## TOTAL PENUMBRAL LUNAR ECLIPSES

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## ABSTRACT

The moon can be totally immersed in the penumbral cone of the earth without touching the umbra. This paper lists all of these total penumbral eclipses for the period AD 1600–2500. The total penumbral eclipses are unevenly distributed with time; their frequency varies in phase with that of tetrads and that of total eclipses in the umbra.

Introduction. On 20 January 1981 there will be a total penumbral eclipse of the moon. What is the mean frequency of such phenomena, and how are they distributed with time?

As seen from the centre of the earth, the extreme values of the apparent diameter of the moon are 1763 arcsec (for an extreme apogee) and 2011 arcsec (for an extreme perigee). On the other hand, the extreme values of the width of the penumbral corona at the moon's distance – the difference between the radii of penumbra and umbra – are 1888 and 1952 seconds of arc. Consequently, it is indeed possible that the moon be totally immersed in the earth's penumbral cone without touching the umbra at all. Such total penumbral eclipses are not possible, however, when the moon is near to its perigee.

It should be pointed out that total penumbral lunar eclipses are only of theoretical interest. For the observer, the important point for a penumbral eclipse is the least separation between the moon's limb and the edge of the umbra. Very small values for this separation are possible even when the moon is *not* totally immersed in the penumbra. Therefore, unlike umbral eclipses, the "total" type of a penumbral eclipse should not be considered to be an important and beautiful phenomenon!

The maximum phase of the eclipse of 20 January 1981 will take place at  $7^{h}50^{m}$  UT, and will be visible from North America. The magnitude\* of the eclipse in the penumbra is 1.014. In the umbra the magnitude is -0.019, negative since the moon does not touch the umbra. At the time of maximum eclipse, the separation between the moon's limb and the edge of the umbra will be only 18 arcsec.

\*The magnitude of a lunar eclipse is the fraction of the moon's diameter that is obscured by the umbra (or penumbra) at the time of maximum eclipse. If the eclipse is partial, the magnitude is a number between 0 and 1. For a total eclipse, the magnitude is larger than 1.

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Note on the Magnitude of Lunar Eclipses. The earth's shadow differs somewhat from a circular cone because the earth is not a true sphere. However, except for the accurate reduction of observations (for example, contacts of lunar craters with the edge of the shadow), it is generally sufficient to use a (mean) circular radius of the earth. Moreover, observation has shown that the atmosphere of the earth has the effect of increasing the apparent radius of the earth's shadow by about one fiftieth. Following an old tradition, in most astronomical almanacs the geometric radii of both the umbra and the penumbra are increased by 1/50.

However, since 1951 the French almanac Connaissance des Temps has used another theory for the computation of the radii. Indeed, the only reasonable way to take into account the presence of an opaque atmospheric layer around the earth is to increase the earth's radius, which can be performed by increasing proportionally the moon's parallax. In that case, the radii of the umbra and penumbra will undergo the same absolute correction, not the same relative correction as the traditional rule states. Thus, even if the factor of 1/50 were true for the umbra, it cannot be correct for the penumbra. As a consequence, the magnitudes of lunar eclipses, as published in the Astronomical Ephemeris, are too large (as compared to the values given by the Connaissance des Temps) by about 0.005 for umbral eclipses, and by about 0.026 for penumbral ones.

In the new *Canon of Lunar Eclipses* (Meeus and Mucke 1979), the magnitudes of the lunar eclipses have been calculated in accordance with the "French rule", and these values are used in the present article.

The Occurrence of Total Penumbral Eclipses. Among the 10936 lunar eclipses given in the above-mentioned Canon, there are 132 total penumbral eclipses. This gives a mean frequency of one total penumbral eclipse every 34.3 years. The strictly penumbral eclipse with the greatest magnitude appearing in that catalogue is the eclipse of +348 October 24, which had a magnitude of 1.100, close to the maximum possible value (1952/1763 = 1.107).

Table I gives the list of total penumbral eclipses from +1600 to +2500. After the date, the magnitude in the penumbra is given. Eclipses belonging to the same saros series are indicated by A, B, C, or D. It is remarkable that there are so few cases between the years 1600 and 1900, and between 2160 and 2420. This gave us the idea to look somewhat closer at the distribution of total penumbral eclipses with time.

In Table II, column (a), the number of total penumbral eclipses is given for every century, between AD 501 and 2500. These values have been plotted as curve (a) in figure 1. We see that there is a cycle with a length of a

TABLE I
TOTAL PENUMBRAL LUNAR ECLIPSES, 1600 TO 2500

Date	Magnitude	Saros Series	Date	Magnitude	Saros Series
1637 July 7	1.008		2070 April 25	1.051	
1665 July 27	1.006		2082 Aug. 8	1.002	
1806 June 30	1.031		2099 Sept. 29	1.033	
1900 June 13	1.001		2103 Jan. 23	1.008	$\boldsymbol{C}$
1901 May 3	1.043		2121 Febr. 2	1.029	$\boldsymbol{C}$
1908 Dec. 7	1.034	$\boldsymbol{A}$	2128 March 16	1.009	
1926 Dec. 19	1.027	$\boldsymbol{A}$	2139 Febr. 13	1.057	$\boldsymbol{C}$
1944 Dec. 29	1.022	$\boldsymbol{A}$	2157 Febr. 24	1.093	$\boldsymbol{C}$
1948 Oct. 18	1.014		2222 Aug. 23	1.052	
1963 Jan. 9	1.019	$\boldsymbol{A}$	2429 Dec. 11	1.085	D
1981 Jan. 20	1.014	$\boldsymbol{A}$	2447 Dec. 22	1.067	D
1988 March 3	1.092	$\boldsymbol{\mathit{B}}$	2458 May 28	1.003	
1999 Jan. 31	1.005	$\boldsymbol{A}$	2466 Jan. 1	1.055	D
2006 March 14	1.031	$\boldsymbol{\mathit{B}}$	2484 Jan. 13	1.044	D
2053 Aug. 29	1.020		2498 Sept. 30	1.007	

TABLE II

Number of Lunar Eclipses per Century

Century	(a) Total Penumbral Eclipses	(b) Total Umbral Eclipses	(c) Tetrads
501-600	1	63	0
601-700	2	58	0
701-800	2	69	3
801-900	2 5	88	8
901-1000	3	78	6
1001-1100	3	62	0
1101-1200	0	60	0
1201-1300	1	60	0
1301-1400	8	77	6
1401-1500	4	83	4
1501-1600	2	76	6
1601–1700	. 2	61	0
1701-1800	0	60	0
1801-1900	2	62	0
1901-2000	9	81	5
2001–2100	5	84	7
2101-2200	5	69	4
2201–2300	1	61	0
2301-2400	0	60	0
2401–2500	6	69	4

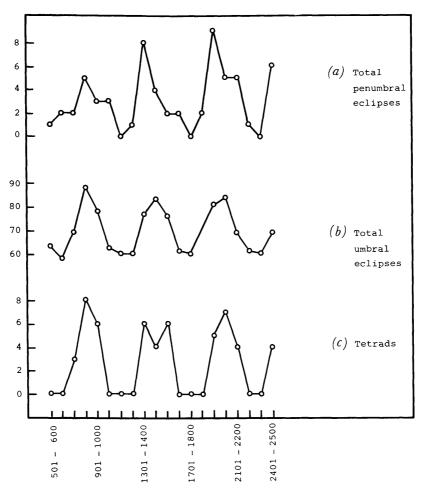


Fig. 1—Frequency of total lunar eclipses, penumbral and umbral, and of tetrads (four consecutive lunar eclipses that are total umbral eclipses), expressed in terms of the number per century.

little less than six centuries, giving alternatively "rich" and "poor" periods. Column (b) of Table II gives the number of total *umbral* eclipses for the same centuries; the values are again plotted in figure 1, as curve (b). Finally, column (c) in Table II and curve (c) in figure 1 give the number of "tetrads" per century. A tetrad is a group of four consecutive lunar eclipses which are all total umbral eclipses; in such a case, the four eclipses occur at intervals of six lunations. One example is the group of four total eclipses of the years 1967–1968.

It appears that the number of total eclipses in the umbra, and the number of tetrads, are exceedingly variable from one century to another. For example, no tetrad took place between the years +1582 and +1908, while 16 occur from +1909 to +2156; then there is again an "empty" period until the year +2448. The cycle of this tetrad variation, which was discovered by

G. Schiaparelli and explained by A. Pannekoek (1951), has a mean period of 586 years.

The correspondence between the three curves is remarkable. From the material presented here, it appears that the number of total penumbral eclipses, that of total umbral eclipses, and that of tetrads, vary in phase with a period of a little less than six centuries. In centuries when there are more tetrads, there are not only more total umbral eclipses of the moon, but also more total penumbral eclipses.

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