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The first confirmed Perseid lunar impact flash

Masahisa Yanagisawa [a,*], Kouji Ohnishi [b], Yuzaburo Takamura [c], Hiroshi Masuda [c], Yoshihito Sakai [d], Miyoshi Ida [e], Makoto Adachi [e], Masayuki Ishida [f]

[a] *University of Electro-Communications, Chofu-shi, Tokyo 182-8585, Japan*
[b] *Nagano National College of Technology, Nagano-shi, Nagano 381-8550, Japan*
[c] *Ichinomiya High School, Ichinomiya-shi, Aichi 491-8533, Japan*
[d] *Ogawa Observatory, Ogawa-mura, Nagano 381-3301, Japan*
[e] *Dynic AstroPark Observatory, Taga-cho, Shiga 522-0341, Japan*
[f] *Moriyama-shi, Shiga 524-0104, Japan*

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Abstract

The first confirmed lunar impact flash due to a non-Leonid meteoroid is reported. The observed Perseid meteoroid impact occurred at $18^{\mathrm{h}}28^{\mathrm{m}}27^{\mathrm{s}}$ on August 11, 2004 (UT). The selenographic coordinates of the lunar impact flash are $48 \pm 1°$ N and $72 \pm 2°$ E, and the flash had a visual magnitude of ca. 9.5 with duration of about $1/30$ s. The mass of the impactor is estimated to have been 12 g based on a nominal model with conversion efficiency from kinetic to optical energy of 2×10^{-3}. Extrapolation of a power law size-frequency distribution fitting the sub-centimeter Perseid meteoric particles to large meteoroids suggests that several flashes should have been observed at this optical efficiency. The detection of only one flash may indicate that the optical efficiency for Perseid lunar impact is much lower, or that the slope of the size distribution differs between large meteoroids and typical sub-centimeter meteoric particles.

Keywords: Impact processes; Meteoroids; Meteors; Moon, surface

1. Introduction

Meteoroids collide not only with the terrestrial atmosphere, resulting in meteoric phenomena, but also with the lunar surface, where impact velocities exceed several kilometers per second. These high-velocity impacts with the lunar surface generate a hot vapor cloud that radiates briefly in the optical spectrum. Laboratory measurements suggest that the optical efficiency for such impacts, that is, the portion of the projectile's kinetic energy transferred to optical energy, is typically less than 10^{-4} at impact velocities of several $\mathrm{km\,s^{-1}}$ (Eichhorn, 1976; Kadono and Fujiwara, 1996). However, theoretical work by Artemieva et al. (2000) and analyses of Leonid lunar impact flashes by Bellot Rubio et al. (2000a, 2000b) indicate that the optical efficiencies may be as high as 10^{-3} for meteoroidal impacts at velocities of several tens of $\mathrm{km\,s^{-1}}$. This would suggest, for example, that the impact flash of a 1 kg meteoroid traveling at 59 $\mathrm{km\,s^{-1}}$ upon impact (impact velocity of the Perseids) could be observed on Earth with a magnitude of 6, assuming that the optical energy were released within $1/60$th of a second (one half-frame exposure time of a video camera). The observation of lunar impact flashes over a large target section of the Moon may provide useful information with respect to the near-Earth flux of large meteoroids. Furthermore, lunar impacts provide novel insights into high-velocity impact phenomena, since lunar impact velocities far exceed those achievable by laboratory experiments.

On November 18, 1999 (UT), for the first time, more than 10 lunar flashes were successfully observed on the night side of a 10 day-old Moon from locations in the United States, Mexico, and Japan (Dunham et al., 2000; Ortiz et al., 2000; Yanagisawa and Kisaichi, 2002). The magnitude of the flashes ranged from 3 to 7. Most of the flashes were less than 0.1 s in duration, and all occurred during the period of the Leonid me-

* Corresponding author. Fax: +81 424 43 5291.
E-mail address: yanagi@ice.uec.ac.jp (M. Yanagisawa).

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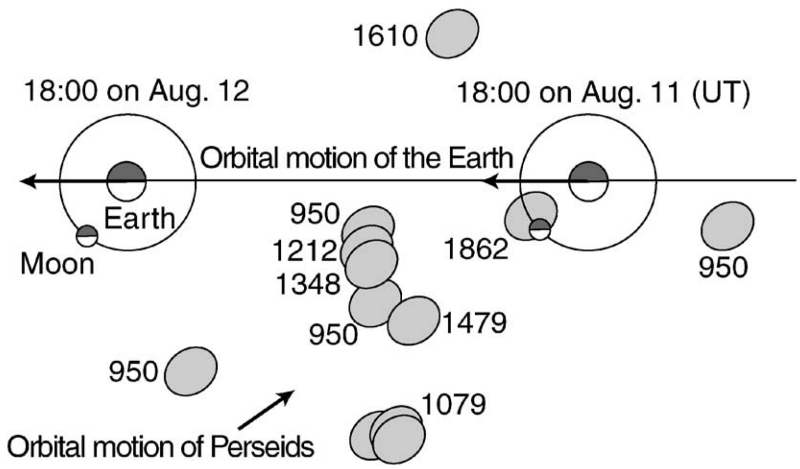

Fig. 1. Cross sections of Perseids dust trails on the ecliptic plane (calculated by I. Sato; personal communication). Number for each cross section shows the year when particles were ejected from the Comet 109P/Swift–Tuttle. The shape and size of the cross sections are arbitrary. The Sun is located far below the figure. The arrow shows the projection of the Perseid velocity vector on the ecliptic plane. The velocity is 41 $\mathrm{km\,s^{-1}}$ and the vector is southward making an angle of 62° with the plane. The orbital motion of the Earth–Moon system (30 $\mathrm{km\,s^{-1}}$) must be considered in order to obtain the Perseid velocity vector relative to the Moon.

teor shower. The observers concluded that these were, indeed, Leonid lunar impact flashes. The lunar phase was again favorable for observing the Leonid impact flashes on November 18, 2001, and Ortiz et al. (2002) observed 4 lunar flashes in that period. Observations from three widely separated stations in the United States confirmed 2 flashes of approximately magnitude 4 on November 18 and 19, 2001 (http://iota.jhuapl.ed/leo01n26.htm). It should be noted that electric noise, cosmic ray hits on charge-coupled device (CCD) detectors, and glints from artificial satellites or space debris could be misinterpreted as lunar flashes. The flashes described above were, however, either simultaneously recorded on videotape by observers in at least 2 different locations, or confirmed as flashes after an exhaustive search that eliminated any possible noise and glints from artificial space objects.

It is interesting to note that the confirmed or carefully checked flashes were only observed during the Leonids. This raises the question as to whether the Leonid meteoroids possess special characteristics that could possibly increase the probability of lunar impact flashes. Some possibilities for this phenomena include the high impact velocity of Leonids (70 $\mathrm{km\,s^{-1}}$), the possible dependence of the optical efficiency on the impact velocity, the unique chemical and physical properties of the meteoroids causing high optical efficiency, or exceptionally high meteoroidal flux during Leonid activity, in particular, when the Moon crosses some of the dust trails in the Leonid stream. Finally, the possibility of a selection effect, since most observations tend to be conducted during the Leonid meteor shower, cannot be discarded. To answer these questions, it is necessary to organize a campaign to monitor the night side of the Moon during the other annual meteor shower periods.

2. Observations and results

2.1. Campaign to search for Perseid lunar impact flashes

The closest approach of the Earth to the dust trail originating from the 1862 cometary activity of the 109P/Swift–Tuttle comet was predicted to occur at about 21:00 on August 11, 2004 (UT) (Lyytinen and Van Flandern, 2004). We found that the Moon encountered the trail at about 18:00 on that day (Fig. 1).

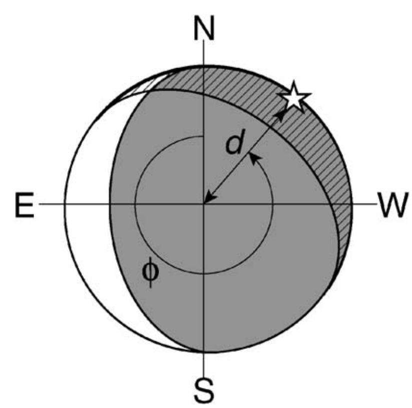

Fig. 2. Lunar disk on August 11, 2004 (UT). White indicates the area illuminated by the Sun, and hatching denotes that area in which Perseids could impact. A flash was observed at the star symbol. The definitions of angular distance d and position angle ϕ are also shown.

Perseid meteoroids mainly hit the far side of the Moon, and the area of the near side exposed to the meteoroids was not large (Fig. 2). The calculated ejection velocity from the comet of particles in the dust trail was 23 $\mathrm{m\,s^{-1}}$ (I. Sato, M. Sato; personal communication). Only small particles could have been captured and accelerated to the required velocity by gas outflow from the nucleus. Large meteoroids were therefore not expected in the trail. These facts decrease the detection probability of lunar impact flashes.

On the other hand, the 25 day-old Moon was not very bright, and the exposed area was far from the sunlit portion. This situation greatly facilitated detection of faint flashes from relatively small meteoroids. A search for lunar impact flashes using video cameras attached to telescopes was organized in Japan for the period 17:00–19:00 on August 11 (UT) by M.Y. and K.O.

Table 1
Observers, locations, and instruments

Group	Observers	Location	Telescope	Video recorder	Time keeping
IHS	Y. Takamura, H. Masuda, Y. Sakai, et al.	36° 39′ 34″ N 137° 59′ 13″ E 1020 m in alti. (Ogawa Ob.)	D = 600 mm f = 2400 mm Newtonian focus	Digital	Telephone time signal
DAP	M. Ida, M. Adachi, and A. Sugie	35° 12′ 40″ N 136° 18′ 16″ E 200 m in alti. (Dynic AstroPark Ob.)	D = 600 mm f = 9000 mm Cassegrain focus with f = 40 mm eyepiece and f = 6 mm camera lens Synthetic f = 1350 mm	VHS	GPS clock
MI	M. Ishida	35° 05′ 13″ N 135° 56′ 47″ E 85 m in alti.	D = 160 mm f = 1000 mm Newtonian focus	Digital	GPS clock

Note. They used the same type of black and white high-sensitivity video camera, WAT-100N (WATEC Inc.).

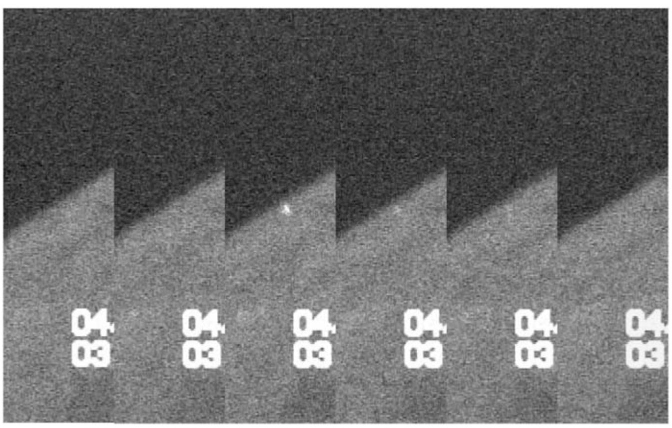

Fig. 3. Evolution of the flash observed by IHS at Ogawa Observatory. Six successive video half-frames are arranged from left to right with a time interval of 1/60 s. Celestial north is to the upper left.

2.2. Detection of a flash

A flash was identified by H.M. and confirmed on videotapes recorded by 2 other independent groups. The locations and instruments used are summarized in Table 1. The groups used the same black-and-white high-sensitivity video camera, a WAT-100N (WATEC Inc.). The image area was 6.3 × 4.7 mm. The 3 groups of observers are denoted hereafter by the group IDs given in the table.

Each video frame consists of an odd and even half-frame. The exposure time for each half-frame was 1/60 s. Therefore, the time variation can be examined at a resolution of 1/60 s by separating each frame into its odd and even half-frames. Six successive video half-frames of the flash as recorded by IHS are shown in Fig. 3. The half-frames recorded by DAP and MI with the brightest appearance of the flash are shown in Fig. 4. Contrast is enhanced in these images in order to show the flash and lunar disk clearly.

The flash may have appeared in the videotapes of 2 other groups, but was too faint to be recognized definitively. Another 9 groups failed to observe the flash due to cloudy sky or use of an insufficiently large telescopic aperture.

The video tapes were scrutinized for impact flashes by visual inspection. It is therefore possible that other flashes may have been missed. However, the authors are confident that there were no other events brighter than this particular flash.

2.3. Confirmation

Time was imposed in each video half-frame using a time imposer (see Fig. 4). Thus, the time of the flash can be measured with a resolution of 1/60 s. The time of the flash was determined to be $18^h28^m27.1^s$ by IHS and $18^h28^m26.9^s$ by DAP and MI. The latter 2 groups synchronized their time imposers with global positioning system (GPS) satellite signals, and synchronization has been confirmed. IHS set their imposer to synchronize automatically with the telephone time signal, but failed to confirm the synchronization. Thus, the 0.2 s difference could be due to incomplete synchronization. The flash is concluded to have appeared at $18^h28^m26.9^s$ without correction for light-time between the Moon and the Earth.

The night-side rim of the Moon can be recognized in the video frames. The coordinates of the lunar disk center in the video frames were determined from the curvature of the rim. Field stars were sometimes within the field of view, and the coordinates of those stars in the video frames can be measured. The position angle of the field of view was calculated given the known celestial coordinates of the stars and the Moon. The angular distance measured from the lunar disk center and the position angle of the flash measured around the lunar disk center were thus obtained (Fig. 2).

The angular distances derived from the 3 observations are in agreement to within 0.005 times the lunar angular radius, or 4″. The position angle is in agreement to within 0.5°, corresponding to 8″ on the celestial plane. Strictly speaking, the observed position (relative to the disk center) of a point on the lunar surface depends on the observer's location on Earth. The difference in position is 0.03 times the lunar angular radius if the observations were made at the 2 ends of the terrestrial sphere. However, the difference between the 3 groups was calculated to be less than 1″. Therefore, the position relative to the disk center can

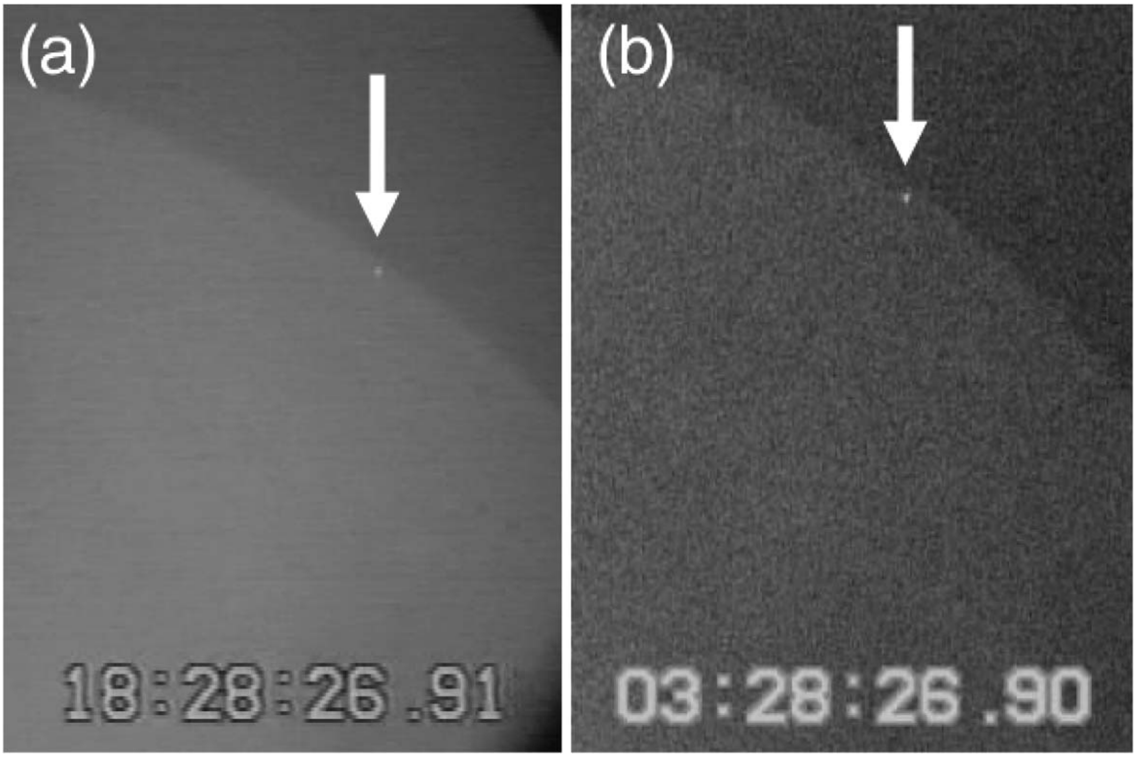

Fig. 4. Two portions of video half-frames showing the flash at its brightest appearance obtained by (a) DAP and (b) MI. Time shown at bottom is in Japanese local time (UT + 9 h) for (b). Celestial north is to the upper right.

be used to examine whether the 3 groups observed the flash at the same spot on the lunar surface.

A distance of ca. 130 km on a plane perpendicular to the Earth–Moon line separated the location of IHS from the locations of DAP and MI. The close agreement in the position relative to the lunar disk center to within about $9''$ demonstrates that the distance to the flash from the Earth was more than 0.9 times the Earth–Moon distance. This completely eliminates the possibility that the observed flash could be attributed to some atmospheric phenomenon, and similarly shows that it is very unlikely to be due to the glint from an artificial object.

To ensure that the flash was in fact a lunar phenomenon, standard orbital two-line elements (TLEs) of 8888 artificial objects (satellites and space debris) provided by M. McCants were also examined. SkyMap 6.6 software (R. Matson) was used to search for possible transits of any of these objects over the lunar disk. For the observations by DAP, no objects were found to transit the Moon. For the observations by IHS, one object (International ID: 92093Q) passed through the lunar disk center, but far from the flash, 30 s after the flash. However, the angular velocity of the object was $20''$ per half-frame, which implies that its glint would appear as an elongated image in each half-frame, and in a different position in each half-frame. This is markedly different to the appearance of the observed flash (Fig. 3), allowing the possibility that the flash was due to the glint of this object to be discarded. For the observations by MI, about 3 min before the flash, an object (ID: 76126AY) passed very close to the flash location with an angular velocity of $6''$ per half-frame. It is thus difficult to discard this object as the source of the flash by examining 2 successive half-frames, yet it is unlikely that the predicted time for this object's lunar transit has an uncertainty of more than 3 min, since its TLE was determined a few days prior. Thus, this object can also be safely rejected as the source of the flash.

2.4. Lightcurves

The signal level is linearly related to the brightness, and the gain was fixed in the video cameras used by IHS and DAP. The camera used by MI was set such that the gain changed automatically. A correction for the brightness derived from MI's observation was therefore applied based on the surface brightness of the lunar disk in the frames, which reveals that the gain at the time of the flash was 1.15 times the gain at the comparison star observation described below. The brightness of the flash was derived as follows:

(1) the total count was measured for the image of a comparison star, TYC1872-1976-1 in the Tycho-2 catalogue, that was in the field of view approximately 20 min before the flash. The V magnitude of the star is 9.50;
(2) the flux from the star in the wavelength range 400–800 nm, where the cameras were most sensitive, was calculated assuming 3900 K black-body radiation;
(3) the total count was measured for the flash in each video half-frame, and the total count ratio between the flash and the star was calculated;
(4) the flux from the flash was obtained as the flux from the star multiplied by this ratio.

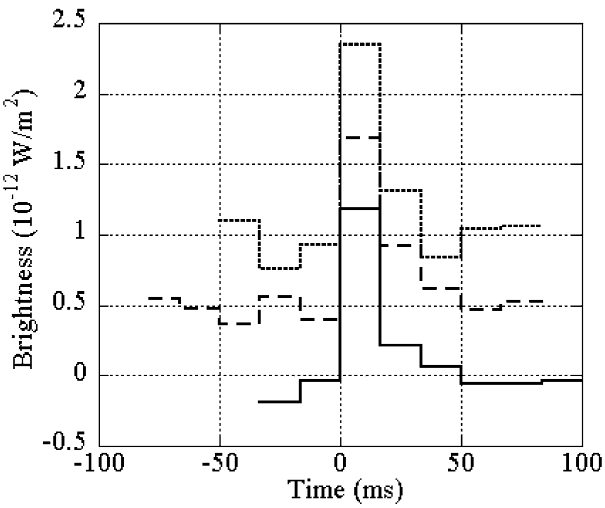

Fig. 5. Lightcurves of the flash derived from the observations by IHS (solid line), DAP (broken line), and MI (dotted line). Brightness is represented by the flux observed on Earth. The brightness is shifted by 0.5×10^{-12} and 1.0×10^{-12} W m^{-2} for the broken and dotted lines, respectively, to avoid overlap. Zero time corresponds to the beginning of the exposure of the video half-frame in which the flash first appeared.

The flux is defined as that in the wavelength range between 400 and 800 nm. The lightcurves thus derived are plotted in Fig. 5. The time-integrated flux over 2 or 3 half-frames, E_d, is 2.7×10^{-14} J m^{-2} based on an average of the 3 lightcurves.

It should be noted that the comparison star is also in the SAO Star Catalog (1966) as a K2-spectral-type star (SAO78012). Its B–V color index (1.38) calculated from the Tycho-2 data, however, corresponds to the index for the M0-type. It is therefore supposed that the overall spectrum of the star is similar to a black-body of 3900 K, corresponding to the surface temperature of an M0-type star.

This derivation contains 4 possible factors of uncertainty:

(a) signal processing in the video camera may not guarantee linearity between its output and brightness for a point source (flash or star);
(b) irreversible data coding in digital video recording may not guarantee a true reproduction of the image for a point source;
(c) the dark- and flat-field corrections commonly used in astronomical photometry were not applied;
(d) the spectral response of the cameras is not flat in the wavelength range between 400 and 800 nm. The sensitivity of the cameras at both ends of this band is about one half of that at 550 nm, and the cameras have some sensitivity at wavelengths outside of this range. The difference between the spectra for the flash and the comparison star will thus lead to some error in the calculated flux.

Due to the similarity in brightness of the flash and the comparison star, factors (a) and (b) above are not considered to be important. The overall error is thus estimated to be within a factor of 2.

3. Discussion

The agreement among the times and positions of the three groups of observations shows that the flash must have been a lunar phenomenon. The occurrence of the flash at the time that the Moon crossed the dust trail indicates that the event was an impact flash caused by a Perseid meteoroid. Lightcurves with very short rise time and afterglow in 1 or 2 half-frames are typical for Leonid flashes (Dunham et al., 2000; Ortiz et al., 2000, 2002; Yanagisawa and Kisaichi, 2002). Thus, it is concluded that an impact of a Perseid meteoroid at 59 km s^{-1} caused the flash.

The selenographic latitude and longitude of the flash calculated from the angular distance and position angle, taking lunar librations into account, were $48 \pm 1°$ N and $72 \pm 2°$ E. The impact angle of the Perseid meteoroid measured from the local lunar horizon was $34 \pm 2°$.

The maximum brightness derived from the total count ratio of the flash to the comparison star was found to be magnitude 9.5 for IHS and DAP, and 9.4 for MI. This is the dimmest impact flash ever documented. The time-integrated flux gives the optical energy on the Moon, assuming that it was radiated uniformly into 3π steradians. Based on the 3 observational groups, an average optical energy of 4.1×10^4 J was determined. The meteoroidal mass can then be estimated if the optical efficiency is known. Numerical simulations for impact of a cometary projectile with solid granite at 72 km s^{-1} afford an optical efficiency of (1–2) $\times 10^{-3}$ (Artemieva et al., 2000). Bellot Rubio et al. (2000a, 2000b), through comparison of a number of the 1999 Leonid lunar flashes with those of meteors observed on the ground, estimated the optical efficiency of lunar impacts to be 2×10^{-3} with an uncertainty of 1 order of magnitude. Although the optical efficiency could be different between the Leonid and Perseid lunar impact flash, it is adopted here as a nominal efficiency. The mass of the meteoroid was then calculated to be 12 g. This meteoroid would have appeared as a meteor of magnitude -6 if it had entered the terrestrial atmosphere, according to Eqs. (1) and (2) in Hughes (1987).

The diameter of the crater formed on the lunar surface can be estimated using Gault's formula for craters of less than 100 m in diameter formed in loose soil or regolith (see Melosh, 1989, p. 120). The parameters used in the calculation are the projectile density ($\rho_p = 0.5$ g cm^{-3}), the target density ($\rho_t = 1.6$ g cm^{-3}), the Perseid impact velocity (59 km s^{-1}), and the meteoroid mass and the impact angle obtained in this work. The diameter of the crater was calculated to be 2.0 m. It should be noted, however, that this value is nominal, since the result includes uncertainties in meteoroid mass, projectile density, and the applicability of the formula to a very low density projectile. The basic data for the flash, as well as the estimated quantities, are summarized in Table 2.

The meteoroids in the dust trail that encountered the Moon were ejected from the comet at 23 m s^{-1} (I. Sato, M. Sato; personal communication). It now remains necessary to examine whether meteoroids with a mass of 12 g can leave the cometary nucleus and be accelerated to 23 m s^{-1}. The major force that lifts particles from the cometary nucleus and accelerates them

Table 2
Basic data and some estimated values of the Perseid lunar impact flash

Time	$18^h28^m27^s$ on August 11, 2004 (UT, no light-time correction)
Position on the Moon:	Near Zeno crater
latitude	$48 \pm 1°$ N
longitude	$72 \pm 2°$ E
Peak brightness	About 9.5th in visual magnitude (on a video half-frame)
Duration	About 1/30 s
Impact velocity and angle	59 km/s, $34 \pm 2°$ from horizon
Energy per unit area received on Earth	2.7×10^{-14} J m^{-2} (±factor of 2) in 400–800 nm
Assuming optical efficiency of 0.002, etc.:	
Impact energy	2.1×10^7 J
Meteoroid mass	12 g
Crater formed by the impact	2.0 m in diameter (by Gault's formula)

to terminal velocity is the drag force due to gas outflow from the nucleus. Making the drag force and gravity equal, the maximum particle size, a_m, that can leave the nucleus is estimated as follows (modified from Eq. (72) in Gombosi et al., 1986, see also Keller, 1990)

$$a_m = \frac{9C_D Z u_{\text{out}}}{32\pi G\rho_d \rho_N R_N}, \tag{1}$$

where G is the gravitational constant. Using typical values for a comet at 1 AU, that is, a gas production rate of $Z = 3 \times 10^{-4}$ kg m^{-2} s^{-1} and an outflow velocity of $u_{\text{out}} = 100$ m s^{-1}, and assuming a drag coefficient of $C_D = 2$, densities of $\rho_d = \rho_N = 5 \times 10^2$ kg m^{-3} for the meteoroids and nucleus, and a nuclear radius of $R_N = 5$ km, this equation yields $a_m = 6$ cm, corresponding to a particle mass of 600 g. Thus, there appears to be no difficulty for a 12 g meteoroid to leave the nucleus.

The acceleration of particles in the inner coma of a comet due to gaseous outflow is a complicated problem (Gombosi et al., 1986; Grün and Jessberger, 1990). The outflowing gas absorbs solar radiation, and the solid particles also absorb solar radiation and heat up the gas. The gas velocity therefore depends on these 2 heating processes, precluding a simple expression for the terminal velocity of the particle. One of the results calculated for Comet 1P/Halley at 0.8 AU (Fig. 1 in Gombosi, 1986) shows that a 12 g particle would be accelerated to 24 m s^{-1}. Even a 120 g particle would have reached 17 m s^{-1}. Thus, no special mechanism would be needed to accelerate the present meteoroid to 23 m s^{-1}.

The peak activity of the 2004 Perseids on the Earth was reported to occur at 21:00 (UT) August 11, with a zenithal hourly rate (ZHR) of 190 (IMO homepage). The population index, r (ratio of the number of meteors of magnitude $M + 1$ or less to that of magnitude M or less) for that activity has not been reported. The typical value for Perseids is therefore assumed: $r = 2.0$ (Brown and Rendtel, 1996). According to the formulae for deriving the spatial number density in a meteoric stream from the ZHR and r (e.g., Brown and Rendtel, 1996), the flux of Perseid particles capable of meteoric phenomena of magnitude less than 6.5 is calculated to be 3.8×10^{-2} km^{-2} h^{-1} at the Earth. The closest approach distance between the trail and the Moon was 5.9×10^4 km, while that between the trail and the Earth was 1.9×10^5 km (M. Sato; personal communication). It was therefore arbitrarily assumed that the flux at the Moon, $F_{6.5}$, would be 3 times the flux at the Earth. The expected number of lunar flashes brighter than the one observed, N, is then estimated according to the formula presented by Bellot Rubio et al. (2000a, 2000b)

$$N = F_{6.5}\Delta t \left(\frac{2f\pi R^2}{\eta m_0 V^2} E_d\right)^{1-s} A, \tag{2}$$

where Δt is the duration of meteoric activity or observation, η is the optical efficiency, m_0 is the mass of Perseids corresponding to meteoric phenomena of magnitude 6.5, V is the impact velocity, E_d is the time-integrated optical energy flux of the flash observed on Earth, and A is the projected area of the observed lunar surface perpendicular to the Perseids stream. The optical energy is radiated into $f\pi$ steradians on the lunar surface, and received on Earth at a distance of R. The differential mass index, s, is related to the population index, r, as follows:

$$s = 1 + 2.5\log(r). \tag{3}$$

In Eq. (2), $\Delta t = 1$ h, $f = 3$, $R = 4.0 \times 10^5$ km, and $V = 59$ km s^{-1}. From Eqs. (1) and (2) in Hughes (1987), m_0 was calculated to be 5.0×10^{-8} kg, and as derived above, E_d equals 2.7×10^{-14} J m^{-2}. Based on the IHS observation, a value of 5.4×10^5 km^2 was adopted for A.

The estimated number of flashes given $r = 2.0$ and $\eta = 2 \times 10^{-3}$ is 6. As this value does not agree with the observations, the value of η was recalculated such that $N = 1$ with all other parameters fixed. The recalculated value, $\eta = 2.1 \times 10^{-4}$ is the lower limit of the optical efficiency obtained by Bellot Rubio et al. (2000a, 2000b) based on the statistical analysis of the Leonid lunar impact flashes.

A population index of 2.4 ($s = 2.0$) with the other parameters fixed was also found to give $N = 1$. The index obtained from Perseid meteoric observations varies between 1.8 and 2.4, with an average of 2.0 (Brown and Rendtel, 1996). The present observations may suggest that the index is larger for meteoroids having a mass greater than 1 g than for meteoroids having a mass much smaller than 1 g.

The maximum meteoroidal mass that could be accelerated to 23 m s^{-1} may therefore be close to the mass of the meteoroid that caused the flash. Fluctuation or spatial anisotropy of the flux and velocity of the gaseous outflow would prevent large meteoroids from reaching this velocity. The number of meteoroids of this velocity would therefore decrease steeply with increasing mass. This may explain the large population index for larger meteoroids.

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