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LUNAR OCCULTATIONS OF BETA SCORPII IN 1975 AND 1976

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ABSTRACT

The complex multiple star β Scorpii (combined magnitude 2.5) will be occulted by the Moon 19 times during 1975–1976. Limiting lines of visibility for these occultations are presented in two maps. From modern observations it is apparent that β Sco is at least quadruple, but there is evidence for the existence of three additional components. The 1971 May occultation of the β Sco system by Jupiter and of its C component by Io raised important questions about β Sco and about Jupiter and Io, making the coming occultation series especially significant. With high-time-resolution photoelectric photometry, it is likely that definitive knowledge of the system's structure can be obtained during the coming series. Detailed predictions of local circumstances are available from the authors.

Subject headings: occultations — stars, individual — visual double or multiple stars

I. INTRODUCTION

Since 1964, a remarkable sequence of occultations has been attracting the attention of both celestial mechanicians and astrophysicists to β Sco, a B1 star of magnitude 2.9 in the northern claw of the Scorpion (1950.0 $\alpha = 16^{h}02^{m}5$, $\delta = -19°40'$). This star had long been believed to be quadruple, until 1971 May when the whole system was occulted by Jupiter and the C component was occulted by the Jovian satellite Io, resulting in the discovery that the C component was itself a double star. The frequency of occultation of a star this bright by Io has been estimated at once per millenium (O'Leary and Van Flandern 1972).

During 1975 and 1976, β Sco is undergoing a sequence of 19 lunar occultations, at intervals of about 4 weeks, from 1975 March to 1976 August. Beginning in 1975 August, most of these events will be photoelectrically observable from areas in which major observatories are located.

II. THE BETA SCORPII SYSTEM

Figure 1 shows the β Sco system as it may appear at the time of the coming occultations. The brightest star is a spectroscopic binary (period $6^{d}83$ [Abhyankar 1959]); we have labeled these two components A and D. The B component was a visual companion of A until about 20 years ago, when its slow orbital motion brought it too close to A for visual separation. Its true brightness is the subject of some controversy. Its magnitude had been estimated at +9 to +10 until Kuiper (1935) showed that very close visual companions of stars were systematically underestimated in brightness by large amounts, due to deceptive optical effects. He estimated the actual brightness to be closer to magnitude +5, using a grating technique. Kuiper's hypothesis and many of his observational results have been confirmed by more recent workers (Worley 1969). The matter is of some immediate consequence, because the present interpretation of the light curves for the occultation by Jupiter (for size, shape, and atmospheric scale height) depend upon the assumption that the B component contributes less than 1 percent of the total light (Hubbard and Van Flandern 1972).

The C component is a relatively distant physical companion. Photometry during its occultation by Io

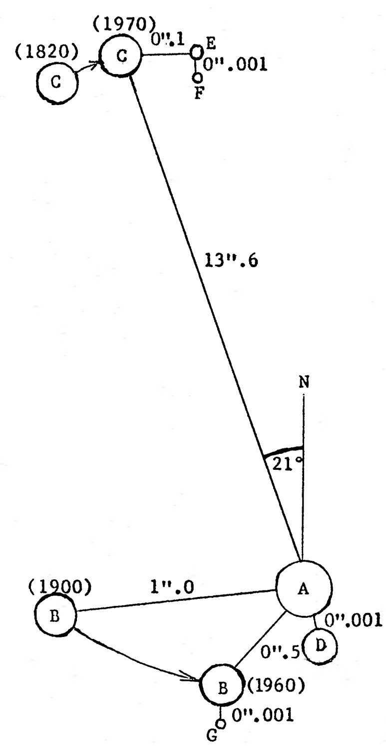

FIG. 1.—The β Sco system. A, B, C, D are components of the classical system. E, F, G are hypothesized components.

suggested that it, too, is double; but the various light curves obtained are not mutually consistent, unless the companion is a very peculiar type of star (discussed further below). Refer to Figure 1 for further general description. We have included in the diagram the hypothetical components discussed in this paper; they are tentatively designated E, F, and G.

III. Additional Components in the System

a) *Distance to β Scorpii*

From the *UBV* photoelectric photometry of the system by Blanco *et al.* (1968), we have the results that the A component (plus B, D, and any other unseen close companions of these) is spectral type B0.5 V, with magnitudes $U = 1.69$, $B = 2.56$, $V = 2.63$; while for C (plus any close companions), the spectrum is B2 V, and the magnitudes are $U = 4.22$, $B = 4.91$, $V = 4.92$. If we accept (based on the high-resolution light curves of the Jupiter occultation) that D has about half the intensity of A (Elliot, Rages, and Veverka 1975), and that B is a little fainter than Kuiper's estimate, we would get individual V-magnitudes for these three components of $V_A = 3.14$, $V_D = 3.89$, $V_B = 5.6$. (The assumption about the relative intensity of B has little effect on V_A.) Similarly, if we accept that the companion of C is about one fifteenth as bright at visual wavelengths (based on the Io-occultation light curve), we would have $V_C = 4.99$ and $V_E = 7.9$. The purpose of deriving the V-magnitudes of A and C is to obtain the difference in their absolute visual magnitudes, $\Delta M_V = 1.85$. This is slightly in excess of the expected difference, based on spectral type, of $\Delta M_V = 1.5$ (Allen 1973). However, we must assume that the spectral type of A is actually closer to B0 V than measured, because the observed type would be biased toward the late side by the presence of D, which must be nearly B1 V. Therefore our best estimates of the absolute magnitudes are $M_V(\text{A}) = -4.0$ and $M_V(\text{C}) = -2.2$. Computing the interstellar absorption from 3.3 times the $(B - V)$ color excess (and noting the consistency in the color excesses for the A and C components), we arrive at the absorption estimate $A_V = +0.74$. This gives us a distance modulus of 6.4, or a distance of 191 ± 28 pc. The uncertainty of about 0.3 in the modulus arises mainly from the observed spectral types; but the distance is in good agreement with that derived from the kinematic analysis of Bertiau (1958), which led to the estimate of 175 ± 14 [mean error] parsecs.

b) *Masses of Components*

From the absolute magnitudes we can calculate the masses of the individual main-sequence components. These are $M_A = 21$, $M_D = 15$, $M_B = 8$, $M_C = 9$, $M_E = 3$, in units of solar masses. For comparison, Elliot *et al.* (1975) obtained the following values from high-resolution Jovian-occultation light curves: $M_A = 21.1 \pm 3.2$, $M_D = 12.7 \pm 1.9$.

c) *Possible Companion of B*

From the position angle and separation measures of the C component with respect to the AD pair covering 150 years (*Double Star Catalogue of Observations*, a card file maintained at the U.S. Naval Observatory), it can be shown that the present rate of change of position angle is $-0°.042 \pm 0°.001$ per year. Of this, about 0°.005 per year is due to the motion of the celestial pole. Taking the maximum mass of the β Sco system as 63 $M_\odot$ (which includes contributions from suspected components not yet observed), and the minimum separation of C from AD as 2600 AU (the distance must be greater if the true separation does not lie in the plane of the sky), it would follow that the minimum period of C about AD would be 16,700 years, which corresponds to a maximum motion in position angle of 0°.022 per year. Therefore we arrive at the improbable conclusion that C is moving so rapidly that it will escape from the system. The easiest way to resolve this difficulty is to make B sufficiently massive that it moves AD about their common center of gravity. Apparently, at least 0°.015 per year of the position-angle change should be attributed to motion of AD induced by B, assuming that the orbit of C is nearly circular and in the plane of the sky. This corresponds to about 0".0037 per year of motion of AD on the sky, as compared with the observed motion of about 0".014 per year for the component of B's motion relative to AD perpendicular to the direction of C. The implied mass of B is therefore 13 $M_\odot$, which substantially exceeds the mass of 8 $M_\odot$ derived from its assumed absolute magnitude.

In order to avoid the necessity of imputing to B a mass as great as 13 $M_\odot$, it is necessary to assume a highly eccentric orbit for C, with its present location at periastron, in addition to the other plane-of-sky constraints. While this is admittedly possible, it seems far more probable that the implied mass is nearly correct and that B will be found to be a spectroscopic binary. In any case, the V-magnitude of B can surely not be much fainter than magnitude 5.6 (as assumed earlier) because of the minimum mass demanded for it by the above analysis.

d) *Possible Companions of C*

During the Io occultation of C, a secondary event indicated the existence of a companion to C which had about one tenth of C's intensity in the blue (Bartholdi and Owen 1972), but which apparently had one fifth of C's intensity in the ultraviolet (Smith and Smith 1972), and made so little contribution at orange wavelengths (Fallon and Devinney 1972) as to pass undetected. The inferred location was at a separation of 0".097, position angle 308° relative to C. If the observations are taken at face value, this is a very puzzling object. Its absolute magnitude must be only about +1.5 at visual wavelength; yet it seems to have a $(U - B)$ color index of about -0.8 mag! Are such objects possible? The only stellar-type object that seems to fit this description is the postulated "ultraviolet dwarf" star, described by Stothers (1966). Since stars of this type remain in the ultraviolet-dwarf stage for only about 10^5 years, the detection of such an object would be an important contribution to our knowledge of stellar evolution. However, we must be conscious of the possibility that the "events" in the photoelectric light curves which led to the implausible color index might have arisen from instrumental problems.

If we assume that this companion of C is real, its mass must be close to 1 $M_{\odot}$. We note two further anomalies: (1) The light curve for this object during the Io occultation had an unusually shallow and irregular slope, possibly supporting the instrumental error idea, or possibly indicating that the object is not a simple point source (Bartholdi and Owen 1972). (2) There is some evidence in the separation measurements of C from AD suggesting that there is a periodic behavior in the separations (*Double Star Catalogue of Observations*, *op. cit.*), with an amplitude of about 0".02 and a period of perhaps 30 to 40 years. Both the separation amplitude and the period (by Kepler's law) suggest that the companion should be more massive than 1 $M_{\odot}$. Taken in conjunction with the light curve irregularities, the evidence weakly suggests that this hypothetical component is itself a spectroscopic binary.

The fact that two of the other three members of the system seem to be spectroscopic doubles, and the tendency of multiple stars to be systems of doublets for reasons of stability, together enhance the probability that the hypothetical companion of C is double. If so, β Sco may be a septuple star system, which would give it the highest known multiplicity for a hierarchical multiple star system (as distinct from a small stellar cluster).

IV. AREAS AND TIMES OF OCCULTATION VISIBILITY

A lunar occultation of a star, when it is visible from the surface of the Earth, can be seen along a path the width of which must ordinarily be at least 3500 km (i.e., about the diameter of the Moon), and may be much greater, especially at high latitudes. Along the centerline of the occultation path, the time from the star's disappearance until its reappearance is about an hour, while near the edges of the path the duration of the occultation approaches zero. Along the edges, the observer may see a *grazing occultation*, in which the star disappears and reappears more than once, owing to the irregular topography of the Moon. Between these narrow "grazing" bands (typically 1–3 km wide) in which such multiple events may occur, the star is said to undergo a *total occultation*.

For most purposes, the greatest advantages in observing occultations of β Sco (or of any star) can be obtained by observing from within the grazing occultation band. Since the topography of the lunar limb typically involves heights of the order of 2", while the separation of the A and C components is 13" in a roughly north-south direction, it is of course impossible to observe a grazing occultation of all components from one location. Under ideal conditions, one might select locations to produce a graze of C and a total occultation of AB at the northern limit, and a graze of AB and a total occultation of C at the southern limit. Also, the grazes, in addition to providing the equivalent of several total occultations in one pass, can be expected to provide increased resolution and sharper distinguishability among close components, because of the highly oblique angle of incidence. (Note that it will be necessary to make simultaneous observations in more than one color in order to resolve ambiguities of interpretation for some of the graze cases.)

Figures 2 and 3 show the paths of visibility of each of the occultations of β Sco in the present series. Labeled lines show the northern and southern limits of the occultation paths, the dates being written on the occulted side of each limit line. Thus, the date is written on the south side of a northern limit line, and vice versa. For occultations of which only a northern limit line is shown, the other limit is off the surface of the Earth, so that the entire south polar region is within the occultation path. Similarly, for occultations of which only a southern limit is shown, the northern limit is off the Earth; but β Scorpii's declination of $-20°$ prevents the star from rising above the horizon at latitudes north of $+70°$. The lines, which proceed in time from west to east, are terminated by circled symbols, which identify the reason why the occultation is not visible beyond that point: MR = moonrise, MS = moonset, SR = sunrise, SS = sunset. (Because of the unfavorable signal-to-noise ratio, daytime events are not usefully observable photoelectrically [except for the brightest components], and for the sake of clarity have been omitted from Figs. 2 and 3. The event of 1975 December 2 occurs at new moon, and is therefore omitted altogether.)

In Table 1 we have provided a summary of the 1975–1976 series of β Sco occultations, corresponding to the limits shown in Figures 2 and 3. It contains the basic information needed in the initial stage of selecting possible events for photoelectric observation. The table shows the following columns of data, respectively: the date and approximate times (UT) of the beginning and ending of the occultation path; the percentage of the Moon's disk that will be sunlit (accompanied by X for waxing or N for waning); an identification of which limit(s) (north and/or south) of the occultation path fall on the Earth; the extreme values of the angle (measured around the perimeter of the lunar disk) between the point of contact of a grazing occultation and the nearest cusp of illumination (a negative value indicates that the graze point is on the bright limb); and the land areas on which the occultation will be visible.

V. CURRENT OBJECTIVES

The employment of photoelectric photometers with high time resolution during the current series of occultations offers prospects of definitively determining the structure of the β Sco system. The same results

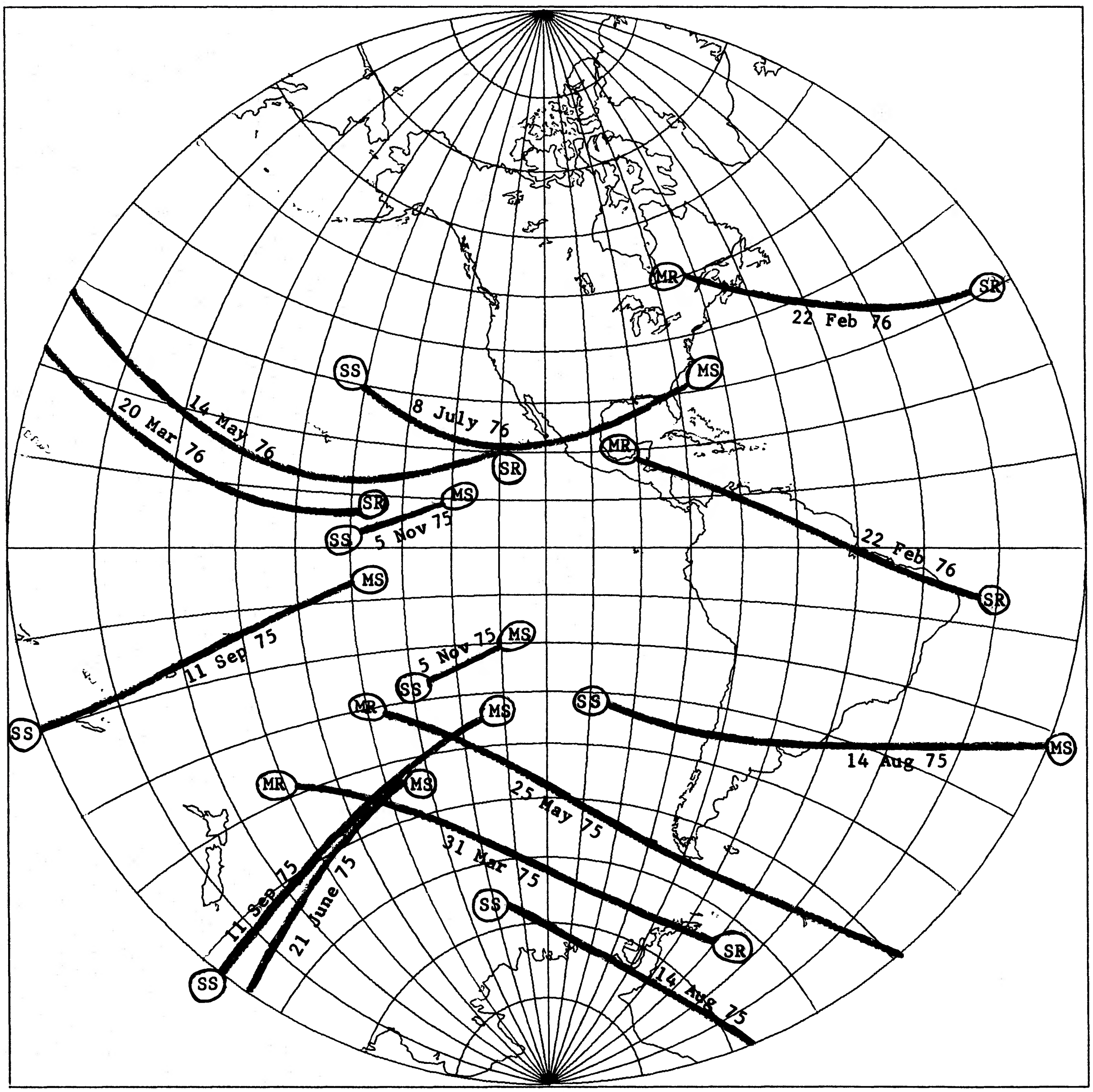

FIG. 2.—Northern and southern limits of β Sco occultation paths, for west longitudes from 200° to 20°

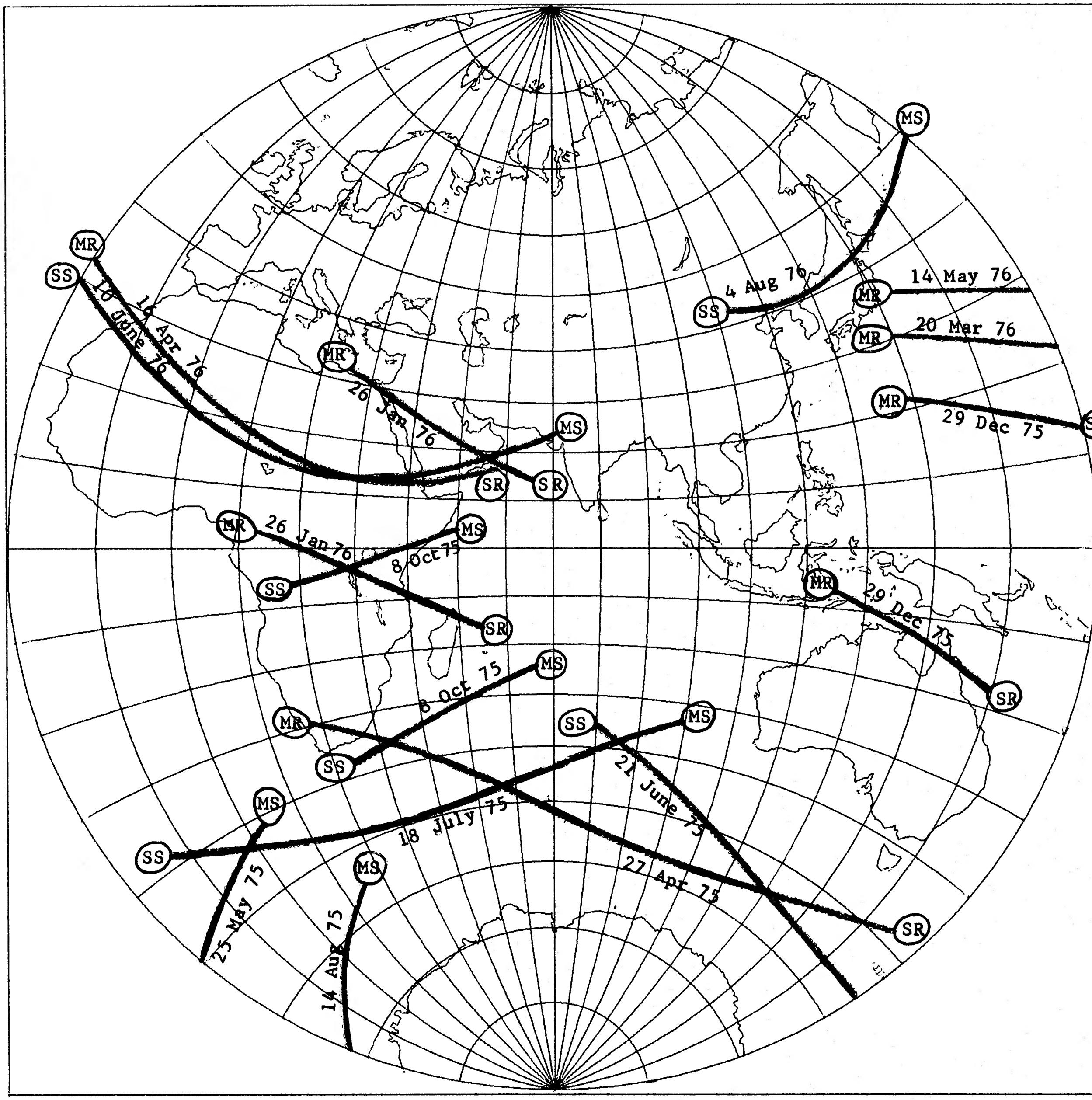

FIG. 3.—Northern and southern limits of β Sco occultation paths, for east longitudes from $-20°$ to $160°$

TABLE 1

OCCULTATIONS OF β SCORPII

Date	Beginning (UT)	End (UT)	Sunlit (%)	Limit	Cusp Angle (range)	Land Areas
1975:						
Mar. 31........	$08^{\rm h}1$	$10^{\rm h}0$	80 N	N	− 2°, + 6°	Antarctica
Apr. 27........	18.0	20.7	95 N	N	− 4, + 9	Rep. So. Africa (Cape), Antarctica
May 25........	03.6	06.4	100 X	N	−55, −72	Antarctica, South Georgia
June 21........	11.5	14.2	95 X	N	+ 1, −13	Antarctica
July 18........	17.8	20.4	80 X	N	+ 3, −13	Antarctica
Aug. 14........	23.8	26.0	60 X	N S	+ 1, −13 + 2, +10	Antarctica, south Chile, south Argentina, south Uruguay
Sep. 11........	07.1	08.4	37 X	N S	− 4, −14 + 4, +12	New Zealand, Fiji, Samoa, Tahiti
Oct. 8.........	16.5	17.0	17 X	N S	−10, −13 + 9, +12	south and east Africa
Nov. 5.........	03.4	03.6	3 X	N S	−11, −12 + 9, +10	Marquesas Is., Pitcairn I.
Dec. 29........	19.1	19.5	9 N	N S	− 3, − 5 + 1, + 3	New Guinea, Caroline Is., Guam, Australia (Cape York)
1976:						
Jan. 26........	01.2	02.2	27 N	N S	− 3, − 5 + 3, + 6	north and east Africa, south Arabia
Feb. 22........	06.7	08.3	50 N	N S	− 3, + 3 + 7, − 1	east USA, West Indies, South America (north coast)
Mar. 20........	13.9	16.0	73 N	S	+ 6, − 7	Hawaii
Apr. 16........	23.5	25.9	91 N	S	+ 6, − 9	Europe, north Africa, Arabia, Turkey
May 14........	10.3	12.9	99 N	S	+12, − 4	Hawaii
June 10........	20.5	23.0	98 X	S	0, +16	Europe, north Africa, Arabia, Turkey, Iran
July 8.........	05.0	07.0	86 X	S	− 2, +13	USA, east Canada, north Mexico
Aug. 4.........	11.7	12.6	68 X	S	+ 2, +10	Manchuria, east Siberia, north Hokkaido

will also determine the interpretation to be made of some of the data obtained during the 1971 occultations of β Sco by Jupiter and Io. To be useful for these goals, photoelectric observations in one or more colors, having a time resolution at least of a few milliseconds, are needed. (Attempts should be made to record reappearances as well as disappearances; and, since the stars are bright, events on the bright limb might possibly be observable with suitable filters.) An extensive discussion of procedures for obtaining photoelectric timings of occultations will be found in a series of papers by Evans, Nather, and McCants (Nather and Evans 1970; Nather 1970; Evans 1970, 1971; Nather and McCants 1970).

We expect that the proposed lunar occultation observations will yield the following results: (i) the magnitude and relative position of B with respect to A (both quantities are important for the interpretation of the Jupiter occultation data), and the possible duplicity of B; (ii) the magnitude, color indices, and relative position of the companion to the C component, in order to establish if it exists, whether it is an ultraviolet dwarf, and whether it is double; (iii) the detection of any other presently unidentified companions of the known members of the system, if their separations are at least a few arc-milliseconds.

At the Naval Observatory, we can compute the local circumstances of the occultations for any observing location within the graze limits or within the area of total occultation. We are offering to make these computations for observers with high-time-resolution photometers; and we encourage the use of multiple-wavelength recording wherever possible in photometric observing, so as to obtain particularly the needed spectral information about the hypothetical companion of C (and, in grazing occultations, so as to eliminate possible ambiguities in the diffraction pattern).

We request that photoelectric observers communicate to us their plans and preliminary results. We will in turn disseminate results of general interest to all those whose plans we have been told of, especially when such results would serve as a guide in planning observations of the subsequent events.

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