DISCOVERY AND MEASUREMENT OF DOUBLE STARS BY LUNAR OCCULTATIONS

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1. Introduction

When a star is occulted by the dark limb of the Moon its apparent intensity drops to zero very quickly. MacMahon (1909) proposed that the time of disappearance would measure the diameter of the star, but Eddington (1909) demonstrated that diffraction effects at the lunar limb would lengthen the apparent time of disappearance to about 20 msec, and suggested that these effects would greatly limit the usefulness of the technique. MacMahon's paper indicates that he was aware that stellar duplicity could be detected from occultation observations, but he did not amplify the point and Eddington did not comment on it. While it has been demonstrated theoretically by Williams (1939) and experimentally by Whitford (1939) and others that stellar diameters of a few arcmsec can be measured by this technique, its use for the discovery and measurement of double stars has been only incidental to other programs (O'Keefe and Anderson, 1952; Evans *et al.*, 1954). Properly exploited, the method can contribute materially to the study of double stars.

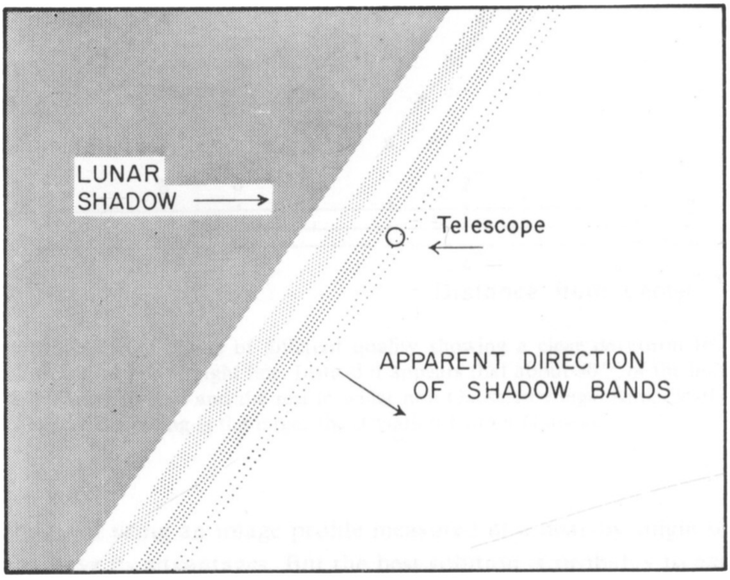

Fig. 1. A drawing of an occultation event, as the diffraction fringes from the lunar limb cross the telescope objective.

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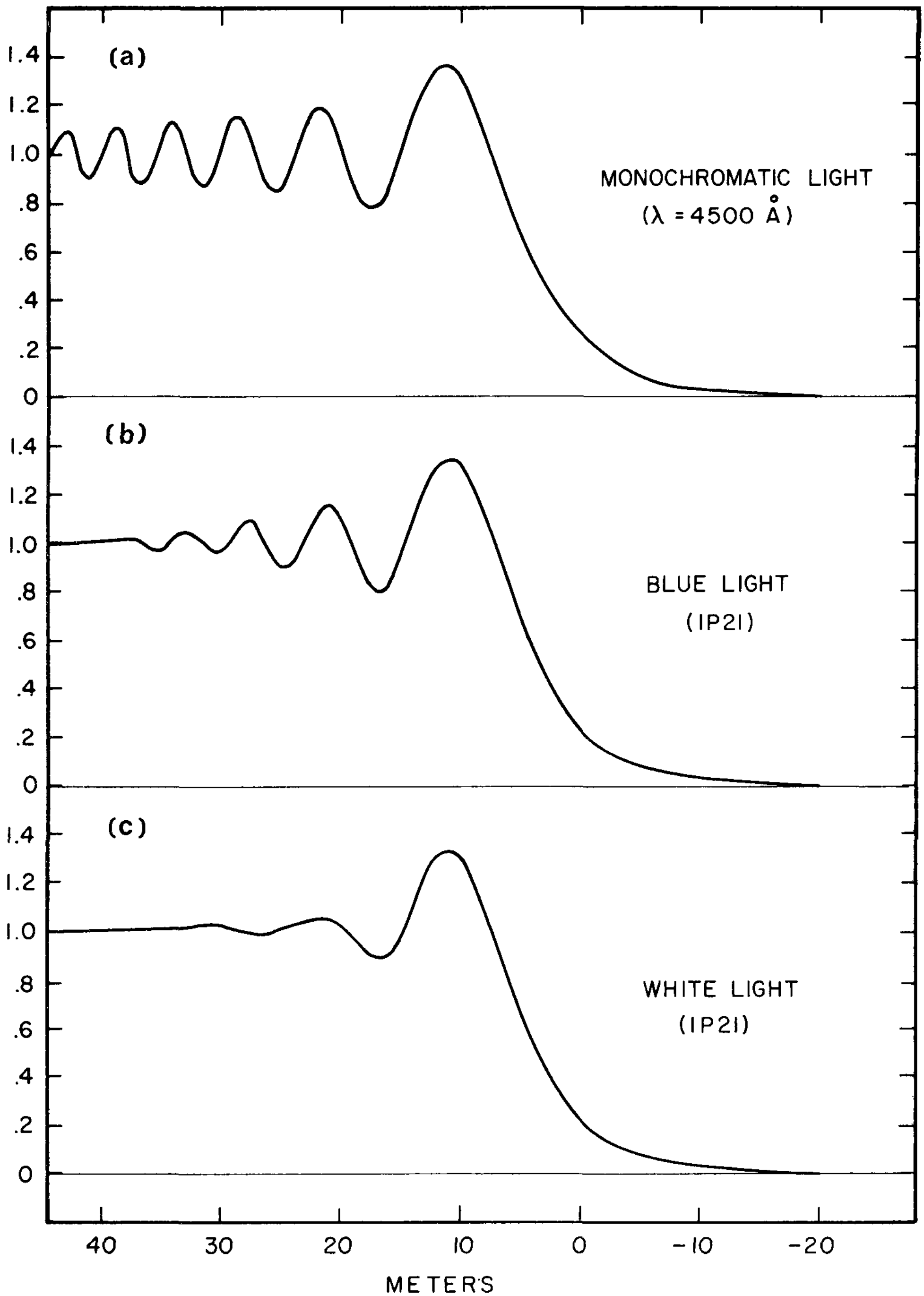

Fig. 2. Theoretical fringe patterns, showing the effects of increasing optical bandwidth.

2. The Process

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 edge of the shadow is not sharp; it is modified by diffraction at the lunar limb into a series of alternating bright and dark bands (Figure 1). If a telescope is pointed at the star during the time of fringe passage it will observe the starlight to fluctuate up and down 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.

If the light were monochromatic and the lunar limb perfectly smooth, the occultation trace would appear as in Figure 2a. In practice a finite bandwidth of optical frequencies is detected. tending to blur the details in the finer fringes. Figure 2b shows this effect, computed for the nomical 'B' filter of the UBV system; Figure 2c shows the response expected from a 1P21 phototube without filter. These curves were computed assuming the observed star is a point source emitting an equal amount of light at all wavelengths.

Figure 3 illustrates that theoretical curves of this type can fit the observed data quite well. Our normal procedure is to assume that an occultation event is a single point-source star, and we have developed a computer program which selects the best least-squares fit to the observed data. The spectral type of the star is taken into account when the theoretical curve is computed, as well as the spectral response of the photo-

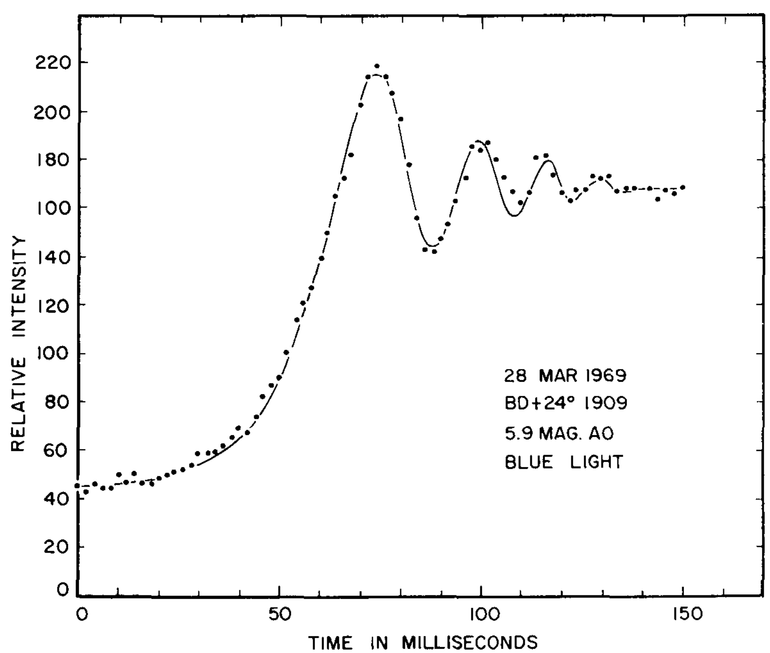

Fig. 3. Observed occultation reappearance of a point source star. The solid line is the theoretical curve of best fit.

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meter. The program is allowed to vary 3 parameters to obtain the fit: the time of occultation, the amplitude of the signal, and the timescale of the event. This last parameter represents the cosine of the occultation angle on the lunar limb. If the limb were everywhere smooth and flat we could compute its value precisely; the difference between our computed timescale and that observed is a measure of the slope of the limb at the point of occultation.

In some cases our assumption that the star is single is incorrect; in these cases we allow 2 additional parameters in the program to be adjusted, representing the amplitude and occultation time of a second point-source star.

When the star is double we do not obtain a measure of separation and position angle for the pair (Figure 4). From a single observation we obtain only the vector separation of the pair in the direction of fringe passage (V1 in the drawing). Star 2

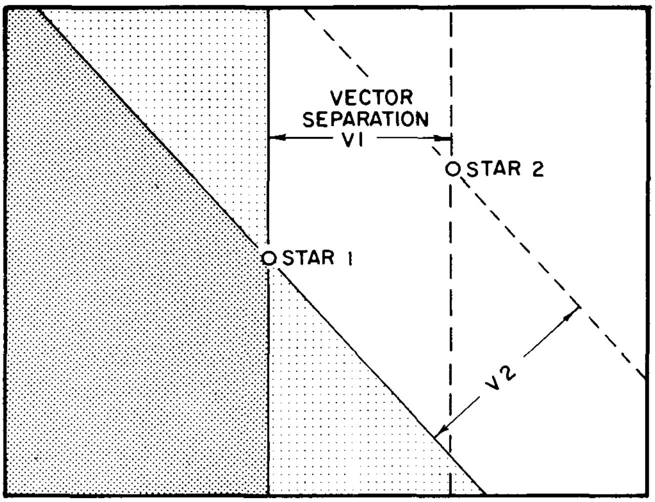

Fig. 4. A single occultation measurement of a double star gives only the vector separation V1; star 2 could be anywhere along the vertical dashed line. A second measurement gives V2 and locates star 2 precisely.

could be anywhere along the vertical dashed line. A second observation at some other position angle on the lunar limb (V2) is required to define the location of the second star with respect to the first.

We are thus faced with one of the major limitations of the technique: the requirement for two or more observations of the same event. There are other limitations as well. Because an occultation event is unique we cannot repeat it later if the night is cloudy. We cannot even choose the stars we want to observe; they are chosen for us by geometry and the laws of celestial mechanics. We can, however, greatly improve our chances of obtaining useful data if we can induce many different observers to try to record the same event from different locations. If there are several, the chances that all will be clouded out is much reduced, and any pair can serve to define a double star.

Multiple observations help overcome another difficulty as well. Irregularities on the lunar limb can, in a few cases, cause severe distortion to the observed diffraction pattern. While it is very unlikely that a lunar lump will cause enough distortion to mimic the trace of a double star, it can affect the timing and thus the measurement of apparent separation. We have performed extensive calculations of these effects for many sizes and shapes of irregularities, and can show that limb distortion effects can, for the most part, be readily distinguished from other forms of noise, as well as from stellar effects. Our experience indicates that severe distortion is very rare in practice. Multiple observations of the same event can serve, at the very least, to identify those traces containing limb distortions.

We have shown theoretically, and hope soon to demonstrate in practice, that occultation observations in two separate colors may be used to recognize, and in some cases remove, limb distortion effects. The amount and character of the distortion is a function of the wavelength of light detected, and a given lunar bump will affect traces in different colors in a systematically different and calculable way. Double star traces which show the same vector separation in two different colors cannot be materially affected by limb distortion.

3. The Observing Equipment

Our detector is a standard UBV photometer head with a cooled 1P21 photomultiplier tube. All of our observations to date have been obtained with the 36″ telescope at McDonald Observatory, using apertures of either 8 or 16 sec arc in diameter.

The basic recording device is a digital multiscaler, shown in Figure 5. Current from the photometer is amplified by a low-noise electrometer and is then presented to control and level-sensing electronics. This control permits adjustment of the amplification, and allows a DC component to be subtracted from the incoming signal to counteract the moonlit sky background and improve the apparent contrast with the star.

The adjusted output signal from the control electronics is converted by a voltage-to-frequency converter into pulses which are counted by the multiscaler. The multiscaler is advanced from channel to channel under control of a digital timing system, which in turn is monitored by the oscilloscope and kept in synchronism with the broadcast time signals (UT2) from WWV. We use 1 ms time channels for direct occultations and 2 ms channels for those nearer to grazing.

The multiscaler has been modified to cycle repeatedly through all 400 channels. As each channel is addressed, the previous contents of that channel are erased and the new reading inserted. In this way the multiscaler keeps a record of the data for the previous 400 or 800 msec, and can be stopped *after* the occultation event is detected. When the input signal level falls below a given threshold and remains for at least 0.1 sec the cycling action is stopped automatically. The millisecond counter indicates the exact elapsed time to the final channel. Data are obtained in direct digital form for input to the computer programs, and the multiscaler display system allows the recorded trace to be examined immediately after the event.

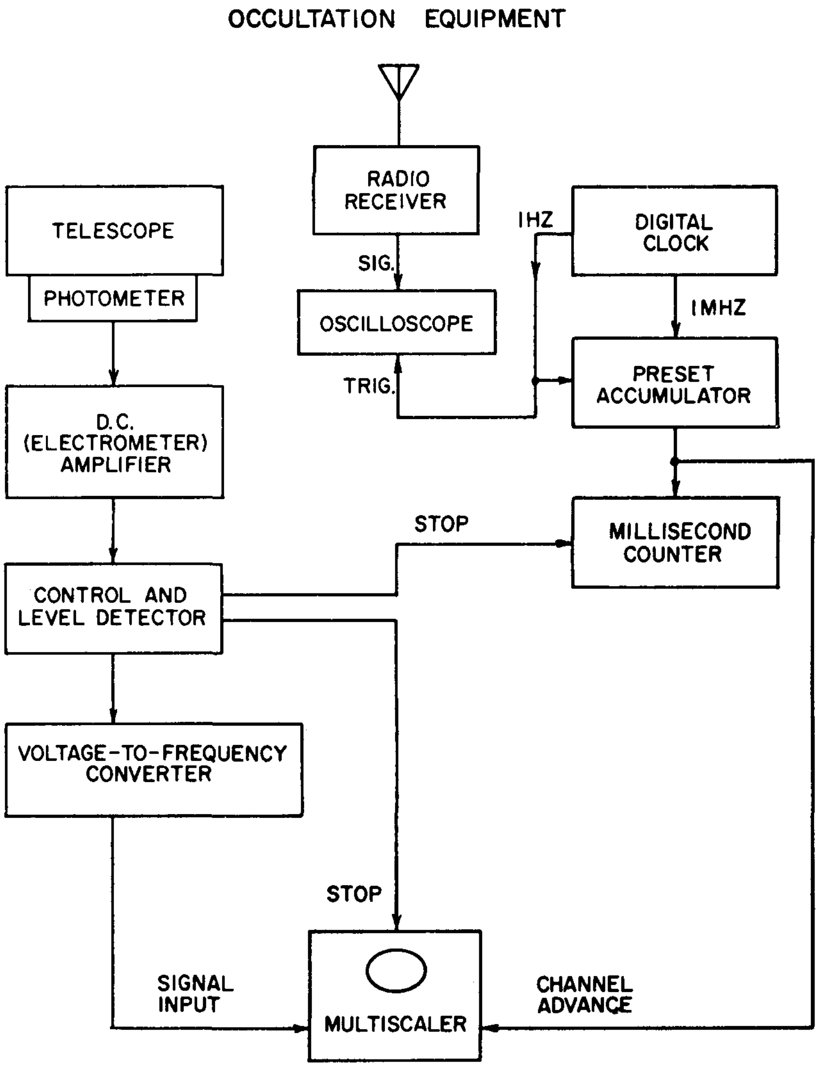

Fig. 5. A block diagram of the observing equipment.

4. The Observations

The trace obtained from BD $+28°$ 1138, which displayed unexpected duplicity, is shown in Figure 6. A coudé spectrogram taken of this star shows no evidence of line splitting; the system may be nearly pole-on. The stars are of equal brightness in blue light, separated by a minimum of 0.0258 sec of arc. At this separation the fringe patterns are seen completely separated and no interpretation problem exists. This is the widest separation we have recorded with our technique, although separations as great as those measured by the eyepiece interferometer (0.1 arc sec) are possible.

Figure 7 shows the trace obtained from BD $-03°$ 3289 in white light; that is, without

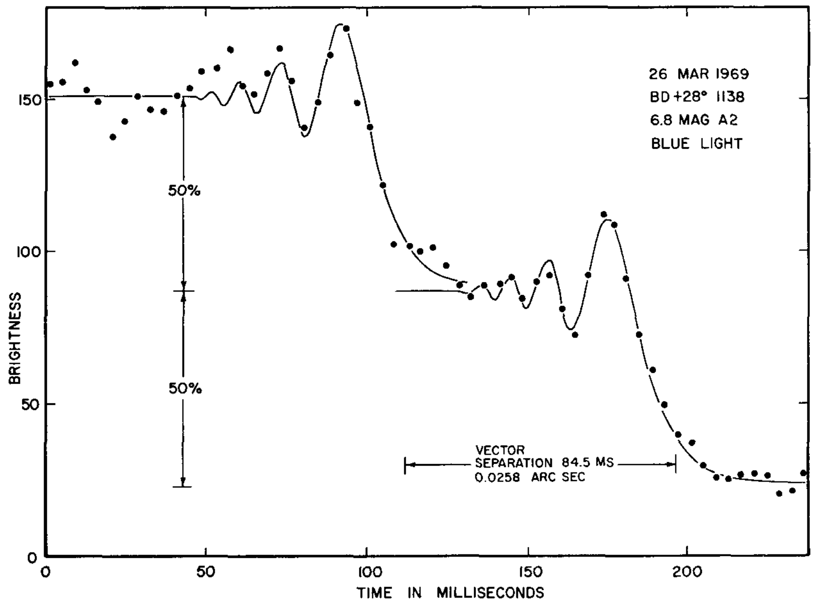

Fig. 6. Clearly separated fringe patterns indicate this is a double star.

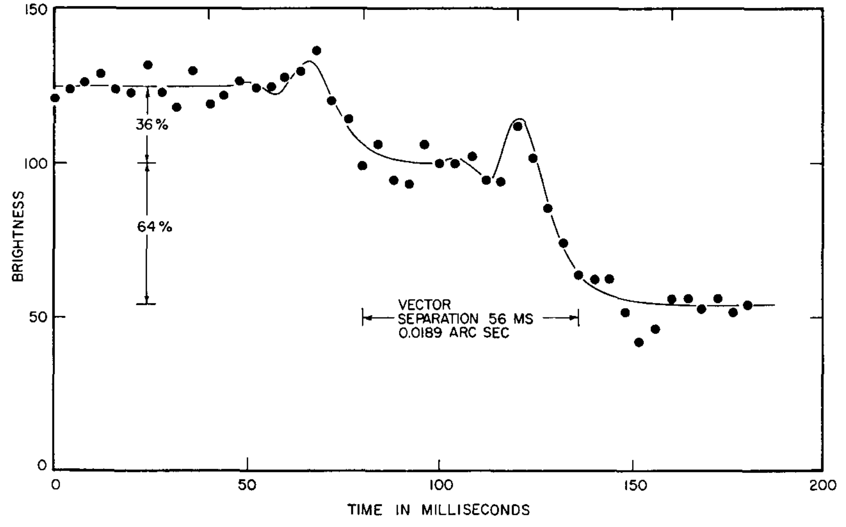

Fig. 7. Another unexpected double, whose combined magnitude is 8.0.

filter. Although less widely separated, this pair is still well resolved because the white light fringe pattern is somewhat shorter that the blue. The solid curves in all of these drawings are the theoretical patterns of best fit.

Figure 8 shows a trace obtained by Dr Howard Poss of Temple University of the bright star α^2 Librae, which he reported to have a vector separation of 0.01 arc sec and a magnitude difference between the components, in blue light, of 0.4. Dr Poss was kind enough to allow us to include his measurement with our own. Our analysis of his curve is shown by the solid lines representing two stars of different brightness, while the crosses show the result of subtracting the smaller curve from the composite ob-

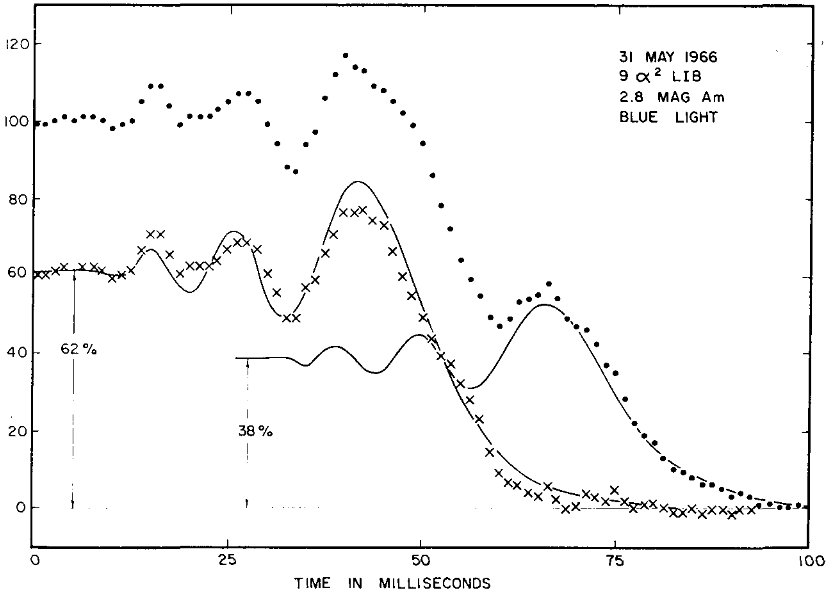

Fig. 8. An occultation curve of a double star obtained by Dr. Howard Poss of Temple University, reproduced courtesy of Dr. Poss.

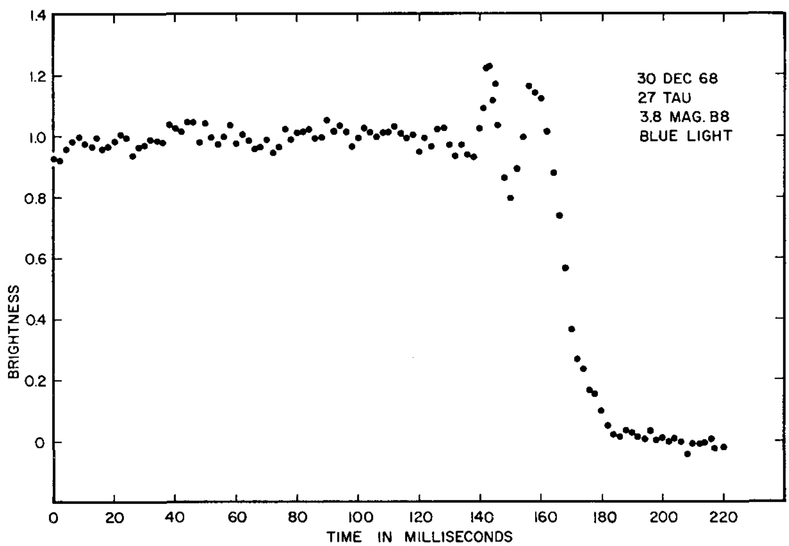

Fig. 9. An occultation trace of 27 Tau (Atlas). The fringe pattern is quite peculiar, with the second fringe larger than the first.

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served trace. The fit to the residuals is not as good as we might expect, and could indicate a moderate amount of limb distortion. The separation and relative amplitudes are quite well defined in spite of this.

An occultation trace obtained from the star 27 Tauri, a member of the Pleiades, is shown in Figure 9. The trace is clearly peculiar. The second bright fringe is larger than the first, and the third is either displaced or missing. Our attempts to find an explanation for this curve from limb effects have not been successful. A remarkably good fit can be obtained, however, on the assumption that the star is double. Figure 10 shows its resolution into two components separated by 0.0061 sec of arc, with a magnitude

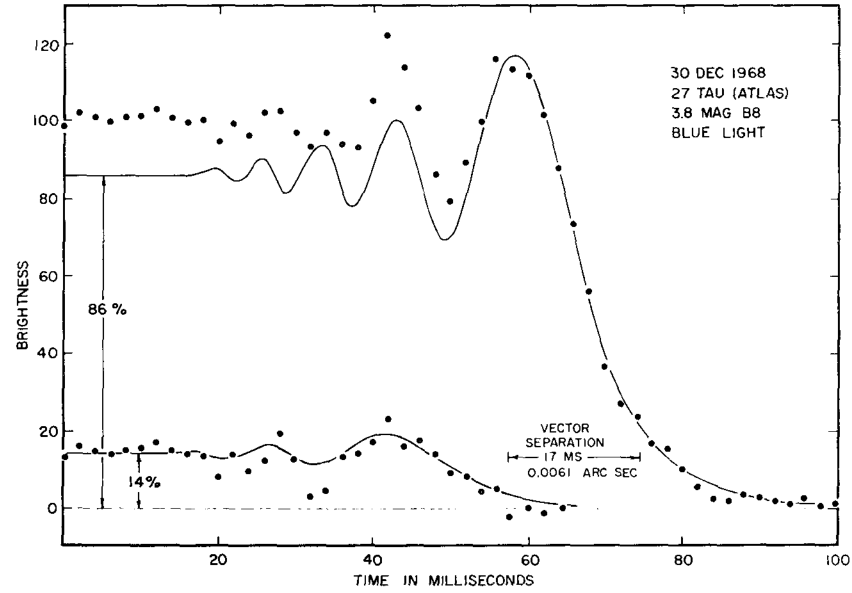

Fig. 10. The trace of Figure 9 resolved into the sum of the traces of 2 point source stars. The time scale has been expanded for clarity.

difference (in blue light) of 1.9. This star was shown by Abt (1965) to be a spectroscopic binary: its apparent resolution into two components of unequal brightness is quite convincing. Dr Poss of Temple University also has a trace of this star which he obtained at Flower and Cook Observatory, but it has not yet been analyzed in detail.

5. Conclusions

A routine program devoted to photoelectric measurements of lunar occultations can both discover and measure double stars of very small separation, and could serve as a useful supplement to more conventional double star studies. As a by-product the occultation timings are themselves useful, and occasionally the diameter of a star may be determined. Multi-color observations are desirable but not essential; what seems to be essential, however, is to obtain multiple observations of the same event from different locations on the Earth's surface. Considered alone, an occultation observation is only an interesting demonstration; in consort with several others, it becomes an important astronomical measurement. Separations ranging from a few to a few hundred milliseconds of arc can be measured, and accurate photometric values for each star can be obtained. Such close doubles will frequently show radial velocity variations. Occultation measurements can provide the necessary supplement to spectroscopic data to allow accurate computations of stellar masses and parallax, and may contribute materially to the study of stellar evolution in binary systems.

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Discussion

Pecker: Si l'on a des bandes plus étroites, non pas de lumière blanche, mais incluant ou excluant Hα dans une des ces bandes et s'incluant dans une autre, on pourrait aussi bien pour les étoiles doubles que pour les simples, améliorer aussi considérablement la qualité de l'information extraite – et sans doute à peu de frais.

Nather: One is limited to stars of magnitude 9 or brighter because of the brightness of the moon's limb. For bright stars I think your suggestion would work.

Rakos: Can you exclude the possibility that the DC amplifier was overloaded at the moment of the first maximum in the diffraction pattern?

Nather: Yes.

Rakos: I would suggest to use a pulse counting method instead of the DC amplifier. A band width of 100 MHz or more is reached today very easily.

Deutsch: Are these double stars new?

Nather: 27 Tauri was found spectroscopically by Abt at Kitt Peak Observatory. BD $+28°1138$ and $-3°3289$ seem to have not been recorded before.