

PHOTOELECTRIC OBSERVATIONS OF LUNAR OCCULTATIONS

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ABSTRACT

The results of a program to record photoelectrically lunar occultations at Jena Observatory are described. The analysis of ten observations is reported. Angular-diameter estimates are given for 97 Tau, ϵ Gem, and μ Psc. The quintuple nature of the star 63 Gem is confirmed by our results.

I. INTRODUCTION

The present paper gives the main results of photoelectric observations of lunar occultations at Jena Observatory carried out from 1982 to 1985. The measurements are directed to the derivation of stellar angular diameters and the investigation of double stars. They were performed in addition to our photometry program and do not cover the whole occultation occurrences during this period. In an earlier paper (Stecklum 1982), the observational method was described in connection with our first results. Since then, our own occultation forecast, as well as the technique of observation, has been improved. With the current development of a high-precision computer control for the 90 cm telescope, it will be possible to reach a new quality also in this kind of observation in the immediate future. So, it seems to be appropriate now to summarize the results of the first period of occultation observations.

A total of ten events are described here, including one occultation binary and three angular-diameter stars. The results of the observations are compared to previous measurements by other authors. Concerning the observational technique, we make a proposal that should permit occultation observations with a better resolution of the diffraction pattern and, therefore, may provide a higher accuracy for the diameter estimates.

II. INSTRUMENTATION

The lunar occultation prediction procedure as described elsewhere (Stecklum 1985a) is based essentially on the Tchebycheff polynomials of the lunar motion given in the Computer Almanac. The SAO catalog provides the database for the occultation candidates.

All observations are carried out with the computer-controlled photoelectric-photometry system at the 90 cm telescope of the Großschwabhausen observing station. The detector is an uncooled EMI 6256B photomultiplier in the photon-counting mode. The system is described in detail by Reimann *et al.* (1984). Depending on the star's brightness and spectral type, Johnson or Strömgren filters are used. In most cases, the time resolution is 1 ms, with a time coverage of about 4 s around the occultation event. The timing accuracy of about 2 ms is maintained using a short-wave receiver in combination with a quartz clock. The synchronization is derived from the time signals distributed by the Czechoslovakian OLB 5 (3.17 MHz) station.

The accurate prediction of the occultation time provides the possibility to apply small diaphragms and to check the tracking accuracy just before the event. A 15" diaphragm is in routine use. A smaller diaphragm would reduce the back-

ground contribution but with the disadvantage of an increased modulation due to image motion caused by observing conditions.

In most cases the data transfer to the computer is interrupted by the observer immediately after the event. In cases of good signal-to-noise ratio, the real-time occultation test stops the observation by the computer itself. Of course, the circumstances of each observation are specified to give optimal results.

III. REDUCTION AND RESULTS

The data reduction is essentially based on a computer program that fits the theoretical diffraction pattern to the data by minimizing the mean-square deviation. The free parameters in the case of single stars are the time of occultation, the stellar angular diameter, and the lunar rate. The intensities of the star and the background are estimated from the mean count rate before and after the event and are kept fixed during the run of the program. Input quantities are the time resolution, the bandpass profile, the telescope diameter, and the detector dead time. For the computation of the mean-square deviation, the influence of the photon statistics is taken into account by weighting the data with the expected number of photons according to the model curve which is normalized to the observed count rates. The estimate of the angular diameter holds for a uniform brightness distribution. Evans *et al.* (1985) pointed out that it is impossible for the signal-to-noise ratio so far achieved to deduce the limb-darkening coefficient from an occultation trace. Assuming full darkening, the diameter results are about 13% larger than for a uniform disk.

In the case of suspected binarity, the free parameters are the occultation time of the primary, the time difference between the occultations, and the brightness ratio of the two components. A formal error of the derived results can be derived using a Monte Carlo procedure that generates synthetic occultation curves, which are analyzed in the same manner as the observed occultation. However, because this method is time consuming, results have been obtained only for some runs up to now. Therefore, and for the sake of comparison in the present paper, the error definition of Beavers *et al.* (1982) is applied. Of course, the quality of the derived results can only be judged by comparison with results from other occultations, as was done by Ridgeway *et al.* (1980) and Evans *et al.* (1985).

A summary of the results is presented in Table I. The individual columns contain the following information: (1) event number; (2) SAO star number; (3) stellar magnitude (V filter); (4) spectral type and luminosity class; (5) date of

TABLE I. Occultation results.

Run (1)	SAO (2)	V (3)	Sp.T. (4)	Date (5)	UTC (6)	Fil. (7)	Rate (8)	S/N (9)	C.A. (10)	Slope (11)	Diameter (12)
10	94136	6.97	G2 V	82 February 3	17 ^h 22 ^m 26 ^s .519	—	0.38	2.8	63		point
11	94164	5.18	A9 IIIIn	82 February 3	18 ^h 36 ^m 56 ^s .316	B	0.57	6.5	43	3	5.3 ± 0.9
18	79386	6.40	G5	82 April 1	20 ^h 04 ^m 04 ^s .345	V	0.78	6.2	15	7	point
19	79403	5.25	F5 IV	82 April 1	20 ^h 32 ^m 23 ^s .242	V	0.81	15.4	-12	0	point
20	79410	7.16	F5	82 April 1	20 ^h 53 ^m 20 ^s .503	V	0.74	3.4	29	3	point
30	109727	6.80	F8	83 December 14	20 ^h 11 ^m 22 ^s .511	V	0.41	5.3	57	-2	point
31	93083	5.18	A7 IV	83 December 16	19 ^h 24 ^m 08 ^s .985	b	0.36	4.4	64	3	point
32	78682	3.00	G8 Ib	84 February 13	20 ^h 22 ^m 33 ^s .927	y	0.30	7.4	68	-5	4.75 ± 0.5
36	78682	3.00	G8 Ib	84 August 23	01 ^h 14 ^m 48 ^s .583	y	0.16	1.6	-82	-1	(≈ 3)
37	109926	4.83	K4 III	85 January 27	19 ^h 14 ^m 29 ^s .598	V	0.74	20.4	17	11	3.1 ± 0.4

occultation; (6) UTC of occultation; (7) filter; (8) predicted lunar rate (meters per millisecond); (9) signal-to-noise ratio (stellar count rate divided by the square root of stellar-plus-sky count rate); (10) contact angle of event (in degrees), measured relative to the direction of the lunar motion—positive values indicate that the star passed north of the center of the lunar disk; (11) local lunar slope (in degrees) computed from the observed lunar rate—a positive value means that the observed rate exceeds the predicted rate; (12) angular diameter (in milliseconds of arc).

IV. DISCUSSION OF SPECIAL EVENTS

Run 11: 97 Tau, SAO 94164, HD 30780. Corresponding to the parallax of $0''.021$ and the spectral type, an angular diameter of $0''.0006$ is expected. However, the occultation analysis yields a value of $0''.0053$. The dependence of the quality of the fit on the angular diameter is shown in Fig. 1

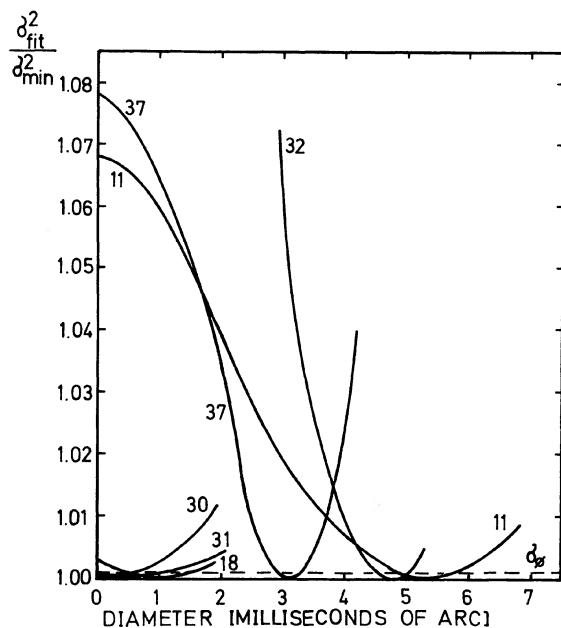


FIG. 1. Dependence of the normalized mean-square deviation on the stellar angular diameter. Each curve is designated by the run number. For runs where the variation of the normalized mean-square deviation is less than 1.002, the curves are not drawn. The formal error of the angular diameter is obtained from an increase of 0.001 of the normalized mean-square deviation (intersection with the dashed line).

for stars with a good signal-to-noise ratio. Figure 2 displays the occultation curve with the best fit superimposed. It seems difficult to assign the discrepancy of an order of magnitude to observational circumstances. The event took place at an airmass of $z = 1.19$ with weak influence of scintillation. The total scintillation power and the correlation time scale of scintillation according to Stecklum (1985b) were estimated to be 6.1×10^{-3} and 8.6 ms, respectively. The suggestion was checked if the discrepancy is due to the presence of a close double star. The best fit was obtained for two components of equal brightness separated by $0''.0025$. However, the minimum mean-square deviation of the double star fit exceeds that of the single star fit by a factor of 1.008. Therefore, the presence of a close double star is not ruled out, but the results favor the single star interpretation.

Run 19: 63 Gem, SAO 79403, HD 58728, ADS 6089. The main component of the visual triple system ADS 6089 is itself a double-lined spectroscopic binary (Batten *et al.* 1978). So, the system is quadruple. As a result of a lunar occultation, Eitter and Beavers (1977) detected a companion with a projected distance of $0''.047$ at a lunar position angle of 304° that is 2.25 mag fainter than the main component. They remarked that the companion cannot be the resolved spectroscopic binary component because this has a value of $a \sin i$ of about $0''.001$. As a consequence, the system becomes quintuple. There is good reason for that interpretation because the values of $M \sin^3 i$ are only a bit smaller than that expected for the masses from the spectral type, i.e., the orbital plane is seen nearly edge-on. Therefore, the spectroscopic binary should be unresolvable by the present techniques.

Subsequent speckle interferometry by McAlister *et al.* (1983) revealed the companion detected by the occultation at a distance of $0''.044$ and a position angle of 168° . Our observation (Fig. 3) shows that 45 ms before the occultation of the main component a 2.3 ± 0.2 mag fainter companion was occulted. The projected separation was $0''.021 \pm 0''.0005$ at a lunar position angle of 281° . We conclude that it is the same object as Eitter and Beavers (1977) and McAlister *et al.* (1983) observed. Further speckle interferometry by Balega and Balega (1985) and Bonneau *et al.* (1986) did not improve the orbit determination considerably. In Fig. 4, it can be seen that the position angles P of the speckle observations and the values $P - 180^\circ$ that might come true (because of the 180° ambiguity of the speckle autocorrelation procedure) are concentrated in a narrow angular range. The observation by Bonneau *et al.* (1986) is very close to the diffraction limit of the telescope. Further speckle interferometry of this object is urgently needed.

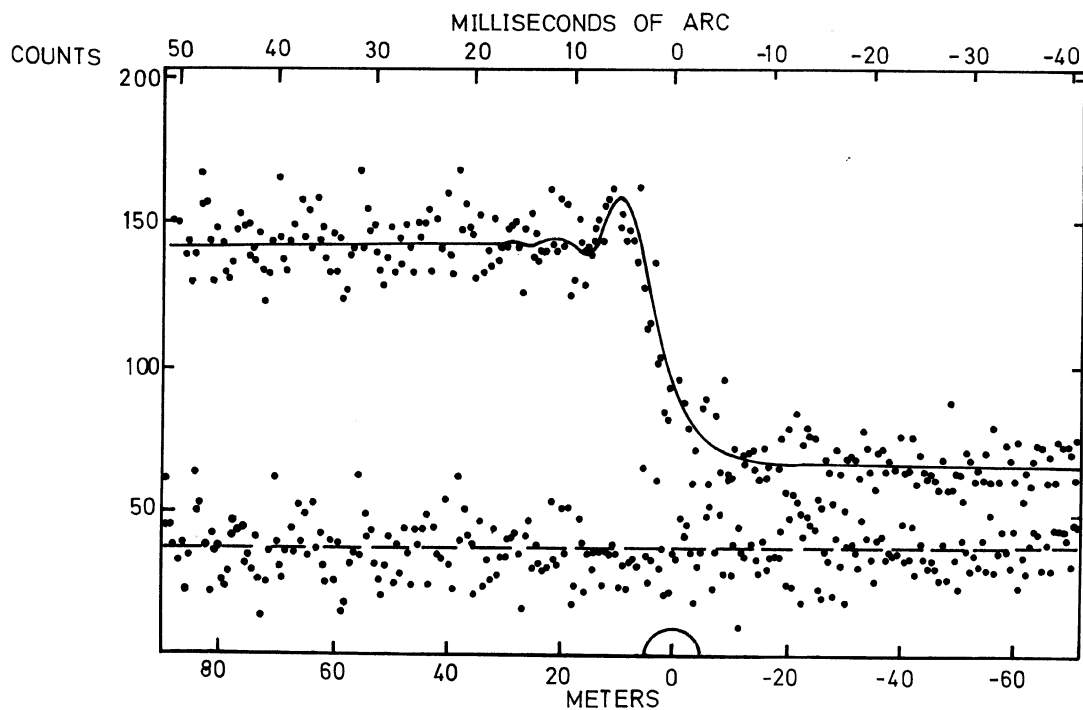


FIG. 2. Occultation of 97 Tau. The observed occultation curve with the best fit superimposed is shown. Abscissa is in counts per millisecond. The dashed line indicates the zero level for the residuals. The half-circle centered at the moment of the event characterizes the size of the angular diameter at lunar distance.

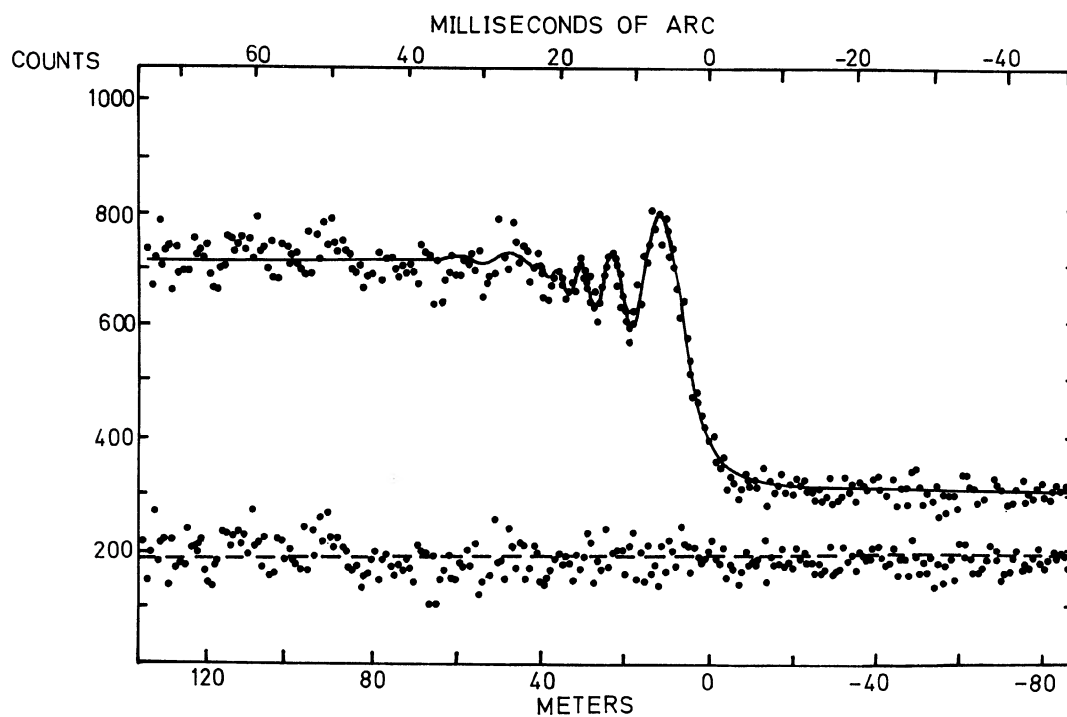


FIG. 3. Occultation of 63 Gem.

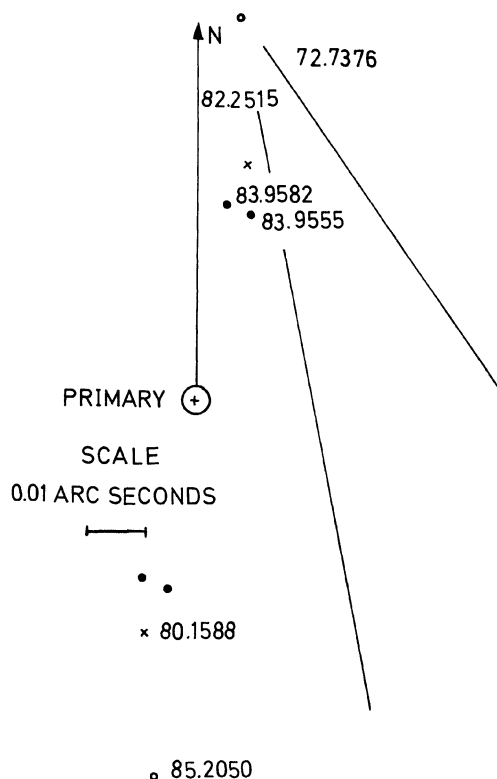


FIG. 4. Speckle and occultation geometry of 63 Gem. The symbols represent the following observations: $\times$ —McAlister *et al.* (1983), $\bullet$ —Balega and Balega (1985), $\circ$ —Bonneau *et al.* (1986). The published position angle is characterized by the date of observation. In the opposite direction, the corresponding symbol represents the 180° ambiguity.

Run 32: ϵ Gem, SAO 78682, HD 48329 (Fig. 5). This star has been observed several times at various observatories. Table II gives the results of the diameter estimations. Our previously published result (Stecklum 1985a) has to be slightly corrected as a consequence of the improvement of the fitting procedure. Relating all values to a uniform disk, a mean angular diameter of $0''.00445 \pm 0''.00018$ can be derived. Interestingly, the error of a single value of $0''.00056$ as derived from the scatter of the diameter estimates is larger than the expected error of $0''.00036$ computed from the given formal errors (neglecting the outstanding value of Evans *et al.* 1985). The use of all published diameters in this comparison is allowed since the star is not pulsationally variable, nor is the diameter correlated with wavelength. The same object was again occulted six months later (Run 32). The event happened at an airmass of $z \approx 3.6$, the largest value at which we have been observing lunar occultations up to now. We tried to observe the reappearance at the dark limb, but during the grazing occultation the star was lost out of the diaphragm because we were not able to correct properly for the refraction changes. However, inspection of the data obtained at the disappearance showed that the star can be distinguished against the bright background. This was due to the small illuminated fraction of the moon of 0.18. The analysis of the occultation trace gave an estimate of the angular diameter of about $0''.003$, which should not be considered significant because of the very low signal-to-noise ratio.

Run 37: μ Psc, SAO 109926, HD 9138 (Fig. 6). This successful run has a very good signal-to-noise ratio. The derived angular diameter of $0''.0031 \pm 0''.0004$ is in good agreement with the expected value for the spectral type K4 and the visual brightness of the star. Former observations were done by Edwards *et al.* (1980) and Beavers *et al.* (1982). Edwards *et al.* (1980) did not determine the angular diameter, whereas a value of $0''.0033 \pm 0''.001$ was given by Beavers *et*

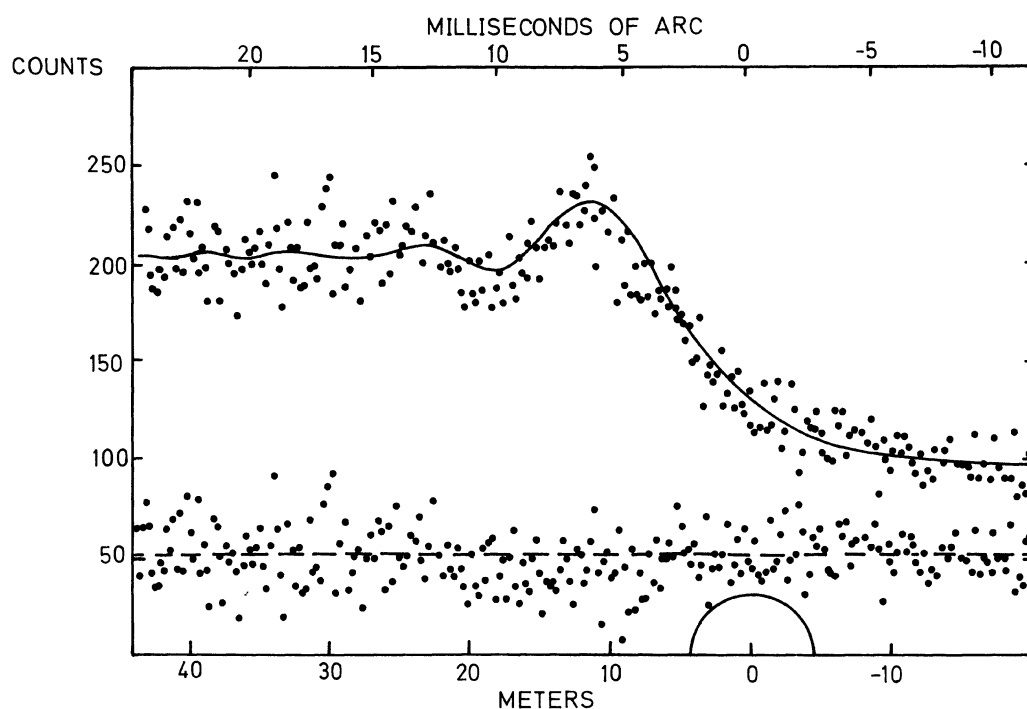


FIG. 5. Occultation of ϵ Gem.

TABLE II. Diameter estimates for ϵ Gem.

Disk	Angular diameter (0.001)	Central wavelength (nm)	Source
uniform	5.6 ± 0.6	500	de Vegt (1976)
fully darkened	4.0 ± 0.2	568	Beavers <i>et al.</i> (1980)
fully darkened	3.0 ± 0.3	749	<i>ibid.</i>
uniform	4.34 ± 0.31	550	Schmidtke and Africano (1984)
uniform	4.72 ± 0.16	450	Schmidtke <i>et al.</i> (1986)
uniform	3.70 ± 0.57	510	<i>ibid.</i>
uniform	4.73 ± 0.09	580	<i>ibid.</i>
uniform	4.13 ± 0.27	1650	<i>ibid.</i>
uniform	4.56 ± 0.10	2170	<i>ibid.</i>
fully darkened	4.0 ± 2.0	430	Evans <i>et al.</i> (1985)
uniform	4.75 ± 0.50	550	this paper

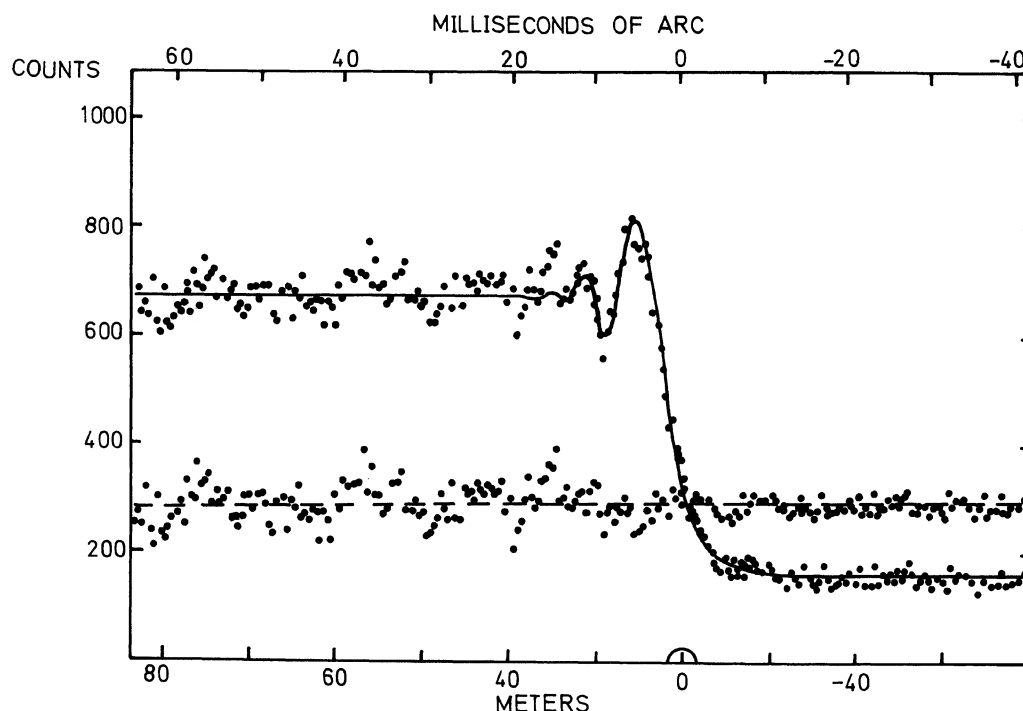
al. (1982). Considering that this value holds for a fully darkened disk and that it is a mean of the results for the blue and the red channel, which differ significantly, we conclude that our result confirms the former findings and raises the accuracy of the angular diameter determination of this star. Figure 7 shows an example of a record for a point source, Run 30: 35 Ceti, SAO 709727.

V. FUTURE OBSERVATIONAL PROSPECTS

In the last of a series of papers, Evans *et al.* (1985) remarked that resolution of about $0''.001$ seems to be the ultimate limit of the lunar occultation technique. Comparing results from simultaneous observations with a 1.3 and a 4 m telescope, Ridgeway *et al.* (1980) noted that the loss of fringe modulation at the 4 m telescope sets a lower limit on the diameter estimation of $0''.0025$, despite the higher quality

of the data. So, with the advent of new large telescopes it seems doubtful that they may give access to smaller angular diameters by the lunar occultation technique. Furthermore, new types of interferometers are under development which should lower the limits of diameter estimation (Davis and Tango 1985). On the other hand, the measurement of the visibility function using an interferometer is a time-consuming task, whereas a lunar occultation happens in some 10 ms. At present, there is no problem in carrying out lunar occultation observations as an interruption of major measurement programs because of sophisticated software. Is it possible to reach very high angular resolutions in a very short time at (very) large telescopes? There may be a positive answer taking the rapid development of detector techniques into consideration. In this context, a first suggestion was given by White (1981), whose idea to use a two-dimensional detector in combination with a spectrograph for occultation studies was a logical extension of the method of multicolor observation. The advantage of simultaneous observation at different wavelengths is obvious in the work done at Kitt Peak National Observatory, McDonald Observatory, and Fick Observatory.

We propose the use of high-sensitivity, fast-readout image detectors such as microchannel plates in connection with a new optical design to observe occultations. In the currently applied scheme of detection, the signal is measured using photomultipliers or infrared detectors. In the typical optical layout, the detector is behind a diaphragm, a filter, and a field lens. The diaphragm serves as a spatial filter, and the field lens images the entry pupil on the detector. Therefore, the aperture integration, which is the major obstacle to reaching higher angular resolution, is entirely done by this kind of spatial detection. In our proposed occultation spectrophotometer (Fig. 8), the intensity distribution of the dif-

FIG. 6. Occultation of μ Psc.

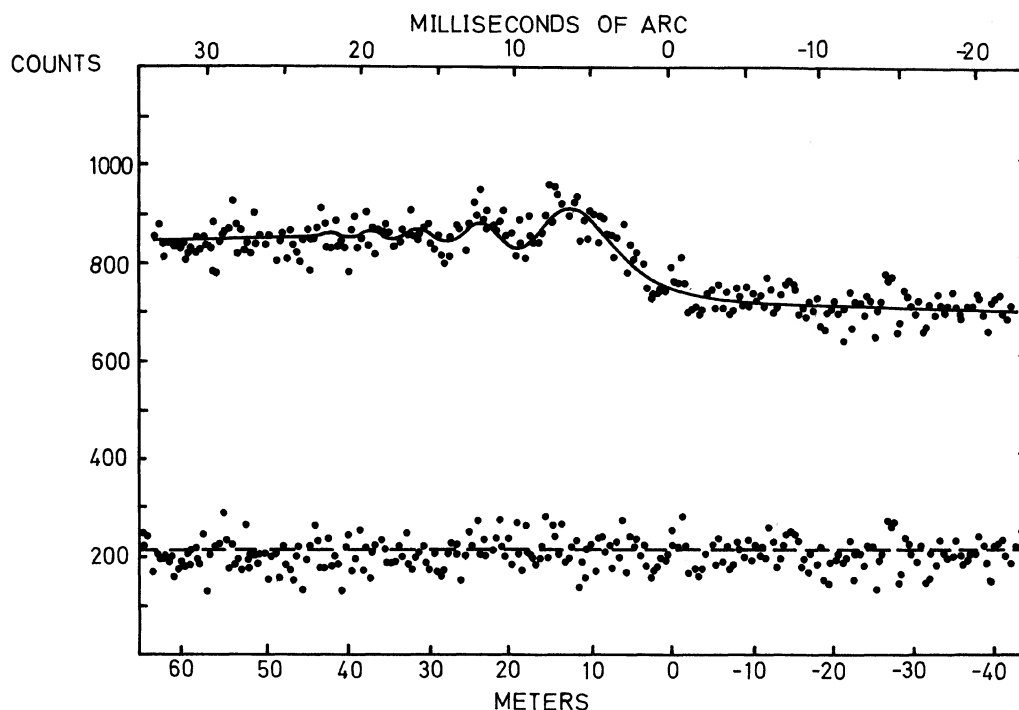


FIG. 7. Occultation of 35 Ceti.

fraction pattern as projected on the telescope's aperture is reimaged by a collimator lens on a smaller spatial scale. Then, the parallel bundle of light enters a dispersive element, for example, a grating. From this it will be imaged by a cylinder lens onto a two-dimensional detector. This optical arrangement permits spatial and wavelength resolution. Of course, the occultation spectrophotometer has to be rotatable around the optical axis to adjust for the predicted limb orientation. The direction of the dispersion has to be perpendicular to that orientation. The *a priori* unknown local lunar slope causes both an integration effect and a mistuning of the readout frequency. Evans (1971) already noted that from a

number of occultations about 70% of the events have local lunar slopes less than 10° . Therefore, these effects should be small compared with the aperture integration unless the local lunar slope is very large.

We suspect that a wavelength resolution of about 5 nm would be adequate for the occultation spectrophotometer. A spatial resolution of 0.1 m along the occultation path, which corresponds to about 0.05 ms of arc, seems to be appropriate, taking the effects of seeing into consideration. Together with the spectral-sensitivity range of the detector and the size of the largest telescopes, a detector format of 128×128 pixels seems to be sufficient. A 12-bit analog-digital conversion for

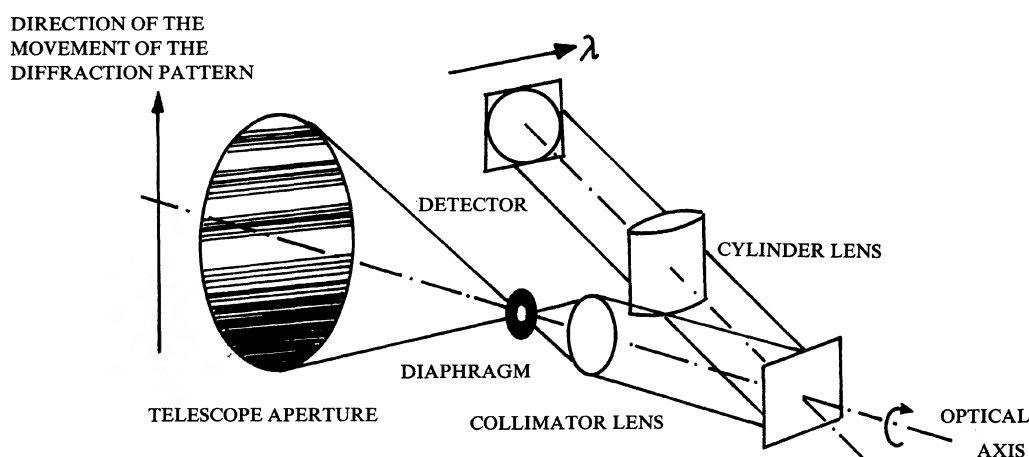


FIG. 8. Optical scheme of the proposed occultation spectrophotometer.

the use of a CCD matrix leads to an information rate of about 2×10^8 bit/s at an integration time of 1 ms which has to be managed. While the high temporal resolution is no problem for microchannel plates, it makes some troubles for CCDs. Another problem is caused by the readout noise of the CCD, while a microchannel plate offers the advantage of photon counting. For the application of CCDs, these problems may be solved using the frame-transfer technique. In this case, the motion of the diffraction pattern is followed by the charge transfer of the corresponding rows leading to a steady exposure and readout process until the storage limit is reached. This requires a variable clock frequency, which is tuned to the expected lunar rate. The advantage of that kind of observation for astrometric purposes is clearly shown by Gehrels *et al.* (1986). However, it is beyond the scope of this paper to give a final design of the device.

Through the two-dimensional detection, new methods of data reduction are needed. For example, the actual lunar rate should be obtainable by analyzing subsequent frames that include the diffraction pattern (in the case where the frame-transfer technique is not applied). Therefore, this quantity would no longer be a free parameter in the fitting procedure.

Summing up, we see three main advantages that would be realized by the use of an occultation spectrophotometer:

- high resolution of the diffraction pattern,
- simultaneous spectral observation,
- direct access to the local lunar slope angle.

Of course, detailed modeling of the device, the detection process, and the data analysis is needed to explore the limits

of angular resolution. It may be possible that this observational technique will permit the reliable determination of the limb darkening.

VI. SUMMARY

The main results of the observation of lunar occultations at Jena Observatory are presented. The angular diameters of three stars have been estimated. The values for ϵ Gem and μ Psc are in good agreement with the data in the literature. The angular diameter of 97 Tau turned out to be tenfold larger than expected. There is no evidence for observational circumstances that could explain this deviation. Future effort should prove whether this is a single star or not. The quintuple nature of the star 63 Gem has been proved by our observation, which showed the companion at a projected angular distance of $0''.021$ at a lunar position angle of 281° being 2.3 mag fainter than the primary.

A novel technique of observation is proposed which might give higher spatial and spectral resolution. This method would be especially suited for large telescopes, where the aperture integration in the common observation mode prevents high angular resolution. The occultation spectrophotometer could be realized using high-sensitivity, fast-readout image detectors.

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