Total penumbral lunar eclipses

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The main canons of lunar eclipses[1,2,3] do not give many details of penumbral lunar eclipses in general or of total penumbral lunar eclipses in particular. This paper investigates the circumstances required for total penumbral lunar eclipses and gives details of all such eclipses occurring from AD 1000 to AD 3000.

Introduction

Penumbral lunar eclipses are not as spectacular as umbral lunar eclipses. Even total penumbral eclipses are probably mainly of interest only to astronomers, although they can quite easily be observed by anyone.

Canons of lunar eclipses do not generally give many details of penumbral eclipses. The canon of Meeus & Mucke[2] gives only the magnitude and time of maximum eclipse. It is not possible to deduce the times of penumbral contact from the tabulated data. This limitation is also true of the eclipse website[3] which is perhaps the definitive source of eclipse information on the Web.

The canon of Bao–Lin & Fiala[1] does give more information. For penumbral eclipses, the canon lists the times of the beginning and end of the penumbral phase in addition to the time of maximum eclipse and the eclipse magnitude. However, from the tabulated data, it is not possible to calculate the duration of total penumbral immersion for a total penumbral eclipse.

In this paper, calculations are made of the durations of total penumbral lunar eclipses. The eclipse elements used in these calculations were kindly supplied to the author by Jean Meeus (private communication). The elements used Bretagnon's VPOP87 theory for the Sun and Chapront's ELP (2002) theory for the Moon using improved mean elements.

Correction for the Earth's atmosphere

Calculations of lunar eclipses must correct for the presence of the Earth's atmosphere. There are two techniques commonly in use for this. One is the so called 1/50 rule, where a 2% increase to the shadow radius is applied to both the umbral and the penumbral shadows. While this adjustment may be correct for either the umbra or the penumbra, it cannot be correct for both.[4]

The other method is known as the 'French' rule where a correction is made by applying an adjustment to the lunar parallax. This, correctly, has a different effect on the umbra and penumbra. The correction is just under 2% for the umbra and just under 1% for the penumbra. The magnitudes of penumbral lunar eclipses calculated using the 'French' rule are typically 0.026 smaller than when calculated with the 2% rule. The elements used in this paper were calculated using the French rule.

Whilst the correction used may seem unimportant, since it is currently not possible to distinguish between the types observationally, it is important for eclipse calculations. Some eclipses which by one correction method are total penumbral may be small umbral eclipses should the other correction be applied and vice versa. A table comparing the two calculation techniques for a period of six centuries, AD 1900 to AD 2500, is given by Bao–Lin & Fiala.[1] Of the 1439 lunar eclipses which occur during these six centuries, only 17 eclipses would have different classifications due to the calculation technique.

Penumbral lunar eclipses

Lunar eclipses can only occur near to the time of full Moon, when the Sun, Earth and Moon align sufficiently well for the Moon to pass through the shadow of the Earth. Since the Sun is an extended source of light, i.e. not a point source, the shadow of the Earth consists of two sections, known as the umbra and the penumbra. The umbral shadow is the region of space where the Earth blocks all of the light coming from the Sun. An observer in the umbra would see a total eclipse of the Sun. The penumbra is a region which surrounds the umbra. An observer in the penumbral shadow would see a partial eclipse of the Sun.

During a total or partial lunar eclipse, some part of the Moon passes through the umbral shadow. For a penumbral eclipse, no part of the Moon enters the umbral shadow. It is possible to have total penumbral eclipses, where the Moon becomes completely immersed in the penumbral shadow without ever entering the umbral shadow. It is these total penumbral eclipses which are the subject of this paper.

If the shadow cones could be seen in the sky at the distance of the Moon, then during an eclipse the appearance would be as shown in Figure 1. The umbral shadow cone would appear as a circle surrounded by an annulus of penumbral shadow. During a total penumbral eclipse, the Moon becomes immersed in the penumbra without touching the umbra. This situation is illustrated in Figure 1. The umbral radius is about 0.70° and the penumbral radius is about 1.23°, when the Sun is 1 AU from the Earth and the Moon is at mean distance from the Earth.

The distance labelled × in Figure 1 is the difference between the umbral and penumbral radii. Typically this is only about 0.53°, which is not much larger than the apparent diameter of the Moon itself. At mean distance, the Moon has an apparent diameter of about 0.52°.

It can be seen that the width of the penumbral shadow is only just large enough to contain the Moon, so total penumbral eclipses are only just possible. By using simple geometry, it is possible to calculate the size of the penumbral shadow at various distances from the Earth for given distances of the Sun. These calculations were performed for Earth to Sun distances from 0.980 AU to 1.018 AU. For each Earth to Sun distance, the minimum Earth to Moon distance at which a total penumbral eclipse is possible was calculated.

The results of the calculations are shown in Figure 2. As can be seen, the result is a straight line. The straight line drawn through the computed points has the equation

Moon distance = (375000 * Sun distance)–1400

where the Moon distance is in km and the Sun distance is in AU. At the current epoch, from November to March, the Moon at perigee will be too close for a total penumbral lunar eclipse to occur. Should the eclipse occur with the Moon not near perigee, then total penumbral eclipses are possible at any time of the year.

Table 1. Date and duration of total penumbral immersion for lunar eclipses from AD 1000 to AD 3000

Date	*Duration*	*Date*	*Duration*
1014 Jan 19	40m 50s	1981 Jan 20	27m 08s
1032 Jan 30	59m 09s	1988 Mar 03	75m 13s
1097 Jul 27	50m 44s	1999 Jan 31	12m 05s
1221 May 08	44m 43s	2006 Mar 14	43m 40s
1322 Nov 24	77m 36s	2053 Aug 29	33m 50s
1340 Dec 04	72m 12s	2070 Apr 25	56m 25s
1344 Mar 29	58m 35s	2082 Aug 08	08m 02s
1358 Dec 16	66m 26s	2099 Sep 29	46m 29s
1373 Sep 02	54m 58s	2103 Jan 23	24m 47s
1376 Dec 26	60m 15s	2121 Feb 02	44m 22s
1390 Apr 29	39m 28s	2128 Mar 16	21m 26s
1395 Jan 06	50m 40s	2139 Feb 13	60m 12s
1413 Jan 17	35m 07s	2222 Aug 23	57m 28s
1455 Oct 25	53m 57s	2429 Dec 11	72m 13s
1496 Jul 25	53m 33s	2447 Dec 22	64m 11s
1502 Apr 22	51m 35s	2458 May 28	12m 14s
1513 Sep 15	36m 38s	2466 Jan 01	57m 28s
1542 Aug 25	55m 08s	2484 Jan 13	51m 14s
1607 Mar 13	55m 06s	2498 Sep 30	19m 41s
1637 Jul 07	22m 23s	2502 Jan 24	44m 38s
1665 Jul 27	19m 50s	2520 Feb 04	33m 27s
1806 Jun 30	44m 20s	2523 Nov 24	35m 42s
1900 Jun 13	07m 23s	2538 Feb 15	04m 24s
1901 May 03	52m 04s	2562 Nov 12	47m 31s
1908 Dec 07	43m 40s	2656 Oct 25	52m 07s
1926 Dec 19	37m 40s	2714 Mar 23	34m 16s
1944 Dec 29	34m 43s	2732 Apr 02	71m 27s
1948 Oct 18	29m 12s	2761 Sep 06	29m 19s
1963 Jan 09	31m 20s	2885 Jun 18	52m 14s

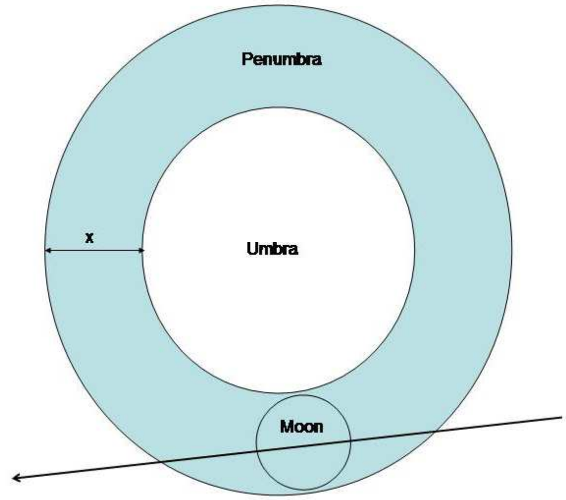

Figure 1. Projection of umbral and penumbral shadow cones on the sky with the Moon during a total penumbral eclipse.

The likelihood of a total penumbral eclipse occurring increases with smaller Earth to Sun distance, so it would be expected that more of these eclipses would occur during northern hemisphere winter months, when the Earth is closer to the Sun, and at times when the Moon is not close to a perigee.

Total penumbral lunar eclipse details

From AD 1000 to AD 3000, there are 4849 lunar eclipses. Of these, 1766 are penumbral. Of the penumbral eclipses, only 58 are total penumbral. Thus, total penumbral eclipses represent only 1.2% of all lunar eclipses.

Precise details for all the total penumbral lunar eclipses occurring from AD 1000 to AD 3000 were calculated. Table 1 gives the dates and the durations of total penumbral immersion for the 58 eclipses found, with the eclipses listed in chronological order. The durations were calculated to an accuracy of ±1 second.

If 'summer' is used to describe the period when the Sun is more than 1 AU from Earth and 'winter' describes the period when the Sun is less than 1 AU from Earth, then it is found that 36 of the eclipses in Table 1 occur during winter and only 22 occur during summer. The bias towards winter months is as expected from the preceding discussion.

It is also to be expected that the longest total penumbral eclipses occur when the Moon is close to apogee, since the umbral shadow will be smaller and the penumbral shadow larger at apogee than at other distances from Earth. Also, the Moon's motion is slower when it is at apogee so it will take longer to traverse the shadow. Table 2 presents the same eclipses as shown in Table 1, but arranged in order of decreasing duration. Two extra columns of information are given in Table 2, one showing the

Table 2. Total penumbral eclipses in order of decreasing duration

Date	*Duration*	*Moon at apogee*	*Eclipse/apogee separation (days)*
1322 Nov 24	77m 36s	1322 Nov 24	0
1988 Mar 03	75m 13s	1988 Mar 01	2
2429 Dec 11	72m 13s	2429 Dec 14	3
1340 Dec 04	72m 12s	1340 Dec 05	1
2732 Apr 02	71m 27s	2732 Apr 01	1
1358 Dec 16	66m 26s	1358 Dec 17	1
2447 Dec 22	64m 11s	2447 Dec 26	4
1376 Dec 26	60m 15s	1376 Dec 27	1
2139 Feb 13	60m 12s	2139 Feb 15	2
1032 Jan 30	59m 09s	1032 Jan 28	2
1344 Mar 29	58m 35s	1344 Apr 01	3
2222 Aug 23	57m 28s	2222 Aug 22	1
2466 Jan 01	57m 28s	2466 Jan 05	4
2070 Apr 25	56m 25s	2070 Apr 28	3
1542 Aug 25	55m 08s	1542 Aug 28	3
1607 Mar 13	55m 06s	1607 Mar 08	5
1373 Sep 02	54m 58s	1373 Sep 01	1
1455 Oct 25	53m 57s	1455 Oct 29	4
1496 Jul 25	53m 33s	1496 Jul 24	1
2885 Jun 18	52m 14s	2885 Jun 20	2
2656 Oct 25	52m 07s	2656 Oct 21	4
1901 May 03	52m 04s	1901 May 02	1
1502 Apr 22	51m 35s	1502 Apr 18	4
2484 Jan 13	51m 14s	2484 Jan 17	4
1097 Jul 27	50m 44s	1097 Jul 22	5
1395 Jan 06	50m 40s	1395 Jan 08	2
2562 Nov 12	47m 31s	2562 Nov 18	6
2099 Sep 29	46m 29s	2099 Sep 28	1
1221 May 08	44m 43s	1221 May 10	2
2502 Jan 24	44m 38s	2502 Jan 28	4
2121 Feb 02	44m 22s	2121 Feb 04	2
1806 Jun 30	44m 20s	1806 Jul 03	3
1908 Dec 07	43m 40s	1908 Dec 14	7
2006 Mar 14	43m 40s	2006 Mar 13	1
1014 Jan 19	40m 50s	1014 Jan 17	2
1390 Apr 29	39m 28s	1390 May 05	6
1926 Dec 19	37m 40s	1926 Dec 26	7
1513 Sep 15	36m 38s	1513 Sep 08	7
2523 Nov 24	35m 42s	2523 Nov 17	7
1413 Jan 17	35m 07s	1412 Jan 18	1
1944 Dec 29	34m 43s	1945 Jan 05	7
2714 Mar 23	34m 16s	2714 Mar 21	2
2053 Aug 29	33m 50s	2053 Aug 24	5
2520 Feb 04	33m 27s	2520 Feb 09	5
1963 Jan 09	31m 20s	1963 Jan 17	8
2761 Sep 06	29m 19s	2761 Sep 02	4
1948 Oct 18	29m 12s	1948 Oct 13	5
1981 Jan 20	27m 08s	1981 Jan 27	7
2103 Jan 23	24m 47s	2103 Jan 24	1
1637 Jul 07	22m 23s	1637 Jul 06	1
2128 Mar 16	21m 26s	2128 Mar 09	7
1665 Jul 27	19m 50s	1665 Jul 30	3
2498 Sep 30	19m 41s	2498 Oct 03	3
2458 May 28	12m 14s	2458 May 23	5
1999 Jan 31	12m 05s	1999 Feb 08	8
2082 Aug 08	08m 02s	2082 Aug 14	6
1900 Jun 13	07m 23s	1900 Jun 05	8
2538 Feb 15	04m 24s	2538 Feb 20	5

date of the lunar apogee occurring closest to the date of the eclipse and one showing the number of days between the eclipse and the apogee. The figure is positive independent of whether the apogee occurs before or after the eclipse.

The longest period of total penumbral immersion was 77m 36s for the eclipse of 1322 Nov 24. This eclipse also had the largest penumbral magnitude, 1.095, and the smallest value of γ at 0.890. γ specifies the least distance of the centre of the Moon's disk to the centre of the Earth's umbra in degrees. In this event he Moon's southern limb passed only about 35km from the edge of the umbra. The eclipse occurred on the same day as lunar apogee, actually about 6 hours after apogee.

The shortest eclipse is that of 2538 Feb 15 at only 4m 24s. This eclipse has the smallest penumbral magnitude, 1.0003. However, this eclipse is not the one with the largest value of γ. The eclipse of 1999 Jan 31 has the largest value at –0.984, the negative sign indicating that the Moon passed to the south of the umbral shadow.

It can be seen from Table 2 that all the eclipses with a duration of more than 70 minutes occur no more than 3 days from lunar apogee. Conversely, all eclipses with a duration of less than 15 minutes occur 5 or more days from lunar apogee.

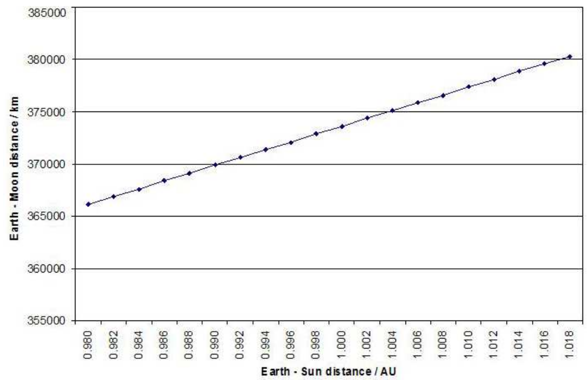

Figure 2. Plot of minimum lunar distance for a total penumbral eclipse to be possible.

Total penumbral eclipses of the 21st century

The tables presented here have used a long time period so as to be able to consider a reasonable number of eclipses from which to draw conclusions. It may also be of interest to readers to have more details concerning eclipses which they may be fortunate enough to be able to observe. In Table 3, details of the total penumbral eclipses which occur between AD 2001 and AD 2100 are given. Times are UT and calculated to the nearest minute.

Table 3. Details of total penumbral eclipses from 2001 AD to 2100 AD

Date	*Start of eclipse*	*Start of total penumbral phase*	*Mid-eclipse*	*End of total penumbral phase*	*End of eclipse*
2006 Mar 14	21:24	23:26	23:47	00:09	02:11
2053 Aug 29	05:45	07:47	08:04	08:21	10:23
2070 Apr 25	06:56	08:51	09:19	09:48	11:43
2082 Aug 08	12:29	14:40	14:44	14:48	16:59
2099 Sep 29	08:09	10:10	10:33	10:57	12:58