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STELLAR INTERFEROMETRY METHODS

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INTRODUCTION

Stellar interferometry may be defined as the art of utilizing interference effects for improving the angular resolution of stellar observations. Resolution is improved in two ways: (*a*) interferometers attached to conventional telescopes can approach the diffraction limit of resolution, which is not accessible to ordinary observation with large telescopes owing to atmospheric turbulence, and (*b*) because interferometers can have baselines appreciably larger than the size of monolithic mirrors, their resolution is subject to improvement in proportion.

Improving the angular resolution of optical observations has been a dream of astronomers from the time of William Herschel, when it became clear that image sharpness was limited by the atmosphere rather than by telescope optics. Following Fizeau's idea of observing through a pair of holes, ways in which the atmospheric limitation could be overcome were brilliantly demonstrated by Stephan (1873), Michelson (1920), and more recently Hanbury Brown (1974). Not only were these pioneers able to approach the diffraction limit in large telescopes, but they also succeeded in reducing this limit further by increasing the baseline spans beyond the size of telescope apertures.

Pease's observation of the brightest red stars provided the first measurements of stellar angular diameters. With still higher resolution, R. Hanbury Brown and J. Davis were able to resolve and measure the angular diameters of the 32 brightest blue stars in the southern hemisphere.

For both red and blue stars, angular diameters provide direct information on how much the object deviates from a black-body source. Indeed, black bodies of given temperature, or color, and apparent magnitude have a predictable apparent size that can be checked against observation. Diameter excess may indicate an absorbing envelope, or temperature

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lower than assumed. Thus, these initial observations provided the foundations for the scale of stellar temperatures that became generally adopted.

At radio wavelengths, multi-antenna systems met with considerable success that has culminated in the operation of intercontinental arrays. Their role in locating peculiar sources for optical identification is well known: the optical discovery of QSO's and pulsars benefited from the accurate positions given by radio interferometers.

At optical wavelengths, early interferometers did not become widely utilized, owing to the considerable difficulties involved in their operation, and their modest limiting magnitude. In recent years, spectacular progress has been made, largely as a result of conceptual advances in understanding atmospheric effects. Existing large telescopes can now be fitted with small instruments that serve to retrieve the diffraction-limited resolution on stellar and quasi-stellar objects; more significantly, prototypes of telescope arrays resembling the synthetic-aperture radio telescopes have begun providing information with angular resolution in the 3-msec range.

The optical principles pertaining to the different types of stellar interferometers were reviewed by Hanbury Brown in 1968, by Labeyrie in 1976, and by Worden in 1977. A recent bibliography compiled by J. C. Dainty (1977, unpublished) contains 136 references, 121 of which were published after 1970. From this wealth of recent literature, this review extracts the main trends in the general evolution of stellar interferometry and their implications concerning observation. Because it is impossible to discuss in detail the many different types of interferometers, we will concentrate on recent observations and the instruments that produced them, notably speckle and two-telescope interferometers. We will devote some thought to space interferometers, which are bound to revolutionize optical astronomy as soon as space hardware becomes compatible with building large structures.

CLASSES OF STELLAR INTERFEROMETERS

Although involving similar optical principles, stellar interferometers can be divided in two broad families depending on whether they serve as auxiliary instruments, temporarily bolted onto some conventional telescope, or consist of a self-standing optical and mechanical structure. Michelson's historical 20-foot instrument is intermediate since it utilized essentially the mount and drive of the Mount Wilson 100-inch reflector, but separate optics.

Alternate classifications could be based upon the degree of aperture "dilution": all intermediate degrees are possible between a highly diluted aperture, such as Michelson's, and nearly filled apertures such as envisaged in some current projects of next generation telescopes involving a dense mosaic of elementary mirrors.

Instruments belonging to the first family have lower resolution, currently limited to 0″015 by telescope size, but can benefit from the larger collecting area to reach fainter limiting magnitudes, on the order of 15, than is possible with the few longer-baseline instruments in current operation. Their operation is comparatively easy since temporal coherence is passively maintained by the highly stable primary mirror, for which coherence is a direct consequence of the accurate figure initially obtained and maintained by the elaborate supporting cell.

The second family of interferometers includes more ambitious instruments, few of which are yet operating. They rely upon segmented optics and aperture-synthesis concepts to achieve giant baselines and the corresponding angular resolution, which is much higher than that allowed by the limited size of monolithic telescopes. Following the pioneering work of A. A. Michelson and F. G. Pease, such systems were extensively developed by radio astronomers before optical sensors and electronics allowed similar progress at optical wavelengths.

Because passive stability cannot be adequate for structures spanning 10 or 100 m, these structures require active mechanisms to achieve tracking stability and maintain the highly critical conditions of temporal coherence at the common focus of several mirrors located far apart. Owing to their modest collecting area, prototype interferometers of this kind currently have a moderate limiting magnitude ($m_v = 4$ at CERGA), which will improve as component mirrors are made larger than the current 25-cm size, and especially when many mirrors are utilized simultaneously. Since the previous review by Hanbury Brown in 1968, considerable progress has been made in this direction: a two-telescope interferometer with a 40-m baseline is already operating, and several others are in the construction stage. Designs that are proposed for N-telescope arrays have unlimited light-gathering power and resolution. Owing to atmospheric disturbances however, the ultimate potential capabilities of such instruments are attained only when they are operated from space platforms.

INTERFEROMETERS ON CONVENTIONAL TELESCOPES

Instruments in this family range from photoelectric versions of the Fizeau interferometer to the most sophisticated "rubber mirror" systems that utilize active mirror deformations to compensate for the atmospheric disturbances. In between these two extreme cases are the speckle interferometer and various types of wavefront-shearing interferometers. A wide variety of configurations are possible, especially in systems utilizing beam splitters. The optical properties of several basic configurations were discussed by Labeyrie (1976). In this article, we will concentrate on the proved configurations that have already yielded results of astrophysical interest. These are mainly the amplitude and the speckle interferometers.

The Amplitude Interferometer

Developed by Currie, Knapp & Liewer (1974), the amplitude interferometer produces interference fringes from a pair of inch-sized apertures. Utilized at the 100-inch and 200-inch telescopes of the Hale Observatories, it has produced angular diameter measurements on the brightest red stars. As reviewed by Tsuji (1976a), the measured sizes are larger than those obtained by other methods, such as Michelson's method, lunar occultation, and speckle interferometry.

A particularly large discrepancy is apparent in the case of α Hercule A: diameters obtained are $0''058 \pm 0''009$ (Knapp et al. 1975), $0''031 \pm 0''003$ (Gezari et al. 1972), $0''030$ (Pease 1931), and $0''030 \pm 0''001$ (Worden 1975). Worden (1975) concludes "in light of the close match between this result and two of the three previous studies it is quite possible that one or more of the techniques used to derive the Hercules diameter is incorrect."

A possible cause of systematic errors is the statistical process through which photodetector counts are converted into fringe visibility, in the presence of phase and amplitude fluctuations. More elaborate versions of the instrument, utilizing the full telescope aperture for increased sensitivity, have been announced.

The Speckle Interferometer

The theory and operation of the speckle interferometer have been extensively discussed in the recent literature. Because the principle is also relevant to the operation of telescope arrays in the presence of atmospheric turbulence, let us recall it briefly.

PRINCIPLE Ever since British astronomer Airy described the pattern of rings that sets the limit to the resolution of optical observations in small telescopes, it has been recognized by observers that the diffraction-limited Airy pattern is in fact rarely seen with apertures larger than 25 cm. The alterations caused by "seeing" in small telescopes were described as temporary splitting of the Airy peak and breaking of the rings. In more severe cases of seeing, the appearance of the image was described as "boiling." Observers of double-stars were best acquainted with these effects. Indeed, they trained themselves to distinguish binary geometry at separations close to the Airy radius. Thus, their brains had to remove the temporary peak-splitting or oblateness effects and retain some average impression of the pattern's possible duplicity. The mental averaging had to be more elaborate than a simple integration of intensities, and probably did not differ much from the autocorrelation process now performed digitally in photoelectric speckle interferometers. In the own words of Dr. Finsen, quoted by McAlister (1977a), observers of binary stars had "exploited the speckle technique without knowing it."

Splitting of the Airy peak occurs for example if the optical phases happen to be opposite on two halves of the aperture. This cancels the resulting intensity in the central part of the peak, and brightens certain parts of the feet, hence the splitting. Through similar interference effects, the more complicated patterns of phase produced by "seeing" on larger apertures generate a diffraction pattern that is broken into many bright granules, or speckles, having a random appearance. Because the effect is dependent on wavelength, only filtered light produces "pure" speckle patterns.

The phenomenon is a general property of coherent radiation fields, such as electro-magnetic and acoustical fields, ocean waves, etc, when random phases are present. It accounts for the bunching tendency attributed to particles in the Bose-Einstein statistics. The statistics of speckles is also largely describable in terms of Rayleigh's random-walk theory. A more detailed description, taking into account the particular scattering properties of the atmosphere, has been evolved by Korff (1973) and refined by Roddier & Roddier (1975). Additional theory is presented by Dainty (1976). Object structure convolves the typical speckle pattern produced by point sources (Figure 1). Because the statistical properties of unresolved speckle patterns are weakly dependent upon "seeing" parameters, the convolution produced by object structures can be derived through simple statistical analysis of the short-exposure image.

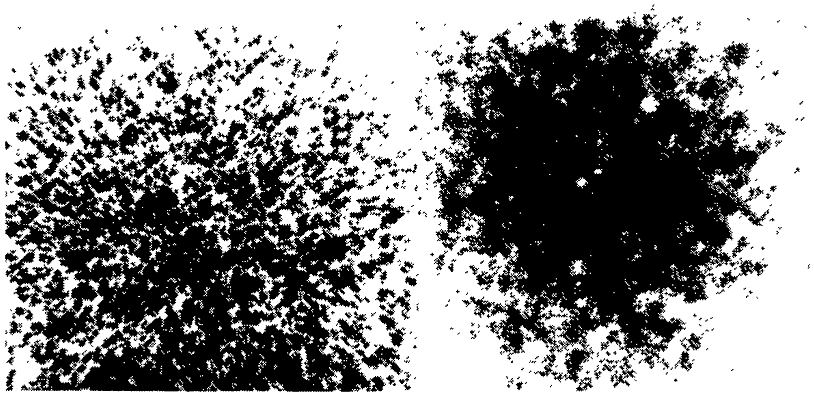

Figure 1 Speckle images of Betelgeuse (right) and an unresolved star (left), showing the resolved star disk on Betelgeuse. These are magnified focal images, filtered to a 300 Å bandwidth and recorded with short exposures (50 msec) at the 200-inch telescope. The speckle structure is caused by random interference of light propagated through different atmospheric cells.

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The basic analysis procedure consists of computing the time-averaged autocorrelation function of the instantaneous image. As shown in Figure 2, the profiles for nonresolved stars contain a narrow central peak arising from the speckle content of images, on top of a wider pedestal. Changing

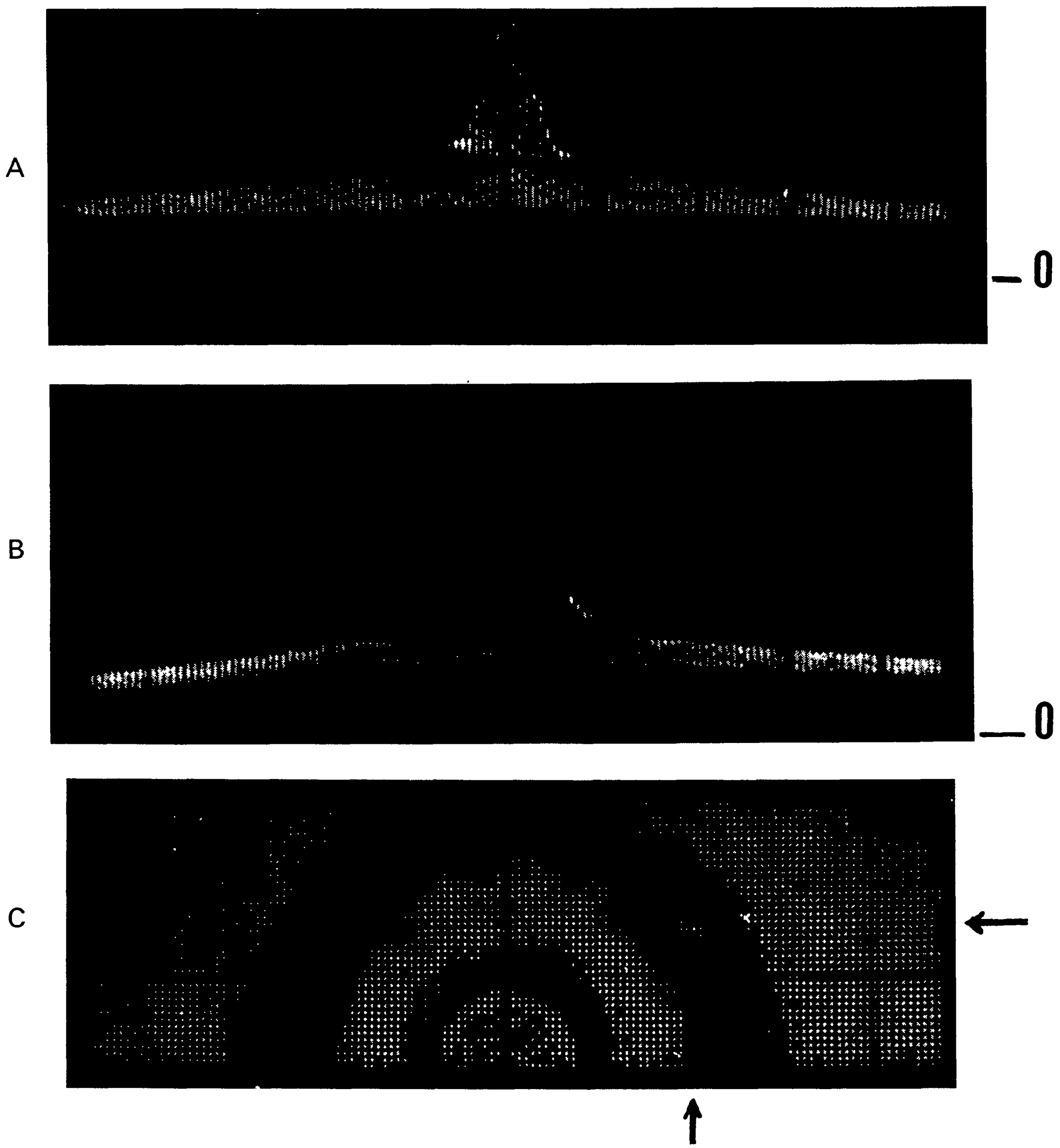

Figure 2 Correlation displays of the digital speckle interferometer operated at the prime focus of the 200-inch telescope (Blazit et al. 1977a). *A*, unresolved correlation profile, β Persei, 4900 Å; *B*, same on α Bootes. The wider peak is evidence of a resolved disk, 0″018 large in this case (scale $3.6 \times 10^{-3''}$ per correlation element); *C*, contour display of correlation, showing a resolved companion of β Coronae Borealis, spaced by 0″26 (arrows). Only the upper half of the symmetrical correlation is displayed (scale $7.2 \times 10^{-3''}$ per correlation element). Correlations are displayed in the prime focus cage during observation.

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"seeing" modifies principally the pedestal width, and the peak a small amount.[1]

Experimental curves are approximately consistent with the theoretical profiles computed by G. Ricort (unpublished) on the basis of Korff's (1973) theory. However, a significant attenuation of the central peak, relative to the pedestal, is always observed at low counting levels. Whether this discrepancy is caused by dark electrons or more fundamental effects is still unclear.

In the case of resolved objects, the time-averaged autocorrelation is convolved with the object's autocorrelation, and therefore is itself obtainable through a deconvolution procedure. The narrow peak component makes it a rather favorable case of deconvolution.

For reasons of experimental convenience, a Fourier-space equivalent of this analysis was generally adopted by observers having first-generation equipment, with photographic film as a recording medium (Labeyrie 1970, Gezari et al. 1972, Beddoes et al. 1976, McAlister 1977a).

The basic reduction procedure just described gives only the object's autocorrelation, which provides usable astrophysical information only for objects with simple morphologies, such as multiple stars or stellar disks. Appreciable efforts have been directed at finding refined reduction schemes capable of true image reconstruction (Knox & Thomson 1974, Liu & Lohmann 1973, Bates, Gough & Napier 1973, Nisenson, Ehn & Stachnik 1976, Lynds, Worden & Harvey 1976). As is discussed later, the practical feasibility and significance of these is still difficult to evaluate in the absence of fully conclusive results.

DESIGN AND OPERATION A speckle interferometer is essentially a focal-plane camera incorporating focal-extension optics, one or several filters, an atmospheric dispersion compensator, and an intensified recording camera capable of repeated short exposures 5 to 20 msec in duration. An image processor, operating in real time or not, completes the system.

Focal extension serves to adapt the speckle size to the pixel format of the sensor. Several pixels are required per speckle for adequate sampling. Focal ratios from 200 to 400 are thus generally adopted with currently available sensors. The filter bandwidth is generally on the order of 300 Å or less. For an improved limiting magnitude, wider bandwidths are expected to become usable with the chromatic corrector lens system designed by J. C. Dainty and R. Wynne (private communication).

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[1] The peak shape remains intermediate between an Airy disk, obtained in extremely poor seeing, and an autocorrelated Airy disk, obtained in diffraction-limited seeing. In practice these two extreme profiles differ very little in shape and width, except for the rings disappearing in the latter case.

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In my interferometer design, described in Labeyrie (1976), a concave holographic grating located in an intermediate image plane serves both as a tunable filter and dispersion compensator. Ordinary filters and Risley prisms are also successfully utilized by others.

Intensified film cameras were initially utilized as the sensor, and McAlister (1977a) and Worden et al. (1977) are still obtaining extensive data in this way. Television cameras have now been adopted by different observers (Blazit et al. 1977a, Schneiderman & Karo 1977). In spite of their poor dynamic range and restricted pixel format, they allow considerable operational simplification and offer the immense advantage of being directly compatible with digital electronics for on-line data reduction. In their photon-counting form, television cameras provide the ultimate in sensitivity and photometric accuracy. A fully digital, photon-counting system developed by Blazit et al. (1977a) has proved sensitive enough for observations on 3C 273. It should eventually reach the fifteenth stellar magnitude at Palomar as tube efficiency improves and as the Dainty-Wynne compensator becomes available.

Observational Results

Cool stars Since the first speckle interferometer observations in 1972, improvements to the apparatus for data collection and reduction have quickly increased the observational output. Initial work at Mount Palomar gave only an approximate confirmation of earlier diameter measurements made by F. G. Pease (1931) on Betelgeuse, Aldebaran, Arcturus, α Hercules A, Antares, β Pegasi, Mira, and a few more red stars with extended atmospheres. It also proved that these objects had spherical symmetry, and demonstrated in a few cases that close binaries could be discovered and measured with improved accuracy.

Then came observations of color-dependent diameters in Betelgeuse and Mira: there appeared to be a continuous size increase from red to blue wavelengths. Also, the limbs of these objects did not appear to have such a sharp boundary as that found for the Sun (Bonneau & Labeyrie 1973).

At Kitt Peak, Lynds, Worden & Harvey (1976) used a better image intensifier and a computerized microdensitometer to analyze their speckle films for a detailed study of Betelgeuse. They found a slight increase in size at the 5180 Å wavelength of TiO with respect to the nearby continuum. From a small number of images obtained with the 4-m telescope, they discovered the possible presence of coarse surface features, which they presented in the form of a reconstructed image. However, the mathematical justification of their procedure is not entirely convincing. Of particular concern is the identification of the speckle pattern with a con-

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volved array of Dirac peaks, an approximation which has led Worden et al. (1977) to mathematical results in conflict with the more rigorous derivation of Korff (1973). In his model-atmosphere study of Betelgeuse, Tsuji (1976b) states that "the presence of homogeneity such as suggested by Schwarzschild (1975) is not clearly demonstrated by the image reconstruction by Lynds et al."

The difficulty of arriving at meaningful image reconstructions from a small sample of speckled images is further illustrated by the different image that McDonnell & Bates (1976) have obtained from the same data. As was the case for the channels of Mars in the last century, repeated observations should eventually clarify the issue.

Tsuji (1976a) gives a detailed discussion of past and recent results concerning Betelgeuse, and the way in which these results fit his atmosphere models. He notes that most modern measurements of Betelgeuse give diameters significantly larger than those published by Pease (1931). From the scatter of diameters measured by different methods, and the spectroscopic variability, he concludes that actual size variations are unlikely and stresses the importance of determining the true value, which would provide a highly desirable confrontation with model calculations. Indeed, the empirical effective temperature near 3200°K, which is deduced from modern observations, is difficult to reconcile with the spectrophotometric observations of Betelgeuse. Finally, Tsuji notes that the observed diameter increase at blue wavelengths disagrees with the increased limb darkening obtained in his models. In a second paper concerning the other red giants that have been measured, Tsuji (1976b) concludes that it is desirable to raise by several hundred degrees the scale of stellar temperatures generally accepted before.

Thus, an interesting situation of theory and observation stimulating each other has now been reached. On the experimental side, appreciable progress is possible in the accuracy of data acquisition and reduction procedures for these relatively bright stars. It should lead to a quick improvement of our understanding of cool star atmospheres.

Mira variables and peculiar stars Angular diameters comparable to those for Betelgeuse were observed on other stars, such as Mira (*o* Ceti) and the other Mira-type variable R Leonis, but these objects have been more difficult to observe owing to their strong variability. On both stars, observed with the speckle interferometer at Mount Palomar, Labeyrie, Koechlin, Bonneau, Blazit, and Foy (1977) find large diameter differences in connection with the red TiO band structure. Apparent sizes vary as shown in Figure 3.

In his interpretation of the observations, one of the above authors, R.

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Foy, found the effect explainable in terms of the opacity modulation caused by TiO absorption in the atmosphere. At least one previous case of a transparent stellar atmosphere that becomes opaque, and thus visible, at certain wavelengths has been known from the observation of γ Velorum by Hanbury Brown et al. (1970). A hydrogen atmosphere was similarly studied by the speckle interferometer on P Cygni: the apparent diameter increased markedly at the H_β emission wavelength in comparison with nearby continuum wavelengths (Blazit et al. 1977a).

On one occasion, it has been possible to resolve a galactic nova, Nova Cygni 1976, 45 days after its outburst. As far as can be judged from the signal obtained, the apparent disk is 0″070 in diameter at 6563 Å (H_α), with no detectable departure from spherical symmetry or trace of inhomogeneity. The observed diameter is consistent with values based upon the measured expansion velocity, 2000 km sec^{-1}, and the approximate distance, 1.5 kpc. It is unfortunate that no spectral scan could be made because of lack of observing time. Nor was it possible to follow the

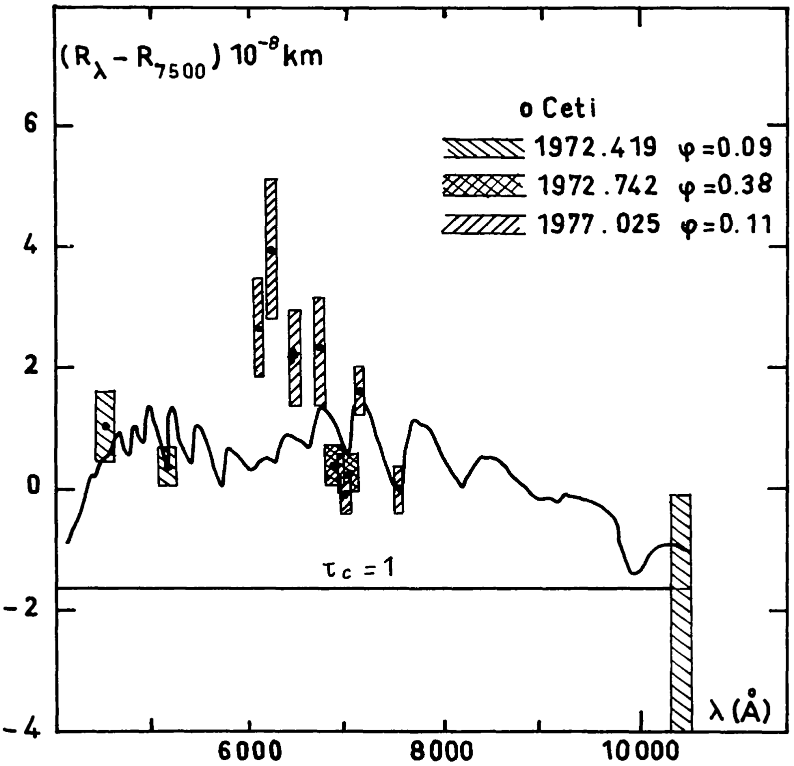

Figure 3 A strong wavelength dependance of Mira's diameter has been recently observed at Mount Palomar with the speckle interferometer. Measured sizes (rectangles) are consistent with a theoretical curve (continuus line). The atmosphere model utilized, however, does not incorporate the γ' band system of TiO at 6200 Å, and this may explain the large discrepancy at this wavelength. Diameter differences seem related to TiO opacity variations. Similar diameter variations are found on R Leonis, also a Mira-type variable (Labeyrie et al. 1977).

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expansion of the resolved shell, a typical problem with scheduled observing at very large telescopes (unpublished result of observation by D. Bonneau, D. G. Gezari, and A. Labeyrie).

Multiple stars Because it utilizes the full telescope aperture, the speckle interferometer proved rather efficient for resolving close binaries and triple stars. The traditional gap between visual and spectroscopic binaries is bridged in many cases, as a result of improved angular resolution, which is on the order of 0″015. Rather unequal pairs, showing a single-line spectrum, can be resolved up to a luminosity ratio of 100:1.

Resolving spectroscopic binaries is of particular interest since stellar masses can be determined most directly from radial velocity and angular separation measurements. Five stellar masses were already obtained in this fashion by Labeyrie et al. (1974), and three more by McAlister (1976). These new masses are consistent with the empirical mass-luminosity relation of Harris, Strand & Worley (1963).

For a systematic study of known and suspected close binaries, McAlister has undertaken a long-term observing program at Kitt Peak. At the rate of 200 stars observed per night, he has already resolved 70 pairs with separations ranging from 0″037 to 1″877. From a careful experimental evaluation of the potential for accuracy, he estimated the error on separation measurements to be 2 msec of arc. In addition, McAlister points out that orbital perturbations by hypothetical planets should be detectable more readily than with conventional astrometric methods (1977b). Whether planets are more likely to exist in binary star systems or around single stars remains a matter for experimental investigation.

On Algol, a faint companion has been discovered and repeatedly observed (Labeyrie et al. 1974). The orbital parameters identify it as the predicted third body that modulates the photometric period of the eclipsing system A-B.

Since intergalactic distance scales are based upon determinations of the distance to the Hyades cluster, it is of interest to measure accurate binary separations in this cluster. This has been achieved by McAlister (1977c), who resolved the spectroscopic binary 51 Tauri. Assuming normal masses for the components, he derived a distance modulus supporting the conclusions of Deutsch, Loewen & Wallerstein (1971). Telescopes of intermediate size can also yield useful results, as demonstrated by B. L. Morgan, D. R. Beddoes, J. C. Dainty, and R. J. Scadden (in preparation). They observed 30 binary star systems with 2.5-m and 1.9-m telescopes.

The Sun and asteroids Both speckle and Fizeau interferometers have been utilized on the Sun. A problem with extended objects lies in the very low visibility of interference features, which requires an excellent signal-to-noise ratio if large resolution gains are desired. However, existing solar telescopes do not allow large resolution gains, owing to their moderate aperture size.

Harvey & Breckinridge (1973) used both types of interferometer to check the presence of fine structure in the solar granulation. Also, the one-dimensional form of speckle interferometry carried out in a scanning mode by Aime (1976) gave accurate power spectra of the solar granulation. His detailed analysis of many observations shows the effectiveness of convective models of the photosphere.

Applying the image reconstruction algorithm of Knox & Thomson (1974), Nisenson, Ehn & Stachnik (1976) have generated "deblurred" images of solar detail. In the absence of possible verification on the Sun itself, a convincing argument in favor of the process is the similar result obtained from two independent subsets of the data. The success of Knox-Thomson reconstruction from speckled images would be welcome if it could be applied to stellar and even cosmological objects, but the crucial, yet unanswered, question is whether or not the process is disasterously sensitive to photon noise. How much resolution can be gained on faint objects remains to be investigated. It should be desirable to generate a photon-counting version of the algorithm that can be used for fully digital processing and is also suitable for faint objects.

Other solar-system objects, such as asteroids and the Saturn satellite Iapetus, have also been observed with speckle interferometers. Again, a problem has been their excessively large apparent size, which favors repeated observing with 60-inch class telescopes. A measurement of Vesta by Worden et al. (1977) is of interest in relation to the discrepancy between asteroid diameters obtained from infrared photometry and visual micrometer estimates.

3C 273 and faint objects In spite of the $m_v = 13$ to 15 limiting magnitude mentioned above for the speckle interferometer, few observations have yet been attempted on faint objects. This has occurred largely because more than enough work remains to be done on bright stars. Instead of minutes, faint objects require hours of observing time, which have proved difficult to obtain at the largest telescopes. Also needed is good "seeing," which cannot be scheduled in advance for overseas visitors.

Technically, the observations are more delicate at low levels. The discrimination of analog video pulses into digital photon events has to be flawless: a low error rate, particularly in the discrimination of close photon pairs from ion events, is enough to alter significantly the integrated autocorrelation profiles.

The attempt made by Blazit et al. (1977a) on 3C 273 has resulted in hour-long integrations featuring the central peak that characterizes unresolved objects. However, confidence in the result cannot be very high in the absence of comparison data from nearby and similarly faint reference stars. More conclusive results will be obtained with improved discrimination and observation of a nearby field star in a switching mode at 5-minute intervals.

Additional control information can also be obtained from extended faint objects, such as Pluto, for which diameter determinations are also of intrinsic interest.[2]

Because efficient work on faint objects also benefits greatly from exceptionally good "seeing," abundant results will be obtained only when speckle interferometers are permanently available to resident astronomers having frequent access to the largest telescopes.

Before space telescopes become available, a hundredfold improvement in optical resolution on QSO's, Seyfert galaxies, X-ray sources, and other poorly understood objects is possible from the ground. This should be a useful contribution to all the efforts currently being made for gaining more information on these objects.

Infrared sources At infrared wavelengths, stellar interferometry methods closely related to the optical methods discussed previously have been utilized on a few objects.

The Fizeau interferometer operated at the Mayall telescope by McCarthy, Low & Howell (1977) gave fringes providing a possible value of 1.5″ for the angular size of Betelgeuse's emitting shell at 11.1 μm. P. Léna (private communication) found that there is a large advantage, arising from throughput and multiplex effects, in using the full aperture of the same telescope in the speckle mode, with a scanning detector. His observation of Arcturus shows it to be unresolved at 3 and 5 μm wavelengths, whereas IRC 10216 is found to be 0″35 in diameter.

Both results prove the possibility of operating long-baseline interferometers at infrared wavelengths. As could be expected, infrared work in the direct interference mode seems easier than in the heterodyning mode. It is not impossible that the large N-telescope arrays currently planned or being built will also serve in the daytime for infrared work.

LONG-BASELINE INTERFEROMETERS

Only a few dozen stars, the closest red giants, shell stars, and novae, can be resolved in diameter with the "limited" class of interferometers, those mounted on existing large telescopes. Although thousands of close binaries

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[2] In his Pluto measurement (1950), Kuyper did not take into account the speckle phenomenon. The result should be considered as highly questionable nowadays.

and cosmological objects are also resolvable, there is considerable interest in increasing the angular resolution. On nearby stars, this would allow more direct confirmation of morphological models deduced from the spectral properties, the photometric variability at visible and X-ray wavelengths, etc. Among the spectacular effects that should become observable are the eclipses of Algol and the pulsations of Cepheids.

According to the elementary laws of wave optics, increased resolution requires larger instruments. Because technological factors preclude the construction of arbitrarily large monolithic mirrors, multimirror systems are necessary.

A similar necessity was apparently experienced by Nature at some point in the evolution of invertebrate animals: as the size of primitive lens-less eyes could not be increased without losing their directional waveguide properties, evolution chose to create spherical arrays of such elementary eyes. These have finally developed into the spectacular compounded eyes of insects. Are these arrays coherent? Although biologists do not seem to agree, after observing live moths, I am convinced that some of them enjoy the large luminosity advantage associated with a direct optical recombination of light captured by neighbouring fibers. It may be wondered how recombination occurs, if it does, and whether resolution is gained in addition to luminosity.[3]

The simplest form of multi-aperture system is the Michelson stellar interferometer, which is abundantly described in the literature (Hanbury Brown 1968, Labeyrie 1976). According to the principle of aperture synthesis, well publicized by radio astronomers, the pair of relatively small apertures can provide the same spatial information as a giant "filled" aperture, by varying the baseline appropriately. Luminosity is, however, proportional to aperture area.

Geometric Accuracy

Initial operation of optical interferometers raised a delicate problem of dimensional stability: in principle, the optical components of a segmented mirror system should be maintained at their assigned position within tight tolerances, comparable to those involved in figuring the shape of a monolithic mirror. This is necessary to insure temporal coherence, and possibly phasing, at the synthetic-aperture focal plane.

However, the tolerances that need to be specified in practice depend on the intended use, and especially on the spectral bandwidth chosen: (*a*) The optical structure of the intensity interferometer, as operated at Narrabri by R. Hanbury Brown and J. Davis (Hanbury Brown 1974), has

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[3] It should be possible to answer these questions by probing insect eyes with optical fibers.

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the lowest precision. (*b*) More precise geometry is necessary for the Michelson interferometer and more recent machines such as the speckle interferometer and the two-telescope interferometer. These machines are characterized by transmitted wave fronts having deformations smaller than a few wavelengths, with tilts not exceeding 1 arc-sec, thus making them better than the atmosphere, optically speaking (there is no reason to specify optical figures significantly better than the atmosphere). Adequate image analysis retrieves the diffraction-limited resolution, but does not produce images, nor does it recover the luminosity that would be obtained in the absence of atmospheric blur. (*c*) In the absence of the atmosphere, i.e. in space, or if atmospheric effects can be suppressed by active mirrors, more ambitious tolerances can be adopted for "diffraction-limited" imaging in the usual sense. These tolerances are usually specified by Rayleigh's criterion of 1/4 wave accuracy. (*d*) Meeting Rayleigh's criterion is insufficient in itself for certain critical observing modes. As demonstrated by Lyot in 1930 with his solar coronograph, the detection of faint features near bright sources can be improved if mirror bumpiness does not exceed a few angstroms of rms amplitude. The full potential of such instruments can be reached only above the atmosphere. With a 3-m space telescope, signal and noise estimates have shown that planets of nearby stars should become detectable directly, at 10^{-9} relative intensity, using a Lyot-type camera and differential image integration in a switching mode to remove the scattered-light background (Bonneau, Josse & Labeyrie 1975). A comparable instrument using active optics, rather than switched integration, to remove scattered light is proposed by Kenknight (1977).

These tolerance specifications apply regardless of aperture shape, monolithic or segmented. Understandably, the practical difficulty of meeting the tolerances increases sharply with system size in the absence of active figure control. Beam flexure is probably responsible for the disappointing career of Mount Wilson's 50-ft interferometer.

With the intensity interferometer, R. Hanbury Brown chose to utilize extremely narrow spectral bandwidths for relaxed positional tolerances. To avoid the resulting loss of luminosity, the tendency of interferometer designers nowadays is to face and solve the accuracy problem rather than to sacrifice bandwidth.

Possible Configurations

Several design philosophies have been considered, and these are well summarized in a study by the AURA engineering offices at Kitt Peak (1977). Additional material has been presented at the 1977 ESO conference in Geneva on "Optical telescopes of the future."

One of the design approaches to giant-aperture systems involves a

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single large mechanical mount supporting a mosaic of elementary mirrors. The multi-mirror telescope under construction at Mount Hopkins belongs to this category. Possible variants differ in the Cassegrain and Coudé arrangements.

Another approach involves component mirrors having independent mounts. Coudé mirrors bring all images to a common focus. Miller (1966), Odgers & Richardson (1972), Code (1973), and Labeyrie (1975) have proposed systems along these lines. The operation of a prototype system involving two small telescopes is described below.

Clearly, independently mounted mirrors are preferable for generating very large diluted apertures, whereas many mirrors on a single mount seem attractive for filled apertures of moderate size. The independently mounted systems have the added advantage that they can grow. Practical limits to their size, if any, are not yet known. Given the stable fringes

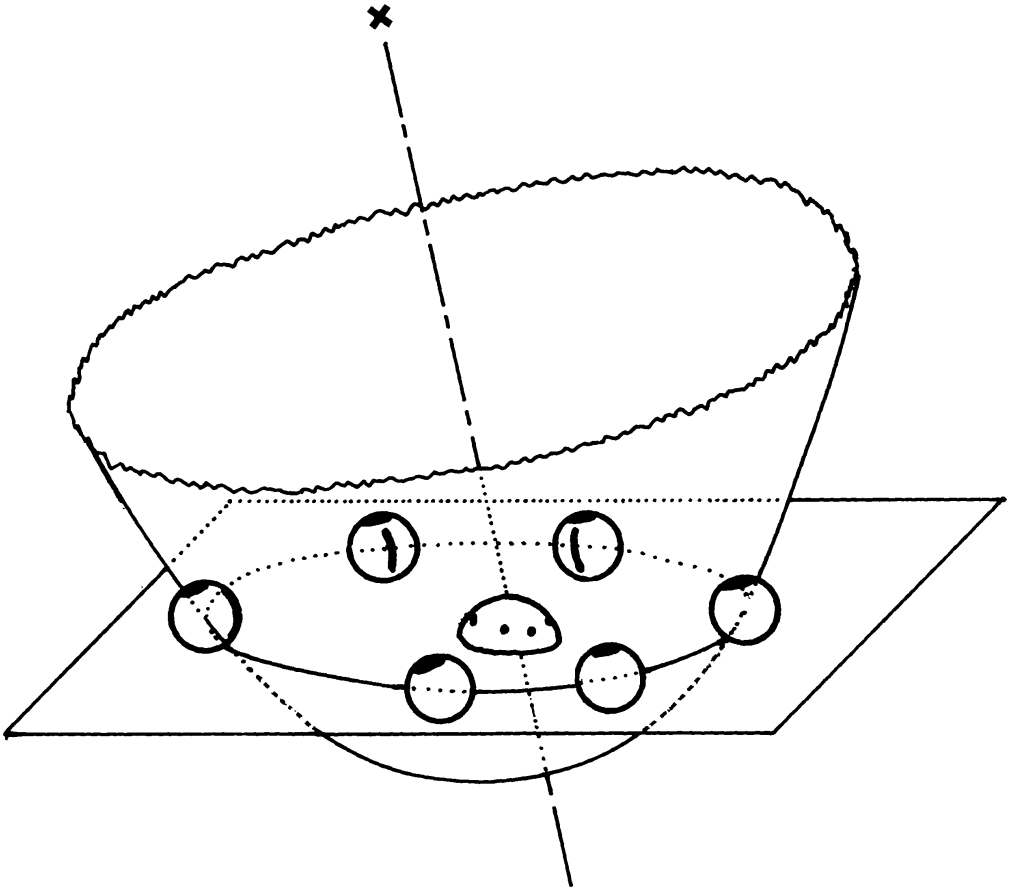


Figure 4 Ring-shaped arrays with radial tracks need no optical delay lines for path-length equalization. Zero path difference can be maintained by positioning the component telescopes along an ellipse, the shape of which varies during observation. Allowed ellipses are intersections of the ground plane with paraboloids aimed at the star. One of their foci is at the central station.

observed at CERGA with a 20-m baseline, 100-m baselines can certainly be operated.

In the single-mount, globally steered approach, small corrections must be applied to mirror positions in order to compensate for flexure of the supporting truss. When dealing with N independent telescopes, optical path variations caused by Earth rotation must be compensated for by large displacements of some element acting as an optical delay line. Optical delay lines involving sliding mirrors have been proposed, but not yet utilized in stellar interferometers.

In the prototype two-telescope interferometer, I found it more convenient to move the central station where both beams are recombined. Future ring-shaped arrays of many telescopes may use a fixed central station if telescopes are moved along radial tracks during observation. Telescopes weighing several tons can probably be moved with adequate smoothness. Generally, the ring of telescopes will have to maintain an elliptical shape, as explained in Figure 4. Such arrangements appear to provide the desired beam recombination with the least possible number of reflections. They probably represent the best approach to N-telescope systems for high-resolution work. Project "Argus", to be completed at CERGA, follows this general scheme (Figure 5).

Instead of component telescopes, heliostats have been considered in some projects. The attendant complexity of beam manipulation makes it difficult and costly to implement in large systems. Instead, component collectors in the form of conventional Cassegrain-Coudé telescopes can provide a Coudé beam of reduced diameter, requiring only one flat mirror, which can be easily manipulated in the central station and is only a little sensitive to atmospheric disturbances along the horizontal propagation path.

Air turbulence along the horizontal path can be suppressed by means of vacuum tunnels. However, wind speeds being generally lower at ground level than at higher altitudes, the corresponding contribution to "seeing" has a negligible influence on interferometric observing. This is especially true with narrow Coudé beams. In any case, insulated metal pipes should prove adequate for undisturbed propagation of Coudé beams in the most critical cases.

Toward Mass-Produced Array Components

The future development of synthetic aperture arrays is largely dependent upon what solutions will be found to the problem of mass-producing the mirror and mount components needed. A tentative solution to the mount problem is currently explored in the form of the 1.52-m spherical telescope that began operation recently at CERGA.

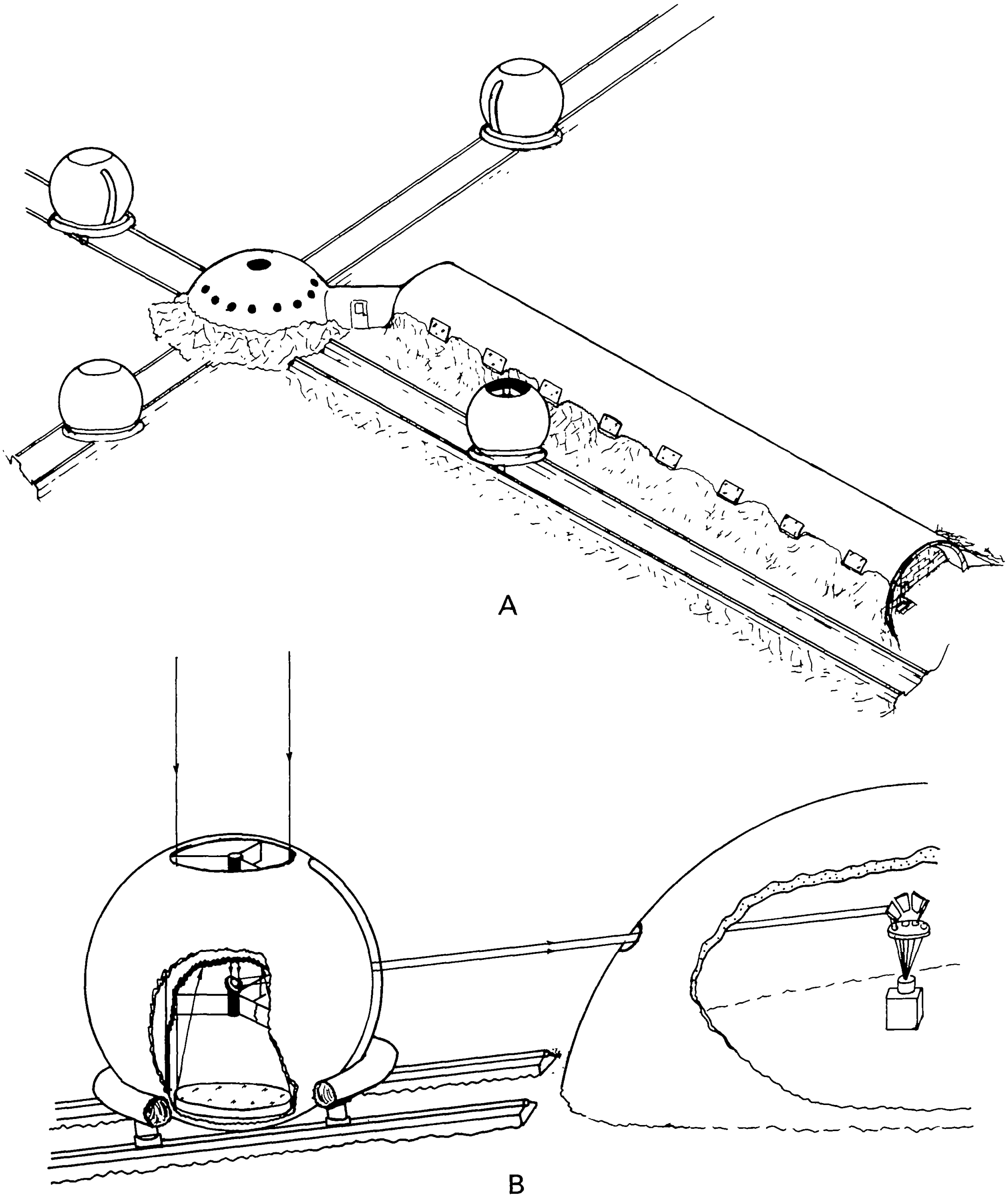
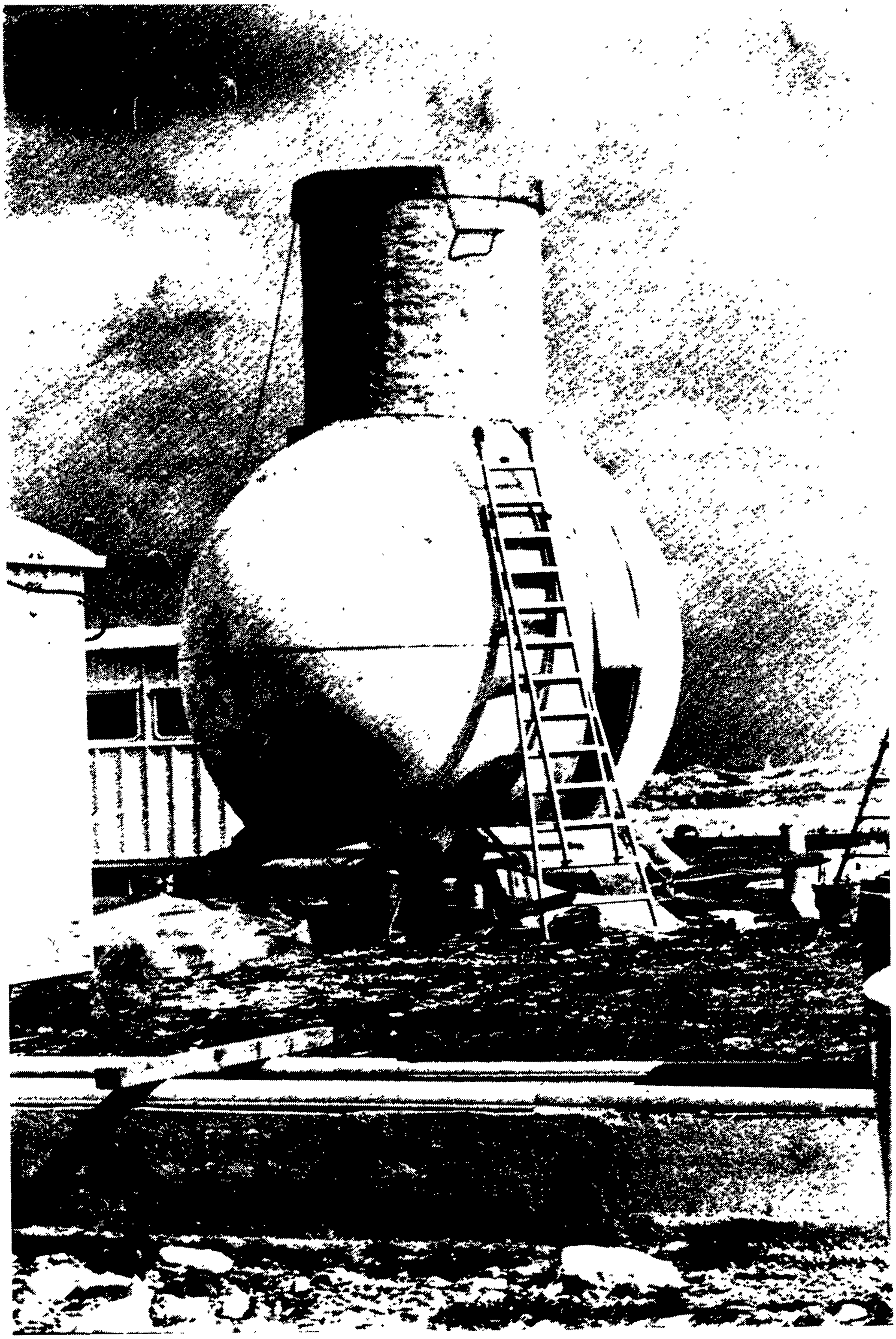


Figure 5 Initial-phase project for "Argus," the many-telescope array to be built at CERGA. *A*, building arrangement for minimum turbulence and wake; *B*, detail of Coudé arrangement. Field rotation requires tilting the set of recombination mirrors in the central station.

→

Figure 6 Prototype 1.52-m (60-inch) telescope with spherical mount, at the time of "first light." This is the first of two identical telescopes currently being built for long-baseline interferometry at CERGA. Mirrors are conventional and cost more than the mount. The 6-ton, 3.52-m sphere is made of ferro-cement and ground to be accurately spherical. The computerized drive has three degrees of rotational freedom, allowing either equatorial, alt-az or alt-alt tracking. The wind-sensitive cylindrical top of the mount can be suppressed if short-focus primaries become available. A precision mold is currently made for low-cost



production of additional spheres. If novel techniques also succeed in reducing the cost of mirrors, it will become possible to build many-telescope arrays for extreme resolution and luminosity.

As shown in Figure 6, the spherical mount consists of a concrete shell, cast and figured to accurate tolerances, which is steerable in all tracking modes by a computer-controlled mechanism of relative simplicity. The concrete structure is well suited to low-cost prefabrication techniques, and also much stiffer structurally than conventional mounts. It can be moved easily for variable baselines.

Equipped with a conventional mirror of f: 3 relative aperture, the prototype sphere is currently operated as a general purpose telescope. A second, identical telescope is being constructed for operation in the interferometer mode, with baselines in the 100- to 300-m range. The expected limiting magnitude for interference observation is on the order of 13.

The conventional mirrors in these telescopes cost more than the mounts. If many telescopes are to be made for work in the array mode, the considerable labor involved in figuring large mirrors with traditional techniques is likely to remain a major item of cost restricting mass production. Ironically, it is possible that large blanks made of glass, silica, or low-expansion vitro-ceramics can be cast and figured in space more easily than in ground-based factories. In particular, the centrifugal casting process utilized by early plateglass craftsmen may prove suitable, in space, for producing directly large paraboloidal dishes, to be figured with ion-beam techniques.

Replication techniques that have proved their value when applied to diffraction gratings should become adaptable for producing mirrors at least one or two meters in size. Such replicas cannot possess the strength, stability, and durability of hard-figured glass mirrors, but could nevertheless prove immensely useful for obtaining large collecting areas in synthetic-aperture systems.

In spite of *a priori* unfavorable characteristics, certain varieties of concrete may have enough dimensional stability for mirror blanks. Studies in the physics and chemistry of concrete aging might make it possible to select suitable compositions.

The Two-Telescope Prototype at CERGA

The only two-telescope interferometer which operates to date is the prototype instrument first installed at Nice and now relocated at the CERGA site in southern France (Figure 7). The expanded configuration, described by Blazit et al. (1977b), has a variable baseline currently spanning 40 m and potentially increasable to several hundred meters. Television systems and computer control of the optical delay mechanism made its operation relatively simple. Fully automated observing is desirable, and probably feasible, although the performance of the human eye for detecting fringes in seeing-affected images is as yet unmatched by computerized television.

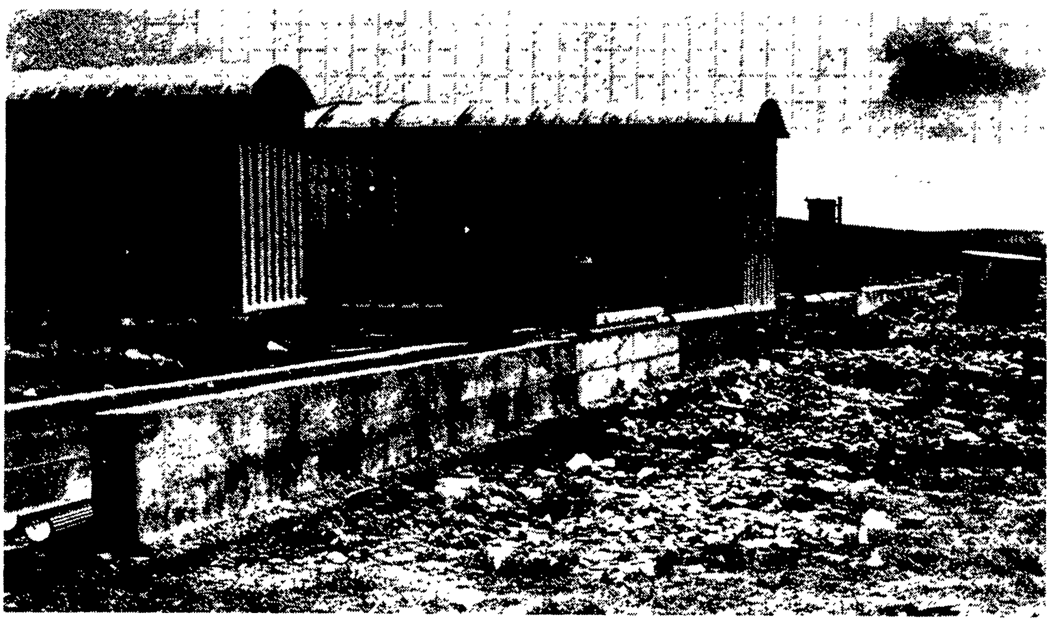


Figure 7 Two-telescope interferometer at CERGA. A 40-m pier carries two 25-cm telescopes, the Coudé foci of which meet in the central station. The telescopes roll on precision steel tracks (spanning only 20 m at the time of this photograph). The mesa site allows future baseline expansions up to 300 m for this first-generation instrument.

A basic limitation of existing photoemissive tubes lies in their moderate quantum efficiency, obviously inferior to that of the eye.

In comparison with instruments such as the 50-ft interferometer at Mount Wilson, considerable advantage is gained from the fact that the ground substrate provides a more stable system geometry than a large cantilever beam. Microseismic activity is believed to affect the fringe stability during periods of seismic storms, but no correlation has yet been made with readouts from Blum-type tiltmeters installed at the site.

With apertures having a size comparable to seeing cells, it is difficult to measure accurately the fringe visibility from which stellar diameters are derived. This is because image wander and splitting affect the superposition of intensity maxima in both images (Figure 8). Computing visibility histograms can probably help us to determine the desired peak value.

However, a more attractive solution, soon to become available, consists of utilizing larger apertures. Indeed, it follows from the principles of speckle interferometry that fringe visibility can be measured accurately, independently from the state of the atmosphere, when many seeing cells are present on the apertures. This is established in detail by Aime & Roddier (1976). For determining fringe visibilities, the other possible approach, which consists of removing "seeing" with active devices such as rubber mirrors, has a lower limiting magnitude.

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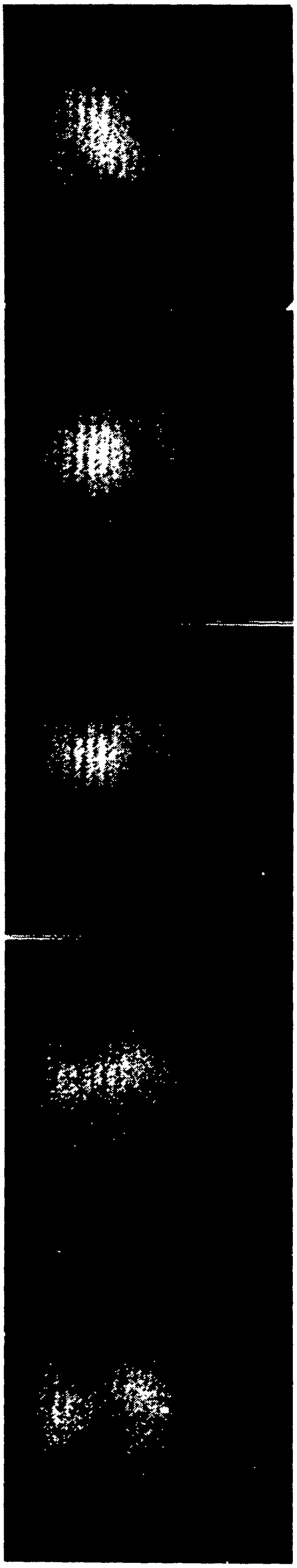

Figure 8 Fringes obtained in images of Vega with the two-telescope interferometer. Frames are recorded at 20 msec intervals with a high-gain television camera with a 400 Å bandwidth. The wandering of both images is clearly visible. Image wander tends to disappear with larger telescopes. These will allow accurate measurements of the fringe visibility to be accomplished in the speckle mode with full luminosity.

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Results with Long Baselines

Early results obtained at Mount Wilson with the 20- and 50-ft instruments were reviewed by Hanbury Brown in 1968. The intensity interferometer measurements of some 32 blue stars by Hanbury Brown, Davis & Allen have been finalized in their 1974 article, and in Hanbury Brown's book (1974), following completion of the observing program accessible to the Narrabri instrument. Matching the remarkable resolution of these long-baseline measurements is a challenging goal for builders of coherent arrays.

More recently, Kulagin observed the spectroscopic binary Capella with the Michelson-type interferometer built in Pulkovo (Kulagin 1970). This provided accurate confirmations to the highly precise orbit of Capella determined in 1920 by Anderson.

The CERGA interferometer has also begun to produce results on bright stars: Blazit et al. (1977a) have measured the sizes of Capella A and B, resolved for the first time in diameter. Prismatic dispersion of the fringed image gave simultaneous information at different spatial frequencies. Thus, for certain orbital positions of Capella A with respect to B, fringe contrast was observed to vary with wavelength, owing to the superposition of both fringe systems: this allowed a determination of both diameters as well as the projected separation. During a more recent observation (unpublished), D. Bonneau and L. Koechlin found that the Vernier effect, arising from the superposition of both fringe systems in the spectrum, yields separation measurements with 0.4 arc-msec accuracy, i.e. approximately a twentieth of the fringe spacing. Also, it appears that the visibility phase information can be extracted from the channelled spectrum, as proposed by Koechlin (1978). Whether a generally applicable method of phase recovery will eventually evolve from statistical measurements of fringe distortions in the spectrum is as yet difficult to predict, but the idea certainly deserves more investigation.

More stars were observed at CERGA with baselines reaching 20 m. Measured angular diameters are, in milliseconds: 3.1 ± 1 for ε Ursae Majoris, 4.1 ± 1 for Vega (to be compared with the intensity Interferometer value 3.08 ± 0.07), and 5 ± 0.7 for α Cygni; α Gemini, η Ursae Majoris, and γ Cygni are unresolved (D. Bonneau and L. Koechlin, unpublished observations).

INTERFEROMETERS IN SPACE

In addition to transparency at ultraviolet and infrared wavelengths, space offers the considerable advantage of suppressed atmospheric disturbances.

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Concerning the stability of their geometry at the wavelength scale, large systems floating in space are liberated from the disturbances caused on Earth by microseisms and wind. Remaining disturbances are the slowly varying thermal deformations, the occasional meteorite impacts, gravity gradients, hypothetical gravitational waves, radiation pressure from the Sun, and on-board generated vibrations.

The first space telescopes should eventually be followed by multi-telescope systems. Different configurations may be envisaged for these, ranging from beam-type structures with two apertures to arrays of independent and free-flying telescopes. In the absence of rigid structural members connecting the component telescopes, it is impractical to steer the system globally. An intermediate solution involves cables for structural linkage and slow rotation of the system for the purpose of tensioning the cables.

How about utilizing the Moon, or a large asteroid, as a stable substrate? It is certainly possible to envisage Moon-based systems resembling some of the current Earth-based projects. Their cost may unfortunately remain excessive until permanent bases are installed on the Moon.

Small systems should be considered initially. S. Vatoux, F. Wouters, and I are currently studying at Meudon a 5-m or 10-m beam arranged for permitting simultaneous observation of two stars spaced one or two degrees apart (Figure 9). In addition to star diameter measurements, which benefit from the 5X resolution gain at 1216 Å relative to the visible, the instrument can in principle provide parallax and proper motion data of extreme accuracy. Observing a faint source, QSO, Seyfert galaxy

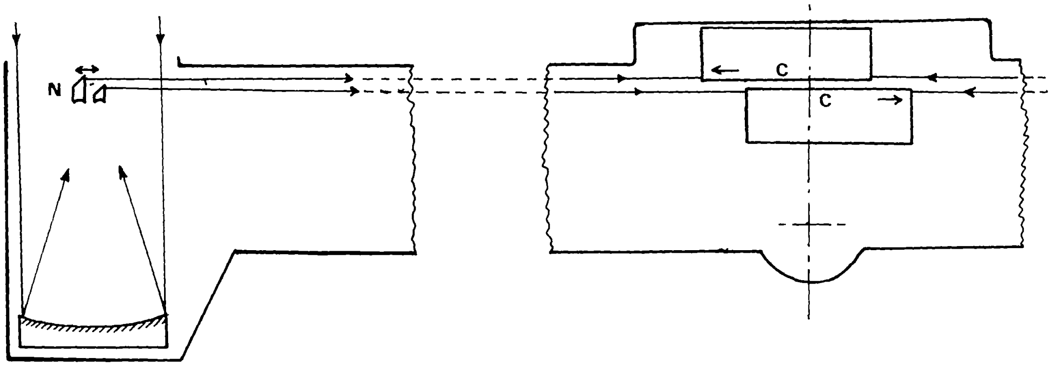

Figure 9 Configuration of a twin interferometer suitable for launch in the space Shuttle: *N*, a pair of miniature Newtonian elements, each combining a prism and a Barlow lens made of fluorine; *C*, a pair of micrometer carriages, carrying beam recombination optics. Two stars can be observed simultaneously for parallax and proper motion studies. Star separation measurements are relatively insensitive to beam flexure. The twin configuration also permits long exposures on faint objects, utilizing a nearby star as a guide for fringe stabilization.

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nucleus, or optical pulsar seems possible with a neighboring bright star serving as a guide to stabilize the fringes during integration.[4]

Needless to say, the current limits of ground-based observation will be vastly improved when large synthetic-aperture systems operate in space. At what stage, if ever, interplanetary, interstellar, or intergalactic disturbances analogous to "seeing" will finally limit the angular resolution is difficult to predict. Because this "cosmological turbulence" is likely to occur far from the solar system, within the star systems observed, it will set the ultimate limits to the possible penetration of optical instruments.

CONCLUSION

If building giant eyes is part of the normal evolutionary fate for advanced civilizations, our Earth-based civilization is now entering a critical period in this respect: within months or years, new optical structures resembling giant flowers will start blooming on certain mountains. These will improve considerably the penetration of optical observations, mainly concerning resolution. Within the last few years, the technology of telescope arrays has been tried and made ready for large-scale development. Initial observations have revealed intimate details of stellar morphology not otherwise detectable.

The experience gained in the operation of ground-based arrays will serve for designing space systems able to reach fainter limiting magnitudes and higher astrometric accuracies.

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[4] 10-m, ground-based, astrometric interferometer is also proposed by Shao & Staelin (1977), who show that atmospheric effects can in principle be removed by observing in several colors. The CERGA interferometer can also be adapted for observing two stars simultaneously. This requires splitting the small Cassegrainian mirror of each telescope.

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Notes added in proof, concerning p. 85

1. Concerning the surface detail on Betelgeuse, Wilkerson & Worden (1977) conclude that no statistically significant structure is present in the reconstructed image (Wilkerson, M. S., Worden, S. P. 1977. *Astron. J.* 82:642).

2. An important analysis now submitted by T. Tsuji (private communication) discusses the effect of circumstellar silicate grains on Betelgeuse observations. Most of the discrepancies mentioned above by Tsuji (1976a) can now be accounted for.