# ADAPTIVE OPTICS AND INTERFEROMETRY

**Since Galileo's time, atmospheric turbulence has limited the resolution of astronomical observations to around 0.5 sec. Now optical and infrared astronomers are on the verge of improving the limiting resolution of their observations by factors of tens or hundreds—even thousands.**

Charles A. Beichman and Stephen Ridgway

During the last 350 years, astronomers have improved the sensitivity of their observations by a factor of almost a billion by using larger telescopes and better detectors. At optical wavelengths, however, there has been little improvement in angular resolution since Galileo's time. Until very recently, atmospheric turbulence limited the resolution of astronomical observations with even the largest telescopes at the best sites to around 0.5″. Astronomy is on the verge of realizing the promise of two new techniques that will improve the limiting resolution of optical and infrared observations by factors of tens or even thousands.

Elementary diffraction theory gives the resolution limit for an optical system as

$$\theta = 1.2\frac{\lambda}{D}\,(\text{radians}) = 250\frac{\lambda(\mu\text{m})}{D\,(\text{m})}\,(\text{milliarcseconds})$$

where $\lambda$ is the wavelength of observation and $D$ is the largest dimension of the telescope, or the largest separation between multiple telescopes. Thus, the diffraction limit of a perfect 10-m telescope would be 25 milliarcsecond at 1 micron, a factor of 10 to 20 better than the best atmospheric "seeing." For positional measurements or for determining the parameters of simple models, the diffraction limit can be exceeded by up to a factor of 10 for bright objects.

Astronomers are pursuing two techniques to achieve diffraction-limited angular resolution at optical and infrared wavelengths. Adaptive optics, the real-time adjustment of optical surfaces to compensate for wavefront distortions, will improve image quality and increase sensitivity. Interferometry, the phased operation of multiple telescopes separated by large distances, promises very high angular resolution and precise positional measurements.

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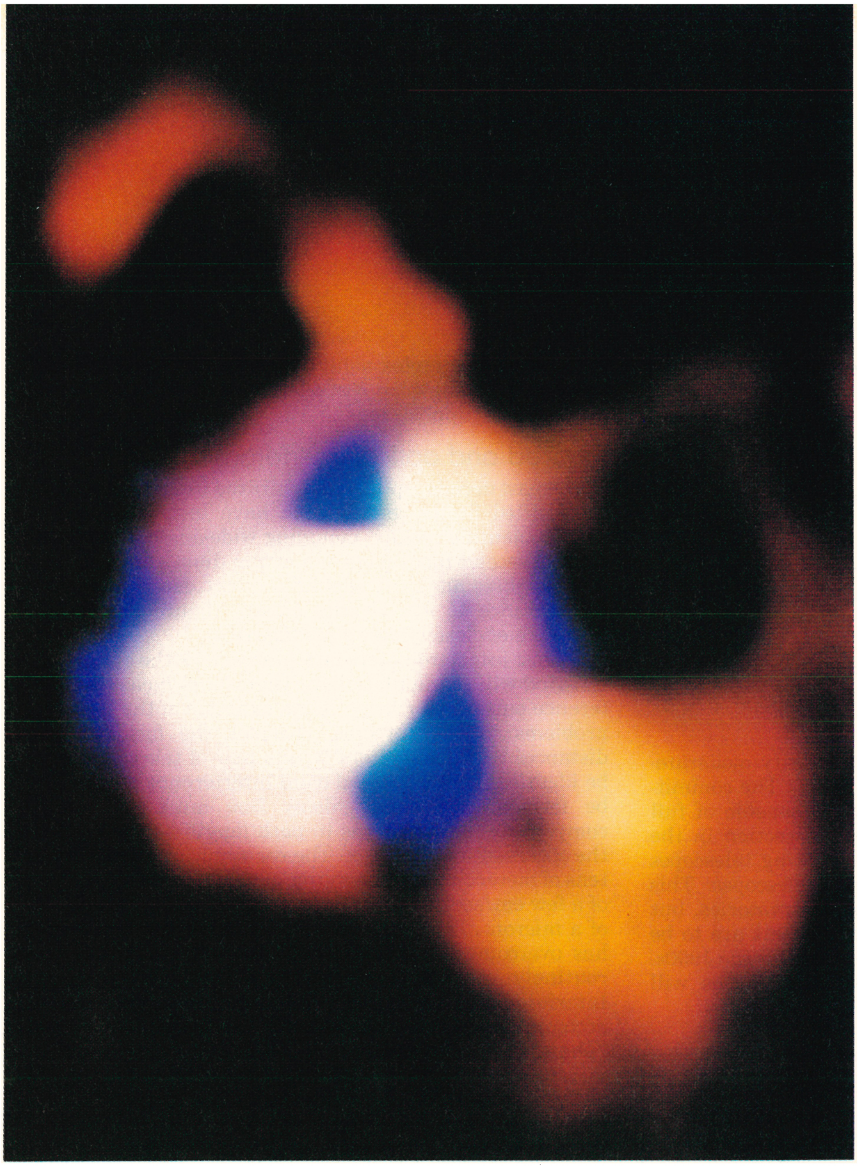
## Adaptive compensation for the atmosphere

Atmospheric turbulence scrambles light waves in patches larger than a characteristic size $r_0$ of about 20 cm at visible wavelengths. Light reaching a telescope of diameter larger than this is so badly disordered that diffraction-limited imaging is normally impossible.

European astronomers, as well as US scientists, have developed techniques to monitor the wavefront errors in each $r_0$-sized patch of a telescope aperture with reference to a nearby star, and to correct them by warping a mirror. Corrections must be made within the "coherence time" $\tau_0$ of the atmosphere, during which the phase of incoming radiation is well-defined. This time is roughly a few milliseconds at visible wavelengths. Complete phase correction in the visible requires a reference star brighter than a visual magnitude of around 8 within an angle $\theta_0$ of about 2″ of the object of interest. Since $r_0$, $\tau_0$ and $\theta_0$ all increase with wavelength, roughly as $\lambda^{1.2}$, it is no surprise that the most rapid progress has been made in the infrared (for example, figure 1). There are three reasons for this: The number of $r_0$ patches across a telescope is much smaller in the infrared than in the visible; corrections are needed less frequently; and fainter, more numerous reference stars can be used.

Adaptive optics can be implemented in stages so that progressively higher orders of wavefront errors are corrected. The simplest correction, tip-tilt, is similar to the rapid guiding used to keep an image in one position in the focal plane and suffices to achieve near-diffraction-limited images for infrared wavelengths beyond 5 or 10 microns. Low-order corrections can provide modest improvements in image quality even at visible wavelengths (see figure 2). Higher-order wavefront corrections can be modeled by additional radial and azimuthal terms. A convenient expansion of the wavefront errors are the Zernike polynomials. Terms up to fourth order in radius and third order in azimuth encompass the familiar image



**Southern star η Carina** is subject to violent outbursts that eject gas and dust. This detailed view of the inner envelope shows a complex jet configuration, possibly indicating mass loss from a precessing accretion disk. In this image, close to the diffraction-limit of the telescope, infrared wavelengths of 2, 4 and 5 microns are mapped into blue, red and green. Blue emphasizes direct or scattered starlight, while red and green, combining to form yellow, show emission from warm dust grains. Data were obtained at the ESO 3.6-m telescope with the COME-ON adaptive optics prototype for the Very Large Telescope. (Courtesy of G. Gehring, F. Rigaut and the COME-ON team.) **Figure 1**

distortions of defocus, astigmatism, coma and the infamous spherical aberration.

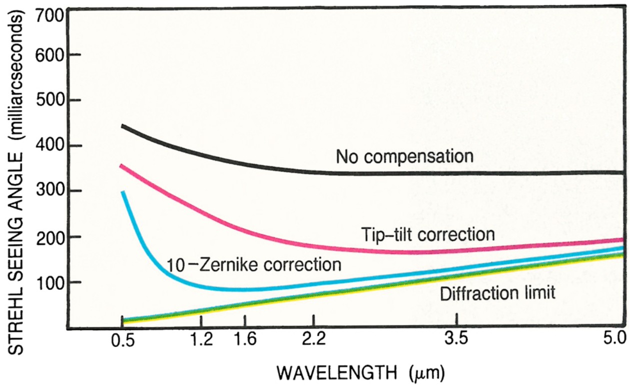
The fraction of sky close enough to adequately bright reference stars depends on wavelength and on the desired order of correction. At 10 microns almost 100 percent of the sky will be fully correctable, while at 0.5 microns less than 1 percent of the sky will be fully correctable. However, for partial corrections almost all of the sky should be available in the visible. Ultimately it may be possible to dispense with the need for a nearby bright star. Renaud Foy and Antoine Labeyrie[1] proposed generating an artificial star with resonant scattering of a laser beam focused in the atmospheric layer of sodium ions located at an altitude of about 100 km. The artificial star could then be positioned near any object in the sky for use as a phase reference. While this concept has been investigated for defense applications, its suitability for astronomy is not yet well understood.

## Scientific rewards of adaptive optics

The first reward of adaptive optics is obvious: images with about 10 times the resolution of seeing-limited telescopes. The second gain is in sensitivity for the study of point sources because of the reduction of background noise possible with the improved concentration of light. At visible wavelengths, a diffraction-limited 3.5-m telescope will be able to reach the same limiting flux as a seeing-limited 30-m telescope. In the near-infrared, adaptive optics will improve the limiting flux of an 8-m telescope by more than a factor of 10.

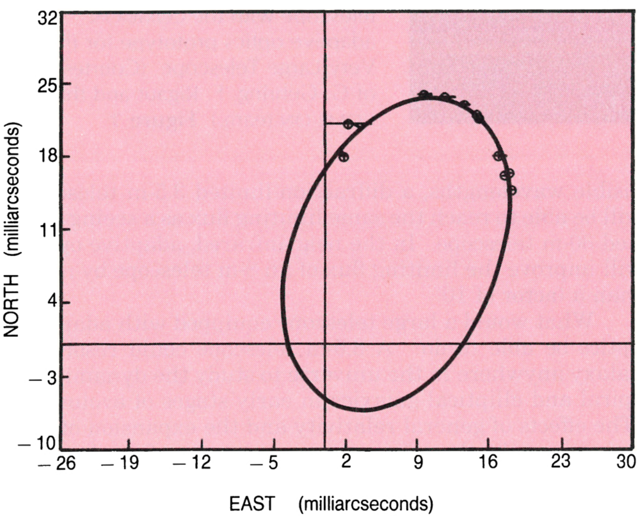
What would a large telescope equipped with adaptive optics be able to do? A 3.5-m telescope could resolve a galaxy anywhere in the universe to study the dynamics of spiral and elliptical galaxies in early stages of evolution. (The effects of general relativity and the expansion of the universe make the minimum apparent size of a galaxy on the order of a few arcseconds, independent of the distance to the galaxy.) Observations with an 8-m telescope of galaxies undergoing bursts of star formation at a redshift $z$ of around 3—tens of billions of light-years away—might result in the detection of a supernova per night. High-resolution observations are critical for searching the cores of globular clusters and the centers of galaxies for black holes, and for measuring the morphology and kinematics of disks around forming stars. Solar astronomers will use the Large Earth-Based Solar Telescope, an international 2.4-m solar telescope in the Canary Islands equipped with adaptive optics, to make detailed studies of the solar magnetic field with a resolution better than 0.1″.

The survey committee made the implementation of




**Improvement in angular resolution** possible with adaptive optics varies with the order of correction and wavelength. The Strehl seeing angle is one measure of the width of the point-spread function. A 10-Zernike correction implies correction of those wavefront errors corresponding to the first 10 Zernike polynomials in radius and azimuth, as described in the text. **Figure 2**

adaptive optics techniques its highest-priority moderate-sized program for ground-based astronomy. The committee expects that first-generation systems capable of full correction in the infrared and partial correction in the visible will be retrofitted on selected existing telescopes and included on new 4-m-class and larger telescopes. This work is already underway at several observatories, but increased efforts are required if these systems are to be integrated into the large telescopes planned for the 1990s. Full correction of images at visible wavelengths will require more complex solutions; significant funding will be required to develop cost-effective systems suitable for astronomical applications.




**Orbit of the star θ² Tau** has been determined from observations with the Mark III interferometer on Mt. Wilson. These data, in conjunction with spectroscopic information, allowed the distance to the Hyades cluster, one of the most important rungs in the cosmic distance ladder, to be determined with an accuracy almost 10 times greater than previous determinations. The horizontal and vertical lines within circles are error bars. (Adapted from ref. 3.) **Figure 3**

## Infrared and optical interferometry

In the past decade, optical and infrared interferometers in the United States and Europe have begun to produce useful scientific results, including wide-angle astrometry, milliarcsecond measurements of the diameters of stellar photospheres and dust shells,[2] a direct determination of the distance to the Hyades cluster (figure 3), and the resolving of close binary stars (figure 4).

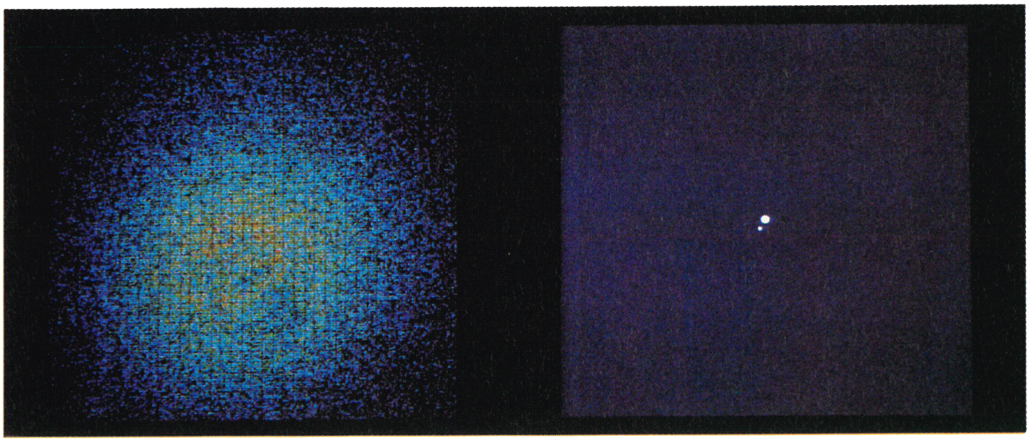
Most interferometers now planned for the optical and infrared will manipulate light beams and measure interference patterns directly. As an example of the technical problems to be overcome, consider the fact that the distances traveled by light from a pair of telescopes must be identical before a broad-band interference pattern can be formed. An optical delay line must be used to compensate for variations in path length as the angle to the observed star changes. The required delay can vary by tens of meters during the course of an observation at a rate of a few cm/sec and must be accurate to a few hundredths of a micron. The Mark III interferometer on Mt. Wilson has overcome these and other technical hurdles and is routinely measuring stellar diameters and positions. Interferometry using three or more telescopes, not yet accomplished at these wavelengths, will permit the use of "phase closure" techniques developed for radio interferometry, which allow the reconstruction of images in the absence of perfect phase information (figure 4). These techniques, now used routinely for very-long-baseline radio interferometry, take advantage of the fact that certain phase errors induced by the atmosphere cancel out around a closed triangle of widely separated telescopes.

Based on the technical successes of the past decade, a number of research groups are planning larger arrays. Also, interferometry is among the goals of several 8- and 10-m telescope projects, most notably the European Very Large Telescope project, which consists of four 8-m telescopes plus an auxiliary array of mobile 2-m telescopes. (See the article by Buddy Martin, John M. Hill and Roger Angel in PHYSICS TODAY, March, 1991, page 27.)

The ultimate power of interferometry will probably only be fully realized with an array operating in space, where no limits are imposed by the atmosphere. From space, ultraviolet wavelengths will be accessible, and more sensitive infrared observations will be possible using cryogenic optics. NASA has sponsored studies of space missions that would be the first steps in interferometry at submillimeter to ultraviolet wavelengths.

## Scientific rewards of interferometry

Even with the adaptive optics techniques discussed above, single telescopes will be limited to angular resolutions around 10 milliarcseconds. Interferometry promises to surpass this limit by a factor of 100 or more. Telescope arrays to be built in the 1990s with 100-m baselines (resolution of 2.5 milliarcseconds at a representative wavelength of 1 micron) will revolutionize stellar astron-



**Refined resolution.** Shown are two images of the binary star system Sigma Herculis taken with the 5-m Hale telescope. The seeing disc of the long-exposure, false-color image on the left is two arcseconds. Photo on right was obtained with non-redundant masking and has 50-milliarcseconds resolution. The resolved binary stars are about 70 milliarcseconds apart; both images are on the same scale. (Adapted from ref. 4.) **Figure 4**

omy, yielding unprecedented detail about stellar surfaces, atmospheres, shells, companions and winds. These instruments will allow milliarcsecond imagery of protostellar jets, the narrow-line emission regions in active galaxies, and the chromospheres and rotational distortions of stars.

A subsequent generation of interferometers with larger baselines and capable of sub-milliarcsecond resolution will resolve the disks of nearby main-sequence stars and map stellar winds from mass-losing giant stars. Maps of disks around forming stars will be critical to theories of planet formation. Resolution of 10 to 100 microarcseconds would yield a new set of observations, including mapping of the inner regions of quasar accretion disks.

Perhaps the most important scientific results of the early years of interferometry will be from ultra-precise astrometry. A space mission launched in the 1990s could measure accurate distances to objects across the Galaxy and measure motions of stars throughout the local group of galaxies. The astrometric determination of the wobble of a star around the star–planet center of mass would provide a sensitive means of searching for extrasolar planetary systems. A search of selected stars out to a distance of 500 light-years would either find planets or show them to be far less common than is now supposed. From measurements of the distances and motions of young stars in the Galaxy's spiral arms, it will be possible to study the density waves that are believed to be responsible for the existence of the arms. Determination of motions of the Magellanic Clouds will lead to a measurement of the total mass of the Galaxy and thus constrain the amount of "dark matter." The distances to RR Lyrae and Cepheid "standard candles" are critical for determining the Hubble constant; an astrometric space mission could improve our knowledge of these distances by an order of magnitude.

The deflection of light by the solar mass is one of the classic tests of general relativity. Interferometric observations near the limb of the Sun might provide the first "second-order" solar-system test of general relativity by determining the contribution to the deflection from the square of the solar potential. The expected deflection is approximately $11(\frac{b}{R_{\odot}})^{-2}$ microarcseconds, where $b$ is the impact parameter and $R_{\odot}$ is the solar radius.

The survey committee recommended significant support for ground-based facilities operating in the visible and infrared with telescopes as large as 2 m. A broad range of technical approaches is critical to the development of the field. It is the committee's intention that by the end of the decade at least one array of five or more 1- to 2-m telescopes be operating in the infrared. The committee also recommended planning for a Very Large Optical Array to be built in the beginning of the next century. Composed of perhaps 20 medium-aperture telescopes, spread over a distance of 1 km and each equipped with adaptive optics, this array would achieve sub-milliarcsecond resolution with high sensitivity and dynamic range.

For space interferometry, the committee recommended initiation of an Astrometric Interferometry Mission to measure positions of widely separated objects as faint as a visual magnitude of 20 with a precision of 3 to 30 microarcseconds. The committee also recommended planning and technology development for a powerful imaging array in space. Such an array might be located on the Moon as part of the Space Exploration Initiative, or in high Earth orbit. The committee urged NASA to develop a long-term program for space interferometry that progresses from small ground-based instruments to modest space-based missions, before undertaking a large orbiting or lunar facility.

Great advances in the understanding of astrophysical processes have been produced by the steady improvement in resolution at radio wavelengths. We can expect similar achievements over the next 25 years, as ground- and space-based interferometers investigate the structure of astronomical sources in exquisite detail at optical and infrared wavelengths.

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