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OCCULTATION RESOLUTION OF σ SCORPII

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An occultation of the β CMa variable σ Sco by the moon was observed photoelectrically from the South African Astronomical Observatory at Cape Town and simultaneously from the S.A.A.O. outstation at Sutherland. Both observations show that the star has a companion 2.2 magnitudes fainter than the primary; the two observations combined show that the fainter star is $0\overset{''}{.}49$ distant from the primary in position angle 268°. Visual observations of occultation events extending back to 1860, in which duplicity was observed or suspected, are combined with these observations to derive some information concerning the relative orbit of the fainter star.

Key words: occultation — binary star

Introduction

The star σ Scorpii is a variable of the β Canis Majoris type (also referred to as β Cephei variables), with a basic period of about 4.5 hours. The star was studied by Levee (1952) who found that the mean (γ) velocity was variable with a period of about 33 days, in addition to the short period variation. As with several (but not all) stars of this class a beat phenomenon was discovered (Struve, McNamara, and Zebergs 1955) showing a period of about 8 days, due to the presence of two nearly identical, short-term periodicities which are apparently pulsational in nature. Levee concluded that the 33-day period must be due to the presence of a close companion, and Struve et al. agreed.

Ledoux (1951) has suggested that the β Canis Majoris phenomenon may be due to nonradial pulsations of the stars, rather than the purely radial pulsations encountered in the Cepheid variables. Osaki (1971) has pointed out that certain nonradial modes can yield a modulation of the γ-velocity (together with other effects), allowing a single object to masquerade as a spectroscopic pair, and cautions that a variable γ-velocity cannot be taken as positive proof of duplicity. Clearly any evidence concerning the presence of a close companion would be of value.

Sigma Sco is regularly occulted by the moon and is sufficiently bright ($m_v = 2\overset{m}{.}9$) so that a considerable number of occultations have been recorded by visual observers. A few such events, obtained primarily to measure the position of the moon with respect to the background stars, have been accompanied by notes suggesting the star is double. For example an occultation reappearance timing obtained at the Cape of Good Hope on 12 March 1860, reported in Volume 1 of the *Annals of the Cape Observatory* (p. 17), contains the footnote: "Not instantaneous. The time recorded is that of the first appearance of light, which was followed at an interval of about 0.5s by the full blaze of the star." A similar effect, this time on a disappearance event, was reported by Dawson (1931) for the same star as seen from the Observatorio de La Plata. Dawson points out, however, that his calculated minimum separation for the pair is much larger than would be expected for two components with a 33-day period.

A single occultation observation, even if recorded in detail at high speed, can only obtain the separation of a close double star in the

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apparent direction of lunar limb passage. Two such observations, however, if made at different locations and thus having different position angles on the moon, can be combined to yield the true separation and position angle of the pair (Nather and Evans 1970). The occulation of σ Sco on 21 July 1972, visible both from the South African Astronomical Observatory at Cape Town and from the Sutherland outstation, offered the first good opportunity to make such a measurement on a star strongly suspected to be double.

The Observations

The disappearance of σ Sco at the dark limb of the moon was recorded at the Sutherland outstation using the 20-inch reflector, a conventional photometer with a B filter, and the electronic system already described (Nather and Wild 1973). Data were obtained at 4 ms/reading to allow the longest possible record consistent with resolving the Fresnel fringe pattern. The recorded trace is shown in Figure 1. The presence of the suspected companion is clearly revealed by the small, early drop in light level; the new level is sustained until the much larger transition representing the occultation of the primary. By averaging the data points prior to and following the first level change, and comparing this change with that of the primary transition, we can show that the secondary contributes 12% of the total light, while 88% is contributed by the primary (in blue light). We thus compute that $\Delta m = 2^{m}2$. The long delay ($1^{s}36$) between the two transitions suggests that the two stars are not very close together.

While observing conditions at Sutherland were good, with no clouds in evidence and moderate scintillation noise levels, conditions at Cape Town were somewhat poorer. A thin layer of cloud was present which absorbed about 30% of the light from the star and contributed, by scattering the moonlight, to the sky brightness in the photometer diaphragm. The scintillation noise was somewhat greater than at Sutherland, as might be expected from the differing altitudes of the two observatories. The observation was obtained with the 18-inch Victoria refractor (which is corrected for the visual) and a V filter. As a consequence of the poorer conditions the occultation record obtained at Cape Town, while showing the primary transition with good contrast, did not at first glance show the small level change due to the secondary component. The analog equipment used to record the event has a characteristic high-frequency roll-off which is extremely leisurely; this awkward characteristic yields records in which the main fringe pattern is attenuated due to poor impulse response, but which contain a considerable amount of high-frequency, low-amplitude noise.

Clearly some smoothing process was required to improve the signal-to-noise ratio. We elected to treat the analog record in a way which would approximate, as closely as possible, the digital record obtained at Sutherland. The analog trace was divided into 10-ms contiguous segments, to approximate a 10-ms digital integration time, and the mean value of the signal in each segment was extracted and digitized manually. This process removed, to a large extent, the excess high-frequency noise contributed by the recording apparatus and yielded a primary transition of good contrast, with a major fringe somewhat attenuated. This transition is shown in Figure 2. The fringe pattern is clearly seen, although it was nearly obscured by small-amplitude noise in the original record. This improvement in quality offered us hope that the secondary transition might also be revealed by the same process.

The same filtering and digitizing process was applied to the trace for the 3 seconds before and after the primary event in a search for evidence of the other component. A slow change in overall level was present, presumably due to changes in cloud transparency or scattering; this was clearly not the level change sought but required that the record be examined in 1-second sections, since an overall change in level could not be used as a criterion. The real transition, if present, would have to take place on a short time scale, yield a change in level which is sustained thereafter, and be of the same relative size as the small transition observed in the Sutherland record.

One, and only one, portion of the record showed a level change which met these criteria. The drop was complete in two readings

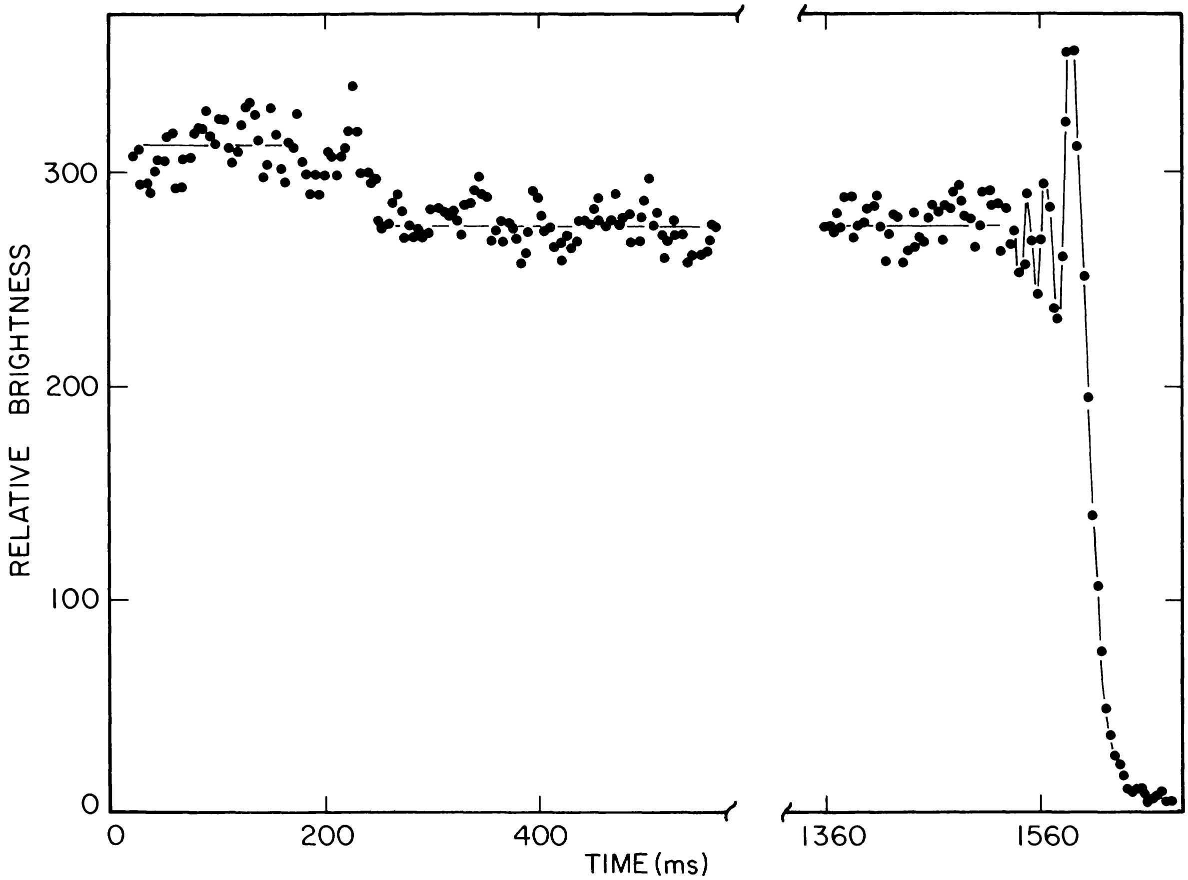

FIG. 1 — The occultation pattern obtained from the disappearance of σ Sco with the 20-inch reflector at Sutherland, 4 ms/point. Note that the trace has been shortened for presentation; the record from about 600 ms to 1300 ms has been removed. The occultation of the faint companion takes place shortly after 200 ms.

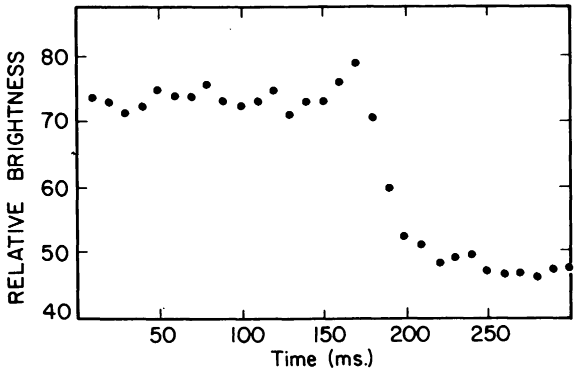

FIG. 2 — Occultation of the primary as observed with the 18-inch refractor at Cape Town, 10 ms/reading. The data have been smoothed to remove high-frequency noise; the height of the first diffraction fringe is somewhat attenuated by the poor impulse response of the recording apparatus.

(20 ms), represented a change of 11% in light level, and was sustained for more than 0ˢ5 after it occurred. This 1-second portion of the trace, with data points averaged in groups of 5, is shown in Figure 3. From the scatter of the data points about the two mean levels shown we can estimate the uncertainty in this level change, compared with that of the primary event; a similar estimate from the Sutherland trace, for the 200-ms portion which includes the transition, yields the following:

Observatory	Ratio of Level Change	Difference
Sutherland	0.142 ± 0.014	0.011 ± 0.021
Cape Town	0.131 ± 0.015	

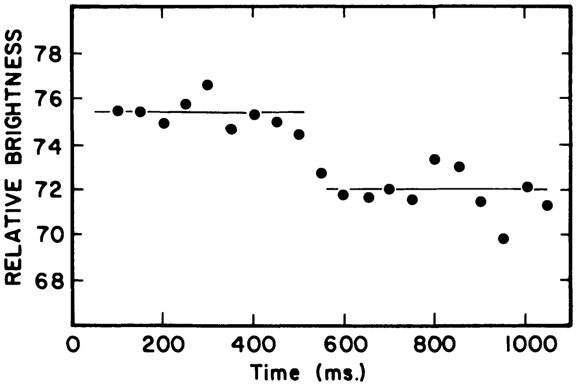

FIG. 3 — Occultation of the secondary component as seen at Cape Town, 50 ms/reading. Horizontal lines show the mean intensity levels before and after the event.

We can see that the rms uncertainty in the level changes is appreciably smaller than the changes themselves, removing any doubt about their reality, and that both small transitions are of the same size within the limits of measurement, compared with their corresponding primary event.

The Positions of the Components

Taken together, these two independent observations can yield unique values for the separation and position angle of the two components since they were obtained at locations sufficiently separated that the lunar limb passed across the pair at a significantly different angle for the two events. The circumstances of the two observations are shown in Table I.

The geometry of the situation is shown in Figure 4, with the angles rotated so that the position angle of the Cape Town event (146°.1) is horizontal. Since we can consider the advancing lunar limb to be moving in a direction perpendicular to itself at a rate diminished by the cosine of the contact angle (this is the rate shown in Table I), we can construct, to scale, the observed vector separations and relative angles involved. The difference between the two positions angles is δ; since the second star may lie anywhere along a line perpendicular to the timing vectors (labeled with their values in milliseconds of arc) these two perpendiculars define, where they cross, the location of the second star with respect to the first. We note that a right triangle is formed whose three sides are 321, Y, and $261 + X$; from this we can obtain the formula

$$\cos \delta = 321/(261 + X)$$

or

$$X = (321 - 261 \cos \delta)/\cos \delta \quad .$$

We also note that the triangle whose sides are W, X, and $Y + Z$ is congruent to the first triangle, and thus the angle of its apex is also δ. This allows us to obtain an expression for W;

$$W = X/\tan \delta$$

and from this we can obtain our two desired quantities: S, the true separation of the pair, and Φ, the position angle (with respect to the P.A. of the Cape Town event)

$$S = (W^2 + 261^2)^{1/2}$$

$$\Phi = \tan^{-1} W/261 \quad .$$

If we wish to avoid taking square roots, an alternative expression for the separation is

$$S = 261/\cos \Phi \quad .$$

Substituting the values given in Table I yields, for the separation and position angle of the pair:

$$\text{Sep.} = 0''.49$$

$$\text{P.A.} = 268^\circ.2 \quad .$$

If we consider only the errors in timing, we would be tempted to place very small errors after these results; the error in separation due only to the uncertainty in timing the two events is about $\pm 0''.004$, while that in angle is about $\pm 0^\circ.6$. This is not the whole story, however, and we must consider the problem of lunar limb condition as it affects the precision of measurement.

First of all, it is clear from the geometry that the lengths W and Z form long "lever arms" and a small error in their values can have a large effect on the apparent position of the second star with respect to the first. We can measure the occultation times very accurately, but we have made an assumption which must be justified: We have assumed that the altitude of the lunar surface, at the two points of occultation, is the same; i.e., that the difference in times is due entirely to the spatial separation between the two stars, and not due to any irregularity in the lunar surface.

TABLE I

σ Sco Occultation Parameters

Observatory	Position Angle	Lunar Vel. (arc sec sec^{-1})	$T_1 - T_2$ (ms)	Vector Sep (arc sec)
Sutherland	137°.4	0.2361	1358	0.321
Cape Town	146°.1	0.2090	1250	0.261

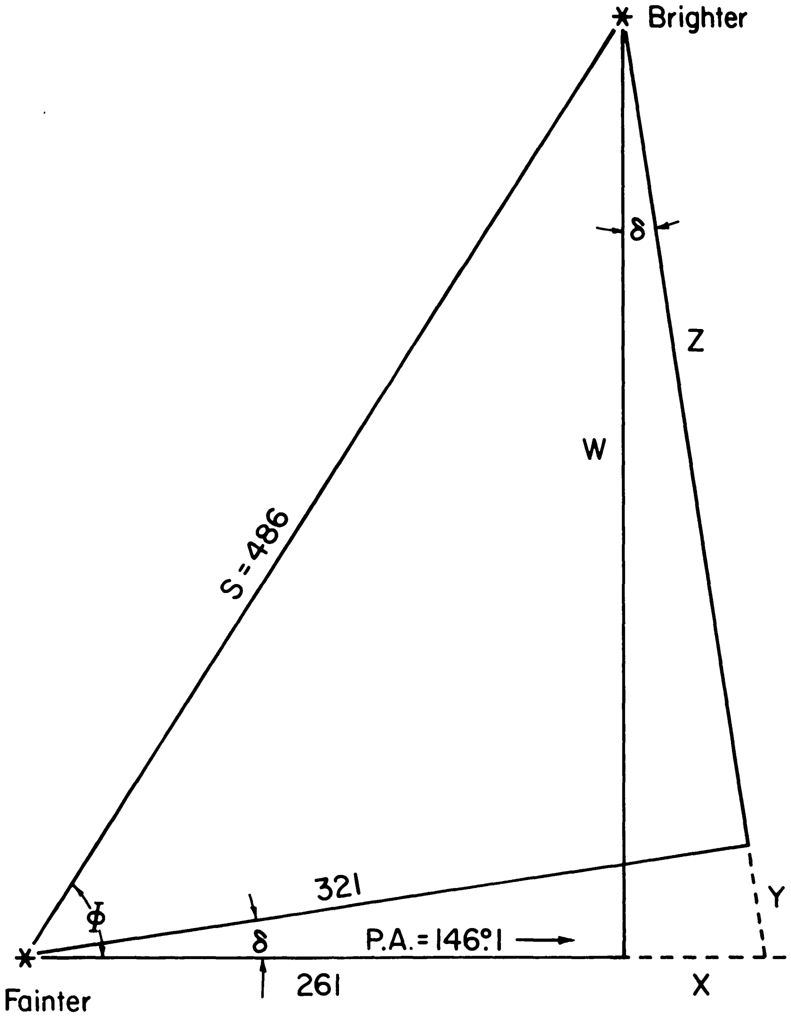

Fig. 4 — The geometry of the pair as derived from the two observations. Distances shown are in milliseconds of arc. The drawing shows the position angle of the Cape Town event as horizontal.

This problem is idealized in the drawing (Fig. 5) which shows a portion of a smooth, perfectly spherical surface on which a small plateau appears; the first star of the pair disappears behind the plateau, while the second is occulted by the smooth surface of our idealized moon. We can see immediately that the apparent times of the two events will be materially changed by the presence of the plateau; the time between them is shortened by just the time the moon takes to traverse the projected height Δh. If the true position angle between the stars is enough different from the direction of lunar motion, then they will disappear at quite different points on the lunar surface and we will not be able to say anything

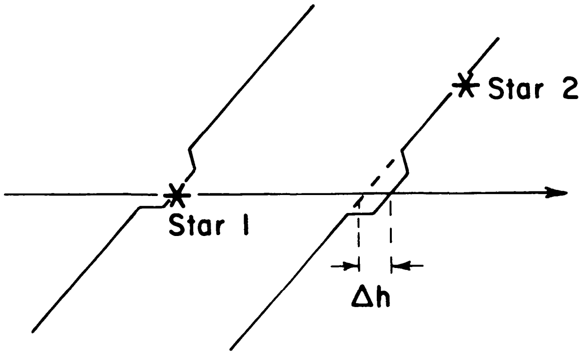

FIG. 5 — Idealized lunar limb with plateau, to illustrate the effect this can have on the observed interval between two occultation events. Observed time is shortened by the time it takes the moon to traverse the distance Δh.

about the errors involved in timing. If they happen to "line up" so they are occulted by the same point on the lunar surface then no altitude error is introduced, since the error is due to the *difference* in altitude at the two points, but this will not in general occur and few such "perfect" events are to be expected. We can expect, usually, that real events will fall somewhere in between these two extremes, and we are then interested in the distance, projected onto the limb of the moon, between the two disappearance events measured.

As seen from Cape Town, the apparent motion of the center of the moon was in position angle 98°.7 for the events in question; if we accept our value of 268°.2 for the true position angle of the stars, then the lunar motion was at an angle 10°.5 different from "dead on". From the distance of the moon at the time (395,873 km) we can determine that the second star disappeared at a point 173 meters due north of the first star; this becomes a linear distance of 310 meters projected along the (presumed level) limb of the moon. The projected distance is slightly less for the Sutherland event.

The effective slope of the lunar surface normally encountered in occultation events is fairly small (for the most part less than 10°). For traces where the fringe pattern is well defined we can get a reasonable measure of the slope, but this doesn't really help very much unless the projected distance on the limb is very small. The plateau in Figure 5 would yield the same slope for both events and we would be tempted to say no altitude error had occurred. Clearly this would be quite wrong. Slope measures, even for closely spaced events, are only indicative and not conclusive. If we assume, for example, a slope of 3° and use our distance of 310 meters, then the altitude error, if the slope is constant, can be 16 meters of height or 32 ms of time at 0.5 m ms^{-1}. This is much larger than our error of timing and much more difficult to evaluate.

The Near Companion

We are now in a position to decide whether or not the companion discovered by lunar occultation can be the same object that is causing the 33-day periodic change in the γ-velocity of σ Sco. If we take the absolute magnitude of the primary to be $M_v = -4.5$ (McNamara and Matthews 1967) and the apparent magnitude as $m_v = 2.9$ we obtain a distance modulus of $7^m.3$, corresponding to a distance of 288 pc (ignoring interstellar absorption). If we assume the masses of the two objects are the same and equal to 11 solar masses each, about typical for the B3 star on the main sequence, we can derive an expected size for the semimajor axis of the pair, in angular measure, of 0″.002. This is clearly *not* the companion whose separation we have measured as 0″.49. From similar assumptions we can estimate that this object will travel around the relative orbit in about 370 years.

Is there any evidence for the presence of the near companion in our present data? Figure 6 shows an expanded view of the primary occulation event recorded at Sutherland, together with a theoretical curve fitted, by least squares, to the observed data (Nather and McCants 1970) on the assumption that the star's diameter has been resolved. The resulting value for the apparent angular diameter is 0″.0013, small enough so that it cannot be considered significant. It does, however, provide an excellent fit to the observed data points and serves to illustrate that little or no distortion, such as might be caused by a near companion star, is present. If the near companion were of equal brightness with the primary we might just be able to identify the distortion it would cause in the trace, providing it were located 0″.002

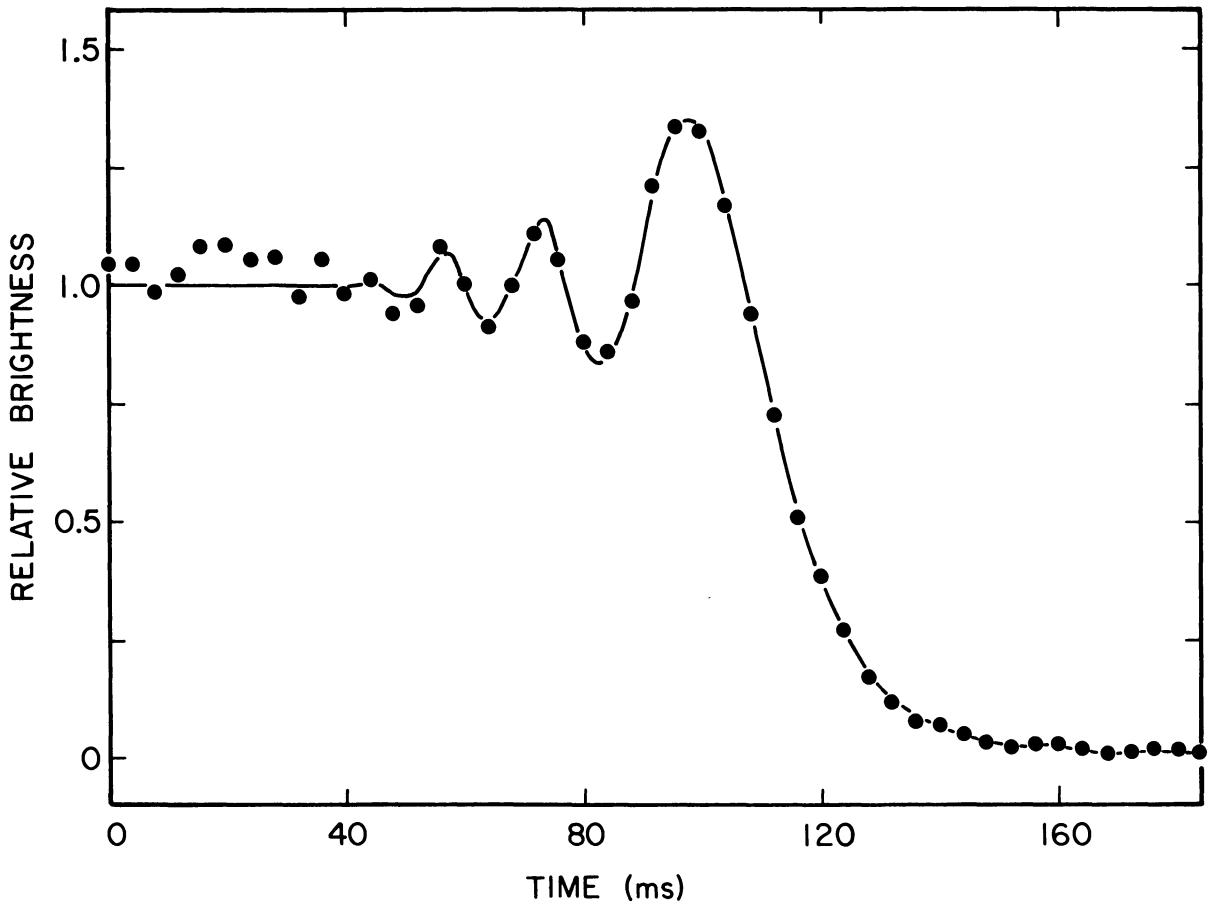

FIG. 6 — Occultation of the primary as seen from Sutherland, expanded. The solid curve is the best least-squares fit to the data for a star of angular diameter 0".0013. The fit is only slightly better than that for a point source and the difference is not considered to be significant.

distant. If the apparent separation were less, as for stars "lined up" along the edge of lunar limb passage, or if it were appreciably fainter than the primary, we would not see its effect on the trace. We have no evidence for its presence, but we cannot rule out its existence from our present data.

The Orbit of the Distant Companion

A series of measurements of the type described here, properly spaced in time, can be expected to define the relative orbit of the distant companion with considerable accuracy. Earlier visual observations are not sufficiently precise to define the orbit, but they do place some severe constraints on the position of the companion and therefore permit some limited positional information to be derived.

From the large difference in the apparent brightness of the two stars we can be quite certain that a visual observer would be unable to detect as double an event in which the fainter component were obscured first, as in the observations reported here. If the brighter star were obscured first (in a disappearance event) or if the fainter component were the first to appear (in a reappearance event) and the time scale were sufficiently large, we would expect an alert observer to notice that the event was not single. At least five such incidents have been recorded in the past, and for two such events the observers have estimated the interval between the two transitions.

For any single occultation observation the angle of the advancing lunar limb defines a line along which the fainter star may be located, while the time interval, combined with the rate of limb advance, defines the vector separation of the pair. We can reconstruct this angle and the rate of limb passage for earlier events, but we must estimate the time interval where it has not already been estimated by the observer.

We can be reasonably sure that two events of the type considered here cannot be resolved in time if they occur with an interval much shorter than 0.1 to 0.2 seconds. Similarly, comments by visual observers indicate that intervals in the range 0.2 to 0.4 seconds can be seen and, lacking more information, we can assign this range of intervals to those events for which intervals were not estimated. While somewhat crude, this procedure does serve to define a rather limited region within which the companion can be found. A summary of the five earlier observations and the two reported in this paper is shown in Table II.

Since we can rule out events in which the transition of the fainter component cannot be seen, we can place the line representing reappearance events to the east, using lines for events where the interval was estimated by the observer, and broader regions where the interval had to be assumed. Such a construction is shown in Figure 7, together with one possible relative orbit which meets all of the imposed constraints, within observational uncertainty. The dates and phenomena (R for reappearance, D for disappearance) are shown, and clearly the companion must (a) pass through the dated regions in chronological sequence, (b) obey Kepler's second law and sweep out equal areas in equal times, and (c) have a period of about 370 years.

From these considerations it can be seen that the orbit is not defined, since other orbits could be drawn which would satisfy the constraints, but all such orbits would have certain things in common. They must all have the faint star travel counterclockwise with respect to the brighter, all must pass through the well-defined point in 1972, and all will therefore show that the separation of the pair decreased from 1860 through about 1953, after which it began increasing and continues to do so. The orbital period is certainly longer than 112 years and is probably much longer; the orbit indicated in Figure 7, for example, has a period of about 300 years. The separation of the pair is nearly large enough to allow more conventional measurements to be made, and can be expected to increase for some time to come. In time it may become possible to make independent spectroscopic observations of the different components.

TABLE II

σ Sco Orbital Construction Parameters

Date & Event	Observatory	Angle (from N) of Limb Passage	Lunar Vel. (arc sec sec^{-1})	Interval (sec)	Vector Sep. (arc sec)
1860R	Royal Obs., Cape	44°	0.47	0.5	0.23
1917R	U.S.N.O., Wash., D.C.	−10	0.34	~0.2	~0.06
1931D	LaPlata, Argentina	26	0.32	0.5	0.11
1953D	Union Obs., Johannesburg	−34	0.38	~0.2	~0.08
1968R*	Royal Obs., Cape	19.	0.36	~0.2	~0.08
1972D	S.A.A.O., Sutherland	47	0.24	1.36	0.32
1972D	S.A.A.O., Cape	56	0.21	1.25	0.26

*Bright limb event

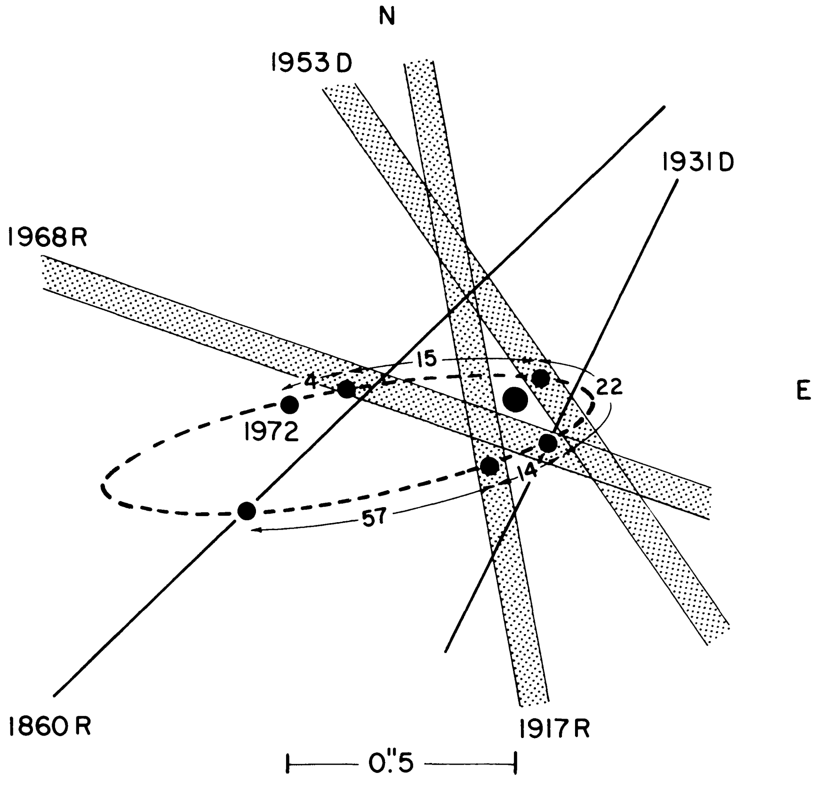

FIG. 7 — Constraints imposed on the relative orbit of the faint star, with a possible orbit shown. The interval (in years) between sightings is indicated. Bands represent regions in which the timing interval had to be assumed.

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