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A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

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WE have recently described[1] a laboratory experiment which established that the time of arrival of photons in coherent beams of light is correlated, and we pointed out that this phenomenon might be utilized in an interferometer to measure the apparent angular diameter of bright visual stars.

The astronomical value of such an instrument, which might be called an 'intensity' interferometer, lies in its great potential resolving power, the maximum usable base-line being governed by the limitations of electronic rather than of optical technique. In particular, it should be possible to use it with base-lines of hundreds, if not thousands of feet, which are needed to resolve even the nearest of the *W*-, *O*- and *B*-type stars. It is for these stars that the measurements would be of particular interest since the theoretical estimates of their diameters are the most uncertain.

The first test of the new technique was made on Sirius (α Canis Majoris A), since this was the only star bright enough to give a workable signal-to-noise ratio with our preliminary equipment.

The basic equipment of the interferometer is shown schematically in Fig. 1. It consisted of two mirrors M_1, M_2, which focused light on to the cathodes of the photomultipliers P_1, P_2 and which were guided manually on to the star by means of an optical sight mounted on a remote-control column. The intensity fluctuations in the anode currents of the photomultipliers were amplified over the band 5–45 Mc./s., which excluded the scintillation frequencies, and a suitable delay was inserted into one or other of the amplifiers to compensate for the difference in the time of arrival of the light from the star at the two mirrors. The outputs from these amplifiers were multiplied together in a linear mixer and, after further amplification in a system where special precautions were taken to eliminate the effects of drift; the average value of the product was recorded on the revolution counter of an integrating motor. The readings of this counter gave a direct measure of the correlation between the intensity fluctuations in the light received at the two mirrors; however, the magnitude of the readings depended upon the gain of the equipment, and for this reason the r.m.s. value of the fluctuations at the input to the correlation motor was also recorded by a second motor. Since the readings of both revolution counters depend in the same manner upon the gain, it was possible to eliminate the effects of changes in amplification by expressing all results as the ratio of the integrated correlation to the r.m.s. fluctuations, or uncertainty in the final value. The same procedure was also followed in the laboratory experiment described in a previous communication[1].

There is no necessity in an 'intensity' interferometer to form a good optical image of the star. It is essential only that the mirrors should focus the light from the star on to a small area, so that the photocathodes may be stopped down by diaphragms to the point where the background light from the night sky is relatively insignificant. In the present case, the two mirrors were the reflectors of two standard searchlights, 156 cm. in diameter and 65 cm. in focal length, which focused the light into an area 8 mm. in diameter. However, for observations of Sirius, the circular diaphragms limiting the cathode areas of the photomultipliers (*R.C.A.* type 6342) were made as large as possible, namely, 2·5 cm. in diameter, thereby reducing the precision with which the mirrors had to be guided.

The first series of observations was made with the shortest possible base-line. The searchlights were placed north and south, 6·1 metres apart, and observations were made while Sirius was within 2 hr. of transit. Since the experiments were all

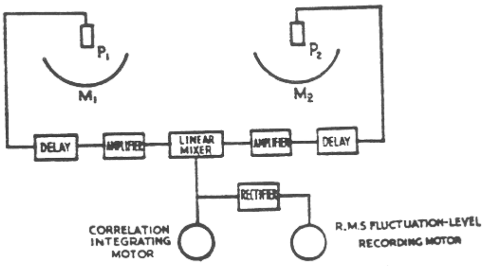

Fig. 1. Simplified diagram of the apparatus

Table 1. COMPARISON BETWEEN THEORETICAL AND OBSERVED CORRELATION

1. Base-line in metres	2·5 (N.S.)	5·54 (E.W.)	7·27 (E.W.)	9·20 (E.W.)
2. Observing time (min.)	345	285	280	170
3. Observed ratio of integrated correlation to r.m.s. deviation: $C(d)$	+8·50	+3·59	+2·65	+0·83
4. Theoretical ratio of integrated correlation to r.m.s. deviation, assuming star has an angular diameter of 0·0063″: $C(d)$	+9·35	+4·11	+2·89	+1·67
5. Theoretical ratio of integrated correlation to r.m.s. deviation, assuming star is a point source: $C(o)$	+10·15	+5.63	+5·06	+4·40
6. Theoretical normalized correlation coefficient for star of diameter 0·0063″: $\Gamma^2(d)$	0·92	0·73	0·57	0·38
7. Observed normalized correlation coefficient with associated probable errors: $\Gamma^2(d)$	0·84 ± 0·07	0·64 ± 0·12	0·52 ± 0·13	0·19 ± 0·15

carried out at Jodrell Bank, lat. 53° 14′ N., the elevation of the star varied between 15½° and 20°, and the average length of the base-line projected normal to the star was 2·5 metres; at this short distance Sirius should not be appreciably resolved.

Throughout the observations the average d.c. current in each photomultiplier was recorded every 5 min., together with the readings of the revolution counters on both the integrating motors. The small contributions to the photomultiplier currents due to the night-sky background were measured at the beginning and end of each run. The gains of the photomultipliers were also measured and were found to remain practically constant over periods of several hours.

In order to ensure that any correlation observed was not due to internal drifts in the equipment, or to coupling between the photomultipliers or amplifier systems, dummy runs of several hours duration were made before and after every observation; for these runs the photomultiplier in each mirror was illuminated by a small lamp mounted inside a detachable cap over the photocathode. In no case was any significant correlation observed.

In this initial stage of the experiment, observations were attempted on every night in the first and last quarters of the Moon in the months of November and December 1955; the period around the full moon was avoided because the background light was then too high. During these months a total observation time of 5 hr. 45 min. was obtained, an approximately equal period being lost due to failure of the searchlight control equipment. The experimental value for the integrated correlation $C(d)$ at the end of the observations is given in the line 3 of Table 1. The value of $C(d)$ is the ratio of the change in the reading of the counter on the correlation motor to the associated r.m.s. uncertainty in this reading.

In the second stage of the experiment the spacing between the mirrors was increased and observations were carried out with east–west base-lines of 5·6, 7·3 and 9·2 metres. These measurements were made on all possible nights during the period January–March 1956, and a total observing time of 12½ hr. was obtained. The observed values of the integrated correlation $C(d)$ are shown in line 3 of Table 1.

As a final check that there was no significant contribution to the observed correlation from any other source of light in the sky, such as the Čerenkov component from cosmic rays[3], a series of observations was made with the mirrors close together and exposed to the night sky alone. No significant correlation was observed over a period of several hours.

The results have been used to derive an experimental value for the apparent angular diameter of Sirius. The four measured values of $C(d)$ were compared with theoretical values for uniformly illuminated disks of different angular sizes, and the best fit to the observations was found by minimizing the sum of the squares of the residuals weighted by the observational error at each point. In making this comparison, both the angular diameter of the disk and the value of $C(o)$, the correlation at zero base-line, were assumed to be unknown, and account was taken of the different light flux and observing time for each point. Thus the final experimental value for the diameter depends only on the relative values of $C(d)$ at the different base-lines, and rests on the assumption that these relative values are independent of systematic errors in the equipment or in the method of computing $C(d)$ for the models. The best fit to the observations was given by a disk of angular diameter 0·0068″ with a probable error of ± 0·0005″.

The angular diameter of Sirius, which is a star of spectral type $A1$ and photovisual magnitude −1·43, has never been measured directly; but if we assume that the star radiates like a uniform disk and that the effective black body temperature[3,4] and bolometric correction are 10,300° K. and −0·60, respectively, it can be shown that the apparent angular diameter is 0·0063″, a result not likely to be in error by more than 10 per cent. (In this calculation the effective temperature, bolometric magnitude and apparent angular diameter of the Sun were taken as 5,785° K., −26·95, and 1,919″, respectively.) Thus it follows that the experimental value for the angular diameter given above does not differ significantly from the value predicted from astrophysical theory.

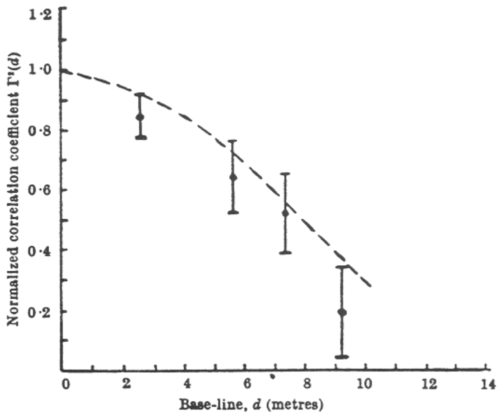

Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

A detailed comparison of the absolute values of the observed correlation with those expected theoretically has also been made, and the results are given in Table 1 and in Fig. 2. In making this comparison, it is convenient to define a normalized correlation coefficient $\Gamma^2(d)$, which is independent of observing time, light flux and the characteristics of the equipment, where $\Gamma^2(d) = C(d)/C(o)$ and $C(d)$ is the correlation with a base-line of length d, and $C(o)$ is the correlation which would be observed with zero base-line under the same conditions of light flux and observing time. The theoretical values of $\Gamma^2(d)$ for a uniformly illuminated disk of diameter 0·0063″ are shown in line 6 of Table 1. For monochromatic radiation it is simple to evaluate $\Gamma^2(d)$, since it can be shown[5] that it is proportional to the square of the Fourier transform of the intensity distribution across the equivalent strip source; however, in the present case, where the light band-width is large, the values of $\Gamma^2(d)$ were calculated by numerical integration.

The theoretical values of $C(o)$, given in line 5, were calculated for the conditions of light flux and observing time appropriate to each base-line by means of equations (1) and (2) of our previous communication[1] (though in the present experiment the r.m.s. fluctuations were smaller by a factor $1/\sqrt{2}$ than the value given in the previous paper, which refers to an alternative electronic technique). The most important quantities in this calculation are the gains and output currents of the photomultipliers and the band-widths of the amplifiers; but it is also necessary to make a small correction for the combined spectral characteristics of the photocathodes, the atmospheric attenuation, the star and the mirrors. Finally, in line 4 of Table 1 the theoretical values of the correlation $C(d)$ are shown; they were calculated from the theoretical values of $C(o)$ and $\Gamma^2(d)$ by means of the relation given above.

The correlation observed at the shortest base-line (2·5 m.) can be used as a rough test of the effects of atmospheric scintillation on the equipment, since the corresponding theoretical value depends only on well-known quantities and is almost independent of the angular diameter of the star. Throughout the observations Sirius was seen to be scintillating violently, although the corresponding fluctuations in the d.c. anode currents of the photomultiplier tubes, which were smoothed with a time constant of about 0·1 sec., were only of the order of $\pm$ 10 per cent, as might be expected with mirrors large by normal telescope standards. Nevertheless, the observed correlation $C(d) = +8{\cdot}50$ does not differ significantly from the calculated value of $+9{\cdot}35$, and it follows that it cannot be greatly affected by scintillation.

The experimental values of $C(d)$ obtained at the four base-lines may be compared with the corresponding theoretical values $C(d)$ by means of lines 3 and 4 of Table 1. However, it is more convenient, since these values depend upon the different values of observing time and light flux at each base-line, to normalize the observed values of $C(d)$ by the corresponding values of $C(o)$, so as to give the normalized correlation coefficients $\Gamma^2(d)$ shown in line 7. In Fig. 2 these experimental values of $\Gamma^2(d)$ are shown together with their probable errors, and may be compared with the broken curve, which gives the theoretical values for a uniform disk of 0·0063″. It can be seen that both the relative and absolute values of $\Gamma^2(d)$ are in reasonable agreement with theory, and that within the rather wide limits of this preliminary test there is no significant difference between the correlation predicted and observed.

In assessing the potentialities of the technique described here, it is important to note that, although the measurements took five months to complete, the visibility was so poor that the total observing time was only 18 hr., while in this limited period additional absorption of 0·25–0·75 magnitudes due to haze or thin cloud was often present. If the observations had been made at a latitude where Sirius transits close to the zenith, the improved signal-to-noise ratio, due to decreased atmospheric absorption, would have made it possible to obtain the same data in a total observing time of about four hours.

Thus, despite their tentative nature, the results of this preliminary test show definitely that a practical stellar interferometer could be designed on the principles described above. Admittedly such an instrument would require the use of large mirrors. Judging from the results of this test experiment, where the peak quantum efficiency of the phototubes was about 16 per cent and the overall band-width of the amplifiers was about 38 Mc./s., one would need mirrors at least 3 metres in diameter to measure a star, near the zenith, with an apparent photographic magnitude $+1{\cdot}5$. Mirrors of at least 6 metres in diameter would be required to measure stars of mag. $+3$, and an increase in size would also be needed for stars at low elevation because of atmospheric absorption. However, the optical properties of such mirrors need be no better than those of searchlight reflectors, and their diameters could be decreased if the overall band-width of the photomultipliers and the electronic apparatus could be increased, or if photocathodes with higher quantum efficiencies become available. It must also be noted that the technique of using two mirrors, as described here, would probably be restricted to stars of spectral type earlier than G, since cooler stars of adequate apparent magnitude would be partially resolved by the individual mirrors.

The results of the present experiment also confirm the theoretical prediction[6] that an 'intensity' interferometer should be substantially unaffected by atmospheric scintillation. This expectation is also supported by experience with a radio 'intensity' interferometer[5,7,8] which proved to be virtually independent of ionospheric scintillation. It is also to be expected that the technique should be capable of giving an extremely high resolving power. Without further experience it is impossible to estimate the maximum practical length of the base-line; however, it is to be expected that the resolving power could be at least one hundred times greater than the highest value so far employed in astronomy, and that almost any star of sufficient apparent magnitude could be resolved.

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