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Measurement of Stellar Diameters

A one-kilometer Michelson stellar interferometer is proposed for optical astronomy.

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Recent technological developments may permit construction of a Michelson stellar interferometer that is large enough to bring many objects of astronomical interest within its working range. In this article, a 1-kilometer interferometer working in the visible part of the spectrum is considered in this context and problems associated with the design and use of a very large instrument are discussed.

A large interferometer is a new kind of astronomical instrument that could provide data not otherwise available. Astronomers have not included it in their thinking about instrumentation for optical astronomy (*1*), but it should be considered, along with other major instruments, in the overall picture of future developments. Whenever a different kind of instrument is proposed, full consideration and discussion within the scientific community should precede its construction; there is a consequent need for widespread appreciation of its potentialities and limitations. The purpose of this article is to provide the basis for that discussion. Recommendations must stand on scientific merit as measured in terms of anticipated research results. The kinds of research results expected and the points at which theory most needs this kind of verification can be stated, but the value of the contribution to knowledge is a matter for judgment by the scientific community.

A stellar interferometer is designed primarily to provide one kind of datum (angular diameters) and to work principally with one kind of object (stars and starlike objects). Angular diameters are important because there are very few kinds of data that are available for stars—any additional datum is therefore very helpful. This is especially true in the case of stars for which we have no satisfactory theoretical models. Good models are lacking for stars in advanced evolutionary stages, and for almost all variable stars. Useful by-products from a large interferometer could include improved stellar distance measurements and greatly improved stellar positions (possibly 100 times better in declination than any currently available). Other by-products include precise seismic data; tidal straining of the elastic figure of the earth should be easily measurable, and wandering of the earth's rotational pole could probably be detected to accuracies on the order of a meter. A large interferometer may be useful in the study of quasi-stellar objects; if the observational problems due to faintness can be overcome, a 1-kilometer interferometer should be able to provide definitive answers concerning the extragalactic nature of these sources.

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History

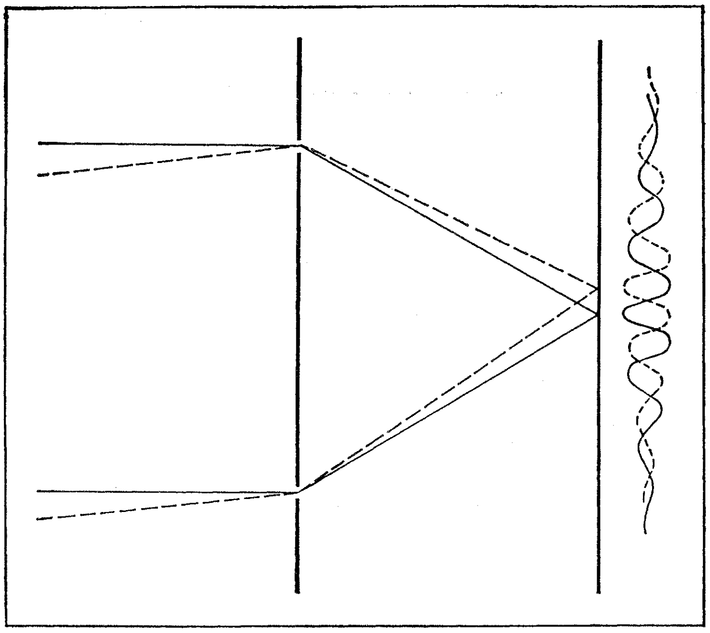
The Michelson stellar interferometer is a reconfiguration of the classic Young two-slit interference experiment (Fig. 1). Parallel light is sampled by two slits in such a way that an interference pattern appears on a screen, with an intensity distribution like that shown by the solid curve at right in Fig. 1. Light from a slightly different direction gives an interference pattern displaced from the first, as shown by the dashed curve at right in Fig. 1. With light coming from both directions, the maxima of one interference pattern can fall atop the minima of the other, and the "visibility" of the resultant fringe is reduced. Michelson defined the fringe visibility in terms of the intensity maxima and minima in the neighborhood as

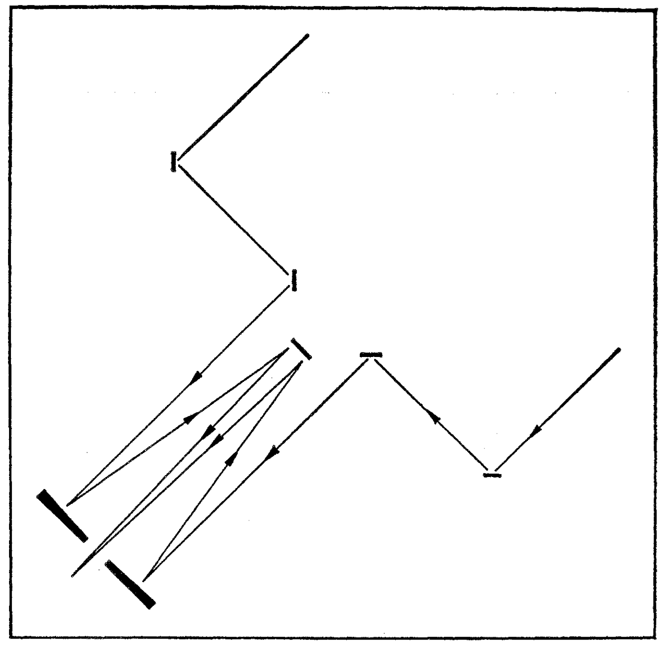
$$V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min}).$$

The same thing happens with light from a range of angles, like starlight. For one star, a measurement with the Michelson stellar interferometer consists of a determination of the fringe visibility for many different values of the spacing between the slits. The detailed shape of the curve of fringe visibility as a function of spacing contains the required information on the brightness distribution and on the angular diameter of the star.

Fizeau first proposed measuring the diameter of a star in this way in 1868 (*2*). In 1873 and 1874, Stephan (*3*) showed that star images are small compared to 1/10 second of arc when he observed fringes at all spacings allowed by an 80-centimeter refractor.

Michelson (*4*) changed the configuration of the Young two-slit experiment, as shown in Fig. 2. A crossbeam mounted at the upper end of a telescope carries a pair of mirrors to sample the incoming wave front and to bend the light into two pencils traveling toward the telescope axis. Near the axis, the pencils are redirected into the telescope by two other mirrors and merged by the telescope optics in a region where the interference pattern may be observed. Michelson and Pease used an instrument like this to measure





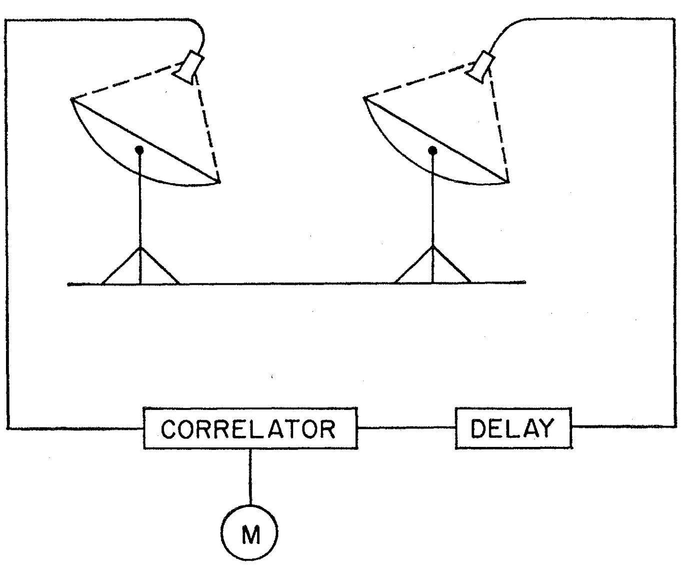
Figs. 1 and 2. Fig. 1 (left). Light paths and interference patterns in a Young two-slit interference experiment. Fig. 2 (right). Light paths in a Michelson stellar interferometer.

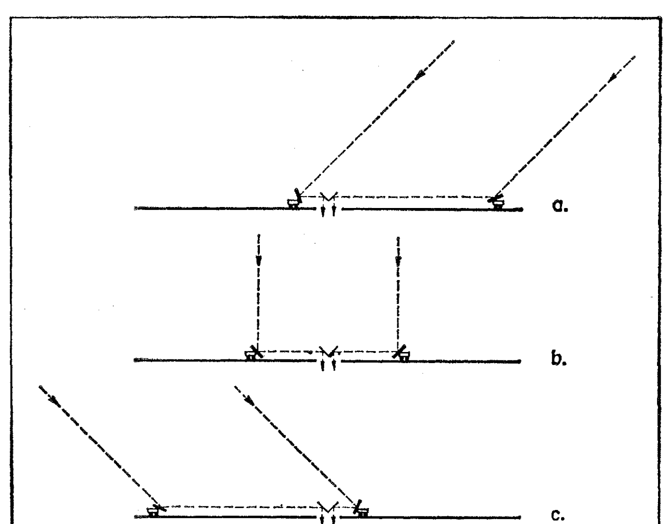
the angular diameter of α Orionis (*5*). In subsequent years Pease, working at the Mount Wilson Observatory, measured perhaps a half dozen stars, all red giants. A special 50-foot (15-meter) interferometer was constructed, but it does not seem to have given useful results. Pease reported his work in 1931 (*6*), and occasional reports appear in the annual reports of the Mount Wilson Observatory (*7*).

Michelson interferometers have been widely used in radio astronomy; the notion of "aperture synthesis" is a sophisticated application of the idea, to produce the effect of a single large aperture by many measurements with pairs (or more) of antennas. The principles are identical in the radio and optical ranges; the principal problem, in each case, is the transmission of phase information over a distance of many (10^6 to 10^8) wavelengths. In radio astronomy, this distance is many kilometers (at 21 centimeters, 10^8 wavelengths is more than the diameter of the earth!). The details are quite different in the two cases.

From Pease's work to the present, very little has been done with optical stellar interferometry. Recently, Beavers (*8*) has conducted some experiments, and Elliott and Scherb at Massachusetts Institute of Technology (*9*) have studied the problem of using automatic methods to detect the presence of fringes in very faint images. Several proposals have recently been made for the construction of specialized stellar interferometers (*10*).

The most interesting recent development in the field of stellar interferometry follows from the proposals of Hanbury Brown and Twiss (*11–15*), which have culminated in the construction of the stellar interferometer at Narrabri in Australia. Measurements have been reported on α Lyrae (*13*), and work on other stars is in progress. The method of Brown and Twiss is illustrated in Fig. 3. Light coming from





Figs. 3 and 4. Fig. 3 (left). Brown-Twiss intensity interferometer. Fig. 4 (right). Proposed configuration for a large Michelson stellar interferometer, showing dispositions of end trolleys for a star north of the observatory, overhead, or to the south. The track runs north-south, with north at right.

a distant star is sampled with parabolic reflectors at two places and is detected by means of a photomultiplier at each sampling point. The product of the photomultiplier outputs is formed in a correlator, and a comparison is made of the correlation in the fluctuations of the incoming light with the fluctuations themselves. Brown and Twiss have shown (*14*) that the normalized correlation so obtained is essentially the square of Michelson's fringe visibility, and that it can be used in the same way for inferring the stellar diameter. The photomultipliers and correlator introduce a narrow bandwidth relative to the light, making the alignment of the instrument much less critical and freeing it from troubles due to atmospheric turbulence ("seeing").

It is not clear whether the best way to build a large stellar interferometer is to follow the route of Brown and Twiss or to reexamine the methods of Michelson. Because of the statistical nature of the method, use of the Brown-Twiss intensity interferometer is limited to objects brighter than magnitude 3.5. For fainter objects, prohibitively large light gatherers are required (*15*). In principle, the Michelson stellar interferometer does not have a brightness limitation of this kind. As long as there is enough light to permit detection of fringes through the image motion caused by the astronomical "seeing," the Michelson stellar interferometer should be able to measure arbitrarily faint objects. Elliott (*9*) has estimated the level at which, in practice, a brightness limitation affects the Michelson stellar interferometer; this brightness is sufficiently faint that measurement of quasi-stellar objects (13th magnitude and fainter) may be possible. Establishment of the configuration of the Michelson stellar interferometer requires very precise measurements, since interference fringes are observable only when optical path lengths are within a coherence length. The coherence length is the distance at which the incoherent superposition of spectral components at different wavelengths no longer shows a distinct fringe pattern. With the limited amount of light available in astronomical observations, a wide spectral range must be used; ten wavelengths may be a typical coherence length. Use of narrower filters increases the coherence length, but the amount of light available for measurement decreases very rapidly. Beavers (*8*) reported having observed fringes with path-length differences as great as 250 wavelengths, with the aid of a spectroscope. Similar observations have been made by Kendall (*16*). The effective operation of the large Michelson stellar interferometer demands a very good measurement system to permit location of the interference fringes.

It is proposed that mechanical rigidity be provided through good foundations and rigid mirror mounts; that problems due to "seeing" on the crossarm (the part of the interferometer where the light rays between the two end mirrors travel toward each other) be eliminated by enclosing the light beams in a vacuum; that the instrument be built large enough to make many interesting objects observable, while the necessary precision of position measurements is retained through the use of laser fringe-counting methods; and that apertures large enough for the observation of faint objects be provided. These features should correct most of the identifiable problems that limited the usefulness of earlier attempts to build and operate stellar interferometers in the visible part of the spectrum.

The Proposed Interferometer

Light from the incoming star is sampled at two points of its wave front, but these two points are at the ends of a horizontal crossarm. The region in which fringes are sought is not at the center of the crossarm; a different configuration is required for each declination, as shown in Fig. 4. The interferometer has two trolleys, one on the north side of a center station and one on the south side. A flat mirror is mounted on each trolley to reflect the light ray along a horizontal line toward the center station (*17*). The center station stays fixed, while the trolleys can motor about to establish the required configuration. All of the optics necessary for forming the interference patterns are located in the center station. The dispositions of the trolleys to provide different mirror separations for observations on a given star are shown in Fig. 5.

From an optical point of view it would be convenient to make the crossarm parallel to the earth's rotational axis by locating the interferometer on a mountainside. The lengths of the arms of the north and south ends of the interferometer would remain constant through an observation. However, it appears difficult to mount the mirrors on a track which is not horizontal.

With a horizontal crossarm, the angle between the crossarm and the incoming light beam from the star changes as the earth rotates under the star. For fixed positions of the end trolleys, the optical path length from the equiphase surface to the center station changes during the observation. Changes in the effective length of the arms can be compensated without moving the trolleys if special controllable delay paths are introduced, as might be done with trombone slides (Fig. 6). The required changes are manageable.

Fine adjustments to bring the fringes into the center station and to keep them there can be made by means of the trombone slides. The precise positions of the mirrors on the trombone slides should be servo-controlled to establish and to maintain the equality of light paths. The end-trolley positions must be measured to the precision allowed by laser methods, to compensate for tidal straining of the earth, seismic disturbances, and so on. Frequency components above about 1 cycle per second should be removed through design and construction of a well-decoupled foundation; lower-frequency components should be within the control capability of the servos. The foundation cannot be made rigid enough to assure the required accuracy; instead the measurements system is the skeleton or framework on which the entire instrument is "mounted."

No laser fringe-counting system proposed to date would provide either the required measurement distances or the required complexity of arrangement (*18*). As many as 20 to 30 laser fringe-counters may be required, with lengths out to half a kilometer. Helium-neon laser coherence is adequate for measurements over distances greater than this (*19*), but systems operating at present seem to have a substantially smaller capability—3 to 10 meters. The principal inaccuracy arises from the dependence of the laser wavelength upon the temperature of the laser environment.

Velocities expected in the trombone slides, to compensate the path-length changes due to the earth's rotation, are about 1 centimeter per second in the worst case. Dynamic control of the trombone slides appears to be well within the error-detecting capabilities of a fringe-counting system. The mechanical design, while manageable, is quite another matter.

The trombone slides also provide extra flexibility, facilitating changeover to make measurements on another star of nearly the same declination. This will permit more effective utilization of the instrument.

The vacuum vessel should have a diameter of 1 to 2 meters, to accommodate the laser beams, as well as an aperture of 120 to 150 centimeters, and it must span the distance between the end trolleys. The changes of the interferometer that are required for work at different separations or at different declinations will require corresponding modifications of the vacuum system. The pressure in the vacuum system must be low enough to avoid loss of coherence in the light beams due to turbulence of the residual atmosphere; a vacuum in the micron range is adequate. Because the light paths of the north and south rays traverse unequal lengths in vacuum, the paths in air must be unequal also, but the dispersion of the air will cause the fringes produced by light of different wavelengths to appear at different places. Compensation for this effect does not seem difficult.

Guiding to an accuracy of about 1 second of arc (the accuracy routinely achieved with astronomical telescopes) is required. Guiding requirements would be more stringent if collimators were used at the ends to reduce the diameter of the light bundle in the crossarm.

Kinds of Measurements

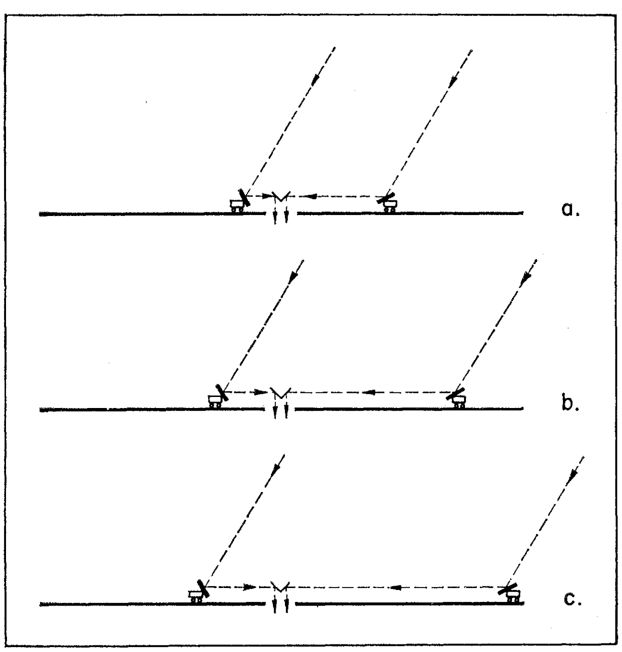
A stellar interferometer provides measurements of the (one-dimensional) Fourier transform of the brightness distribution of the object being studied (*20*). A large instrument is useful with objects of very small angular dimensions. The principal objects of study would be stellar or quasi-stellar, although some extended nebulosities that might enclose pointlike sources would also be of interest.

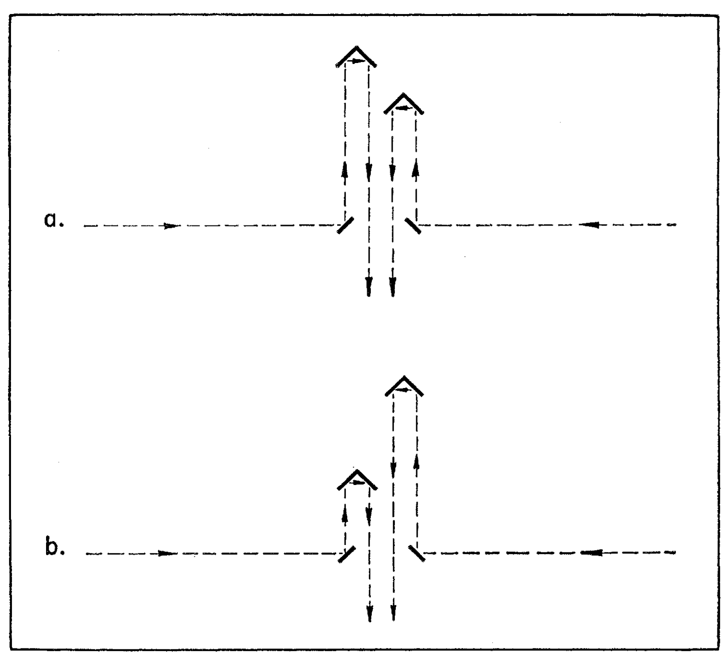
The Narrabri intensity interferometer (*12*) is built on a circular track that permits measurements at different azimuths, to develop information concerning the shape of the object. The proposed interferometer would not have that capability, but it could make use of the earth's rotation to obtain limited information about shape.

In principle, it should be possible to derive information concerning stellar limb darkening from interferometer measurements. This goal was mentioned in Michelson's proposal (*4*), and reference to it frequently recurs. In practice, it is quite difficult to derive data on limb darkening; the detailed shape of the curve of fringe visibility is affected in a subtle manner. It may be possible, by utilizing many measurements and by comparing results at different wavelengths, to obtain data concerning limb darkening in bright stars. However, this is not easy, and it is not clear that measurements of the required precision can be made. The inference of angular diameters from the observational data involves adjusting parameters of a curve for best fit to statistically uncertain data; variations in the parameters due to limb darkening will be strongly correlated to variations in the parameters governing the inferred angular diameters. The fringe-visibility curve as far out toward the first zero as possible should be utilized in the measurements. Partway to the first zero of fringe visibility the quadratic variation leads to very small decreases in the fringe visibility; it is unlikely that measurements of the precision required for reasonable angular-diameter determinations can be made without the use of a prohibitively large number of individual observations unless the measurements are carried to the first zero of fringe visibility.

Angular diameters of single stars can probably be determined to a precision of a few percent (5 to 10 percent). Conversion to linear diameters requires knowledge of the distance of the star. In many cases distances of comparable precision may not be available; then the arguments could be inverted to provide independent distance determinations of 10- to 15-percent accuracy for several thousand stars, based on other estimates of the linear diameter of the star.

While the configuration is unortho-





Figs. 5 and 6. Fig. 5 (left). Proposed configuration for a large Michelson stellar interferometer, showing dispositions of end trolleys to provide different mirror separations for observations of the same star. Fig. 6 (right). "Trombone-slide" adjustable-delay sections to compensate for changes in the effective arm lengths due to the earth's rotation.

dox, the optics of each arm of the interferometer form a standard telescope. The function is just the same as that of a standard telescope, with the added conditions of equal light paths and controlled separation. If necessary, a given object can be isolated in a field of objects by means of a diaphragm, just as it can be with a standard telescope that is being used for photoelectric photometry. The proposed interferometer would not be useful for double-star measurements (*21*), or for the high-resolution spectral analysis that is now being carried out in several places by interferometric techniques (*22*).

The setup for obtaining a point on the curve for fringe visibility plotted against separation will be complicated because of the precise measurements required. Observing programs should be worked out in which measurements on several objects are interleaved to achieve a balance between the amount of time spent making observations and the setup time. A search for the configuration which will provide maximum fringe visibility must be made after the initial setup. This search will be difficult when the fringe visibility is small, although it can be simplified by restricting the spectral width of the starlight to increase the coherence length. A spectroscope built into the fringe detection equipment can facilitate the search while utilizing all the available light (*8, 16*). By making use of the trolley positions at maximum fringe visibility, improved positional data can be obtained that may be as much as 100 times more precise than measurements obtained in any other way (in declination; the measurements in right ascension are no better than those that can be obtained with any standard telescope). The accuracy will be limited by the stability of the foundation or by the angular diameter of the star.

Objects for Study

The proposed interferometer can be expected to yield information on the angular diameter of single astronomical objects. A study of main sequence stars would seem to be the best initial program with such an instrument. Present astrophysical knowledge yields good information about the diameters of stars in the central parts of the main sequence. The Narrabri intensity interferometer can provide information

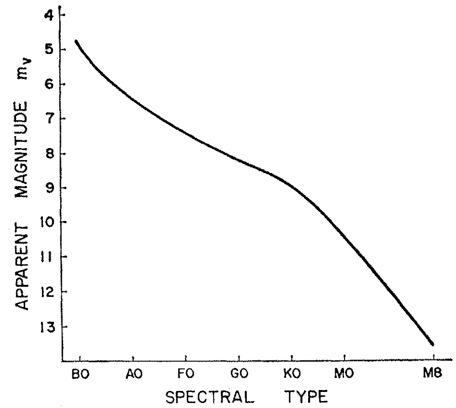


Fig. 7. Limiting apparent magnitude for stars of various spectral types for a 1-kilometer interferometer.

about the brighter blue stars in the early main sequence, but the number of stars bright enough to be studied with that instrument is limited. The late main sequence stars, particularly the M dwarfs, cannot be studied with the intensity interferometer. This is an area in which a Michelson stellar interferometer could provide very useful results. The Population II subdwarfs, about whose radii stellar models leave considerable uncertainty, present a second set of problems that can be attacked. Attention would naturally turn to objects that are less understood and perhaps more exciting than main sequence stars. Such objects include variable stars that might be studied over the range of their periods. Several cepheids would be within the range of the 1-kilometer instrument, and some variables of other types would be well within its range. A few variables have recently been shown to be very close double stars that are unlikely to be resolved into separate images; studies of these should be particularly interesting.

Finally, if measurements can in fact be made on such faint objects, measurements of the quasi-stellar objects are an important goal. The best optical estimates for angular diameters of these objects indicate that mirror separations on the order of a kilometer (an extragalactic source whose linear diameter is about 1 parsec and whose distance is 10^9 parsecs would have an angular diameter of 10^{-9} radian or 10^{-4} second of arc) may be required (*23*). The quasi-stellar objects present challenging problems other than those due to the intrinsic faintness; the brightness distribution of such an object might not lead to any zeros of the fringe visibility curve. Even so, it should be possible to place meaningful limits on the size of such an object if a measurable diminution of fringe visibility can be observed. Elliott (*9*) has proposed that quasi-stellars be studied at separations obtainable with existing telescopes.

Other Ways of Getting Diameter Data

The information now available concerning stellar diameters comes mainly from stellar models or from observations of lunar occultations and eclipsing binaries. Stellar models do not provide an adequate alternative to actual measurements of stellar diameters, since the object of observations is to check and guide the theory. In an eclipsing binary each star must have another very near to it, giving rise to perturbations whose effect is difficult to estimate. Relatively few stars are of a type which permits measurements of this kind. Similarly, relatively few stars (there are perhaps 100 good candidates) are subject to lunar occultations; those that are lie in a narrow band across the sky. The problems of brightness are very severe in any attempt to use lunar occultations for stellar measurements. A star of apparent magnitude +8, such as an M dwarf, might be expected to yield 100 to 1000 photoelectrons in a 100-inch telescope in the time it takes the moon to "turn off" the stellar image. In this same time (on the order of milliseconds) many photoelectrons will be obtained from the moonlit sky. Infrequent occurrences, irregularities of the lunar limb, and the uncertainties of weather further limit the utility of this method.

Number of Stars Resolved

An idea of the size required for a stellar interferometer may be obtained by considering ordinary stars. As the mirror separation is increased (corresponding to an increase of the distance between the slits of Fig. 1), the fringe visibility will decrease, and may vanish. The first zero of fringe visibility for a star the size of the sun at a distance of 1 parsec is about 18 meters of mirror separation (for an interferometer operating at a wavelength of 6000 angstroms, fairly generous assumptions being made about the limb darkening). The same star twice as far away would require twice this mirror separation.

A star twice as large as another of the same surface temperature (of the same spectral type) emits four times as much energy; if it were just twice as far away it would have the same angular diameter and the same apparent brightness. Thus the resolution capability of a large Michelson stellar interferometer can be displayed as a plot of limiting apparent magnitude against spectral type (Fig. 7).

The number of stars that might be studied can be estimated from data tabulated in star catalogs (*24*); such a study shows that mirror separations of 300 to 400 meters are required to obtain a good selection of stars of interesting spectral types (M dwarfs, O and B stars), while separations up to a kilometer would be useful.

Accuracy of Visibility Measurements

The problem of measuring the fringe visibility has several interesting aspects. The fringes will be distorted into irregular curves that move rapidly and irregularly because of the astronomical "seeing." They must be detected and measured under these circumstances when the image is so faint that it could not be seen with the eye.

Any error in the adjustment of the interferometer tends to make the fringe visibility less than it should properly be. The statistical distribution of errors of measurement is therefore not Gaussian but contains a component with a different distribution; the errors cannot be treated under the usual simple assumptions.

Fringe visibility is variable, at close separations, because of atmospheric conditions (*6*, *8*, *16*). A control station is needed to provide a reference for the degree of diminution of fringe visibility attributable to the quality of the "seeing."

"Seeing" affects the operation of an interferometer in two important respects: by causing relative phase shifts of the beams entering the two ends of the interferometer and loss of phase coherence within one of the apertures. It is unlikely that Michelson and Pease could have observed fringes if either of these effects had played a destructive role in the operation of their instrument. The kinds of data required for predicting the possible effect of "seeing" on an interferometer of 1-kilometer size are not currently available (*25*).

Many different factors associated with the instrument can affect the measurements: atmospheric turbulence in the crossarm, birefringence in the windows, diffraction at the windows, guidance errors, inaccuracies in the alignment of the tracks, quality and flatness of the reflecting surface, and so on. These are technical matters that can be handled through proper design.

Feasibility Study

The proposed instrument will embody several major extensions to existing techniques. Such a program should not be initiated directly; rather, questions left unanswered in this discussion should be investigated in a detailed feasibility study. Two major concerns are the practicality of making the necessary measurements and the effect of the astronomical "seeing." Both these questions should be studied with models.

The study of the measurements system involves the establishment of a laser fringe counter operating over a long path, possibly 200 meters. It also requires the construction of some small servo-operated trolleys to check the engineering feasibility of controlling the position of mechanical devices with the readouts of laser fringe counters, especially over the large distances involved. Valuable information about the extent of earth strain movements and the influence of various environmental factors might be expected from such a study. The large interferometer will require measurements substantially more accurate than any that have been undertaken over a distance of a kilometer, and some feeling must be developed for the problems to be encountered. The results should be of value to geophysics.

In the study of the influence of "seeing," the critical question is that of the loss of phase coherence over a large aperture. This loss can be studied on existing astronomical telescopes, with special interferometers that accept light from most of the aperture and measure the fringe visibility that can be obtained in cases where fringe visibility is expected to be unity. Tests should be made with various apertures, at various sites, and under various "seeing" conditions. The special interferometer used for "seeing" tests would be very similar to a standard double-star interferometer (*21*).

Integration methods for measuring fringe visibility at very low light levels, along the lines proposed by Scherb and Elliott (*9*), should be studied. Laboratory bench tests of the equipment should be followed by its incorporation into the special interferometer used for "seeing" tests. The instrument that results from this combination could be used for studies of valid astronomical interest, such as studies undertaken to set an upper limit on the size of quasi-stellar sources, as proposed by Elliott and Scherb (*9*). Production of a useful research result during the feasibility study is a worthwhile goal.

A site-selection survey might be undertaken. The same site might be used for other astronomical installations, but because of the space required for the interferometer, it is not likely that an existing observatory site would be suitable.

Future Prospects

For any instrument whose utility is so strongly dominated by "seeing," the question naturally arises, What would be gained by placing the instrument on a space station where it would be free from atmospheric effects? The Michelson stellar interferometer does not seem suitable for operation aboard an orbiting observatory because of the extremely precise guidance which is required; it must be guided to keep its ends parallel to the incoming wave front to within a few wavelengths of light during an observation. The guidance problem is therefore more severe by many orders of magnitude than any whose solution has thus far been attempted. A platform with a very large moment of inertia is required. The earth provides such a platform. Similarly, the moon might conceivably provide such a platform. An instrument of this type might be considered for a lunar observatory of a very advanced stage—for what might be regarded as a third-generation lunar observatory. In the meantime, some of the problems, such as measurements, which would be involved in the operation of the instrument appear to be sufficiently severe that it is desirable to have a working terrestrial model before any orbiting or lunar observatory is planned. An instrument like that discussed here is an essential prerequisite to any serious attempt to undertake programs of this type from a space or lunar station.

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Fungus-Growing Ants

A symbiotic relationship exists between an insect and a plant, involving an effective culturing technique.

Neal A. Weber

The fungus-growers are a New World tribe of myrmicine ants, the Attini, that has developed a unique relation with saprophytic plants. The ants eat only the fungus that they culture, and it is not found outside the ant nest. Many animals feed on fungi, and certain beetles and termites grow them in their nests, but the culturing of fungi as described here is believed to be unique. In this process a flourishing growth of one fungus is produced, and of this fungus only, although the medium on which it grows (the substrate) is suitable for the growth of many other kinds of organisms. When the ants are removed, these other organisms multiply and replace the fungus.

The vital part of the attine nest is the fungus garden. It is the abode of the queen and brood as well as of the fungus. Despite the diversity in morphology of the species, the development and care of the garden are fundamentally similar for all varieties.

Fungus-growing is distinguished from leaf-cutting. All members of this tribe subsist solely, in nature, on the fungus that they culture, but some are leaf-cutters and others are not. The latter pick up vegetal particles of suitable size, or insect excrement, and grow the fungus on these. The leaf-cutters go in files, often on well-formed trails, and cut leaves, flowers, or stems. They are most commonly members of the largest species and belong to the genera *Acromyrmex* and *Atta*. Inconspicuous *Trachymyrmex* and *Sericomyrmex* species may also cut leaves and flowers.

It is the purpose of this article to review the chief features of the life of these ants and of the fungus on which they depend. Because of the economic importance of the large species of *Atta*, and particularly of *Atta sexdens* L. in Brazil, a considerable body of literature has grown up, here summarized, and *A. sexdens* may be taken to represent a high expression of this symbiosis. Studies of other species and genera have made significant contributions to the knowledge of the biological role of the attines and are here reviewed.

Species of this tribe were listed by Linnaeus in 1758, and the type genus *Atta* was named by Fabricius in 1804. Latreille called such ants *Oecodoma* in 1818, and this name was used by the early naturalists, such as Bates, Belt, and Smith in Latin America, for the conspicuous leaf-cutters with soldiers now known as *Atta*. Mayr, from 1862 to 1865, originated the generic names *Cyphomyrmex*, *Apterostigma*, *Sericomyrmex*, and *Acromyrmex*, and he has been the chief contributor to the generic classification. Outlines of the wings, heads, and side views of the ants show differences characteristic of the genera (Figs. 1–4).

The tribe has a wide distribution, from approximately 40° north latitude to 44° south latitude (Fig. 5). The economically important *Atta* species have smaller ranges (Figs. 6 and 7). Their general distribution in South

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