OCCULTATIONS OF BRIGHT STARS BY THE ECLIPSED MOON

G. P. KÖNNEN AND JEAN MEEUS

Introduction

If we neglect the Earth's flattening and the enlargement of the Earth's umbra by the atmosphere, the radius of this umbra at the distance of the Moon is given by $\sigma = \pi' - s + \pi$, where π', s and π are the parallax of the Moon, the semidiameter of the Sun, and the parallax of the Sun, respectively.

To find the greatest possible value for σ, we take the maximum value of π' (61′ 30″), the smallest value of s (15′ 44″), while π is ever 9″ to the nearest second; whence $\sigma_{max} = 2755'' = 0°{\cdot}765$.

Consequently, as seen from the centre of the Earth only stars whose absolute ecliptic latitude β is less than $0°{\cdot}765$ may be reached by the Earth's shadow, and thus may be occulted by the *eclipsed* limb of the Moon—either by the totally eclipsed Moon, or at the eclipsed limb of the partially eclipsed Moon.

As seen from the polar regions, however, the limiting latitudes are $\pm(\pm\sigma_{max} - \pi'_{max})$; this is $+0°{\cdot}765 - 1°{\cdot}025 = -0°{\cdot}260$ and $-0°{\cdot}765 - 1°{\cdot}025 = -1°{\cdot}790$ for the northern polar regions, and $+0°{\cdot}260$ and $+1°{\cdot}790$ for the southern polar regions. Thus, as seen from the northern polar regions of the Earth, the umbra may reach stars up to latitude $-1°{\cdot}790$, but stars lying north of the ecliptic, for example Regulus ($\beta = +0°{\cdot}46$) may then no longer be occulted at the eclipsed lunar limb.

In Table I, some data of the 11 brightest stars lying less than $1°{\cdot}790$ from the ecliptic are given.

TABLE I

Star	*Mag.*	*Long. and Lat., 1950* °	°	*Date, 1950*
η Gem	var.	92·74	−0·89	Dec. 25·1
μ Gem	3·2	94·60	−0·83	Dec. 27·0
δ Gem	3·5	107·82	−0·18	Jan. 8·7
α Leo	1·3	149·13	+0·46	Feb. 18·4
ρ Leo	3·8	155·69	+0·15	Feb. 24·9
β Vir	3·8	176·45	+0·69	Mar. 17·6
α Lib	2·9	224·39	+0·34	May 5·5
β Sco	2·9	242·49	+1·01	May 24·2
ξ Sgr	3·6	282·75	+1·67	July 5·4
π Sgr	3·0	285·55	+1·44	July 8·3
λ Aqr	3·8	340·88	−0·39	Sept. 4·0

The dates in the last column are those of the conjunction of the anti-sun with the star. These dates are actually varying with time, by reason of the precession of the equinoxes. Moreover, there are jumps of $\frac{1}{4}$ or $\frac{1}{2}$ day by reason of the bissextile years.

In Table II, the longitude, latitude and conjunction date of the three brightest stars of the list as well as for ϵ Cancri, the brightest star of the Praesepe cluster, are presented as a function of time. The longitudes and latitudes are referred to the equinox and ecliptic of the date.

In this paper, we will discuss first the occultations of the first-magnitude star Regulus in detail for the period A.D. 0–2450. Secondly, the occultations of the Praesepe cluster, β Sco and α Lib will be given for 1600–2150, and the results for the remaining stars of Table I will be mentioned briefly for 1900–2050. Finally, we give results for stars which can only be occulted on the bright limb of the partially eclipsed Moon.

TABLE II

Year	*Long.*	*Lat.*	*Date of Conj. with anti-sun*
	α LEONIS (Regulus)		
	°	°	
1650	144·97	+0·45	Feb. 13·4
1950	149·13	+0·46	Feb. 18·4
2250	153·31	+0·47	Feb. 22·3
	α LIBRAE		
1650	220·21	+0·38	Apr. 30·6
1950	224·39	+0·34	May 5·5
2250	228·57	+0·30	May 9·4
	β SCORPII		
1650	238·31	+1·05	May 19·3
1950	242·49	+1·01	May 24·2
2250	246·68	+0·98	May 28·1
	ϵ CANCRI		
1650	122·51	+1·13	Jan. 22·3
1950	126·70	+1·16	Jan. 27·2
2250	130·89	+1·18	Jan. 31·1

Regulus

As this is the only 1st-magnitude star lying close to the ecliptic, its occultations by the eclipsed Moon have been investigated in detail for the period A.D. 0 to 2450.

Several types of occultations of a star by the eclipsed Moon can be considered, and the following symbols have been chosen by the authors:

T For some places on the Earth's surface, immersion *and* emersion of the star by the totally eclipsed Moon,

t For some places, immersion *or* emersion by the totally eclipsed Moon (and for *no* places immersion *and* emersion during the total phase),

t′ For some places, immersion *and* emersion at the *dark* limb during the partial phase preceding or following the totality (and nowhere *T* nor *t*, etc.),

(t) The same, but at the *bright* limb,

(t′) For some places, immersion *or* emersion at the *bright* limb during the partial phase preceding or following the totality,

P For some places, immersion *and* emersion at the *dark* limb by the partially eclipsed Moon; the eclipse is a partial one,

(p) The same, but at the *bright* limb,

(p′) For some places, immersion *or* emersion at the *bright* limb by the partially eclipsed Moon; again, the eclipse is a partial one.

In Table III our results are given for Regulus for the period A.D. 0–2300.

TABLE III

(p′)	64 Jan. 22	(t′)	864 Jan. 27	P	1710 Feb. 13
t	83 Jan. 22	t	929 Jan. 27	T	1729 Feb. 13
(p′)	102 Jan. 22	t′	948 Jan. 28	P	1775 Feb. 15
P	129 Jan. 23	T	994 Jan. 30	T	1794 Feb. 14
T	148 Jan. 23	T	1013 Jan. 29	P	1813 Feb. 15
P	194 Jan. 24	P	1059 Jan. 31	P	1840 Feb. 17
T	213 Jan. 24	T	1078 Jan. 30	T	1859 Feb. 17
T	232 Jan. 25	(p)	1124 Feb. 1	P	1878 Feb. 17
P	259 Jan. 26	T	1143 Feb. 1	(t′)	1924 Feb. 20
T	278 Jan. 26	P	1162 Feb. 1	(p)	1943 Feb. 20
P	297 Jan. 25				
(t′)	343 Jan. 27				
T	362 Jan. 26				
P	382 Jan. 26				
(t′)	408 Jan. 29				

The event of 1859 February 17 was a very favourable one; Regulus was occulted by the totally eclipsed Moon as seen from the central and south Pacific Ocean (Samoa, Tahiti). The occultations of 1878 and 1924 were visible from the southern hemisphere.

Although the phenomena in the Earth's *penumbra* have not generally been taken into consideration in our investigations, the following events are worth mentioning:

Regulus has been occulted during the first half of the penumbral eclipse of 1962 February 19. The star will be occulted (for some places) during the initial *penumbral* phase preceding the total lunar eclipses of 1989 February 20 and 2008 February 21.

Considering the results in Table III, we find some interesting facts. Firstly, the occultations of Regulus by the eclipsed Moon occur in series. So we have 15 events in the period 64–408, then no other phenomenon before A.D. 864, and so on. The event of 1943 February 20 was the last one of a series which began in 1710. The next two occultations of α Leonis by the totally eclipsed Moon will occur on 2445 February 22 (type *t*, and the first event of a new series) and on 2510 February 25 (type *T*).

Secondly, there are periodicities of 19 and 65 years, for example 1775–1794–1813 and 1710–1775–1840. As a consequence, all the occultations of a series

can be grouped in a "panorama"; for example, we have the following panorama for the series of 1710–1943:

1710	1775	1840	
1729	1794	1859	1924
	1813	1878	1943

In the vertical direction the phenomena are separated by intervals of 19 years, while horizontally the separation is 65 years.

The period of 19 years is known as the Metonic cycle (235 lunations), which should not be confused with the Saros (223 lunations). A Full Moon will recur on the same date (± 1 day), and thus near the same star, after 19 years because the two lengths of time, 19 sidereal years and 235 lunations, differ by only 0·18 day, having durations of 6939·87 and 6939·69 days, respectively. However, after 235 lunations the displacement of the Moon with respect to the node of its orbit is 7°·6. Consequently, there is not a lunar eclipse every 19 years. Thus, there was a small partial eclipse on 1970 February 21, preceding the total ones of 1989 February 20 and 2008 February 21; the eclipse of 2027 February 20 will be only penumbral, and on 2046 February 20 there will be no eclipse.

On the other hand, the period of 65 years corresponds to 804 lunations. After such a period, the displacement of the Moon with respect to its node is only 0°·9. Thus the period of 65 years is much more exact for predicting eclipses than the cycle of Meton. For instance, there were or will be lunar eclipses on the following dates, and all are total ones:

1664 February 11	1924 February 20
1729 February 13	1989 February 20
1794 February 14	2054 February 22
1859 February 17	2119 February 25

Unfortunately, the displacement with respect to the stars is more important: 65 sidereal years = 23741·66 days, while 804 lunations = 23742·59 days. The difference is 0·93 day, corresponding to a displacement of 0·92 degree relative to the stars.

Thus, while the 19-year period is fairly exact for conjunctions of the Full Moon with a given star, but not good for eclipses, it's just the opposite for the 65-year period. This is the reason why both the 19-year and the 65-year periods give short series in our panoramas.

Finally, let us mention the longer period of 800 years, which connects several series, for instance 259–1059–1859 or 1710–2510. After such a period (9895 lunations), the displacement of the Full Moon relative to the stars is only 0°·09, but amounts to about 5° with respect to the node.

The Praesepe Cluster

Dr David W. Dunham, the American grazing occultations expert, wrote to one of the authors (J.M.):

"Although the stars in the Praesepe cluster are fainter [than those of the Pleiades], the cluster is more compact, so that when conditions are favorable, passages of the Moon across it are quite spectacular. Epsilon Cancri, Z.C. 1299, is the brightest star, near the center of the cluster.

"On January 30, 1972, the Moon occulted some of the southern stars of the Praesepe cluster as seen from Antarctica, only a few hours before a total lunar eclipse. It seems to me that, at least for the southern hemisphere, it would be possible for the totally eclipsed Moon to cross the southern part of the Praesepe cluster. It would be interesting to know when was the last time this occurred, and when it will next occur."

A photograph of the eclipsed Moon near the Praesepe cluster has been published in *Sky and Telescope*, 1972 May, page 330. ϵ Cancri is a star of magnitude 6·3, and the cluster has a diameter of 1½ degrees. As the star's latitude is greater than 0°·765 (see Table II), no occultation by the *totally* eclipsed Moon can be visible from the Earth's centre, nor *a fortiori* from the northern hemisphere. But the latitude is less than the limit of 1°·790, so occultations of ϵ Cnc by the totally eclipsed Moon can actually be visible from a part of the southern hemisphere. Between A.D. 1600 and 2150 the following cases occur:

1628 January 20: in a part of the southern hemisphere, occultation during the final *partial* phase of the total eclipse;

On 1647 January 20, 1674 January 22, 1777 January 23 and 1804 January 26, the star was occulted by the partially eclipsed Moon;

1823 January 26: for some regions of the southern hemisphere, occultation by the totally eclipsed Moon. This is the last case in the period 1600–2150 taken into consideration.

As additional cases can be mentioned the following:

On 1953 January 29, ϵ Cancri was occulted in the southern hemisphere a few hours before the beginning of the eclipse;

1972 January 30: no occultation of ϵ Cnc; the geocentric conjunction occurred at 6^h UT, three hours before the first contact with the umbra. A part of the Praesepe cluster was actually occulted;

2037 January 31: occultation of the star in the southern hemisphere, but once again a few hours before the first contact with the umbra.

Finally, during the *penumbral* eclipses of 1991 January 30 and 1999 January 31, the Moon will be not far from ϵ Cnc, but nowhere on the Earth will it be occulted, the Moon being well south of the ecliptic.

Occultations of the other stars which can be occulted by the totally eclipsed Moon

β Scorpii. For some places this star was occulted during the second half of the partial eclipse of 1742 May 19, but at the limb which was in the penumbra. During the eclipses of 1826 May 21, 1845 May 21 and 1891 May 23, the star has been eclipsed by the totally eclipsed Moon for some regions in the southern hemisphere.

During the small partial eclipse of 1872 May 22, β Scorpii was occulted. For some observers, the star disappeared *and* reappeared at the eclipsed limb; thus it was an occultation of type *P*. But for many other places these phenomena took place at the limb which was in the penumbra.

On 1975 May 25, the star will be occulted by the totally eclipsed Moon for observers in the southern hemisphere.

During the small partial eclipse of 1994 May 25, β Sco will be occulted, for some observers at the eclipsed limb, for others at the illuminated one.

2021 May 26: for some observers, the star will be occulted during the beginning of this eclipse, but only emersions at the still non-eclipsed limb will be visible, thus type (t′).

On 2040 May 26, there will be an occultation in a part of the southern hemisphere shortly *before* the first contact with the umbra.

These are the only cases for β Sco in the period 1600–2150.

α *Librae.* There are 11 cases in the period 1600–2150, namely:

1836 May 1: occultation during the last $\frac{1}{4}$ hour of the eclipse, the disappearance taking place at the illuminated limb;

1855 May 2 and 1920 May 3: occultation during the final partial phase of these total eclipses;

1939 May 3: as for 1836;

1985 May 4, 2004 May 4, 2050 May 6 and 2069 May 6: occultation by the totally eclipsed Moon;

2088 May 5 and 2115 May 8: occultation by the partially eclipsed Moon;

2134 May 8: occultation by the totally eclipsed Moon.

On 1958 May 3, there was occultation $1\frac{1}{2}$ hours *after* the last contact with the umbra. On 1966 May 4, α Librae has been occulted during a *penumbral* eclipse; this was visible in Western Europe.

The other bright stars. For μ *Geminorum*, there was only one case between 1900 and 2050, namely on 1917 December 28, when for some places the emersion took place at the very beginning of the partial phase preceding the total eclipse, and at the bright limb.

δ *Geminorum:* For some regions on the Earth's surface, occultation by the *totally* eclipsed Moon on 1917 January 8, 1936 January 8, 1982 January 9 and 2001 January 9. Moreover, on 1955 January 8 the star was occulted during the penumbral eclipse.

ξ *Sagittarii:* Two cases in the period 1900–2050, namely: on 1936 July 4, occultation in the southern hemisphere, but for all places immersion and emersion both took place at the illuminated limb; on 1963 July 6, in a part of the southern hemisphere there was emersion during the very beginning of the umbral eclipse, but at the illuminated limb.

π *Sagittarii:* No case between 1900 and 2050. On 1963 July 6 there was occultation in the southern hemisphere shortly *after* the last contact with the umbra.

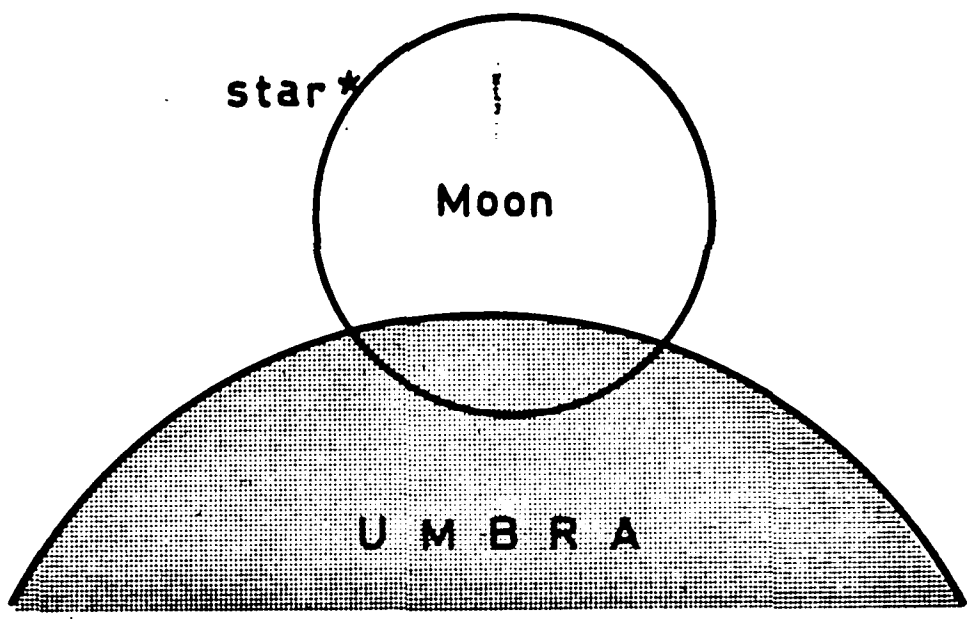
λ *Aquarii:* Three cases between 1900 and 2050. On 1914 September 4, occultation in the northern hemisphere by the partially eclipsed Moon. On 1960

September 5 and 1979 September 6, for some regions occultation during the initial partial phase of the total eclipse, but at the non-eclipsed limb.

Between A.D. 1900 and 2050, η *Geminorum*, ρ *Leonis* and β *Virginis* are *not* occulted by the eclipsed Moon.

Occultations of other stars by the partially eclipsed Moon

The greatest value of the Moon's apparent diameter is 0°·56. Consequently, a star whose absolute latitude is between 1°·79 and 1°·79+0°·56 = 2°·35 may still be occulted by the partially eclipsed Moon, though *not* at the eclipsed limb. The situation is as illustrated by the figure. Thus, for these stars, only occultations of types (*p*) and (*p'*) are possible.



In Table IV, the data are given for the six brightest stars whose absolute latitude is between 1°·79 and 2°·35. In the last column, the date of conjunction with the anti-sun is again given.

TABLE IV

Star	*Magn.*	*Long. and Lat., 1950* °	°	*Date, 1950*
ζ Tau	3·0	84·08	−2·20	Dec. 16·6
ϵ Gem	3·2	99·24	+2·06	Dec. 31·5
α Vir	1·2	203·14	−2·05	Apr. 13·7
δ Sco	2·5	241·87	−1·98	May 23·6
θ Oph	3·4	260·70	−1·84	June 12·2
λ Sgr	2·9	275·62	−2·13	June 27·9

α *Virginis* (*Spica*): There is *no* case between A.D. 1600 and 2100. On 1708 April 5, Spica was occulted about 6 hours after the end of the partial eclipse.

Spica will be occulted for places in the northern hemisphere during the *penumbral* eclipse of 1987 April 14. There will also be an occultation of the star in a part of the northern hemisphere during the penumbral phase preceding the partial eclipse of 1995 April 15.

On 1949 April 13, the totally eclipsed Moon was in conjunction with Spica, but there was no occultation. This was also the case on 1968 April 13; see the picture in *Sky and Telescope* of 1968 June, page 351. It will occur again at the total eclipses of 2014 April 15 and 2033 April 14.

ζ *Tauri* and λ *Sagittarii:* No case between the years 1900 and 2050.

ϵ *Geminorum:* In the period 1900–2050, there is only one case, on 2009 December 31. During the small eclipse of that date (magnitude 0·08), the southern limb of the Moon will be eclipsed, while the northern limb will occult the star for observers in the southern hemisphere. Maximum eclipse will occur at $19^h\ 25^m$ E.T., about half an hour after the geocentric Moon–star conjunction in longitude.

On 1963 December 30, the totally eclipsed Moon was close to the star, but there was no occultation. This will again occur on 1982 December 30.

δ *Scorpii:* No case in the period A.D. 1900–2050. During the nearly total eclipse of 1956 May 24 the Moon was not far from the star, but there was no occultation.

θ *Ophiuchi:* No case in the period 1900 to 2050. A few hours before the partial eclipse of 1992 June 15, the star will be occulted for part of the northern hemisphere, probably for Europe.