# Leonid flashers—meteoroid impacts on the Moon

M. BEECH (1)(2) and S. NIKOLOVA (2)

(1) *Campion College, The University of Regina - Regina, Saskatchewan, Canada S4S 0A2*
(2) *Department of Physics, The University of Regina - Regina, Saskatchewan, Canada S4S 0A2*

(ricevuto il 17 Giugno 1998; approvato il 15 Settembre 1998)

**Summary.** — We examine the conditions under which optical impact flashes might be observable on the Moon's disk during the times of annual meteor shower activity. Our attention is primarily directed towards the Leonid shower given the high probability that it will undergo repeated outburst activity during the next several years. The Leonid stream to Moon encounter geometry is discussed, and we find that the best probable times to perform optical surveys will be in 1999 and 2002. We estimate that a one kilogram Leonid meteoroid might produce a magnitude-2 optical transient on the Moon's disk.

PACS 96.50.Kr – Meteors and metoroids.
PACS 96.20 – Moon.

## 1. – Introduction

In common with all of the planets within the inner Solar System, the Moon is subject to impacts from both stream and sporadic meteoroids. Since the Moon has no substantive atmosphere, however, impacting meteoroids will strike its surface with zero velocity modification and there will be likewise no associated atmospheric ablation phenomena. While, therefore, there is no lunar analogy to the terrestrial meteor, an optical impact "flash" may nonetheless be produced when a meteoroid hits the Moon's surface. In this note we explore the possibility of observing impact flashes on the Moon's visible disk during the times when annual meteor showers are active. In particular, we examine the possibility of observing optical flashes from Leonid meteoroid impacts.

The Leonid meteoroid stream is associated with the periodic comet 55P/Tempel-Tuttle, and historically the Leonid meteor shower has shown enhanced activity whenever the parent comet is near the perihelion [1]. Comet 55P/Tempel-Tuttle was last at perihelion in February, 1998 and a number of recent studies [2, 3] have concluded that high Leonid meteor rates are likely to be realized in 1998 and 1999. Indeed, enhanced Leonid rates are likely to be observed well in to the next century.

Impacts of large Leonid meteoroids upon the Moon's surface have, in fact, already been recorded with the Apollo lunar seismic network (hereafter LSN). Oberst and Nakumura [4] have analyzed the data collected by the LSN between 1972 and 1977, and interestingly they found a strong temporal grouping of impacts at the time of the 1974

Leonids. Impact clusters could also be associated with several other annual meteor showers. While the LSN could not directly measure the masses of impacting meteoroids, Oberst and Nakumura estimate that the data are consistent with hits from meteoroids in the mass range 0.1 to 1 kg. At first scan, the results of Oberst and Nakumura analysis are a little surprising in that Leonid impacts were not recorded in each year of the survey—after all, the Leonid meteor rates were not enhanced over normal in 1974 [5]. In order to understand the possible reasons for the apparent selectivity of the LSN, we have to consider the meteoroid encounter geometry.

## 2. – Lunar encounter geometry

The essential geometry of interest is shown in fig. 1. The Leonid meteoroids approach the Earth-Moon system at an angle $\varepsilon$ to the apex of the Earth's way. Likewise, the perpendicular to the Earth-Moon radius vector makes an angle $\delta$ to the direction of the Earth's motion. The angle $\sigma$ corresponds to the angular separation of the Moon's center, as seen from the Earth, and the direction of the Leonid stream

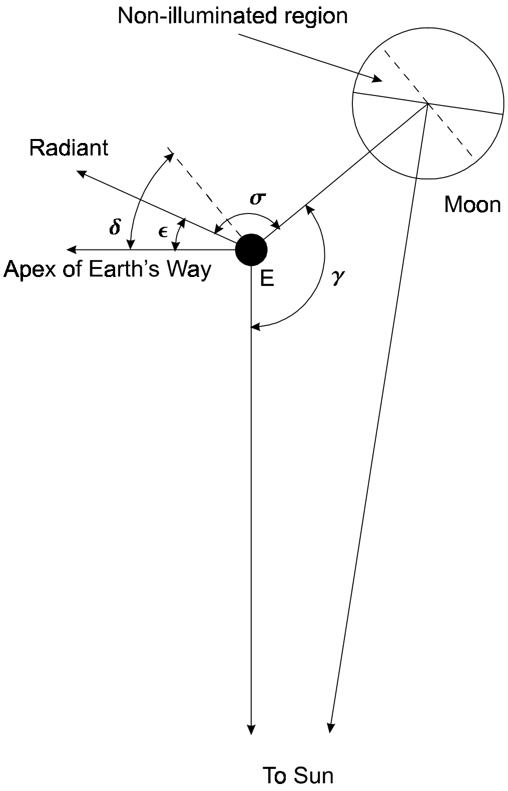

Fig. 1. – Encounter geometry for a meteoroid stream and the Earth-Moon system. We assume planar geometry for simplicity, but note that in the case of the Leonid stream its high orbital inclination dictates that the meteoroids are almost in the ecliptic plane when they are near the perihelion.

TABLE I. – *Moon age and radiant-Moon separation angle at a solar longitude of* $\lambda_{\odot} = 235.2$. *The* LSN *data studied by Oberst and Nakamura* [4] *was collected between* 1972 *and* 1977, *but the* 1977 *data did not extend to the Leonid epoch.*

| Year | Nodal crossing time (UT) | Moon age (days) | $\sigma$ (degrees) | Year | Nodal crossing time (UT) | Moon age (days) | $\sigma$ (degrees) |
|---|---|---|---|---|---|---|---|
| 1972 | Nov. 17.18 | 11 | 208 | 1998 | Nov. 17.83 | 28 | 75 |
| 1973 | Nov. 17.44 | 22 | 15 | 1999 | Nov. 18.07 | 10 | 198 |
| 1974 | Nov. 17.69 | 4 | 134 | 2000 | Nov. 17.33 | 21 | 21 |
| 1975 | Nov. 17.95 | 14 | 110 | 2001 | Nov. 17.60 | 2 | 121 |
| 1976 | Nov. 17.21 | 25 | 31 | 2002 | Nov. 17.90 | 13 | 122 |

radiant. The angle $\gamma$ between the Sun-Earth radius vector and the Earth-Moon radius vector determines the phase of the Moon at the time of the encounter.

For comparative purposes, the angle $\varepsilon$ may be "fixed" at the time when the Earth cuts through the mean Leonid stream orbit—the shower maximum, as seen from Earth, is always within a few hours of this nodal crossing time which occurs to a solar longitude of $\lambda_{\odot} = 235.2$. We find $\varepsilon \approx 10°$ for the Leonid stream. The Moon age and Moon-radiant separations at the nodal crossing time for the period covering the LSN study [4], and during the next five Leonid returns are given in table I. On purely geometrical grounds, one would expect the best detection geometry to correspond to a separation of $\sigma = 180°$. When this condition is met, the Moon's Earth-facing hemisphere is also pointing directly towards the stream radiant. When $\sigma = 90°$, only one half of the Moon's visible disk is subject to stream meteoroid impacts. The smaller the angular separation of the Moon and the Leonid radiant, the smaller the probability of recording meteoroid impacts. Table I indicates that the impact geometry was not favorable for detecting Leonid impacts in 1973 and 1976. While fig. 3 of Oberst and Nakamura's paper [4] does indicate a small activity peak at the time of the Leonids in 1972, it is not presently clear why no distinctive Leonid impacts were recorded in 1975 (but see the discussion below).

The angular separations given in table I indicate that the best years to look for Leonid impact flashes will be the returns in 1999 and 2002. The return in 1999 is possibly most favored in the sense that the flux of Leonid meteoroids is expected to be high in that year [3]. The chances of detecting Leonid meteoroid impacts optically are, in fact, better than those realized by the LSN. Provided a meteoroid strikes the Moon on its Earth-facing hemisphere, an appropriate optical system may record the impact flash. The LSN required that a meteoroid impact the Moon's surface near one of its seismographs. With reference to fig. 1, the surface area over which impacts are potentially visible from the Earth is $S_{\mathrm{M}} = 4\pi R_{\mathrm{M}}^2\,(90 - \alpha + (\delta - \varepsilon))/360$, where $R_{\mathrm{M}}$ is the Moon's radius and $\alpha$ is the Moon's semi-angular diameter. Under optimal viewing conditions $\delta - \varepsilon \approx 90°$ (*i.e.*, $\sigma \approx 180°$), a potential "detector" area of some $2 \times 10^7$ km$^2$ is realized.

## 3. – How bright an impact flash?

Leonid meteoroids will strike the Moon's surface with a velocity of about 70 km/s. A 1 kg Leonid meteoroid will therefore release some $2.5 \times 10^9$ joules of energy upon impact (this is equivalent to the explosive energy of some 0.5 tonnes of TNT). Clearly, large amounts of energy are liberated during a Leonid impact and useful to our purposes, some of this energy will be radiated in the form of light. Eichorn [6] has conducted a series of hypervelocity impact studies and finds that the light intensity of an impact flash varies as $I = \beta m v^{4.1}$, where $\beta$ is a constant, $m$ is the particle mass and $v$ is the impact velocity. Eichorn's result was derived for particle masses between $10^{-19}$ and $10^{-12}$ kg and impact velocities between 0.5 and 35 km/s. Clearly, if we are to use Eichorn's result for the Leonids we have to extrapolate over many orders of magnitude. Given, however, the complete lack of any alternative formulation, we use Eichorn's intensity formula but caution that the results are well beyond the experimental limits.

From Eichorn's [6] fig. 4, we find that $\beta = 10^7$, and consequently we proceed to calculate the apparent magnitude of a Leonid impact flash as $M_F = -2.5 \cdot \log(I/(4\pi d^2) F_0)$, where $d$ is the Earth-Moon distance and $F_0$ is the visual flux density of a zero magnitude star. Inserting constants and known terms, we find for the Leonids $M_F = -2.5 \log(m) + 5.5$, where $m$ is the meteoroid mass in grams. Figure 2 shows the variation of flash magnitude with meteoroid mass. The figure indicates that a 1 kg Leonid meteoroid may potentially produce a visual magnitude-2 flash during a lunar impact event.

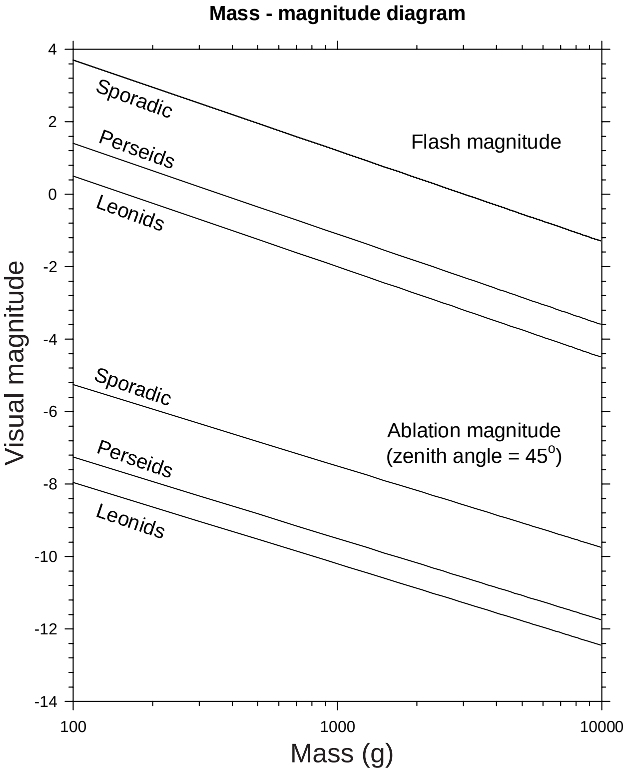

Fig. 2. – Mass-magnitude diagram for meteoroid impacts upon the Moon. The mass-flash magnitude relationship has been calculated for sporadic meteoroids ($v = 30$ km/s), Perseid meteoroids ($v = 60$ km/s) and Leonid meteoroids. The ablation magnitudes for meteoroids entering the Earth's atmosphere are also shown.

## 4. – Discussion

The cumulative flux of Leonid meteoroids, to a limiting mass of $10^{-5}$ g, during a non-storm, annual display is of order $5 \cdot 10^{-12}$ meteoroids/m$^2$/s at shower maximum [7]. If to first order we approximate the activity profile of the Leonid shower by a "top-hat" function of "width" 3 hours, then the Leonid fluence is some $5 \cdot 10^{-8}$ meteoroids/m$^2$. If the number of meteoroids in the mass interval $m$ to $m + \mathrm{d}m$ is $\mathrm{d}N \sim m^{-s}\,\mathrm{d}m$, where $s$ is the mass index, then the cumulative flux at a limiting mass of 100 g (the lower mass limit for detection by the LSN) will be $(100/10^{-5})^{1-s}$ times smaller than that at $10^{-5}$ g. The mass index is not a constant function of time and/or epoch, but for the Leonids it typically falls between $\sim 1.7$ and $\sim 2.0$. For $s = 1.7$, the number of 100 g and larger Leonid meteoroids that should impact upon the Moon's surface is about 10—which is consistent with the LSN results in 1974 [4]. If $s = 2.0$, however, then the number of expected impacts falls to near zero. The fact that no obvious Leonid impacts were recorded by the LSN in 1975, in spite of apparently favorable conditions (see table I), may reflect a high-mass index among the Leonid meteoroids sampled in that year. Under meteor storm conditions the Leonid meteoroid fluence may easily increase by a factor of 100 [7, 8], and, consequently, several tens of impact flashes might be recorded under optimal viewing conditions.

As a final comment, we note that the Moon's tenuous sodium atmosphere is partially maintained by impact-driven vaporization [9]. Consequently, close monitoring of the sodium $D_2$ line near the Moon's limb might yield useful information on the overall flux of Leonid meteoroids during outburst returns.

## REFERENCES

[1] Yeomans D. K., *Icarus*, **47** (1981) 492.

[2] Brown P. and Jones J., in *Physics, Chemistry and Dynamics of Interplanetary Dust, ASP Conference Series*, edited by Gustafson Bo A. S. and Hanner M. S., Vol. **104** (1996), p. 113.

[3] Jenniskens P., *Astron. Astrophys.*, **295** (1995) 206.

[4] Obserst J. and Nakamura, Y., *Icarus*, **91** (1991) 315.

[5] Jenniskens P., *Astron. Astrophys.*, **287** (1974) 990.

[6] Eichorn G., *Planet. Space Sci.*, **24** (1976) 771.

[7] Beech M., Brown P., Jones J. and Webster A., *Adv. Space Res.*, **20** (1997) 1509.

[8] Foschini L. and Cevolani G., *Nuovo Cimento C*, **20** (1997) 211.

[9] Potter A. E. and Morgan T. H., *Science*, **241** (1988) 675.