OCCULTATIONS, PAST AND FUTURE

David S. Evans
Department of Astronomy
University of Texas
Austin, Texas 78712
U.S.A.

ABSTRACT. The techniques, advantages and limitations of photoelectric observations of occultations of stars by the Moon are reviewed. The results for timings, lunar limb slopes, double and multiple stars, and the determination of angular diameters of stars are considered. Possible effects of lunar limb irregularities are discussed. Observers are strongly recommended to pursue the upcoming series of occultations of Antares and other important stars.

1. INTRODUCTION

Modern observations of occultations of stars by the Moon date from the work of Whitford (1939) who first demonstrated photoelectrically the phenomenon of diffraction of starlight at the lunar limb. His paper was accompanied by an analysis by Williams (1939) of the effects produced by stars of different angular diameters (Figure 1). The fringes had previously been detected photographically by Arnulf (1936) who used them to determine the angular diameter of Regulus.

Following a suggestion of David Thackeray occultation observations of Antares were made at Pretoria (Evans et al. 1953), Johannesburg (Evans, 1955) and Cape Town (Cousins and Guelke, 1953) of the Antares series of the early nineteen fifties and some other stars. My interpretation of these results was severely criticised with such effect that other observers were deterred for many years. I shall return to this topic later in my talk. I believe that a renewed and quite widespread interest in photoelectric observation of occultations can be attributed to the initiative of R. E. Nather and myself at the McDonald Observatory of the University of Texas starting in 1968.

The data derived from photoelectric observations of occultations relates to the following fields which I shall discuss in turn. (i) Timings, leading to information on the position of the Moon in relation to the star background. (ii) Information on the character of the lunar limb. (iii) The discovery and in some cases, investigation of double and multiple stars. (iv) The determination of angular

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diameters of stars with numerous astrophysical applications of the results. (v) Some stars of special interest.

2. TIMINGS AND THE LUNAR LIMB

Timings of occultations of stars by visual means have a long history and are surprisingly accurate. The rate of movement of the lead point of the lunar limb against the star background only surpasses 0.5 arc seconds per second of time when the Moon is near the horizon, often not even then. Even in such adverse circumstances a visual timing by a skilled observer good to one fifth of a second specifies the position of a point on the lunar limb to about 0.1 arc seconds or some 200 metres linearly.

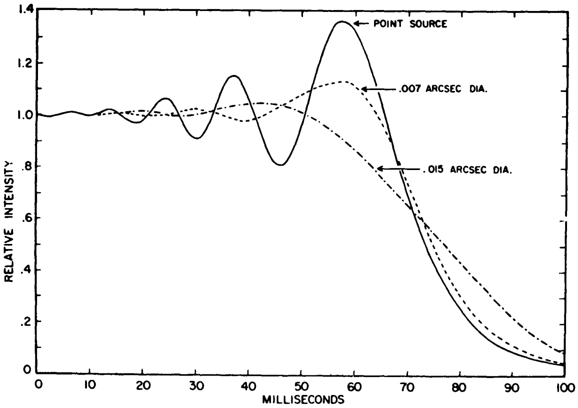


Figure 1: Typical theoretical traces for various angular diameter stars (McGraw et al. 1973).

In Figure 1 we see an ideal photoelectric trace for a point source in which the brightest diffraction fringe attains a peak level of 1.37 if the unobscured light of the star is counted as 1.00. The moment of geometrical occultation occurs at level 0.25. In practical cases the ideal trace is modified by the bandwidth of the filter used, the colour of the star, the photocell response, by seeing noise and in rather rare cases by the fact that the star may have a sensibly non-zero angular diameter.

The source of seeing noise is largely the scattered light from the illuminated part of the Moon. In the case of a faint star the intensity of this may exceed that of the star by a hundred times or more, so that the fringes are obliterated completely and all that is seen is a sudden drop or rise in the light level as the star disappears or reappears. The classical photoelectric technique is thus almost entirely restricted to events at the dark limb of the Moon, though we have on rare occasions for bright stars using specially selected narrow interference filters made observations at the bright limb.

I should mention here the technique of Dommanget (1980) who uses a TV camera to record the field on tape. On playback he can at his leisure determine the fraction of a picture scan at which the star disappears or reappears, even at the bright limb and so obtains timings, though he cannot observe the diffraction fringes or any subtle details of the fading or reappearance. He does however provide data on the position of the lunar limb at phases not ordinarily accessible to the standard photoelectric method.

Even for the noisiest photoelectric trace a proper computer reduction program which takes account of star colour, system response and the rest, can produce a timing good to a few milleseconds corresponding to fixing a point on the lunar limb with an accuracy of a metre or even less.

There are elevations and depressions on the lunar limb which are presented differently at different conditions of libration (Watts 1963). These may exceed some tenths of an arc second up to an arc second and it is clear that their effects can swamp the intrinsic accuracy of photoelectric timings when used to improve the lunar ephemeris. Indeed Morrison (1971) while recognising that photoelectric occultation timings should be free of systematic and accidental errors considered that they should not be given much more weight than visual ones.

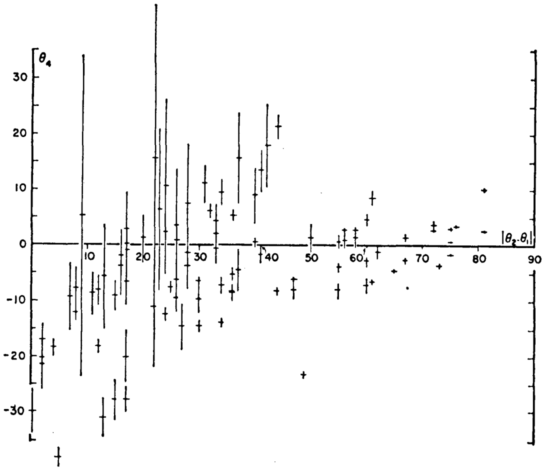
Considering that lunar laser ranging to reflectors placed on the surface by American and Russian missions began over ten years ago and can produce range figures accurate to a few centimetres it might be supposed that occultation timings are no longer useful for ephemeris studies. However I consulted Dr. Raynor L. Duncombe formerly Director of the U. S. Nautical Almanac Office, who hoped the program would continue and remarked that these observations were the best available up to the beginning of the laser ranging program. Dr. Peter J. Shelus who directs the lunar laser ranging program at Texas points out that occultation observations serve to locate the Moon with respect to the standard star positions of the FK4 catalogue, whereas the lunar laser ranging program does not do this directly. The occultation results were used by Mulholland (1981) to locate the centre of figure of the Moon with respect to its centre of mass.

There thus seems to be some expert opinion in favour of the continuation of a program of timings. At Texas we have made nearly 7000 observations starting in 1968 and so have not quite emulated the example of Edmond Halley who, starting at age 63, observed the position of the Moon through an entire rotation of the nodes of its orbit, which takes 18.61 years, but we have come fairly near it. After this interval the same zodiacal stars tend to be occulted again. This shows up in the entries on my card catalogue of all photoelectric observations. Our program is no longer supported by the U. S. National Science Foundation and I intend to retire in 1986. I hope other observers will continue the work and perhaps someone will take over the catalogue and even prepare it for publication.

If an occultation trace shows good fringes we can compare their rate of passage with that predicted for a level limb, and can attribute the differences to the presence of a limb slope which applies, I think, to some 50 metres of its length. The deduced value is usually ambiguous since all we are determining is the angle between the limb and the line of relative travel of the star. One value is usually small, almost never exceeding 30°, whereas the other is often very steep or overhanging and can almost always be rejected with confidence. The Moon models of James Nasmyth with their exaggeration of vertical scale led to a general belief in the existence of steep slopes on the Moon, but even a cursory study of visible shadows on the lunar disk shows that steep slopes are rare, while at the lunar limb, the fact that double disappearances of stars only occur at grazes, supports the same conclusion.

Our convention is that a slope which spreads the fringes counts negative, one that compresses them counts positive. Only negative slopes can occur for occultations at nearly normal incidence and values with large uncertainties since it requires a large slope to make a significant change in rate. At large angles of incidence most events take place on forward slopes and errors tend to be small. The situation is illustrated in Figure 2. (Evans, 1971)

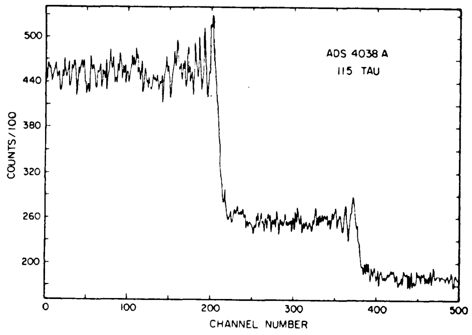
Figure 2: Statistics of limb slope determinations as a function of contact angle.



3. DOUBLE AND MULTIPLE STARS

The occultation method has proved valuable for the detection and in some cases analysis of double and multiple stars. In the simplest case of a double star the disappearance or reappearance is in two distinct steps (Figure 3) (Africano, et al. 1978). The separation

Figure 3: Disappearance of 115 Tau A. Vector separation 0.0987 arc seconds.



between these in time, multiplied by the lunar rate adjusted for the local lunar limb slope defines the "vector separation" between the pair that is their true separation projected on to a line perpendicular to the lunar limb, taking slope into account, at the point of occultation.

If the separation is small the fringes due to the two components may overlie each other producing what appears to be a distorted trace (Figure 4) (McGraw et al. 1974). If the trace is very noisy it may be difficult to be certain of possible duplicity. In this case a device introduced by Bartholdi is of great help. This is to plot the integral of the deviation of the measures from the mean value for the whole trace. This plot is little affected by seeing noise and consists of two straight line segments for a single star, three for a double and four for a triple star (Figure 5) (Dunham et al. 1973). We have adopted the practice of assigning a quality parameter 3 for a certain double, 2 for a probable double, 1 for a possible double, and zero for no duplicity. In the best cases vector separations down to a few arc milliseconds can be determined, together with magnitude difference between the components, and, if a dual channel system is used, differences of colour.

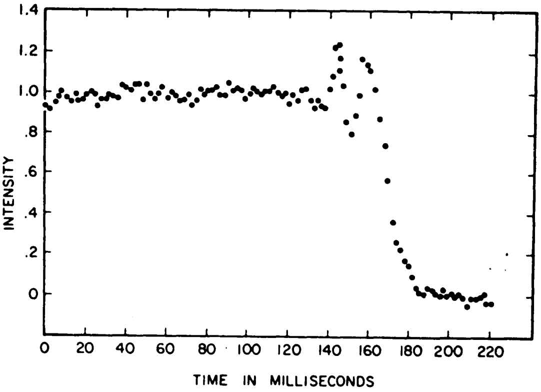


Figure 4: Disappearance of the Pleiades double star, Atlas.

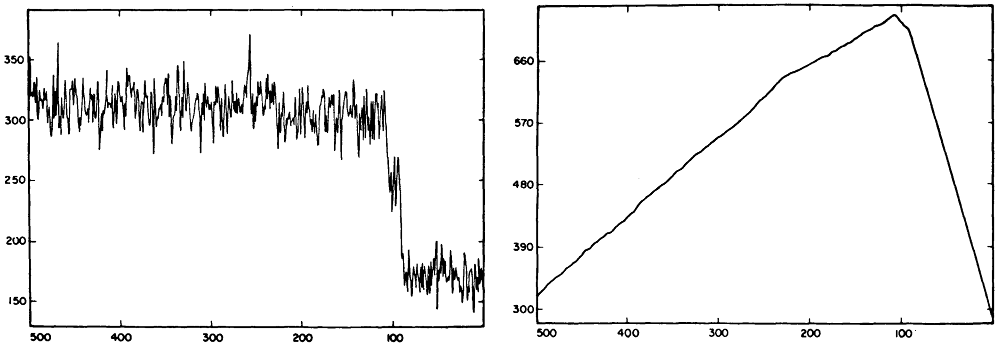


Figure 5: Original trace and integral plot for disappearance of of triple star, SAO 118786.

For the brighter A, B and O stars some 20-30 percent are found to be double with smaller values for later types (Evans, 1983) and a few years ago a catalogue was produced. Because of severe selection effects, these numbers must gravely underestimate the real incidence of duplicity, which, for these stars seems to increase the closer the pairs under consideration. At the present time this is one of the most powerful methods of angular resolution available, having the advantage over speckle interferometry that it is not subject to the Dawes limit and is not ambiguous as to the order of the components. It has, of course, the severe limitation of applying only to the stars of the zodiacal band. The statistics have been of interest to those concerned with the guidance systems of the Space Telescope and Hipparcos missions.

A single observation of a double star tells that the secondary lies on a certain position line parallel to the effective lunar limb. Simultaneous observations of the same event from two different observatories, or in the case of no orbital motion, from the same or different observatories on different occasions, can yield measures of true separation and position angle from the intersection of two or more position lines. Some judgement must be exercised, since if the difference in position angle is too small, observational errors will make the position lines nearly parallel and a false result will be obtained. Best results are usually obtained for position angles on the lunar limb differing by at least 30 degrees.

Many zodiacal double stars have been discussed so I shall select only two for special mention. The first is the quintuple star Beta Scorpii (Evans et al. 1978) in which New Zealand observers played an important part. Beta Scorpii is overtly a pair separated by 13.6 arc seconds. Star A, B0V with V=2.63, is itself a close spectroscopic binary with a fainter companion Star B about half an arc second away. Star C is B2V with V=4.92, with a close faint companion. This star system was of special interest because it was occulted by Jupiter in 1971 (Hubbard et al. 1972) and the analysis of the observations made then required a knowledge of the star's multiplicity, not yet known in detail. Occultation observations were made in 1975 at Dunedin and Auckland and at various American observatories in 1976. These served to fix the separation and position angles of the pairs AB and AC as shown in Figure 6. I have no time to go into detail but this figure shows how well the close pair could be analysed, to give a separation of0.463±0.017 arc seconds in P.A 116°5±2°6. The analysis of the wider pair is not so satisfactory, demonstrating that to make this method work both components of a pair must be close enough to be occulted on essentially the same piece of lunar limb.

My second example is Beta Capricorni (Evans and Fekel, 1979). This is a triple star of which the primary is a K0 II-III in orbit, with a very long period for a spectroscopic binary, of 1374 days, with a B8V star, itself a spectroscopic binary with a period of 8.68 days. Fekel made an intensive spectroscopic study of the system and obtained all the usual parameters with their usual limitations. It will be realised that if a visual orbit were also available for the primary pair then complete data for the system could be obtained and this with a certain amount of contriving could be got from 10 occultation observations made in various places between 1975 and 1977. There was also

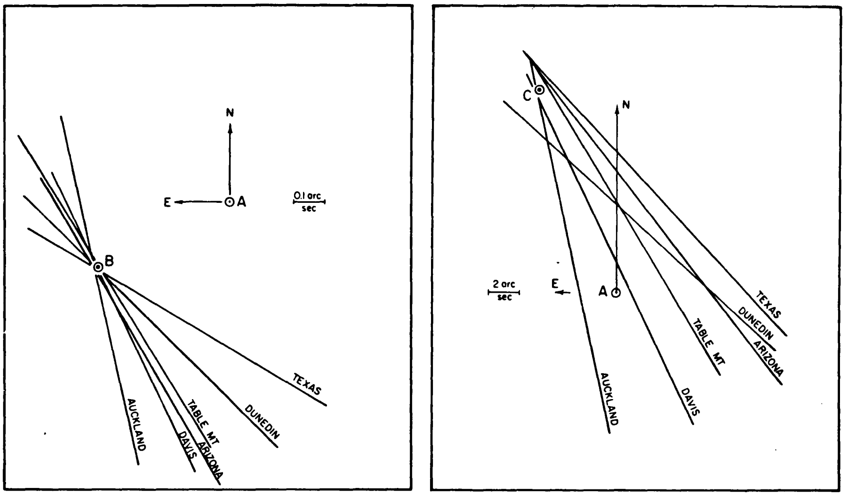


Figure 6: Concurrences of position lines for occultation observations of components of Beta Scorpii.

an early speckle observation (Blazit et al. 1977) which did not fit well and we now think ought to have been rejected, which distorted our original conclusions to a minor degree (Figure 7). The point is that

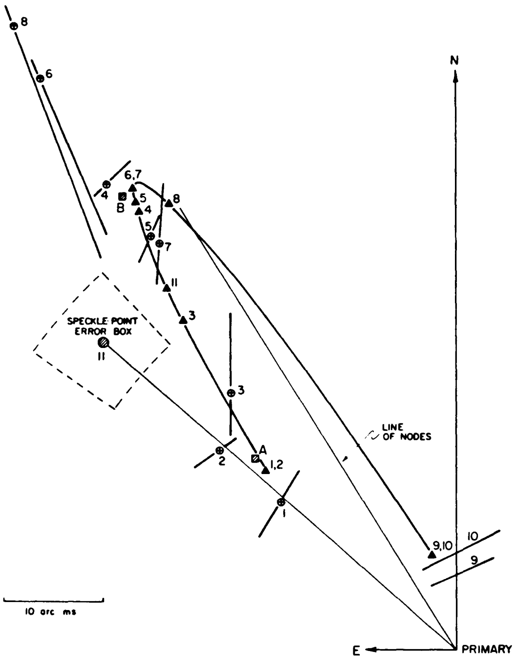


Figure 7: Visual orbit of the B-type secondary of Beta Capricorni as deduced from occultation observations.

through occultation observations this system became one of the best known in the sky with relative magnitudes (Figure 8), masses of the primary and secondary pair, parallax, linear diameter of the primary, and age all determined.

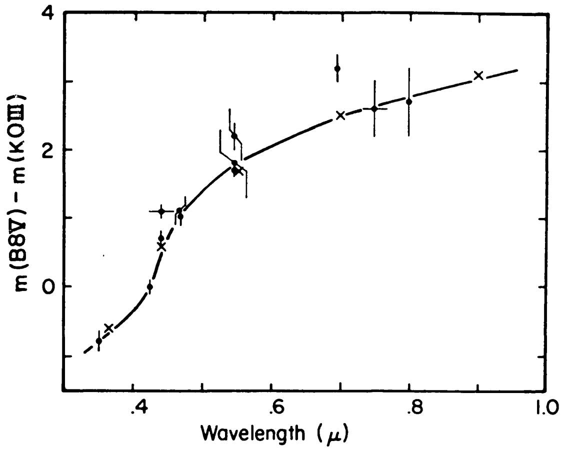


Figure 8: Relative magnitudes of B-type and K-type components of Beta Capricorni from occultation observations.

4. ANGULAR DIAMETERS

If a star has a significant angular diameter each strip of its surface parallel to the lunar limb produces its own set of diffraction fringes, which, suitably displaced, fall on top of each other. The consequence is that the fringes become less and less prominent for larger stars (Figure 1). In particular the first fringe becomes more and more depressed and some early workers have used the amount of the depression to determine the angular diameter. This short cut is risky because of the influence of seeing noise and the traces should be analysed using a suitable computer program. A recent compilation of angular diameter measures by Feierman (1985) lists more than 300 measures of 113 stars ranging from 67 arc milliseconds for R Leonis in the near infrared to just under 2 arc milliseconds. Some infrared sources have given much larger values and this is also true of R Leonis in the far infrared. Leaving out these exceptional objects the lower limit for such determination seems to lie between 1 and 2 arc milliseconds for traces of very high quality where the seeing effects on the fringes are minimal. The contribution to knowledge of angular diameters from occultation observations is thus considerable though new interferometry techniques are promised capable of measuring much smaller stars following the successful lead of Hanbury Brown et al. (1970). In spite of these new developments I do not think we need pronounce the funeral oration of the occultation method just yet.

Measurements of angular diameters of stars have had a wide impact on stellar astrophysics. It is easy to prove that

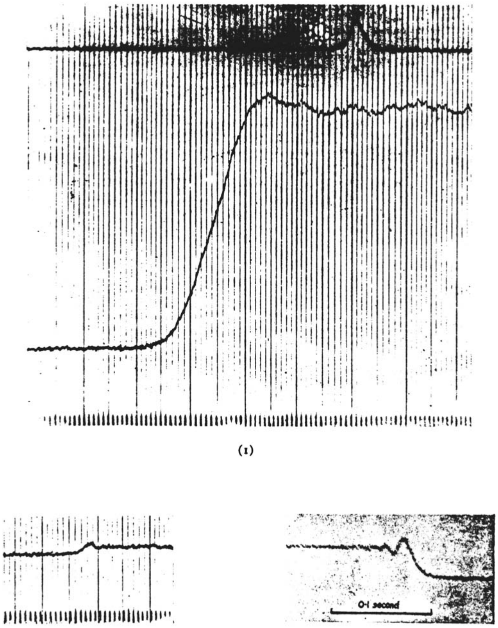
$F_V = \log T_e + 0.1C = 4.2207 - 0.1V_0 - 0.5 \log \phi'$

where T_e is the effective temperature, C the bolometric correction,

$V_\odot$ the apparent V magnitude adjusted for interstellar extinction and ϕ' the angular diameter in arc milliseconds of a star. The constant is derived from the solar calibration. F_V is a visual surface brightness parameter which Barnes et al. (1978) showed, based on the assemblage of known angular diameters, could be deduced from photometric measures in the V (Johnson) and R(Johnson) bands. Thus angular diameters of any sort of star can be determined. Applications have been made to Cepheids, RR Lyraes, red giants, white dwarfs, flare stars and even to portions of star surfaces such as starspots on red dwarf stars and RS CVn stars. The addition of new angular diameter measures will help to improve the definition of this calibration curve.

5. ANTARES AND ALDEBARAN

These stars are each occulted in series separated by about 19 years with their series separated by about 9 years. Figure 9 shows the trace obtained at Pretoria in 1952 (Evans et al. 1953). A close examination of this shows that the trace begins to rise far sooner than expected and this must be taken seriously because a few seconds previously the trace obtained for the companion was hardly larger than this deviation. Several authors have tried to attribute this to irregularities on the lunar limb (e.g. McCants and Nather, 1971) but their argument is faulty. The effect can however be produced by a sort of



(2) (3)

Figure 9

Occultations of Antares as observed at Pretoria.

(1) *Antares*, 1952 *April* 13. *Top line*, 1 *second pulses; centre line, occultation trace; bottom line*, 100 *c/sec timing trace.*

(2) *Antares B*, 1952 *April* 13. *Same scale as* (1).

(3) *Antares B*, 1953 *March* 8.

dome on the limb carefully placed with respect to the star disk. Many critics thought that lumps on the lunar limb would commonly invalidate occultation results. In principle they can even produce bogus double stars (Evans 1970) but the effects are very sensitive to the wavelength band used, which should help in rejecting dubious cases. One certain result is that if the first fringe exceeds the canonical level of 1.37 this must be due to limb irregularities. The first and I think the only times we have encountered this was on Runs Nos 1218, 2754 and 4160 (Evans, 1971; Africano et al. 1975; Africano et al. 1977) and we believe such incidents are very rare. Antares was observed on the same occasion (Figure 10) at Cape Town (Evans 1957) and produced essentially the same result. Again in 1953 Antares was observed at Johannesburg and Cape Town with matching results which differed from the previous ones. It therefore seems very improbable that lunar limb irregularities could have been responsible. What is more Feierman's compilation lists 45 observations of Aldebaran during the last series for that star, with closely accordant results and apparently no necessity to appeal to lunar limb irregularities.

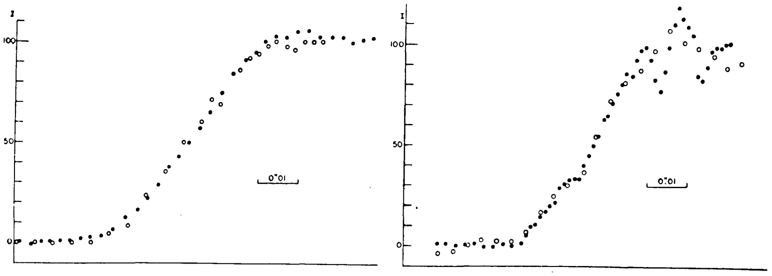


Figure 10: Duplicate observations of Antares occultations. Left: 1952 April 13, Pretoria and Cape Town. Right: 1953 March 8, Cape Town and Johannesburg.

My analysis of the Antares results suggested that they were not consistent with a star model which was circular in outline and centrally symmetrical. At the time this was regarded as heresy but now with suggestions that stars such as Betelgeuse may have large blotches or starspots this does not seem so far-fetched.

I mention Antares now since a new series of occultations starts in 1986 - and there will be other interesting stars such as the Pleiades and Sigma Scorpii coming up soon - and I would strongly encourage observers to go after Antares and other interesting objects in the expectation that there are some important astrophysical results waiting to be found.

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DISCUSSION

Rowe: With β Sco, spikes were observed during occultation by Jupiter, usually in pairs. An interpretation has been made in some (obscure) papers in terms of a resolved, close-spaced pair - 10 or 20 microarcseconds - a record in both optical and VLB radio astronomy and explicable in terms of the number of halfwaves of light refracted towards the common observing telescope by a high Jovian atmospheric refracting layer or layers.

Evans: Thank you for your remarks; of course this was a planetary not a lunar occultation. Evidently this could indicate a detection of the secondary component found in 1976.

Graham: Could you outline the basic equipment needed for occultation observations?

Evans: A photometer with recording equipment capable of say two or four millisecond data-rate and good tie in to an absolute time system. One should use a circulating buffer to avoid being swamped by the quantity of data. (The total amount of useful telescope time we have used in undertaking 7000 observations is ~ 3 minutes.)

Orchiston: Would you care to comment of the value of visual observations of grazing occultations?

Evans: A great deal of effort has been expanded on such observations and I would like to see a synthesis of the results.

Kurtz: Could you estimate what percentage of B stars are double?

Evans: Among HR stars we found 29 per cent. As there are several selection factors working against detection by the occultation method, the real percentage must be higher. Independent evidence plus occultation data for the Pleiades would suggest two or three times this percentage.