# THE SCOPE OF THE LUNAR OCCULTATION TECHNIQUE FOR MEASUREMENT OF STELLAR ANGULAR DIAMETERS

Stephen T. Ridgway
Kitt Peak National Observatory, Tucson, Arizona 85726

## ABSTRACT

This review of the lunar occultation technique summarizes results of 94 diameter measurements for 62 stars. The range of angular diameters measured, the coverage of spectral types, and the wavelengths studied are illustrated and discussed. Comparison with other techniques, magnitude limits and possible future developments are also considered.

## 1. INTRODUCTION

Almost 70 years ago, MacMahon[1] suggested that stellar angular diameters could be measured from a recording of the light flux obtained as the moon occulted a star. Systematic implementation of the technique became possible with the development and availability of fast digital data recording systems. Only within the last four years, however, have the results obtained with the occultation technique contributed significantly to measurements of the fundamental stellar parameters - angular diameter and effective temperature. Rapid development of the occultation technique has now fully justified the confidence of early workers in this erstwhile lonely enterprise.

Initial skepticism about the occultation method, though due in part to a hesitation to use a "gimmick" to obtain a fundamental measurement, can also be attributed to several clear shortcomings of the method. These include the severely restricted number of opportunities, the brevity of the events, deviations of the lunar limb from assumed perfection, and the interfering effects of scintillation. While the number of opportunities is indeed limited, it is sufficient (as will become clear below) to obtain good statistics for high luminosity members of the late spectral classes. The temporal frequency content of an occultation event is, in fact, well matched to the observational bounds set by low frequency scintillation on one hand and photometer response

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

on the other. Within the electrical bandwidth carrying the diameter information scintillation is usually low[2]. The data analysis procedures diagnose serious distortions due to lunar limb irregularities[3]. Multichannel photometry readily discriminates limb effects from stellar multiplicity[4]. Less obvious interference due to subtle limb irregularities may produce "noise", but such noise is evidently small by standards of our current state of the art.

In the face of these possible problems and limitations, we find substantial reason to believe that the occultation technique actually works quite well. This conclusion is based on three points: internal consistency of each observation, external consistency in intercomparison of observations, and consistency of astrophysical implications.

Internal quality of the data can be illustrated by specific observations. The disappearance of the M0.5 giant BD+16°625 (V = 6.92) is shown in Figure 1. This event was recorded at the Coudé focus of the KPNO 4 m Mayall telescope at a wavelength of 2.2 μm. This observation was recorded in the *daytime*. The fringe pattern is relatively long because the stellar diameter is small (our analysis yields a diameter 2.92 ± 0.15 milliseconds of arc). The substantial detail in the observed data string is reproduced well by the 5 parameter model (time of event, stellar flux, background flux, local lunar slope and stellar diameter). It appears, from the quality of the fit, that the model assumptions are not grossly violated. It is also interesting to note that owing to the circumstances of the event (star offset substantially from the center line of the moon's path) the line of sight to the star "slid" along the lunar limb approximately 60 meters during the recording of the prominent fringes. The excellent model fit is thus evidence for a smooth lunar limb at the point of disappearance. The residual error of fit may be a measure of limb roughness.

With increasing observational activity, multiple measurements are becoming available for some stars. At present, repeat observations are available for 19 stars (average 2.6 observations/star). An earlier study of a subset of these results strongly indicated that independent measurements are consistent to within the bounds estimated from purely internal error estimates[2].

Finally, studies based on observed angular diameters[5,6] show both internal consistency and consistency with other types of observational material. These

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

and other considerations convince us that the occultation technique is working well at its present state of sophistication.

The basic features of occultation events, their observations and analysis, were treated very early in the game[4,7-10]. Our present purpose is to review recent activity in this area. Topics discussed below include productivity in recent years, range of angular diameters measured, error levels, cross checks with interferometric techniques, spectral type coverage, wavelength coverage, magnitude limits, and expected developments.

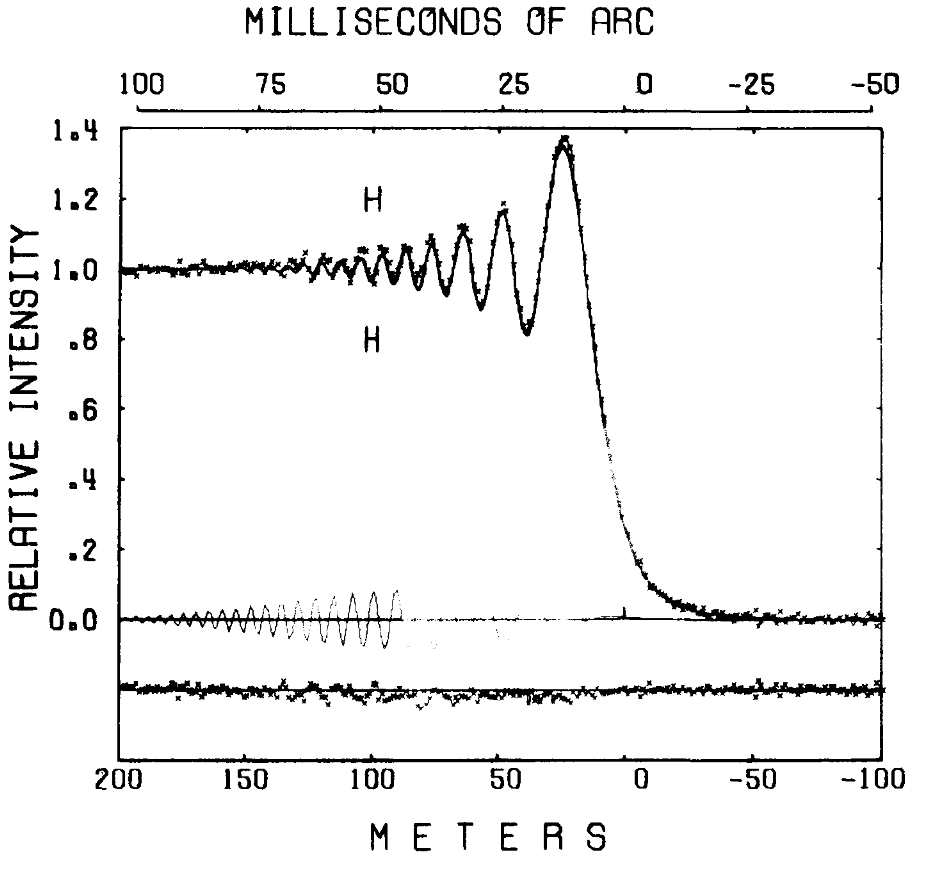


Figure 1. Occultation of BD+16°625 recorded on the KPNO 4m telescope. The wavelength of observation is 2.16 μm. The observed flux as a function of time is displayed (equivalently) as a function of the projected spatial coordinates meters (on the ground) and milliseconds of arc (on the sky). Shown are the data, the model fit, and the difference (model-data). The partial derivative of the model curve with respect to diameter is shown to indicate which portions of the data are sensitive to diameter. The bars above and below the data indicate the stellar diameter and telescope diameter, respectively. The deduced stellar diameter is 2.92 milliseconds of arc.

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

## 2. RECENT ACTIVITY

My records currently contain reports of 94 occultation angular diameter measurements for 62 stars. A chronological histogram in Figure 2 shows the strong concentration of these results to the last two years. While it is tempting to fit the usual exponential function to this graph (e-folding time two years), the figure actually represents a series of step functions generated by the activation of observing programs at various observatories and the introduction of new, more productive instrumentation.

At present most of the observations are being obtained by a small number of groups. Table 1 summarizes the contributions.

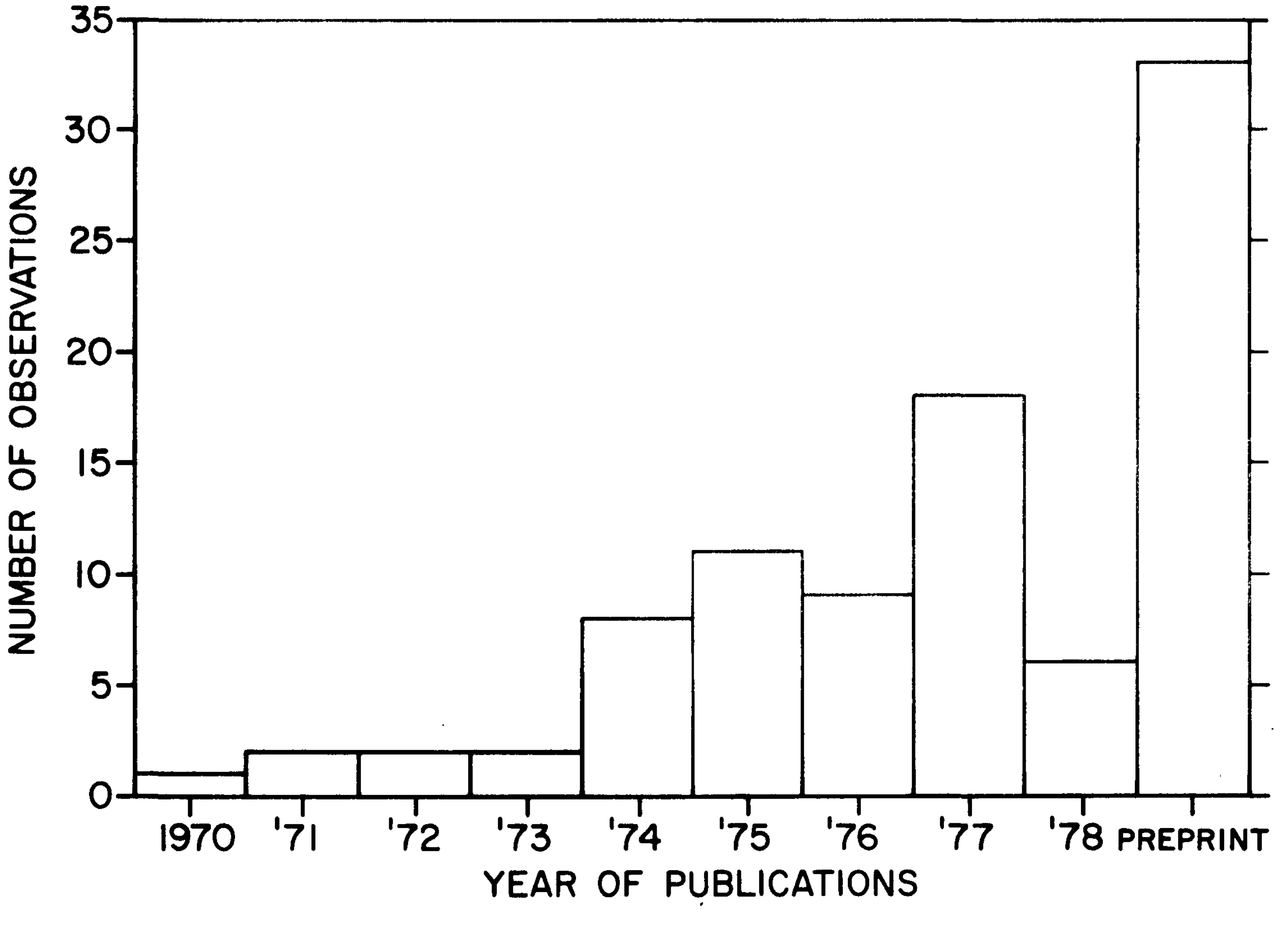


Figure 2. Recent productivity of the occultation technique illustrated by the number of stellar diameter observations published each year.

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

Table 1. Number of Angular Diameters Reported

| | |
|---|---|
| KPNO | - 42 |
| Texas | - 23 |
| Lowell | - 9 |
| Hamburg | - 7 |
| Sutherland | - 4 |
| CTIO | - 3 |
| Other | - 6 |
| Total | - 94 |

It is evident that additional observing programs would substantially boost the productivity of the occultation method. Since this work is normally done on a small (1 m class) telescope with relatively simple equipment (by modern standards) there is every reason to encourage new groups to join the effort. The most important prerequisite to success in this endeavor is access to a telescope at a good site with excellent weather statistics.

## 3. RANGE OF ANGULAR DIAMETERS

The range of measured stellar angular diameters is illustrated in Figures 3a and 3b. The histograms show the number of stars with empirical angular diameters due to the most productive techniques (to cover the diameter range the data have been sorted by equal intervals in the log of the diameter.) Figure 3a shows the occultation results. The decrease in numbers on the large diameter end of the histogram is due to a shortage of occultable stars of large diameter. The cutoff in observations near 1.5 milliseconds of arc is due to a plethora of limitations which converge to disable the technique near 1 millisecond of arc. As noted by early workers in the field, diameter dependent constraints on optical bandwidth, electrical bandwidth and telescope diameter render observations at the small diameter limit exceedingly difficult.

These difficulties are also revealed by the trend of errors with diameter. In Figures 3a and 3b the *average* and *minimum* fractional errors within each angular diameter bin are plotted. The strong increase toward small

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

diameters in Figure 3a is fully compatible with the associated observational problems.

For comparison, Figure 3b shows similar distributions for the intensity interferometer[11] and the amplitude interferometer[12]. The amplitude interferometer, which can pick up all of the large angular diameter stars in the sky,

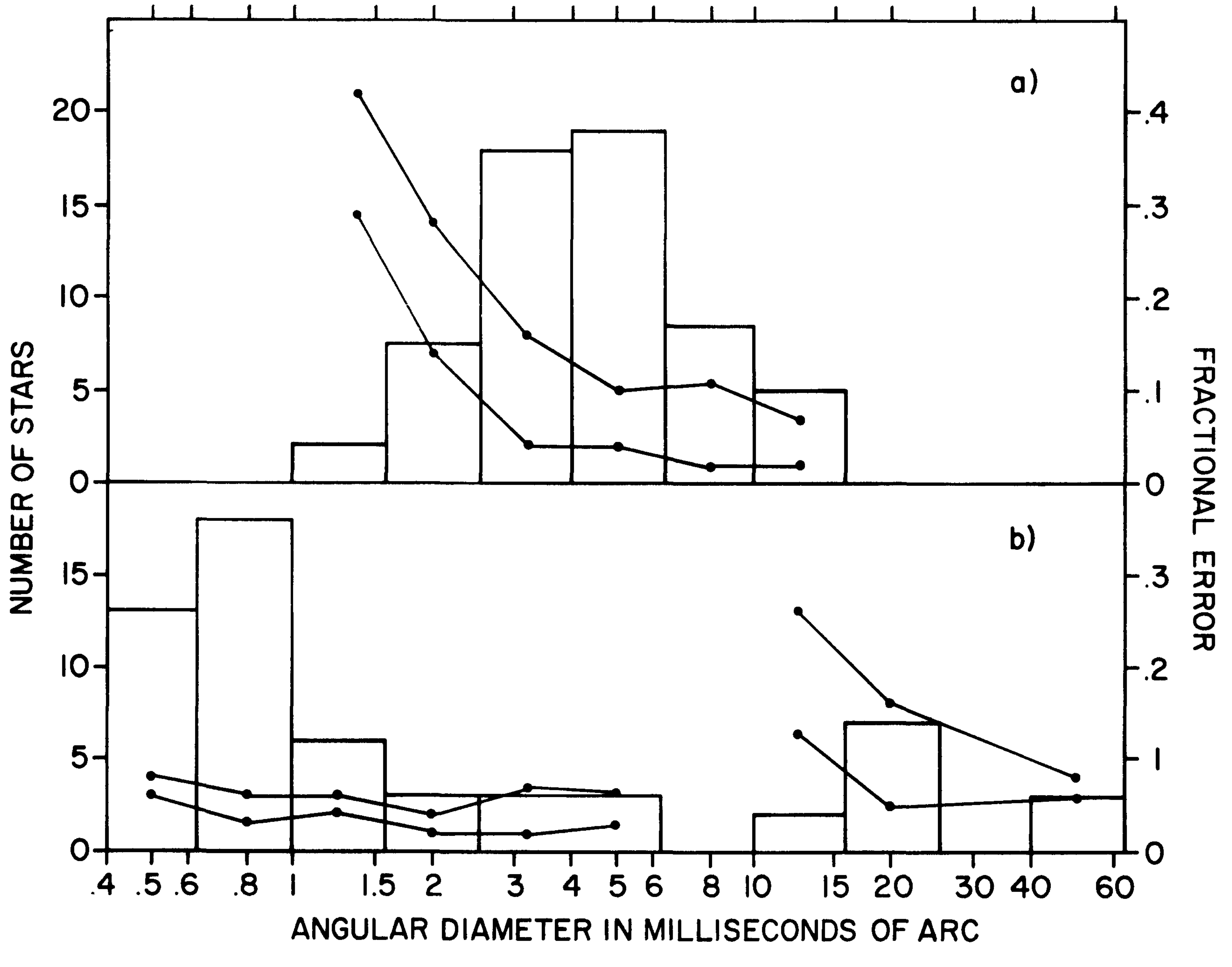


Figure 3. The number of stars with measured angular diameter as a function of diameter for the three most productive techniques (histograms). The dots connected by line segments indicate the mean and minimum quoted errors as a function of diameter for each technique. (a) Results from occultation work. (b) Results from intensity interferometer ($\leq$ 10 ms-arc), and amplitude interferometer ($\geq$ 20 ms-arc).

shows a clear deterioration in performance as the diameter drops below the theoretical diffraction limit of the largest available telescope.

For evaluation of the relative errors, we note that various applications have different requirements. To obtain astrophysically useful accuracy in specification of stellar effective temperature, a fractional error $\lesssim 0.1$ is required. To obtain limb darkening information an error $\lesssim 0.03$ is required. For useful study of extended emission or scattering shells an error even as large as $\sim 0.5$ may be useful.

## 4. COMPARISON BETWEEN MEASUREMENT TECHNIQUES

The complementary character of the three principal techniques for angular diameter measurement is well illustrated in Figure 3. Since the occultation method overlaps the intensity interferometry regime near 1 millisecond of arc and the amplitude interferometry regime near 20 milliseconds of arc it is natural to seek a comparison between measurements of the same star by two techniques.

Table 2 collects information on occultable stars which are also accessible to one of the other techniques. Measurements of α Sco by occultation and amplitude interferometer are completely consistent. Results for α Tau and μ Gem are of particular interest since they are near the 5 m telescope diffraction limit and present a distinct challenge to the interferometric techniques. Mira type stars are poorly suited for such a comparison.

Table 2. Stars for Intercomparison of Techniques

| Star | Technique | Reference | Angular Diameter* | Next Occulted |
|---|---|---|---|---|
| α Tau | Ampl. IF | 12 | 19 ± 2 | 1978 - 1980 |
| μ Gem | Ampl. IF | 12 | 15 ± 2 | 1982 |
| | Occult. | 2 | 12.2 ± .25 | |
| α Leo | Inten. IF | 11 | 1.32 ± .06 | 1980 |
| α Vir | Inten. IF | 11 | 0.85 ± .04 | 1995 |
| α Sco | Ampl. IF | 12 | 42 ± 5 | 1986 - 1987 |
| | Occult. | 13 | 41 ± 1 | |

*Diameter of equivalent uniform disk in milliseconds of arc.

Direct comparison with the intensity interferometer is exceedingly difficult. The largest occultable stars measured with the intensity interferometer are a factor of two smaller than stars that have been measured with satisfactory accuracy by the occultation technique. With reasonable developments of the observational capability of occultation work, however, the test may be possible.

The most critically needed comparison, however, is in the angular diameter range where the occultation technique is most productive, ~3-6 milliseconds of arc. This must await the two-telescope interferometers, which are a principal topic of the present conference.

## 5. COVERAGE OF SPECTRAL TYPES

Closely related to the distribution with angular diameter in Figure 3 is the distribution with spectral type in Figure 4. In this figure all of the results for types < GO are from the intensity interferometer, while all

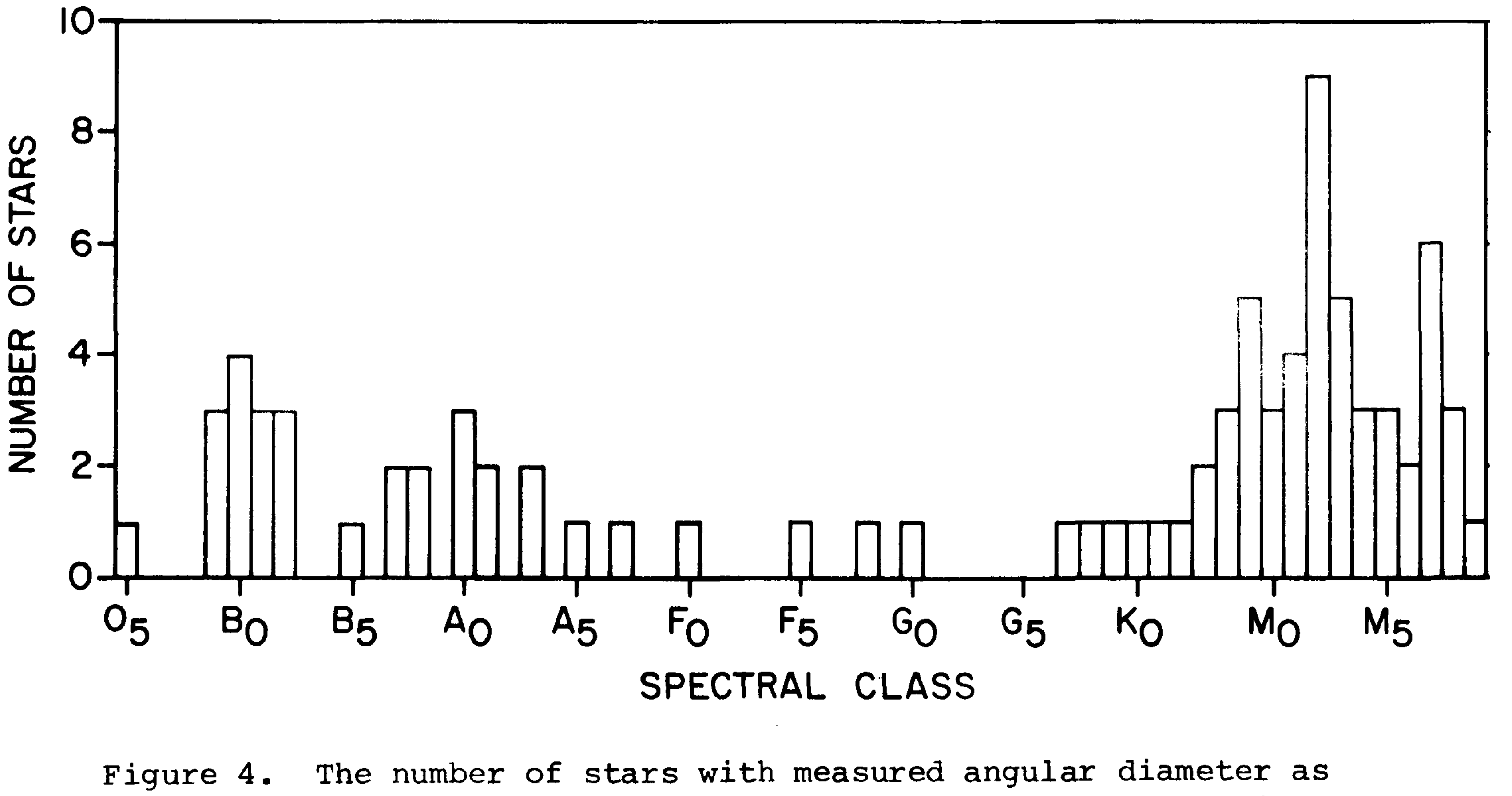


Figure 4. The number of stars with measured angular diameter as a function of spectral class by the two techniques of intensity interferometer (earlier than GO) and occultation (GO and later).

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

for types $\geq$ GO are by occultation. Again the complementarity of the techniques is apparent. The distribution of occultation data with spectral type is due in part to the dimensions, luminosity and space density of cool, luminous stars. For example, M giants are both cooler and more luminous than K giants, hence much larger in diameter. As a result, the "observability" increases with spectral type. However, the space density of M giants drops ~2X for each subclass[14]. These competing trends result in a peak near M2. A third factor is the lack of a sufficiently deep 2 μm sky survey. The event prediction lists for types $\gtrsim$ M8 are incomplete.

## 6. WAVELENGTH COVERAGE

The occultation technique can be readily adjusted to any wavelength for which an appropriate detector system is available. For simplicity, however, most work is done at popular visible and IR wavelengths. The distribution of observations with wavelength is shown by the histogram in Figure 5. Although the filters actually used are often narrower than the filters of the UBV system, the histogram has been constructed on the central wavelengths of standard UBV. Virtually all of the stars observed at wavelengths beyond the R filter are of spectral type M, C and S. The BVR measurements are for mixed G, K and M spectral classes. For measurement of stellar photospheric diameters, the wavelengths beyond K are not very useful. Fluxes are lower and, at least for ground based work, the thermal background degrades photometric sensitivity.

The occultation technique has been used for stellar measurements over almost a factor of 8 in wavelength. This capability has substantial significance for study of stellar atmospheres. Only by multi-wavelength measurement can the occultation technique yield limb-darkening. A limb-darkened star will have a reduced apparent diameter when measured by occultation. The *predicted* apparent relative diameter as a function of wavelength is shown by the solid line in Figure 5. These numbers apply to a $T_{eff}$ = 4000K, log g = 2.0 radiative model[15]. Limb darkening is predicted to cause the diameter to appear 10% larger in the K filter than in the B filter. The required

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

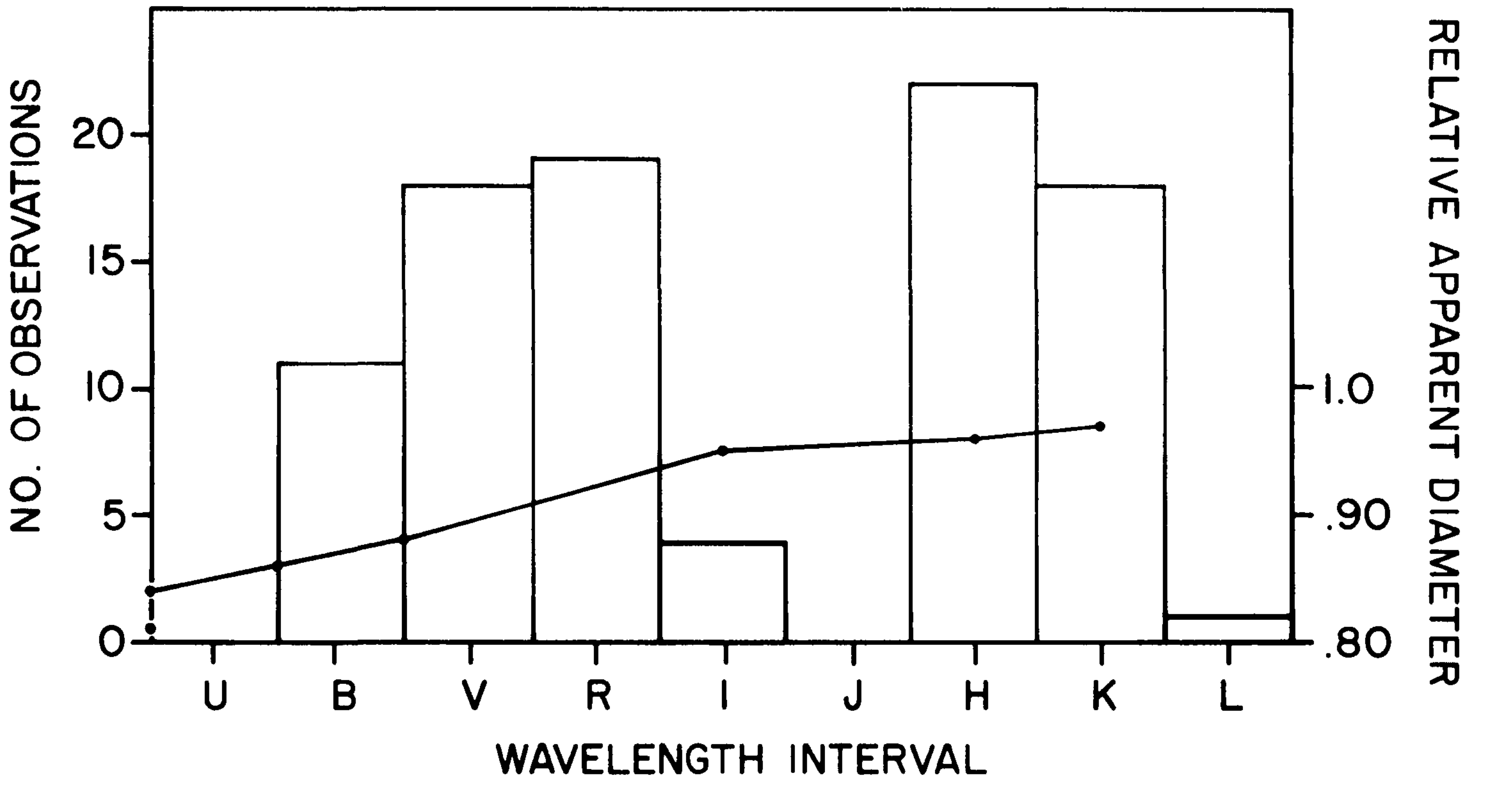


Figure 5. The distribution of number of occultation diameter observations as a function of wavelength of observation (histogram). Model atmosphere predictions of the relative apparent angular diameter due to limb darkening are shown by the dots and line segments.

measurement accuracy is achievable in occultation work, but so far suitable multi-wavelength observations of a single star have not been obtained.

A competing wavelength-dependent effect is expected owing to the variation of continuum opacity with wavelength. Near 1.6 μm (the $H^-$ opacity minimum) the star will have a smaller photospheric diameter than at a longer or shorter wavelength. In the very extended atmospheres of supergiants this effect may be substantial.

At longer wavelengths, the occultation technique is well suited to measurement of circumstellar shells. Important results for the shells of the carbon rich object IRC+10 216 and the oxygen rich object IRC+10 11 have been obtained by the Cal Tech group[16,17]. Numerous other types of objects possess strong infrared excesses; in most cases extended dust shells are believed to contribute part or all of the excess flux. Many of these objects are occulted regularly. Table 3 collects statistics on the number of various objects which will be occulted in the period 1978-1985 and which may have sensible shell diameters.

Table 3. Bright Sources with Infrared Excess

| Type of Object | Number Occulted 1978-85 |
|---|---|
| T Tauri stars | 22 |
| Wolf-Rayet stars | 5 |
| Anonymous AFCRL/GL objects | 12 |
| Anonymous IRC objects | many* |
| Ae - Be stars | 10 |
| The galactic center | the IR point sources |

*Available predictions show 14 objects occulted in the 16 month interval September 1977 to December 1978.

## 7. MAGNITUDE LIMITS

The angular diameter vs. limiting magnitude relations for a single channel photometer have been discussed recently[18]. Graphical results for V and K magnitudes are shown in Figures 6a and 6b; the most recent measurements near the small diameter limit are indicated, and appear to confirm the predicted capability of the technique.

A crude lower limit to the number of stars that can be studied by occultation is obtained from Figures 2 and 3 which show results for 62 stars in approximately 4 years. Extrapolated over the 18 year precession of the lunar orbit, this suggests availability of at least 150 cool stars for occultation measurement. From Figure 3a it is clear that this estimate is based on an angular diameter limit ~ 3 milliseconds of arc. The technique has more recently been extended to ~ 2 milliseconds of arc, corresponding to approximately 1 magnitude fainter. Hence the estimated lower limit to the number of candidate stars should be increased to ~ 500.

## 8. FUTURE DEVELOPMENTS

Foreseeable developments will improve and extend the capability of the occultation technique. A straightforward application of dollars could provide a many-channel photometer ideally suited for measurement of diameters in the range 1-2 milliseconds of arc with a ~ 2-3 m telescope.

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

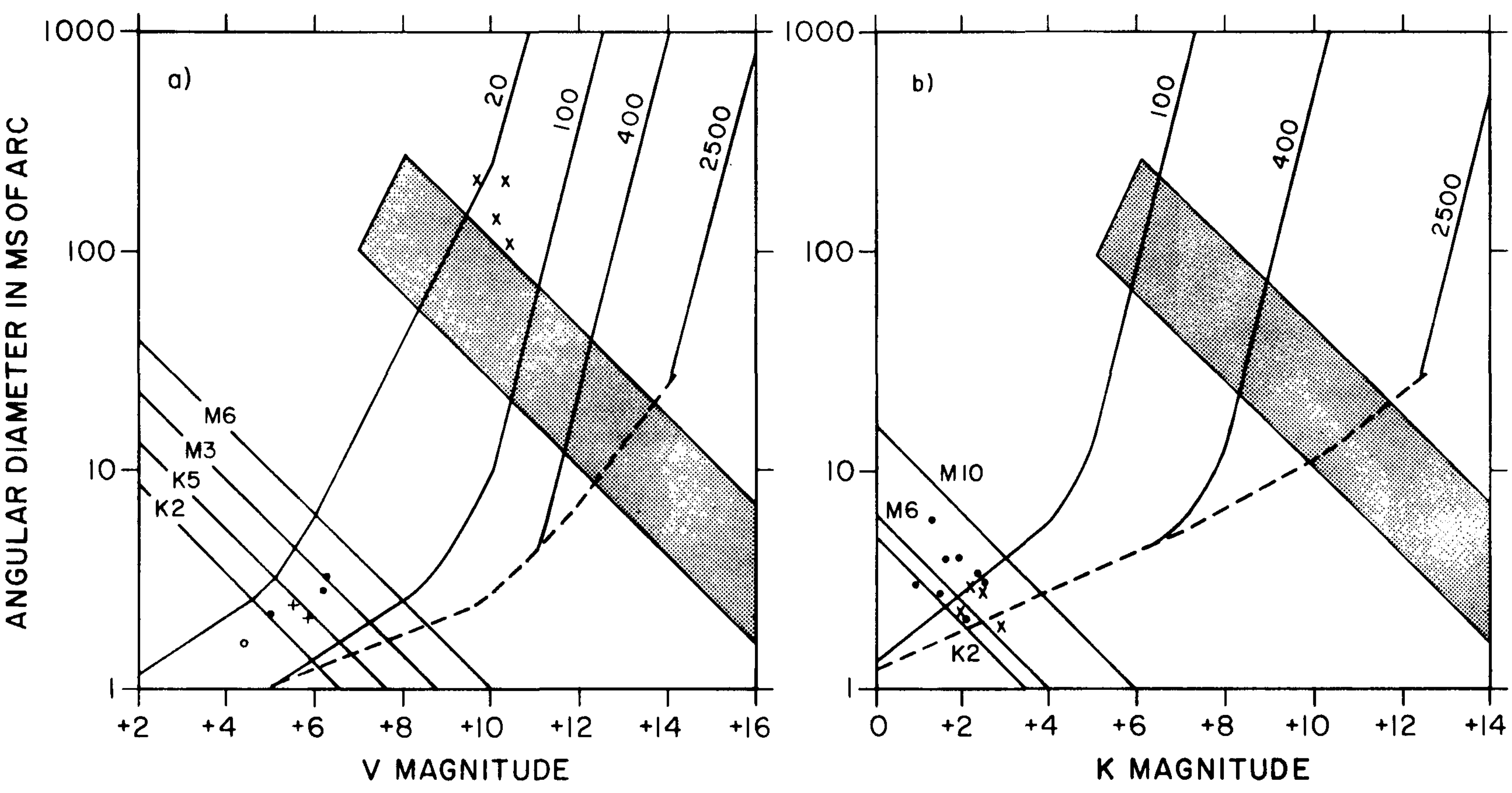


Figure 6. Limiting angular resolution of the occultation technique vs. V and K magnitude (for observations at 0.5 and 2.2 μm respectively) for telescope apertures of 20, 100, 400 and 2500 cm with a single channel photometer. The regions of the diagrams occupied by the normal stellar spectral types are indicated. Cross hatched areas represent the domain of the asteroids. Symbols represent actual observations. In (a) all observations were obtained with an aperture of 75 cm or less; in (b) filled circles indicate an aperture of 130 cm, crosses an aperture of 400 cm.

Provision of a fast photometer for the space telescope (if occasionally available for a few seconds of bright star study) could improve the quality and quantity of observations, and extend the technique to the UV.

Increasing numbers of ground based stations will substantially improve the regularity of multiple observations, and hence the reliability of the results. Continuing developments in the analytical techniques will improve treatment of such difficult noise sources as scintillation[19] and lunar limb irregularities.

Very likely, a decade or more hence, the multiple telescope interferometers will operate so well at all wavelengths that our use of the moon as

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press

a knife-edge will be seen as a temporary expedient which served its purpose and was superceded. And perhaps this conference, at which I am able to report such substantial advances in one technique, will serve equally as a forum to communicate progress towards its replacement.

## REFERENCES


1) P. A. MacMahon, Mon. Not. Roy. Astron. Soc. 69, 126, 1909.

2) S. T. Ridgway, D. C. Wells and R. R. Joyce, Astron. J. 82, 414, 1977.

3) J. L. Africano, D. S. Evans, F. C. Fekel and T. Montemayor, Astron. J. 82, 631, 1977.

4) D. S. Evans, Astron. J. 75, 589, 1970.

5) T. G. Barnes, D. S. Evans and T. J. Moffett, Mon. Not. Roy. Astron. Soc. 183, 285, 1978.

6) S. T. Ridgway, R. R. Joyce, N. M. White and R. F Wing, (in preparation).

7) R. E. Nather and D. S. Evans, Astron. J. 75, 575, 1970.

8) R. E. Nather, Astron. J. 75, 583, 1970.

9) R. E. Nather and M. M. McCants, Astron. J 75, 953, 1970.

10) R. E. Nather, Ph.D. thesis, University of Capetown, 1972.

11) R. Hanbury Brown, J Davis and L.R. Allen, Mon. Not. R. astr Soc., 167, 121, 1974.

12) D. G. Currie, S. L. Knapp, K. M. Kiewer and R. H. Braunstein, University of Maryland Technical Report #76-125, 1976.

13) D. S. Evans, Astron. J. 62, 83, 1957.

14) H. Neckel, Ap. J. 128, 510, 1958.

15) D. F. Carbon and O. Gingerich, in Theory and Observation of Normal Stellar Atmospheres, ed. O. Gingerich (MIT Press, Cambridge) p. 377, 1969.

16) R. R. Zappala, E. E. Becklin, K. Matthews and G. Neugebauer, Ap. J. 192, 109, 1974.

17) R. K. Toombs, E. E. Becklin, J. A. Frogel, S. K. Law, F. C. Porter and J. A. Westphal, Ap. J. 173, 271, 1972.

18) S. T. Ridgway, Astron. J 82, 511, 1977

19) G. Knoechel and K. v.d. Heide, Astron. Astrophys. 67, 209. 1978.

## DISCUSSION

P. Boyce: How many channels are required for the multichannel work you mention?

S.T. Ridgway: For complete optimization, the bandpass must be selected to match the diameter. The approximate constraint is

$$\Delta\lambda < \theta^2/100$$

where $\theta$ is the angular diameter in milli-arcseconds and $\Delta\lambda$ is the filter bandpass in microns. For $\theta = 3 \times 10^{-3}$ arcsec, the requirement is $\Delta\lambda < 0.1$ μm. For this case, "many channels" would be of order 10.

S.P. Worden: Why haven't there been occulation observations in the near ultraviolet, a region which seems interesting from a stellar atmospheres viewpoint?

S.T. Ridgway: Currently, the occultation technique is limited to angular diameters greater than about $2 \times 10^{-3}$ arcsec. Most stars in this range of angular size are cool giants and hence relatively fainter at U than at V or R. Also facilities for multiple wavelength observations, which are what one really requires, are not extensively available. I would hope that the coming series of occultations of α Tauri will be widely observed at many wavelengths, including the blue.

M.L. Aizenman: Do you have any data on variable stars? Have any been observed at different phases?

S.T. Ridgway: The angular diameter of the Mira variable U Ori has been obtained at two epochs. The diameters are the same, which is the result predicted by D.W. Strecker (Ph.D. Thesis, Univ. of Minnesota, 1973) for this pair of phases. We have many diameters for anonymous IRC sources. Some of these are Mira types, but no information is available regarding the periods or phases of these stars, so it is not possible to complete the interpretation of the data at present.

M.L. Aizenman: Have any Cepheids been observed?

S.T. Ridgway: The bright Cepheid ζ Gem, V = 3.70, will be occulted next in 1981. The approximate angular diameter is $2 \times 10^{-3}$ arc sec. It should be possible to obtain an accuracy of 5-10% in a single observation.

https://doi.org/10.1017/S0252921100118652 Published online by Cambridge University Press