

Photoelectric Measurement of Lunar Occultations. I. The Process

R. EDWARD NATHER AND DAVID S. EVANS

McDonald Observatory and The University of Texas at Austin

(Received 27 February 1970)

The history of previous work on the determination of angular diameters of stars and the associated study of diffraction patterns produced by lunar occultations is reviewed. Other applications, to ephemeris theory, to astrometry, and to the detection of very close binaries are mentioned. The effects of bandwidth, telescope diameter, and spectral type on the diffraction patterns are discussed. The effects on time scale of the angle of the vertex of relative lunar motion, of latitude, and of hour angle are considered. The observation of occultations from Earth-orbiting spacecraft is mentioned. The application of the occultation technique is limited by the natural selection of stars, by the level of scattered moonlight, and by scintillation. Distortion of traces by lunar limb effects is mentioned as also are timing errors due to elevations and depressions of the lunar limb. A preliminary discussion of the type of data obtainable from observations of close double stars with "vector separations" of the order of a few arc milliseconds is given. The importance of cooperative observations at several different observatories is emphasized. A final section discusses the determination of angular diameters of stars with special reference to the selection of those likely to yield sensible values.

INTRODUCTION

WHEN a star is occulted by the dark limb of the moon the observed intensity of its light drops to zero in a very short time. MacMahon (1909) proposed that the time of disappearance could be interpreted in terms of the diameter of the star. He estimated that a star with an apparent diameter of 0.001 sec of arc should disappear in 1/500 of a second, and that this might be measurable by photographic recording techniques then available. Eddington (1909) promptly replied, showing that diffraction effects at the lunar limb from a point source star would limit the time of disappearance to about eight times this value, and suggested that the technique would be useful only for very large stars. His paper gives a drawing of the classic diffraction pattern which would be observed. Both MacMahon and Eddington indicated that the critical size of an irregularity would be about 42 ft, the size of the first Fresnel zone at the lunar distance.

A remarkable observation was reported by Arnulf (1936), who used a spinning photographic plate to detect an occultation of Regulus; diffraction fringes were observed, from which he deduced a diameter of 0".0018 for the star. Unfortunately, he gave no details of his observing procedure or data analysis, so it is difficult to evaluate the result. It is, nevertheless, in substantial agreement with the value of 0".0013 obtained for the diameter of this star by the intensity interferometer at Narrabri (Brown 1968).

Here the matter appears to have rested until Williams (1939) showed that Eddington's diffraction argument, while correct, was incomplete. While it is true that the time scale of the event is not changed by stars with apparent diameters in the range from about 0.001–0.010 sec of arc, the shape of the diffraction pattern is modified in a way that can be interpreted directly in terms of stellar diameter. Whitford (1939) had already begun a series of high-speed photoelectric observations of this type, and confirmed Williams' analysis by comparing his observations (made before the invention of the

photomultiplier) with the expected fringe pattern, suitably modified for the wide optical bandwidth of his detector. He later reported on four stars (Whitford 1946), two of which he considered to have sensible diameters, but has not published the details of his observations.

An extended series of occultations of the red supergiant Antares in 1950–1952 was observed photoelectrically in South Africa (Evans 1951; Cousins and Guelke 1953; Evans *et al.* 1954) and the diameter of this star was determined. The diameter of μ Geminorum was also reported (Evans 1959). In the case of these two stars the diameters are so great (0.040 and 0.023 sec of arc, respectively) that diffraction effects play only a minor role. The effects of lunar irregularities in the case of large diameter stars were discussed (Evans 1955).

A deconvolution technique for analysis of occultation data was proposed by Scheuer (1962) for obtaining the apparent brightness distribution of radio sources; this technique was applied by Taylor (1966) to the optical data obtained from Antares, and the brightness distribution across the star was obtained.

A discussion of deconvolution techniques applicable to the optical case will be given in later papers in this series. The matter is still under discussion, but it does appear that there may be significant differences between the optical and radio cases, particularly with respect to bandwidth. For the majority of optical cases, that is those from which only an occultation timing can be obtained, we are concerned only with sources of negligible angular diameter and for this purpose we have employed the technique of fitting the best point-source theoretical curves to the observed traces.

Application of the occultation technique to the determination of stellar diameters seems to have been inhibited by the remarkable success of the intensity interferometer (Brown 1968) and by the technical difficulties of high-speed recording and complex data analysis. Direct digital recording of data at the required speed is now possible with commercially available

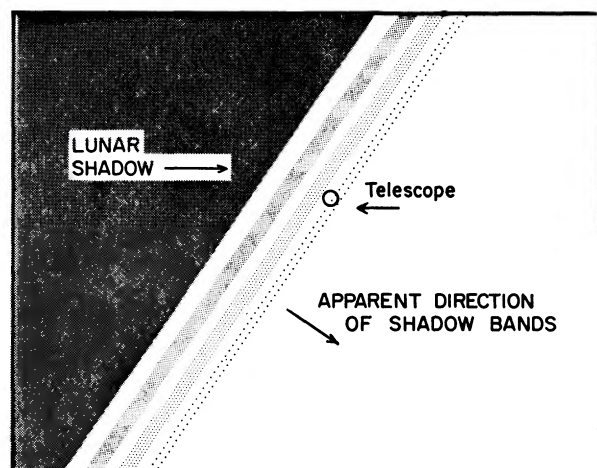


FIG. 1. A drawing of an occultation event, as the diffraction fringes from the lunar limb cross the telescope objective.

equipment, which provides output in computer-readable form, and presently available computers are sufficiently powerful to permit precise models of the process to be constructed.

The measurement of stellar diameters is not the only application of this technique, and, indeed, may not even be the most fruitful one. Occultation timings are used by the Nautical Almanac offices for the determination of Ephemeris Time and to improve the theory of the moon, while the incidental discovery of double stars has been frequent but almost totally unexploited.

As part of a program of high-speed electronic astronomy at McDonald Observatory, appropriate apparatus was constructed and a regular program of occultation observations was begun in December 1968. It is the purpose of this series of papers to describe the occultation process, the electronic equipment used, the data analysis and reduction procedures, and to report on the results of the observations so far obtained. It is hoped that this detailed information may induce other observatories to include the photoelectric observation of occultation events in their regular observing schedules.

POINT-SOURCE OCCULTATIONS

As the moon moves between a distant star and a point on the Earth's surface, it casts a shadow which moves at high speed across the landscape. The shadow is not observable because of competing light from the night sky, from the moon, etc., but would appear much like the drawing in Fig. 1 if it could be seen directly. The edge of the shadow is not sharp; it is modified by the effect of diffraction at the lunar limb into a series of alternating brighter and darker diffraction fringes. If a telescope is trained on the star during the time of fringe passage it will observe the starlight to fluctuate in intensity as the shadow bands cross its objective, and finally to disappear as the lunar shadow becomes total.

The record of these fluctuations constitutes an occultation observation.

Fringe spacing is a function of the wavelength of the detected light, and the classical pattern calculated by Eddington is observed only when the light is monochromatic. In a practical observation a band of optical frequencies is usually detected; this tends to blur the finer fringes as the optical bandwidth is increased. The effect is shown in Fig. 2. These curves were computed on the assumption that the observed star is a point source emitting an equal amount of light at all wavelengths, using the nominal sensitivity curves for a 1P21 photomultiplier tube (S-4 photocathode) both with and without the blue filter from the *UBV* set. The abscissa scale is computed for a nominal lunar distance of 384 000 km.

From the distance scale given in Fig. 2 it can be appreciated that only telescopes of limited aperture can be used without serious blurring of the fringe pattern. The amount of this blurring can be computed, and corrected theoretical curves can be constructed taking the effect into account. Some information is lost by use of a large telescope, but, at least initially, is compensated by an improved signal-to-noise ratio. The optimum size is not directly computable because the noise

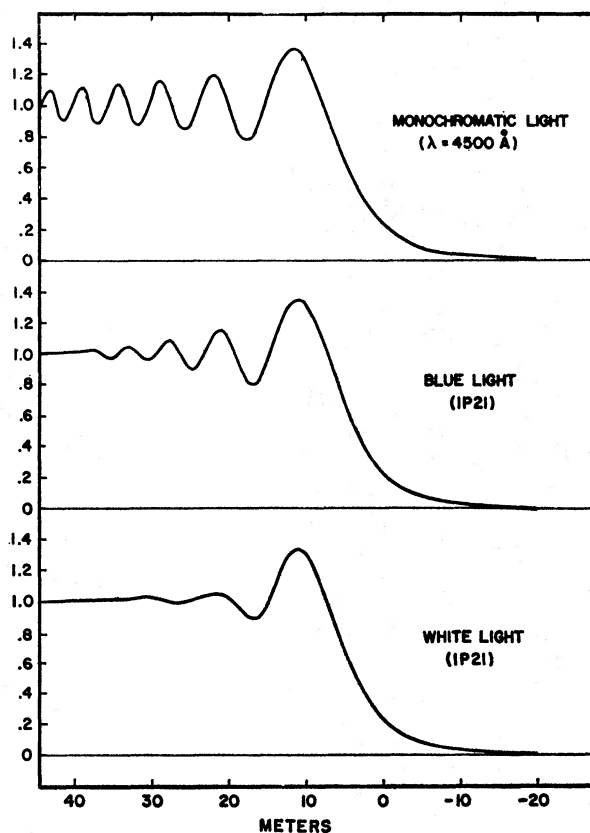


FIG. 2. Theoretical fringe patterns, showing the effects of increasing optical bandwidth (full width at half-maximum about 1000 Å for blue light and about 2200 Å for white light).

level observed for stars of moderate brightness is dominated by atmospheric scintillations whose intensity and effect vary widely from moment to moment and night to night. Since both finite bandwidth and telescope aperture result in blurring the finer fringes of the pattern, each limits the effective spatial resolution in a similar, though not identical, way. A two-meter aperture limits resolution to about $0''.001$, while a bandwidth of $\sim 200 \text{ \AA}$ (centered at $4000 \text{ \AA}$) has about the same effect.

The spectral type of the star must also be considered if the computed curve is to be used to fit the observed occultation traces. The assumption of equal brightness at all wavelengths makes computation easy but is quite wrong for either very early- or very late-type stars. For example, the computed optical bandwidth (full width at half-maximum) for the 1P21 without filter is $2200 \text{ \AA}$ centered on $3900 \text{ \AA}$, while the measurement of an M0 giant star with the 1P21 (without filter) results in an effective bandwidth of $1800 \text{ \AA}$ centered on $4400 \text{ \AA}$. The resulting theoretical fringe patterns are quite different in scale and in fringe detail.

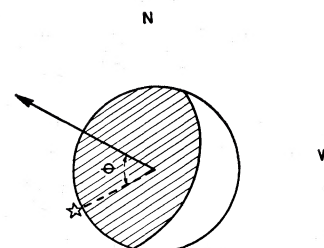
THE TIME SCALE

The moon moves at a rate of about $0.5 \text{ arc sec per sec}$ against the stellar background as seen from the center of the Earth; this results in a fringe passage rate of about 0.9 km per sec (0.9 m/ms) for a star occulted at the leading edge of the moon's disk. MacMahon (1909) recognized that the time scale of events would be modified by the angle of occultation on the disk with respect to the motion vector, and suggested that the most favorable occultations would be those nearly grazing the edge of the moon. Figure 3 illustrates this effect. The arrow indicates the direction of lunar motion, forming an angle θ with the lunar radius to the star at the point of occultation. The effective time of fringe passage, as seen from the Earth, will be lengthened by the factor $\sec \theta$. An increase in the time scale by this effect can materially improve the quality of an occultation trace.

An additional effect on the time scale must be considered. Earth rotation is in the same sense as the lunar motion and thus reduces the apparent lunar rate because of changing parallax. When the moon is on the meridian near the zenith, the effect can amount to about 50% of the lunar rate for an equatorial observer, but is diminished as latitude is increased and as the moon approaches the horizon.

It is interesting to note that an Earth-orbiting spacecraft, because of its much greater velocity, would see the moon in retrograde motion at its "meridian." This indicates some exciting possibilities for observing lunar occultations from such a platform, including a disappearance-reappearance-disappearance sequence for a star as the moon apparently moves from normal motion, through retrograde and back to normal. In favorable

FIG. 3. The arrow represents the lunar motion vector. Occultation time scale is extended by the factor $\sec \theta$.



circumstances, almost complete cancellation of apparent lunar motion can result, with occultation times measured in seconds instead of milliseconds. The complete absence of atmospheric scintillation noise would also greatly improve the quality of the data for bright stars.

As indicated in Fig. 3, lunar motion is not confined to the east-west direction; appreciable motion in the north-south coordinate is the rule rather than the exception. This allows a favorable occultation to be observed as a disappearance followed by a reappearance, both at the dark limb. We have observed two such events successfully, while a third failed because the star reappeared while the bright lunar terminator was still in the photometer diaphragm. Such dual observations of the same star are of great value for interpretation; such events are almost always near grazing, and thus have an expanded time scale.

LIMITATIONS ON THE TECHNIQUE

The most obvious limitation on the lunar occultation technique is the limited selection of stars and observation times. If clouds intervene the observation cannot be repeated after they disperse, since each event is unique. Stars very far from the ecliptic are not occulted at all. This is not quite as bad as it seems, however, since a good representative selection of stars is available, and the lunar cycle is such that a given star is often occulted several times within a relatively short period, and then not again for many years. The cycle repeats every 18.6 yr, the period of rotation of the moon's nodes.

This limitation largely determines the *modus operandi* of observations. It is natural for observers to select first objects of interest and then arrange to observe them; in our case the objects are selected by geometry and the laws of celestial mechanics. Detailed occultation predictions are available from the U. S. Nautical Almanac Office. Potentially interesting objects can be selected from this list for a given site. Our procedure is to select a series of nights particularly rich in occultations, then attempt to observe all that are possible. Useful timings can be obtained from faint stars, and any moderately bright star might show unexpected size or duplicity.

Any observation is limited by the amount of information which can be obtained during the observation time; this limit is fairly severe in the case of lunar occultation phenomena. O'Keefe and Anderson (1952) have computed the basic limitations due to the number of

photons arriving from a star during the brief time of fringe passage, and conclude that the stochastic error due to this source for stars brighter than 9th mag is negligible. They were, however, concerned only with occultation timings for geodetic measurements, while we require that the fringe pattern be defined clearly for analysis. Their equipment was designed with a time constant of about 0.01 sec; ours is normally operated with an integration time $\frac{1}{5}$ to $\frac{1}{10}$ this value. Their analysis includes the problem of scattered light from the moon, which limits the technique by minimizing the contrast between star and sky, making it difficult both to find the star and to measure the fringe pattern photoelectrically. We have successfully observed the occultation of a G8 star of mag 9.4 with the moon just past quarter; this is about the limit possible with our detecting equipment on the McDonald 36-inch reflector. The fringe pattern was lost in the noise. A more practical limit (other than for timing purposes) is indicated by the trace shown in Fig. 4. The star is seen to be double, with the fringe pattern evident though not precisely defined; the combined magnitude of the pair is 8.0.

A somewhat more frustrating limitation is imposed by atmospheric scintillation. Calculations which take into account only photon noise limitations are unreasonably optimistic. Our experience indicates that scintillation noise is the limiting factor for any star brighter than about 5th mag using the 36-inch telescope. Its effects are quite variable, however, and we have traces where the scintillation effects account for amplitude changes of 20% to 30% of the signal, and other traces where scintillation noise is too small to be measured. In the cases where the effect is severe it is possible that the star had drifted near the edge of the diaphragm, which allows a small amount of image motion to have a large modulation effect. If scintillation

effects could be predicted, it would be possible to compute an "observability index" for each occultation event. Such an index would be extremely useful in determining the optimum optical bandwidth for a given event; the importance of this selection was pointed out by von Hoerner (1964).

In his re-analysis of the Antares occultation data, Taylor (1966) noted that a major source of error in the analysis could be laid to the uncertainty in the lunar slope at the point of occultation; this has a direct effect on the time scale. It should be noted that this uncertainty exists only for stars with diameters so large that the fringe pattern is completely obscured. If the fringe pattern is observable the effective time scale of the event can be determined quite accurately from the fringe spacing. Such a measurement, when combined with the known direction and rate of the lunar motion, can be used to determine the slope of the lunar surface at the point of occultation.

Irregularities at the limb of the moon, if they are of a size comparable with that of the first Fresnel zone at the wavelength of observation, can cause serious distortion of the fringe pattern. The first quantitative investigation of this problem appears to be that of Diercks and Hunger (1952). They demonstrate that irregularities smaller than a few meters cause little or no trouble, but that hills or lumps with a characteristic size of around 16 m can cause appreciable distortion of the diffraction pattern. A mountain large with respect to 16 m is less troublesome, since it then simply appears as a displaced limb location with a characteristic slope which can be directly determined from the observed pattern. Paper III in this series (Evans 1970) is devoted to a detailed discussion of this problem.

Observations in more than one color are desirable for many reasons, and since the effective size of the first

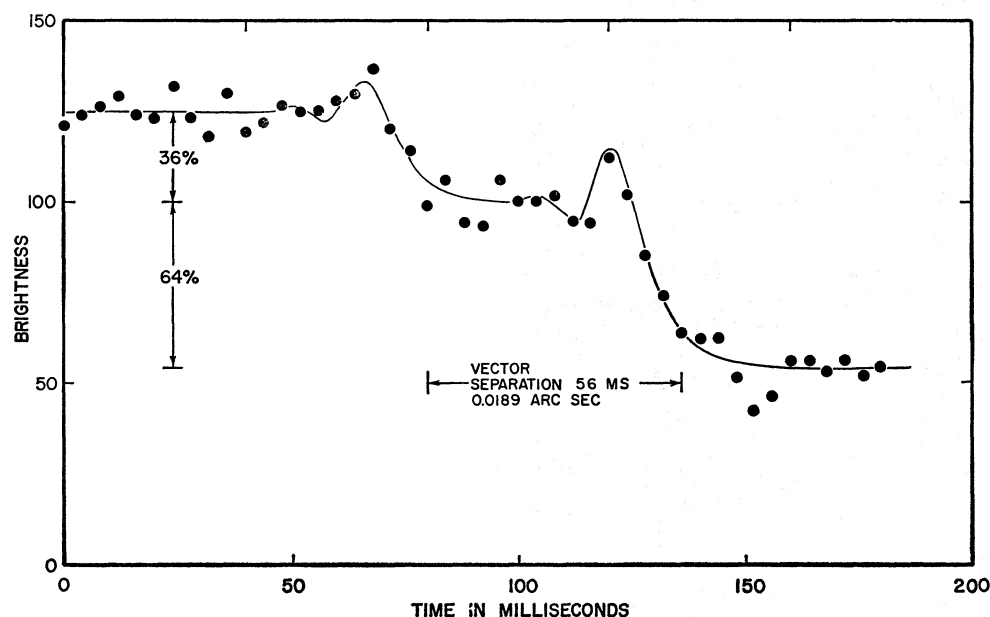


FIG. 4. Occultation trace of BD $-03^{\circ} 3289$; 1P21 without filter, combined mag 8.0. Solid curve is the fitted theoretical sum of two patterns with separation and amplitudes as indicated.

Fresnel zone is a function of wavelength, a record in two or more colors could be searched for the effects of a limb irregularity with the assurance that a given size of lump must appear systematically different in the different colors. A double point source would not be affected thus, nor would an apparent stellar diameter. At the very least, suspicious traces can be discarded if they show such a systematic effect and otherwise interpretable traces can be exonerated, particularly if observed from two different locations.

TIMING OF OCCULTATIONS

Timing the occultation of a star by the lunar limb from a known point on the Earth's surface can yield the effective position of the moon at that instant, given the distance from the limb to the moon's center and the position angle of the occultation. Limb corrections now in routine use by the Nautical Almanac Office were determined from Earth-based photographs, and represent a marked increase in precision over the assumption of a smooth lunar limb. These corrections, however, still constitute the major source of error in making use of occultation timings, limiting the accuracy of any one determination to about 0.1 sec of time. Since the actual time of an event can be determined photoelectrically to 0.001 or 0.002 sec, it is clear that measurement precision of perhaps 50–100 times greater is available but cannot be utilized. If a new set of limb corrections could be obtained, based on Lunar Orbiter or Apollo photographs (now available, or taken for this purpose in the future), much greater precision could be realized. With this possibility in mind we have made every attempt to keep our timing uncertainties to 0.001 sec or less, referred to the broadcast WWV time signals, in hopes that such measurements may have some future value when the limb corrections are better determined.

When limb corrections become available which are accurate to about 1 m, then the separation of two stars occulted by the moon on the same night can be determined with an accuracy approaching 0.001 sec of arc. Such measurements may be of real value to astronomy and perhaps to the determination of trigonometric parallaxes.

DOUBLE-STAR DISCOVERY AND MEASUREMENT

In his original proposal MacMahon (1909) mentions the discovery of stellar duplicity from “. . . peculiarities observed during occultation . . .” implying that the phenomenon was quite well known. While the oscillation frequency of the fringe patterns (ca. 50 Hz) is usually well beyond the human flicker frequency except when the occultation is near grazing, stars of about equal magnitude and separated by 0.03 sec of arc in the direction of fringe passage would be seen to disappear about 0.1 sec apart.

Visual observers have frequently reported events

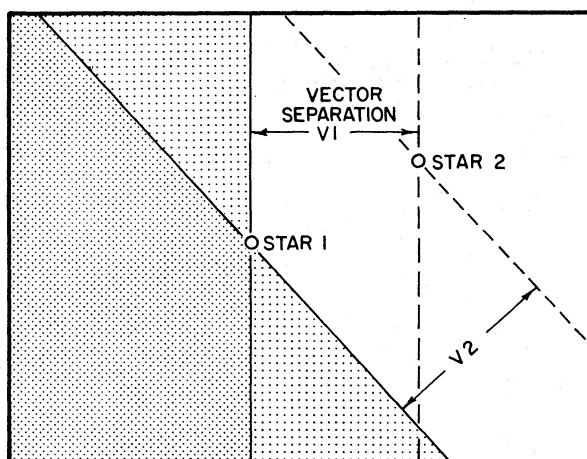


FIG. 5. A single occultation measurement of a double star gives only the vector separation V_1 ; star 2 could be anywhere along the vertical dashed line. A second measurement gives V_2 and locates star 2 precisely.

interpretable as occultations of a close pair. The first such event to be detected and measured photoelectrically appears to be that of O'Keefe and Anderson (1952). They found that the star 228B Aur is double, and measured the separation to be 0.05 arc sec in the direction of fringe passage (255°) on that date. O'Keefe had set up his observational teams so that this star was observed at exactly the same lunar position angle from all three observing stations. This was required for his geodetic purposes, but seems unfortunate since a second observation at some other lunar position angle would have defined completely both separation and position angle of the double. This is illustrated in Fig. 5. If a single occultation of a double star is obtained, the "vector separation" of the pair is measured (V_1 in the drawing) but the second star can be anywhere along the parallel dashed line. Thus, only the minimum separation between two stars is obtained, that minimum being in the direction of fringe passage. If, however, a second measurement is available at some other position angle on the moon (and hence some other direction of fringe passage) a second vector separation (V_2 in the drawing) is obtained and the combination of the two measurements serves to fix the location of the second star with respect to the first.

The desirability of having more than one observation of an occultation is immediately apparent. While a separation in the latitude of the observing stations is desirable, it is not essential; a difference in longitude on the Earth translates into a difference in position angle on the moon due to the north-south component of the moon's motion.

When two stars are sequentially occulted the observed traces will be the linear sum of the two separate fringe patterns, displaced in time corresponding to their spatial separation in the direction of fringe passage. A composite trace can thus be analyzed (see Fig. 4) and

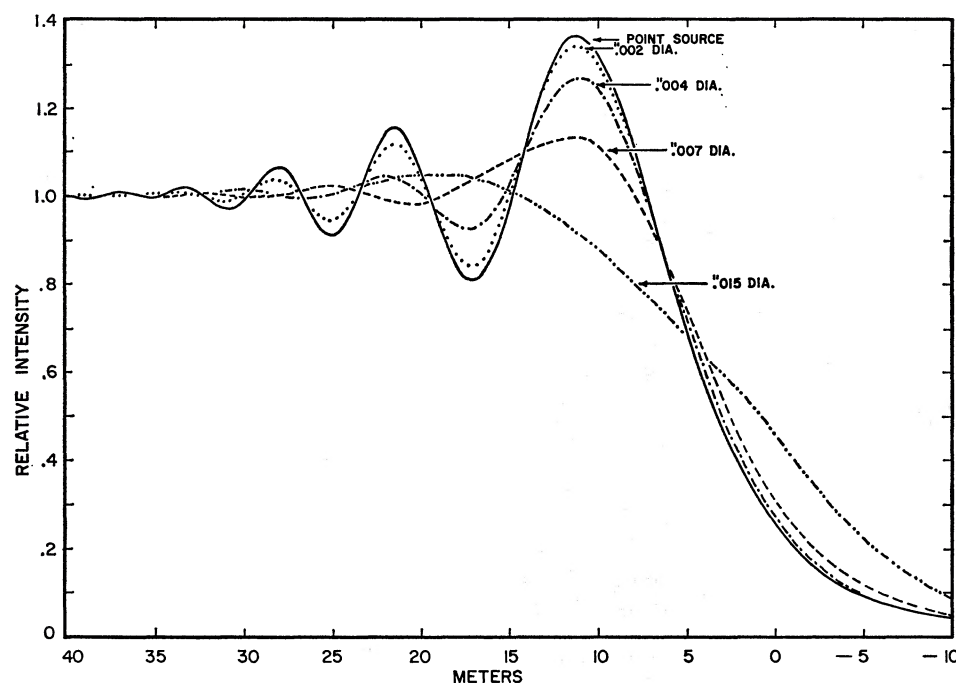


FIG. 6. Theoretical curves showing the systematic effects expected as the size of the stellar disk is increased.

the vector separation of the components and their relative intensities (in the color of the light recorded) can be determined. If traces are recorded in more than one color (perhaps by the use of dichroic filters to make maximum use of the available light) then photometry of very close double stars becomes possible.

While some occultation traces are obviously produced by close double stars (O'Keefe and Anderson 1952, and Fig. 4) the interpretation of others is more uncertain, particularly if the fringe patterns overlap or if one star is much fainter than its companion. Detectability depends in a complicated way on photon noise, scintillation distortions, magnitudes and colors of the stars, the optical bandwidth selected, and the position angle of the stars with respect to the direction of fringe passage. A certain number of doubles will fail to be detected if they are too close to be resolved by this technique, either because they are too far away, because their orbit is too small, or because they just happen to be in the wrong part of their orbit to be resolved. Discovery chances thus seem to be limited by the same factors as for the discovery of visual doubles, but with a separation scale perhaps 100 times less.

The star 27 Tau is a spectroscopic binary (Abt 1965). We have obtained an occultation trace of this star which indicates that the secondary is 1.9 mag fainter than the primary (in blue light) and the vector separation at the time of observation was 0.0061 sec of arc (Nather and Evans 1970). A trace of the same event by H. A. Poss (private communication) does not confirm this interpretation, however, and it must be considered tentative until further data are available.

In time, useful data will accumulate that allow

statistical study of the frequency of occultation binaries, supplementing the data already obtained for visual pairs and spectroscopic binaries.

STELLAR DIAMETERS

Figure 6 shows the fringe patterns which can be expected from stars exhibiting various sizes of uniformly illuminated disks, assuming the bandwidth of light detected is that defined by the "V" filter of the *UBV* system. It is clear that the departure of the patterns from that due to a point source is most marked in the finer fringes, becoming obvious in the greater fringes as the apparent diameter increases. For apparent diameters greater than 0.010 arc sec the fringe pattern is essentially obscured, but diffraction effects still play a part in defining the shape of the curves.

As the optical bandwidth is increased fewer and fewer of the finer fringes are seen, and hence sensitivity to stars of small angular diameter is reduced. If the bandwidth is chosen narrow, so that the finer fringes are well defined, they may be obscured by noise; if the width is chosen too great, the noise may be reduced but the fringes are obscured. If the apparent noise (including scintillation effects) could be predicted in advance, optimum optical bandwidth could be selected for any given star, but this does not yet seem possible. A quick measurement of the apparent noise level just prior to an occultation seems the only practical approach; the appropriate filter can then be selected for those stars expected to exhibit a measurable diameter.

Simple calculations can show the likelihood that any given star will show a sensible disk. Figure 6 shows that the limit of sensitivity is probably about 0.001 to

0.002 sec of arc, if a bandwidth of 500–1000 Å is chosen. If we know the spectral type and luminosity class for a star, we can compute its expected absolute magnitude; from this and its apparent magnitude we can determine its probable distance, and hence its probable diameter. Using the relationship

$$m - M = 5 \log (\text{distance in pc}) - 5 + A, \quad (1)$$

where m is the star's apparent magnitude, M its absolute visual magnitude, and A the interstellar absorption (for our purposes we will neglect the absorption, since this will give us a conservative estimate of a star's expected diameter), we can solve for the apparent distance of the star in parsecs. This can be converted into an apparent diameter:

$$\log d_* = \log d_\odot + \log R/R_\odot - \frac{1}{5}(m - M + 5), \quad (2)$$

where d_* is the apparent diameter of the star in arc seconds, $d_\odot$ is the diameter of the sun in a.u., and $R/R_\odot$ is the ratio of the star's radius to that of the sun.

Values tabulated by Allen (1953) for $\log R/R_\odot$ can be substituted in Eq. (2) to determine the expected angular diameter of a star, and we can then compare the computed diameter with some of the measurements reported by Brown (1968) for different spectral types and luminosity classes. This comparison is shown in Table I.

This comparison is intended to be indicative only, to serve as a guide to the selection of likely candidates for observation. The differences between computed and observed values should not be emphasized and arise from the neglect of interstellar absorption, from Allen's adoption of mean values for particular spectral types, and from considerations connected with the assumption of particular limb-darkening coefficients. Closer consideration of these topics will be given in further publications.

Figure 7 shows the results of a computation in which Eq. (2) was solved for the apparent magnitude m and the value of d_* was established at 0.001 sec of arc. It shows, as a function of spectral type and luminosity

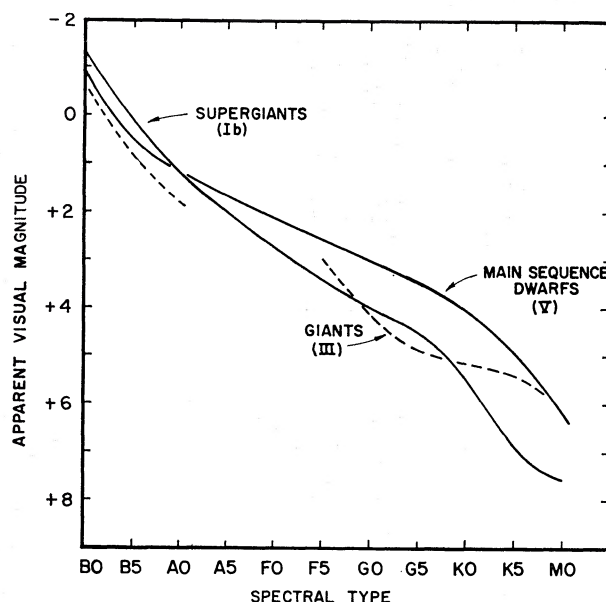


FIG. 7. In order to be a candidate for a diameter measurement, a star must lie on or above the curve for its luminosity class. Curves are based on a uniform disk 0.001 arc sec in diameter.

class, the apparent magnitude a star must have in order to display a barely detectable diameter.

It may be a cause for surprise that the prospects for measurement of a sensible angular diameter are only little dependent on luminosity class, particularly since at some spectral types supergiants have linear diameters hundreds of times as great as dwarfs. This lack of dependence is important in the selection of stars for observation. As can be readily shown, if ϕ is the angular diameter, T_e the star's effective temperature, and m_b the bolometric magnitude, then for any star $\log \phi + 2 \log T_e + 0.2 m_b$ has a constant value, equal to that found for the sun. At a given visual apparent magnitude and spectral type, the only difference between luminosity classes arises through the often minor differences in effective temperature and bolometric correction. Thus any M-type star brighter than 6th mag is a candidate, as is any star brighter than 3rd mag and later than G0. Blue stars must be much brighter in order to qualify.

It would seem that occultation measurements of stellar diameters can profitably supplement the measurements made with the intensity interferometer, which is most effective in measuring blue stars but is unable to measure red stars at all (Brown 1968). The few very bright blue stars which are occulted (e.g., α Leo, β Tau) can be used to intercompare the two methods.

CONCLUSIONS

Photoelectric observations of lunar occultations can provide useful and important astronomical information of several different kinds. Timings provide data from

TABLE I. Comparison of computed and measured star diameters.

Star	Spec.	m_{vis}	Computed dia. (10^{-3} arc sec)	Measured dia. (10^{-3} arc sec)	Method
γ Ori	B2 III	1.7	0.4	0.7	I
α Eri	B5 IV	0.6	0.9	1.9	I
α Leo	B7 V	1.3	0.9	1.3	I
α Aql	A7 V	0.9	1.5	2.8	I
α Car	F0 Ib	-0.9	5.1	6.9	I
α CMi	F5 V	0.5	2.6	5.3	I
α Boo	K0 III	0.2	11	20	M
α Tau	K5 III	1.1	15	20	M
β And	M0 III	2.4	10	11	M

Method I is the intensity interferometer of Brown and Twiss; method M is the Michelson interferometer, measurements by Pease, as reported by Brown (1968).

which Ephemeris Time is routinely determined and contribute toward improvements in the lunar theory. Stellar diameters of bright stars can be measured which supplement measurements by the intensity interferometer, particularly for red stars which are not accessible to that instrument. Double stars can be discovered and their important parameters measured for separations about 100 times smaller than for any other technique. A routine program of occultation observations can be expected to contribute materially in all of these areas.

The nature of the measurements is such that multiple observations by observers at different locations are needed to exploit the potential of the method fully. The unique nature of an occultation event precludes its repeated measurement from the same location and makes cooperative observations by several different observatories essential. It is hoped that this series of papers will provide the incentive for others to consider seriously the addition of a routine program of lunar occultation measurements to their observing programs.

REFERENCES

- Abt, H. A. 1965, *Astrophys. J.* **142**, 1604.
 Allen, C. W. 1953, *Astrophysical Quantities* (Athlone Press, London), 2nd ed.
 Arnulf, M. A. 1936, *Compt. Rend.* **202**, 115.
 Brown, R. H. 1968, *Ann. Rev. Astron. Astrophys.* **6**, 13.
 Cousins, A. W. J., and Guelke, R. 1953, *Monthly Notices Roy. Astron. Soc.* **113**, 776.
 Diercks, H., and Hunger, K. 1952, *Z. Astrophys.* **31**, 182.
 Eddington, A. E. 1909, *Monthly Notices Roy. Astron. Soc.* **69**, 178.
 Evans, D. S. 1951, *ibid.* **111**, 64.
 —. 1955, *Astron. J.* **60**, 432.
 —. 1959, *Monthly Notes Astron. Soc. S. Africa* **18**, 158.
 —. 1970, *Astron. J.* **75**, 589 (Paper III).
 Evans, D. S., Heydenrych, J. C. R., and Van Wyk, J. D. N. 1954, *ibid.* **113**, 781.
 Hoerner, S. von 1964, *Astrophys. J.* **140**, 65.
 MacMahon, P. A. 1909, *Monthly Notices Roy. Astron. Soc.* **69**, 126.
 Nather, R. E., and Evans, D. S. 1970, *Astron. Astrophys. Suppl.* (to be published).
 O'Keefe, J. A., and Anderson, J. P. 1952, *Astron. J.* **57**, 108.
 Scheuer, P. A. G. 1962, *Australian J. Phys.* **15**, 333.
 Taylor, J. H. 1966, *Nature* **210**, 1105.
 Whitford, A. E. 1939, *Astrophys. J.* **89**, 472.
 —. 1946, *Sky and Telescope* **6**, 7.
 Williams, J. D. 1939, *Astrophys. J.* **89**, 467.