capella with a resolution of 30 milliarcseconds on (a) 13 September and (b) 28 September 1995. The orbital period is 104 days. The two component stars are only 6 light-seconds apart. From our distance of 40 light-years, that's an angular separation of 55 milliarcseconds, beyond the resolution of any previous optical telescope. The COAST facility at Cambridge, which made these images, will eventually have milliarcsecond resolution, good enough to image each individual star clearly. (Adapted from ref. 1.)

Radio mapping

Radio telescope arrays with separations of thousands of kilometers have been making two-dimensional maps of celestial radio sources with milliarcsecond resolution for more than a decade. The angular resolution limit of an interferometer is given, in radians, by λ/D, the ratio of the wavelength being observed to the separation of the observing elements. So in principle one should be able to achieve the same millisecond resolution at optical wavelengths, with telescopes separated by football fields rather than continents.

It turns out, however, that interferometric imaging gets much more difficult when you shrink the observing wavelength a millionfold. The telescopes and the system that brings their light together have to be extremely stable and precise. The phase-distorting effect of atmospheric turbulence becomes troublesome on much shorter spatial and temporal scales; phase measurements have to be made in milliseconds, and telescope apertures larger than about half a meter become problematic. Furthermore, optical astronomers have nothing like the low-noise, phase-coherent amplifiers that facilitate interferometric imaging at radio frequencies.

If the light (or radio emission) from a celestial point source is collected by two telescopes separated by a baseline vector **D**, bringing the wavelength-filtered light together produces a pattern of interference fringes much like what one sees in a Young's double-slit experiment. It gets more interesting if the source is not a point—that is to say, if its size or structure subtends an angle larger than the resolution λ/D. Then different regions of the source will produce separate interference patterns. The light from these different regions is, of course, incoherent, but the fringe patterns overlap.

As the orientation of the baseline relative to the source changes with the diurnal rotation of the Earth, this overlap sometimes enhances the fringe contrast and at other times tends to wash it out. Michelson introduced the so-called visibility function, $V(\mathbf{D})$, a quantitative measure of the contrast between fringe crests and troughs. The basis of interferometric imaging is the fact that the spatial distribution of the source on the sky is just the Fourier transform of $V(\mathbf{D})$ times a complex factor that tracks the changing phase of the interference pattern as the Earth rotates.

Closure phase

If it were as simple as that, a pair of telescopes defining a single baseline would, in principle, suffice for imaging. But, in fact, wavefront distortion by atmospheric turbulence plays such havoc with fringe phases that one can't do the Fourier transform with just a single baseline. One needs at least three baselines, and therefore at least three separate observing apertures, to do the "closure phase" trick: It turns out that if one has three or more baselines forming a closed polygon, the sum of the interference phases (the closure phase) is unaffected by turbulence. All the phase distortions cancel out when one does the sum. If one can measure the variation of the visibility function for each baseline *and* the overall closure phase as the Earth rotates, one can construct an image of the source.

The effect of turbulence on radio telescope phases is slow enough that the measurement of the closure phase is no great problem. But at optical wavelengths, where one would have to measure the three jittering baseline phases simultaneously within milliseconds, it had never been done. But in 1985 Baldwin and his Cambridge radio-astronomy colleagues thought it could be done. "So we started off with something very simple," Baldwin recalls. "We covered up the aperture of the 88-inch telescope on Mauna Kea in Hawaii with a mask with three holes. That produced three sets of crossing fringes, and we measured the closure phase. It turned out to be surprisingly easy."

"Next we had to demonstrate that such interferometric masking could reach the diffraction limit of a large telescope," Baldwin told us. In conventional use, of course, atmospheric turbulence limits a large optical telescope to a resolution of half an arcsecond at best, far from its diffraction limit. A mask improves resolution at the cost of seriously reduced light-gathering power. By 1989 the Cambridge group had a rather spectacular demonstration: With a five-hole mask fitted over the 4.2-meter UK telescope in the Canary Islands, they succeeded in imaging surface structure on Betelgeuse, the red supergiant in Orion, with a diffraction-limited resolution of 30 milliarcseconds. It was the first image ever made of structure on the surface of any star other than the Sun. Very soon thereafter Britain's Science and Engineering Research Council gave Baldwin's group the go-ahead to build COAST.

Optical Aperture Synthesis Telescope

The Mullard Radio Astronomy Observatory, a few miles from Cambridge and a mere 20 meters above sea level, is not the kind of location where one usually finds important optical telescopes. The cost of building COAST was about $1.3 million, modest by the standards of frontier astronomical facilities. Its four constituent optical/infrared telescopes have aperture diameters of only 40 cm, so that turbulent wavefront phase variation across each face will be tolerable. The mobile telescopes can be separated by as much as 100 meters, but once their placements are set for an observing run, they remain motionless to ensure mechanical stability. The nightly wandering of the star under observation is followed by external "siderostat" mirrors that feed its light into the fixed apertures. Other mirrors convey the four telescope beams to a thermally benign, grass-covered bunker, where they are split, filtered and combined in all the possible baseline pairs. The resulting interference fringes are measured with avalanche photodiodes.

Precisely movable optical-delay trolleys in the beam paths move slowly during the night to equalize path lengths (to within a few wavelengths) as the baseline orientations change with the Earth's rotation. Superimposed on these leisurely nocturnal excursions of many meters are 40-micron jitters at about 10 hertz, so that each photodetector can sweep continually back and forth across about 50 interference fringes.

The Capella images, described by the COAST collaboration as "the first aperture-synthesis maps obtained using closure-phase techniques with a separated-element optical interferometer,"[1] were reconstructed from two 5-hour nights of observing last September. The 104-day period of the Capella binary is accurately known from Doppler spectroscopy. The figure shows the different positions of the component stars on the two observing nights, 15 days apart. "For the Fourier transform and model fitting, we were able to use, without any modification, the Caltech image-reconstruction programs routinely employed for radio astronomy," Baldwin told us.

Only three of the four telescopes were used in these first imaging runs, and their separation was only 6 meters. The observations were made in a narrow wavelength band centered at 830 nm in the "far red." That yields a resolution of about 30 milliarcseconds, enough to separate the two Capella stars but not enough to provide a sharp image of either one.

As COAST undertakes longer baselines and shorter wavelengths over the next year, it should eventually be producing images with milliarcsecond resolution. At that level, astronomers will be able to image starspots and flares, stellar atmospheres and the exchange of hot gases between binary partners. How far away they will be able to see such features is limited not only by angular resolution; because the actual telescope apertures are, perforce, quite small, their light-gathering power is rather meager.

Elsewhere

The US Navy's Prototype Optical Interferometer, an array of six 12.5-cm telescopes in Arizona, is expected to produce its first images later this year. Elsewhere in Arizona, two of the three 45-cm interferometer telescopes planned by a collaboration of Harvard, MIT and the universities of Massachusetts and Wyoming have begun observing. The collaboration has also proposed a scheme for doing a variant of interferometric imaging with only two telescopes.[2]

The W. M. Keck Observatory in Hawaii and the European Southern Observatory in Chile are dominated by gargantuan optical telescopes with apertures much larger than the coherence length for turbulence. Therefore, if they are to do interferometry at optical wavelengths, both observatories will have to install compensatory adaptive optics. At infrared wavelengths longer than 10 microns, however, adaptive optics will not be essential. Both observatories also have plans for adding smaller, mobile "outrider telescopes." But the Keck expects to do some kinds of interferometric imaging with just its two 10-meter telescopes, by exploiting another alternative to closure-phase measurement, called phase referencing.[3]

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References

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GaN Laser Diode Brightens Hopes for a Long-Lived, Short-Wavelength Device

Researchers at Nichia Chemical Industries in Tokushima, Japan, reported in January that they had succeeded in getting a diode based on gallium nitride to lase at a wavelength of 417 nanometers, giving forth a blue-violet light.[1] (See the figure on page 19.) Since then, at the International

In the race to produce a short-wavelength semiconductor laser, diode lasers based on gallium nitride were late leaving the starting gate, but they have the potential to challenge the current leader.