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Twin light collectors on the circular track at Narrabri Observatory, New South Wales, Australia. A number of the small mirrors have been removed, for recoating, from each of the 22-foot reflectors. A boom 36 feet long supports a photoelectric detector at the focus of each reflector. This equipment has already been used to measure the angular diameter of the star Vega. All illustrations with this article, and the front cover, are from the University of Sydney.

The Stellar Interferometer at Narrabri Observatory

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During the past few years a novel type of astronomical instrument — a stellar intensity interferometer — has been under development at Narrabri Observatory in Australia. Its purpose is to measure the apparent angular sizes of stars.

If we determine the angular diameter of a star, then from its parallax we can calculate its physical size, and from its light flux its temperature can be deduced. Both size and temperature are of fundamental importance to stellar astronomy, and in particular to understanding stellar structure. Our present knowledge of the sizes of stars is mostly indirect, gained from theoretical models or from observations of eclipsing binaries. However, for a very few stars direct angular diameter measurements have been made, and astronomy textbooks usually quote the results for six stars observed with the 20-foot Michelson interferometer on the 100-inch telescope at Mount Wilson about 40 years ago. The resolving power of that interferometer was limited by the maximum separation of its mirrors to about 0.02 second of arc. Consequently, all six stars are relatively large, cool, and nearby ones in the spectral range K2 to M6.

In a subsequent Mount Wilson attempt to extend the measurements to more stars, a larger instrument was built with a maximum separation between the mirrors of 50 feet, but it was not successful and observations were discontinued about 1930.

If we inquire why this work was not carried further, we find two major difficulties in extending the resolving power of Michelson's interferometer. The diagram shows a simplified outline of the instrument. Light from the star reaches the observer by reflection at two separate mirrors, M₁ and M₂, and forms an interference pattern of alternate bright and dark bands crossing the focal image of the star. The angular diameter of the star is measured by separating the two mirrors until this interference pattern disappears. The diameter in radians is approximately equal to the wavelength of light divided by the spacing between the mirrors.

The first difficulty in designing a very large Michelson interferometer is the requirement that the light paths via the two mirrors must be very precisely equal: roughly speaking, they should differ by less than a wavelength. In practice, this requirement sets such stringent limits to any differences in flexure and thermal expansion between the two arms of the instrument, and demands such precise guiding, that a large instrument is both difficult and expensive to construct.

The second obstacle is the fact that the
The arrangement of (above) an astronomical Michelson interferometer and of (right) the intensity interferometer.

interference pattern is not stationary in the focal plane. Atmospheric scintillations introduce random and very rapid phase changes in the light paths from the star to the two mirrors, thereby distorting and displacing the pattern. This makes the instrument very difficult to use and demands extremely steady seeing.

Probably an improved version of the Michelson interferometer could now be built by using modern devices such as narrow-band filters and photoelectric detectors. Nevertheless, it is uncertain how to overcome atmospheric scintillation, nor does it seem likely that an instrument of reasonable cost could be built with sufficient resolving power to measure the very small disks of the hot stars of types O and B.

Both of these major limitations of the Michelson interferometer are avoided in the intensity interferometer. Light from a star is received on two separate mirrors, \( M_1 \) and \( M_2 \), and is focused on two photoelectric detectors \( D_1 \) and \( D_2 \). The output currents of these detectors contain a steady or d.c. component, which is rejected, together with a fluctuating or a.c. component extending over a wide range of frequencies.

It is convenient to think of these fluctuations as consisting of two distinct parts: shot noise due to the discrete charges of the photoelectrons, and wave noise due to fluctuations in the intensity of the incident light. Shot noise we can regard as being completely uncorrelated in the two detectors, but wave noise is correlated if the light falling on the two detectors is mutually coherent. Generally speaking, two light beams are said to be mutually coherent if, after combination in a suitable optical system (such as a Michelson interferometer), they can be made to interfere.

This correlation between the wave noise components is measured by amplifying the fluctuations in the outputs of the two detectors, and then evaluating their cross product in an electronic correlator. The correlation is repeatedly determined for several different separations between the two mirror-detector units, and from the results we can find the angular size of the star.

A Michelson interferometer combines the light fields at two separated mirrors to form fringes, and the observer measures the visibility of these fringes for different mirror spacings. On the other hand, with an intensity interferometer we "detect" the light at each mirror, extract the rapid fluctuations of intensity electrically, and then measure the correlation between these fluctuations as a function of mirror spacing. The relationship between the two observations is strikingly simple, for the correlation measured with the intensity interferometer is directly proportional to the square of the fringe amplitude or fringe visibility in a Michelson interferometer with the same mirror spacing.

What advantages does an intensity interferometer offer? First, there is no need for high mechanical precision either in constructing it or in guiding it on a star. Any difference between the star-to-detector light paths, or in the electrical currents from the detectors to the correlators, needs only to be less than the wavelength of the highest electrical frequency transmitted from the detectors to the correlator. Since a convenient value for this frequency is about 100 megacycles per second, corresponding to a wavelength of three meters, it is vastly simpler to build an intensity interferometer than one of the Michelson type. We can construct an extremely large interferometer without running into acute and very costly mechanical problems.

A further attraction is that the intensity interferometer does not seem significantly affected by atmospheric scintillation. Both theory and the few observations that have been made support this conclusion. This valuable property can be explained in terms of the limited range of electrical frequencies that are accepted by the correlator. If we restrict the highest frequency to 100 megacycles, the atmosphere can affect the observed correlation only if it introduces a differential time delay into the star-to-detector light paths of at least one billionth (10^-9) of a second. It is unlikely that the minor atmospheric irregularities responsible for scintillation can produce such a large effect.

Another advantage is that the results of the measurement are presented as printed numbers on a chart. Thus they are almost completely objective and independent of the observer's judgment and skill.

Nevertheless, the intensity interferometer is rather complicated and it is big. Very large mirrors are needed to reduce observing times to a few hours, even for bright stars. However, these large mirrors can be relatively crude by astronomical standards, since their principal function is to color the star image to form an optical image.

The Narrabri stellar intensity interferometer is an attempt to put the peculiar advantages of such an instrument to work in astronomy, specifically to measure the tiny disks of the hotter stars. The first stage was to build a crude pilot model with 61-inch-diameter searchlight mirrors at Manchester University in England. In 1955 this measured the angular diameter of Sirius at 0.0068 ± 0.0005 second of arc (Sky and Telescope, February, 1957, page 176). After this successful test, it was decided to build a full-scale instrument as a joint project of Manchester and Sydney universities.

The instrument itself was built in the United Kingdom and then installed at Narrabri, which is in flat pastoral country about 780 feet above sea level some 500 miles north of Sydney. Our observatory forms part of the Chatterton Astronomy Department of Sydney University.

Design of the instrument had the limited objective of measuring the angular sizes of all stars brighter than about apparent magnitude +2.5 accessible from

August, 1964, Sky and Telescope 65
The general layout of the instrument at Narrabri. This and the diagrams on page 65 are from a chapter by the author in the book, "The Universe of Time and Space," edited by University of Sidney physicists S. T. Butler and H. Messel, recently published by Pergamon Press and Macmillan.

Our latitude of 30° south. We assumed that it must be possible to determine the correlation for one baseline spacing with about 10-percent accuracy in a single observing period of not more than eight hours. For brighter stars the times would, of course, be much shorter. It is hoped by this program to improve the temperature scale for the hot stars, and to gather some new information about particular stars. For example, it may disclose double stars that lie in the present gap between visual and spectroscopic binaries, or it may prove possible to check theories of the structure of hot bright-line stars such as Gamma Velorum.

The diagram shows the layout at Narrabri. Two large reflectors are mounted on trucks which run on a circular railway track with an inside diameter of 600 feet and a gauge of 18 feet. Each reflector is controlled by a computer that calculates continuously the star's direction. To follow the star in azimuth the trucks move around the track, and to follow it in elevation the reflectors tilt about horizontal axes. In addition, the turntable carrying each reflector permits aiming directly at the star. The separation between the two reflectors can be varied from about 30 to 618 feet, and the trucks move so that this baseline remains at right angles to the star's direction. This last feature is important, because it ensures that the light reaches each mirror at the same time.

One minor complication, introduced by the garage over the southern part of the track, is that all travel of the reflectors must take place without passing through the garage. Thus, for stars that transit north of the zenith, the reflectors look outward from the track, while for stars that transit south the reflectors look inward.

The computer and control system would be able to point the reflectors with an accuracy of two or three minutes of arc, if the track were perfectly flat. But irregularities in the track, together with the clearances between the wheel flanges and the rails, introduce errors up to ±15 minutes. A photoelectric guiding system on each truck corrects these errors by making small adjustments to turntable angle and reflector elevation. The guiding phototube is mounted at the reflector's focus, alongside the main photoelectric detector, in such a way that it also compensates for any pointing errors due to flexure of the long mast supporting the equipment at the focus.

The pointing accuracy of both reflectors is monitored continuously during observation by means of a television camera at the focus, arranged to display the stars in the field of view on a monitor at the control desk. At wind speeds less than about 20 miles per hour, the overall pointing accuracy of each reflector is about ±1 minute of arc with the complete system operating and the trucks in motion.

Each truck has three electro-hydraulic driving motors and their associated servo amplifiers for controlling the three motions of the reflector. Power for the motors, together with all the control and signals, is carried by cables suspended from a catenary attached to a tower in the center of the circle. The radial pull of this catenary — about two tons — is taken by a small tender towed behind each reflector truck through an articulated joint and vibration damper. The tender has a set of wheels, mounted on vertical axles, which bear on the sides of

Through an entrance to the garage we see one of the reflectors, showing especially the grid of broad panels to which the individual mirrors are attached. At the left side of the reflector is the mechanism for turning it in altitude. The curvature of the track is well shown here.
Reflector trucks are separated by the two tenders so that, during observations on the other side of the circle, the tenders shall not restrict the minimum baseline.

Very large but optically crude, each reflector is made of a light-allow frame about 22 feet in diameter, which is paraboloidal to ensure that all the light reaches the focus at the same time. On this framework are 252 hexagonal mirrors, each mounted on an adjustable three-point suspension for focusing. Furthermore, each mirror mount can be deflected by a cam. This is useful when the mirror assembly is being focused, for by rocking a cam it is possible to identify the image of a particular mirror. Alignment of the mirrors has to be carried out by two people, one at the focus and one behind the reflector. With the reflector directed horizontally at a distant light, the individual mirrors are adjusted to bring their images into the required pattern at the focus.

The small hexagonal mirrors are of glass, front-coated with aluminum and protected with silicon dioxide. They are all of spherical figure, and at their nominal focal length of 11 meters focus all the light from a distant point source into a circle about one centimeter across. Each mirror has an electric heating pad cemented to its back to prevent the formation of dew. At Narrabri, about 12 watts per mirror was sufficient for the weather encountered in 1963.

The equipment at the focus is supported 36 feet from the mirror by a steel pole held by stainless-steel guy rods. The photoelectric detectors are in lighttight boxes, screened electrically and magnetically, into which light can be admitted through a shutter actuated electrically by the operator at the control console. Converging starlight from the reflector is first rendered parallel by a negative lens three
The control desk of the interferometer, with one reflector visible through the window at the right. On the left-hand panel are six large dials that indicate solar and sidereal time, right ascension, declination, hour angle, and the length of the base line between the reflectors. Star azimuth and altitude are shown by the large dials at the top of the center panel. Below them are two cathode-ray oscilloscopes, each driven by the star-guiding phototube at the focus of one reflector; by means of a bright spot, the scope displays continuously the direction of the star with respect to the reflector’s optical axis. Four dials show the total correction in azimuth and elevation that the star guiders have applied to the output of the computer, while six small indicators (bottom of center panel) display the error signals of the six servo systems that control azimuth, turntable, and elevation of the reflectors. Six large dials on the right-hand panel give truck and reflector positions. The console in the picture’s lower half shows further the complex controls required to operate the interferometer.

Inches in diameter, and then goes through an interference filter with a bandwidth of 80 angstroms centered at a wavelength of 4385. It is then focused by an aspheric positive lens through an iris diaphragm onto the cathode of a 14-stage photomultiplier. The output of the phototube is transmitted to the correlator through a coaxial aluminum cable suspended from the catenary.

In the original design of the reflectors, it was calculated that a star image would be roughly 0.75 inch in diameter, corresponding to an angular resolution of about six minutes of arc. The first tests showed that although an image size of 0.5 inch could be obtained with the mirror directed horizontally, the size and shape of the image varied considerably with elevation. A laborious investigation traced this trouble to flexure in one component of the framework, which is to be strengthened. In the meantime, image size over the working range of elevations is minimized by focusing the small mirrors to yield a predetermined pattern as the reflector points horizontally. Star observations show that the image can be contained within a 1½-inch circle.

The control building near the center of the track houses the console, correlator, and much auxiliary equipment, such as rotary converters and an air-conditioning plant.

Contained in the control console are the computer, the electronic circuits associated with star guiding, and all the switches and indicators needed to control the two moving trucks and reflectors. Except for parking in the garage, the reflectors are directed entirely from the console. For parking, servicing, and testing, there is a subsidiary console on each tender.

Precautions against collisions between trucks or reflectors are important, since the whole instrument must work at night without the operator being able to see the track. An ingenious system of collision probes, safety rails, and various interlocks make it impossible to run the trucks into each other or to hit one truck with the focal pole of the other. It is also impossible for an operator at the control console to bring the trucks within a dangerous distance of the garage.

The correlator accepts the noise outputs from the two photomultipliers, multiplies them together, and records their product every 100 seconds. It also measures the anode and cathode currents of the photomultiplier averaged over 100 seconds and records them as well. Although the idea is simple, the correlator was the most difficult part of the instrument to develop.

In principle, the limit to the interferometer’s sensitivity is set by statistical fluctuations in the correlator output, which in turn are determined by the statistical fluctuations in the output currents of the photoelectric detectors. Experience shows that the main problem in approaching this limit is to make a correlator that is free from spurious drifts in output. Our aim at Narrabri is to improve the correlator until such drift is negligible in observations lasting all night. This goal is not yet reached, and further modifications of the system are being made.

After the mechanical parts of the interferometer were delivered to the observatory in January, 1962, about one year was spent in assembling and adjusting them. Achieving sufficiently smooth rolling motion on the track proved un-
expectedly difficult: not only was it necessary to improve the profiles of all the wheels, but all the axles had to point more accurately to the center of the track than had been anticipated. Focusing the mirrors into a pattern that would compensate for flexure was a lengthy and tedious process.

On the other hand, it proved relatively simple to optimize the dynamical characteristics of the control system, and in particular the star-guiding servomechanism with the trucks in motion. Perhaps the worst difficulty was that the plastic coating that protected the mirrors during their voyage to Australia attacked the reflecting surface. This was only discovered after most of the mirrors had been installed on the reflectors, and about 20 percent of them had to be dismantled and returned to the makers for recoating.

The electronic correlator was delivered in January, 1963, and minor modifications and adjustments took six months. In addition to matching the electrical characteristics of the cable system and of the two channels of the correlator, the delays in the photomultiplier were equalized. In the latter operation, the two phototubes were illuminated by a very brief spark, and the arrivals of the corresponding pulses were observed with a fast oscilloscope.

Finally, the whole instrument was ready for initial tests in July, 1963. Ideally, we should have measured Sirius again, but the minimum spacing between the two reflectors is too great to allow a satisfactory measurement. Hence we chose Vega, a similar but more distant star.

The results of this successful trial have been described in detail on page 348 of the June SKY AND TELESCOPE. Here we need only mention that the angular diameter of Vega was deduced to be 0.0037 ± 0.0002 second of arc. From the known distance of this star, its linear diameter is then 5.2 ± 0.2 the sun's. A comparison with the sun yields 9.200° ± 300° Kelvin for the effective surface temperature—in good agreement with recent estimates by several astrophysicists. The temperature of Sirius from the 1955 experiment was 9.400° ± 400°.

Broadly speaking, the results of the first test on Vega were satisfactory, and the whole system worked reasonably well in view of its many novel and untried features. But the electronic correlator proved to be insufficiently stable and rather too complicated to maintain; also, the overall sensitivity was almost one stellar magnitude poorer than anticipated. Both these troubles are now being investigated. Already the correlator stability has been improved, and the loss of sensitivity has been traced to the photomultipliers. Replacing them by more highly developed models soon to become available should improve the sensitivity by roughly one magnitude. It should then be possible to measure stars as faint as +2.5 to +3.0; meanwhile the instrument will be fully occupied in measuring the brightest stars.

The equipment described in this article was designed in collaboration with R. Q. Twiss and the firms of Dunford and Elliott (Sheffield), Ltd., and Mullard, Ltd. Financial support for the project has been provided by the British department of scientific and industrial research, the University of Sydney, and the U. S. Air Force. Prof. Harry Messel organized and sponsored the project in Australia. C. Hazard, J. Davis, L. R. Allen, and Graham Gifford did most of the testing of the interferometer and made the observations of Vega.

ED. NOTE: Dr. Hanbury Brown has supplied the following technical description of the correlator's operation:

The two noise outputs from the photomultipliers are carried to the correlator, where they have a level of about one millivolt at 70 ohms and a frequency band from about 110 megacycles per second. At the correlator, one input is phase-reversed 5,000 times per second, the other input phase-reversed every 10 seconds. They are then amplified in closely matched transistor amplifiers and applied to a linear multiplier.

This multiplier is followed by a narrow-band 5-kc. amplifier and a phase-sensitive detector. The output of this detector is applied to a linear integrator, a digital voltmeter, a number-storage bank, and an electric printer. Any correlation between the two input signals appears as a 5-ke. signal at the output of the multiplier, and thus as a d.c. output from the phase-sensitive detector. This output is integrated for 10 seconds, measured by the digital voltmeter, and stored in one side of the memory bank. At the end of the 10-second period the phase of one of the inputs to the correlator is reversed, the output of the phase-sensitive detector is again integrated, digitized, and fed into the other side of the memory bank. This process continues for 100 seconds, during which the outputs of the integrators in alternate 10-second periods are added in the two halves of the memory. At the end of 100 seconds the contents of the two halves of the memory are printed, together with their cumulative difference.

The difference between these two numbers represents the correlation in the particular 100-second period, and their cumulative difference is a useful check on the total correlation observed in any 100-second periods. At the same time, separate integrators measure the average cathode and anode currents of the two photomultipliers, and a printer records these data every 100 seconds.

When analyzing the observations of a star, the correlation found in each 100-second interval is normalized by the product of the corresponding anode currents and by the gain of the correlator, the gain being measured every few hours by means of a diode noise source. It is necessary in carrying out this normalization to allow for the general night-sky brightness, and this is measured occasionally throughout the observing period.

Arthur Browne of Mullard, Ltd., operates the electronic correlator. The electric printer can be seen at the right.