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# Detection of sporadic impact flashes on the Moon: Implications for the luminous efficiency of hypervelocity impacts and derived terrestrial impact rates

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## Abstract

We present the first redundant detection of sporadic impact flashes on the Moon from a systematic survey performed between 2001 and 2004. Our wide-field lunar monitoring allows us to estimate the impact rate of large meteoroids on the Moon as a function of the luminous energy received on Earth. It also shows that some historical well-documented mysterious lunar events fit in a clear impact context. Using these data and traditional values of the luminous efficiency for this kind of event we obtain that the impact rate on Earth of large meteoroids (0.1–10 m) would be at least one order of magnitude larger than currently thought. This discrepancy indicates that the luminous efficiency of the hypervelocity impacts is higher than $10^{-2}$, much larger than the common belief, or the latest impact fluxes are somewhat too low, or, most likely, a combination of both. Our nominal analysis implies that on Earth, collisions of bodies with masses larger than 1 kg can be as frequent as 80,000 per year and blasts larger than 15-kton could be as frequent as one per year, but this is highly dependent on the exact choice of the luminous efficiency value. As a direct application of our results, we expect that the impact flash of the SMART-1 spacecraft should be detectable from Earth with medium-sized telescopes.

*Keywords:* Impact processes; Moon; Collisional physics; Cratering

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## 1. Introduction

Several techniques have been used in the past to estimate the flux of incoming bodies to the Earth. Each technique is suitable to a size range of the impactors and no single technique is valid for the whole range of sizes. Therefore, results from different techniques have to be linked. The flux of large meteoroids (in the 0.1–1 m diameter range) has traditionally been estimated from the records of fireballs detected by all-sky camera networks (e.g., Ceplecha, 1988; Halliday et al., 1996), whereas the flux of larger meteoroidal bodies (with diameters between 1–10 m) has recently been determined from a combination of military satellite and infrasound data (Brown et al., 2002). On the other hand, the flux of asteroidal bodies larger than 10 m has been inferred from forward orbital integrations of the discovered near-Earth objects by different telescopic surveys. A time-averaged flux can also be inferred from the counts of lunar craters using scaling laws to relate crater size to impactor diam-

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eter. Crater counting techniques can also be applied to the Earth in order to derive rates of impacts of large bodies, but erosion and plate tectonics make this analysis difficult. All these techniques have large uncertainties and possible systematic biases, which are difficult to evaluate and compare. The development of new techniques to compute impact fluxes is therefore convenient in order to have a good estimate of the impact rates of meteoroids in our planet. Recently, a new technique to evaluate impact rates of large meteoroids has been proposed and attempted (Ortiz et al., 1999). The idea is to monitor the night side of the Moon for impact flashes using CCD detectors attached to small telescopes. This technique has the advantage that the area covered by just one single instrument is much larger than the area covered even with detector networks on Earth. The use of CCD detectors is also an advantage compared to the use of photomultipliers, as proposed by Melosh et al. (1993), because the background at each pixel is small enough so that the threshold for flash detection is much smaller than using a photomultiplier. Impact flashes on the Moon using the CCD technique have been unambiguously detected during meteor showers, like the 1999 Leonid meteor storm (Dunham et al., 1999; Ortiz et al., 2000; Yanagisawa and Kisaichi, 2002), the 2001 Leonids (Cudnik et al., 2002; Ortiz et al., 2002), the 2004 Perseids (Yanagisawa et al., 2006), the 2004 Leonids (Ortiz et al., 2005), the 2005 Perseids (Ortiz et al., in preparation) and possibly the 2005 Taurids (Cooke et al., 2006). After the successful lunar monitoring experience of the 1999 and 2001 Leonids, a systematic search for sporadic impact flashes was conducted by our team. Here we present the first results of such a survey and some consequences that can be drawn from the data.

## 2. Observations and reductions

Two specific instrumental setups were used for our lunar impact flash survey, located at Sierra Nevada and Huétor-Santillán Observatories in Granada, Spain. The Sierra Nevada instrumental setup consisted of two identical 0.36 m Schmidt–Cassegrain telescopes equipped with high sensitivity CCD PAL video cameras and VHS tape recorders. This pair of telescopes was designed to image the same area of the Moon. We considered that a flash was real when it was recorded by both instruments. Cosmic rays and electronic as well as video tape noise can occasionally be mistaken with impact flashes; therefore, redundancy checks were done. Thus, if an intensity spike was detected simultaneously in two telescopes at the same lunar coordinates, the flash was considered a real impact event. The lunar area covered by this instrumental setup was $2.1 \times 10^6$ km$^2$ ± 3%. The Huétor-Santillán instrumental setup was identical to that in Sierra Nevada except that the telescopes were a 0.2 m Schmidt–Cassegrain telescope and a 0.4 m Newtonian telescope with focal lengths adjusted so that both telescopes had a very similar field of view. The lunar area covered redundantly by this setup was $5.8 \times 10^6$ km$^2$ ± 10%.

Here we report the results of 34 nights of observations started in late 2001 and carried out mostly during 2002, 2003 and 2004. The observations were restricted to periods with lunar phases ranging from 10 to 40% so that a large area of the night side of the Moon was visible without too much glare from the dayside part. The observing log with details on the dates and total time observed is shown in Table 1. The total number of effective hours of observation was 24 and 39 h with the Sierra Nevada and Huétor-Santillán setups, respectively. We have developed a specific computer code that digitizes and analyzes the stream of 25 images per second (from the video tapes) in real-time. Basically the code searches for intensity spikes in residual images obtained by subtracting the average of 3 previous images from the one being analyzed. The spikes detected are later compared with the spikes detected in the second videotape from the redundant telescope. This last step is done by visual inspection of the images containing the spikes.

From the analysis of the Sierra Nevada data, one impact flash was detected in the effective 24 h of observations. The impact flash as recorded by the two telescopes is shown in Fig. 1. The analysis of the Huétor-Santillán data, with longer observing time and larger lunar coverage, yielded two impact flashes. One of the Huétor-Santillán flashes is also shown in Fig. 1 to illustrate the different image scales. The relevant data concerning all three flashes are shown in Table 2.

The absolute calibration to standard astronomical magnitude was carried out by referring the total data counts from the impact to the best fit for 2004 Earthshine surface brightness mea-

Table 1
List of observing campaigns

| Date | Observatory | Recording time |
|---|---|---|
| 19/02/02 | Huétor S. | 1 h 30 m |
| 10/11/02 | Huétor S. | 3 h |
| 06/03/03 | Huétor S. | 2 h |
| 05/02/03 | Huétor S. | 2 h 30 m |
| 13/09/02 | Huétor S. | 2 h |
| 16/04/02 | Huétor S. | 2 h |
| 13/08/02 | Huétor S. | 2 h |
| 19/04/02 | Huétor S. | 3 h |
| 25/04/04 | Sierra Nevada | 3 h |
| 24/04/04 | Sierra Nevada | 3 h |
| 01/09/03 | Huétor S. | 1 h 30 m |
| 01/12/02 | Sierra Nevada | 1 h |
| 02/06/03 | Huétor S. | 30 m |
| 02/07/03 | Huétor S. | 1 h |
| 02/09/03 | Huétor S. | 2 h |
| 03/06/03 | Huétor S. | 1 h 30 m |
| 03/07/03 | Sierra Nevada | 2 h |
| 04/04/03 | Huétor S. | 1 h 30 m |
| 04/07/03 | Sierra Nevada | 1 h |
| 05/02/03 | Sierra Nevada | 2 h 30 m |
| 06/02/03 | Sierra Nevada | 3 h |
| 06/03/03 | Sierra Nevada | 30 m |
| 06/04/03 | Sierra Nevada | 3 h |
| 07/12/02 | Sierra Nevada | 2 h |
| 09/03/03 | Huétor S. | 2 h 30 m |
| 09/10/02 | Huétor S. | 30 m |
| 12/10/02 | Huétor S. | 2 h 30 m |
| 12/10/02 | Sierra Nevada | 3 h |
| 25/10/04 | Huétor S. | 1 h 30 m |
| 26/12/03 | Huétor S. | 1 h |
| 29/12/03 | Huétor S. | 1 h |
| 30/08/03 | Huétor S. | 1 h |
| 18/11/01 | Huétor S. | 1 h 30 m |
| 19/11/01 | Huétor S. | 2 h 30 m |

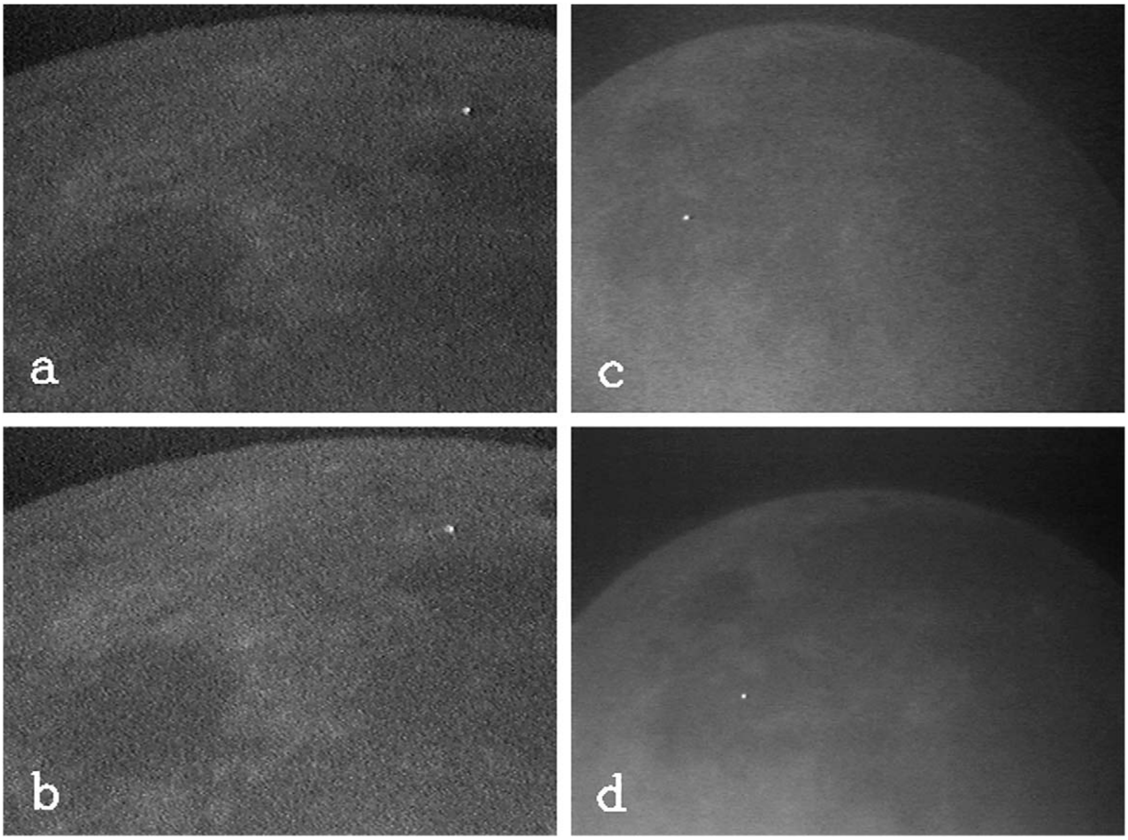


Fig. 1. (a) Impact flash detected from one of the telescopes at Sierra Nevada on February 5th, 2003. (b) The same impact flash as (a) but seen from the second telescope at Sierra Nevada. (c) Impact flash from one of the telescopes at Huetor-Santillán on December 26th, 2003. (d) The same impact flash as (c) but seen from the second telescope at Huetor-Santillán. The Lunar area covered by the Sierra Nevada and Huetor-Santillán setups is $2.1 \times 10^6$ km$^2 \pm 3\%$ and $5.8 \times 10^6$ km$^2 \pm 10\%$, respectively.

Table 2
Characteristics of the impact flashes detected

| Date (UTC) | Selenographic coordinates | | Integration time (s) | *V* magnitude |
|---|---|---|---|---|
| | Longitude (°) | Latitude (°) | | |
| 05 Feb 2003 19:24:43 ± 3 | 61 ± 1.0 W | 11.1 ± 0.4 S | 0.04 | 8.32 ± 0.18 |
| 26 Dec 2003 17:36:38 ± 3 | 19.4 ± 0.8 W | 14.8 ± 0.7 N | 0.04 | 7.09 ± 0.25 |
| 19 Feb 2002 19:40:04 ± 3 | 15 ± 2 W | 20 ± 2 S | 0.04 | 7.58 ± 0.40 |

surements. The Earthshine Project accomplishes these continuous observations for five Earthshine regions (Qiu et al., 2003; Pallé et al., 2003). We did this rather than using standard star calibrations in order to ensure that a possible change in the gain setting of the cameras would not affect the results. This method also avoided problems with extinction corrections, which were not needed in our Earthshine calibration scheme (because the calibration source was always at the same air-mass as the impact flash).

## 3. Results and discussion

Our impact flashes correspond to sporadic events because no major meteor showers were active or exhibit favorable impact geometry on the impact dates. Other minor streams were also discarded by checking the activity periods and impact geometry for particles associated with minor streams lists (Cook, 1973; Terentjeva, 1990; Jenniskens, 1994). Artificial satellites are also easily discarded because they leave elongated brightening streaks.

The luminous energy released in the impact events can be computed using the known luminous flux received on Earth after correcting for the Earth–Moon distance. The initial kinetic energy of the meteoroid has been computed in previous impact flash works by means of the luminous efficiency concept, which is the fraction of the kinetic energy that is emitted in the visible. We have followed the same formalism and equations as in Bellot Rubio et al. (2000), and Ortiz et al. (2002) to derive the kinetic energy. This kinetic energy can be translated into impactor mass assuming a typical sporadic impactor speed. According to the statistics of a large meteoroid orbit database (Steel, 1996) this speed is approximately 20.2 km/s on Earth and 16.9 km/s on the Moon, after correcting for the different escape velocities of the Earth and the Moon. The value for the

Moon is close to the 16.1 km/s average obtained by Ivanov (2001).

Using the luminous efficiency $\eta = 0.002$ (the nominal value determined from Leonid impact flashes, e.g., Bellot Rubio et al., 2000; Ortiz et al., 2002) the masses of the impactors would be $1.9 \pm^{3.0}_{0.9}$ kg for the Sierra Nevada detection and $5.9 \pm^{9.0}_{3.0}$ kg and $3.7 \pm^{5.0}_{1.8}$ kg for the Huétor-Santillán detections. The uncertainties in the masses arise from the uncertainties in the velocity and absolute calibration. We have used a 5-km/s uncertainty for the impact speed (which is close to the standard deviation of the lunar impact velocity distribution by Ivanov, 2001), but the distribution is not Gaussian and it may well happen that the impact speed of the particular events that we observed were much higher or lower than the average. Therefore, the masses calculated here are just estimates. However, the kinetic energy is well determined and is only affected by the luminous efficiency adopted. The luminous efficiency $\eta = 0.002$ is already a very optimistically high value according to numerical models (Nemtchinov et al., 1998; Melosh et al., 1993) or based on hypervelocity impact flash experiments (Ernst and Schultz, 2005; Kadono and Fujiwara, 1996; Eichhorn, 1975). Besides, the 0.002 value was derived from 71 km/s impacts, whereas at 16 km/s, a much smaller luminous efficiency would be expected.

The lunar impact rates as a function of energy can be translated into terrestrial impact rates by scaling them to the appropriate terrestrial surface area and using a 1.3 gravitational focusing factor. A small correcting factor for the kinetic energy has to be applied to the terrestrial case, because the larger Earth's gravity causes a larger impact speed on Earth as compared to the lunar case. This factor is assumed to be 1.4, based on the statistics of impact speeds on Earth and the Moon. The exact correction factor depends weakly on the actual impact speed of the meteoroid. It is useful to express the energy in kilotons in order to compare with previous works in the field (note that 1 kton is $4.185 \times 10^{12}$ J). We use energy rather than mass because expressing the impact rate as a function of mass would require a correct choice of each meteoroid's impact speed, whereas if the impact rate is expressed as a function of kinetic energy, no critical assumption is made. In other words, the calculation of masses is only done for illustrative reasons. The fluxes are shown in Figs. 2a and 2b for two different luminous efficiencies (0.002 and 0.006, respectively). In Figs. 2a and 2b we plot the results along with Brown et al. (2002) impact hazard fit and other data as explained below.

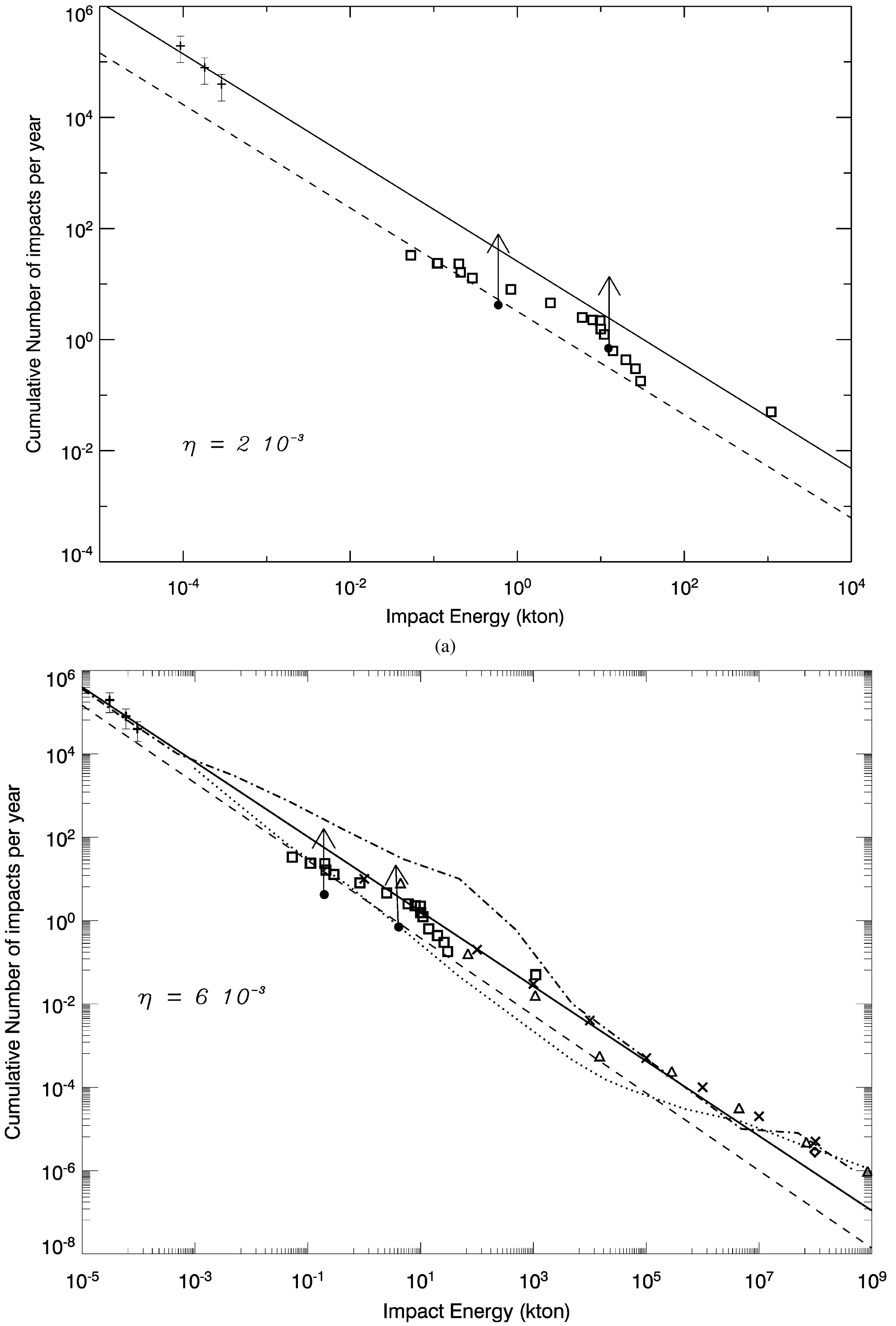
We have added to our analysis what we consider two other candidates to lunar impact flash data. One is the lunar flash recorded serendipitously on film in 1953 (Stuart, 1956). Although it may be argued that the duration of that flash seems too long for an impact into a body without atmosphere, recent works (Ortiz et al., 2002; Yanagisawa and Kisaichi, 2002) have shown light curves of lunar impacts that lasted in the order of 1 s. Therefore the 1–8 s duration reported by Stuart is compatible with the phenomenology observed in some impacts (Ortiz et al., 2002; Yanagisawa and Kisaichi, 2002).

Taking into account the Earth's larger area (a factor of ∼27 times that of the lunar area visible from Earth) and Earth's gravitational focusing factor (1.3), the rate of impacts on Earth should be ∼35 times that of the Moon. Therefore the rate of impacts with similar energy to the Stuart event should be at least 35 × (1/52) per year on Earth because 52 years have elapsed since the Stuart event. This value is a lower limit because the Moon has not been continuously imaged during these years. Therefore the value of the flux that we get on Earth (for ∼10 kton blasts, assuming a 0.002 luminous efficiency) is a very conservative lower limit. The terrestrial rate of impacts with similar energy to the 1953 event on the Moon is shown in Figs. 2a and 2b. In these two figures, two different luminous efficiencies have been used as indicated in the plots (0.002 and 0.006, respectively).

Another candidate to lunar impact data is the flash recorded serendipitously on film in 1985 by Kolovos et al. (1988), although the preferred explanation by the authors at the time was an out-gassing event and subsequent flash triggered by a piezoelectric phenomenon. Other investigators claimed that this flash might have been related to the passage of artificial satellites (Maley, 1991; Rast, 1991) but Kolovos et al. (1992) clearly demonstrated that the image features were inconsistent with satellite passage. Here we have calculated the energy released using Kolovos et al.'s calibration and relate it to impactor mass (assuming the same luminous efficiency as before). Using a similar reasoning as with the Stuart flash, a lower limit to the flux of ∼1 kton blasts on Earth can be derived. In this case one has to take into account the fact that this flash would not have been detected photographically if it had hit the sunlit portion of the Moon, because its brightness was smaller than the surface brightness of the sunlit side of the Moon. The effective area of the Moon for the observation of Kolovos-like events is a factor 2 smaller than for the observation of Stuart-like events. This is because the total lunar night area that is observable on average per lunation is half the lunar semisphere area. Therefore, the impact rate of Kolovos-like events on Earth would be 2 × 35 × (1/20) per year, where 20 is the number of years elapsed since 1985. The lower limit on the terrestrial impact rate based on the 1985 flash is shown in Figs. 2a and 2b for $\eta = 0.002$ and $\eta = 0.006$, respectively.

Assuming that the terrestrial cratering rate for impactors with diameters larger than 1 km (Grieve and Shoemaker, 1994) is valid (actually this rate is consistent with the lunar cratering rate for impactors of the same size range Werner et al., 2002), we have estimated the influx at intermediate sizes by fitting a power law to the data (Fig. 2a). The impacts of objects larger than 1-km is equivalent to blasts larger than ∼100,000 Mton (assuming typical asteroid density and impact speed of $2700\ \mathrm{kg/m^3}$ and 20.2 km/s, respectively). The resulting impact fluxes from the fit are at least 1 order of magnitude higher than those from an equivalent fit to the latest results on terrestrial impact rates by Brown et al. (2002). This discrepancy indicates that something must be revised, like perhaps the luminous efficiency.

Therefore we have tested the use of a much larger luminous efficiency ($\eta = 0.02$). In this case, the masses of the impactors would be $0.19 \pm^{0.30}_{0.09}$ kg for the Sierra Nevada detection and $0.59 \pm^{0.90}_{0.30}$ and $0.37 \pm^{0.50}_{0.18}$ kg for the Huétor-Santillán detec-



(a)

(b)

Fig. 2. (a) Cumulative impact rates on Earth as a function of the kinetic energy of the impactors. Minus symbols denote the results from our survey for a luminous efficiency of $2 \times 10^{-3}$ and filled circles correspond to unexplained phenomena on the Moon (Stuart, 1956; Kolovos et al., 1988) that we interpret here as impact flashes (using the same luminous efficiency of $2 \times 10^{-3}$). The impact rates from the unexplained lunar events are only lower limits and this is indicated by the arrows, whose length is arbitrary. Solid line: best fit to the lunar impact flash data and the impact rate of objects larger than 1 km by Grieve and Shoemaker (1994). Dashed line: best impact hazard fit from Brown et al. (2002). Squares: Revelle (2001) data. See the text for a description of each data set. (b) Comparison of different estimates of impact rates on Earth from different authors. Minus symbols: Impact fluxes from our systematic survey using a luminous efficiency of $6 \times 10^{-3}$. Filled circles: Impact rates from the Stuart (1956) and Kolovos et al. (1988) events interpreted here as impact flashes with a luminous efficiency of $6 \times 10^{-3}$. These two impact rates from the unexplained lunar events are lower limits and this is indicated by the arrows, whose length is arbitrary. Thick solid line: our preferred fit. Dotted dashed line: Ceplecha (1996) data. Squares: Revelle (2001) data. Dotted line: fluxes from the lunar cratering rate (Ivanov et al., 2003) scaled to match the 1-km impactor rate. Diamond: Impact rate for objects greater than 1 km from Grieve and Shoemaker (1994). Crosses: Shoemaker (1983) fluxes. Dashed line: best impact hazard fit from Brown et al. (2002). Triangles: data from Rabinowitz et al. (2000) scaled to match the 1-km impact rate. See the text for a description of each data set.

tions. Also the masses of the 1953 and 1985 impactors are considerably reduced. Using this value for the luminous efficiency the large discrepancy between our values of the terrestrial impact rates and those from Brown et al. (2002) is removed. The main difficulty here is the fact that $\eta = 0.02$ for sporadics, at 16.9 km/s, would imply at least $\eta = 0.06$ for the lunar Leonids (using a linear dependence of the luminous efficiency with speed, see the last paragraph of the discussion) but this is much larger than the maximum value compatible with the lunar Leonids in 1999 and 2001 as reported by Bellot Rubio et al. (2000) and Ortiz et al. (2002). Also, a recent work (Yanagisawa et al., 2006) on the detection of a Perseid lunar impact flash in 2004 seems to be incompatible with a 0.02 luminous efficiency, as the size distribution of the Perseids would be very different to what is obtained from meteor observations on Earth.

Thus, if we consider that lunar impact flashes have a 0.02 luminous efficiency, the frequency of sporadic impact flashes is entirely consistent with Brown et al. (2002), but $\eta = 0.02$ is not consistent with previous works on luminous efficiency and Brown et al. data is not consistent with other data sets like those of Ceplecha (1996) and other data discussed below. The most likely explanation to the discrepancies between our results and those from Brown et al. (2002) is that both the luminous efficiency and the impact hazard may be larger than assumed. In fact, a different analysis of satellite data (Nemtchinov et al., 1997) shows a larger terrestrial impact rate, very similar to that of Shoemaker (1983). The impact rates of large bolides from infrasound measurements (Revelle, 2001), plotted in Figs. 2a and 2b are clearly above Brown et al.'s. Also, Revelle (2001) cautions that the infrasound technique is only sensitive to deeply penetrating bodies and therefore would miss a fraction of the impactors. Results from terrestrial impact flashes detected by military satellites in the infrared are unavailable and were not published by Brown et al. (2002), who dealt with visible data only. We have found an indirect citation in the literature for a rough estimate of an 80 kton blast per year (Beatty, 1994) from infrared detectors. Such a frequency is even above our initial estimates, but there is no detailed account of the observations or the calibration system in that paper. Tagliaferri et al. (1994) mention that "because of the scanning nature of the infrared sensors and the manner in which the satellite data were collected, the true number of events was at least 10 times what we report here. The objects observed exhibited energies of approximately 10 kton equivalent down to a 1 kton; therefore our observations indicate a much higher rate of impact of objects in this size range than indicated in Shoemaker (1983)" and this referred to the period of time from 1975 to 1992 for which they reported 136 impacts. Therefore, the flux would be much higher than that by Brown et al. (2002).

The Neat and Spacewatch dataset (Rabinowitz et al., 2000) is the only asteroid survey dealing with small-size bodies (some of them in the 10-m size range), although it does not provide a direct estimate of the impact rate. Despite this, the size distribution from that data set can be used to derive impact rates as a function of energy by using the impact rate of 1-km bodies to scale the data. In order to translate the Rabinowitz et al. (2000) absolute magnitude ($H$) distribution to kinetic energy distribution one has to assume an average albedo, an average density and an average impact speed (we have used values of 0.12, 2700 $\mathrm{kg/m^3}$ and 20 km/s, respectively). After this is done, the impact rate obtained is larger as well (see Fig. 2b). It must be noted that the cometary contribution to the impact rate, supposed to be between 10 and 30% of the total (e.g., Shoemaker, 1983) is not included in the asteroid survey data. By using the lunar impact flash and the infrasound and Neat and Spacewatch data in the smaller size end we get our best estimate for a luminous efficiency of 0.006 (Fig. 2b) which implies a very small crater for the 1953 event, much smaller than what was estimated by Buratti and Johnson (2003), who used a smaller luminous efficiency. A value of 0.006 for the lunar sporadics implies a value of nearly 0.02 for the Leonids (if a linear dependence of luminous efficiency with speed is assumed) and this is within the error bars of the luminous efficiency reported from the Leonids in 1999 and 2001. Overplotted in Fig. 2b are Ceplecha (1996) influx values (obtained from a compilation of a variety of techniques), and translated into impact rates as a function of energy by using the average 20.2 km/s impact speed on Earth. These results are considerably higher in the 1–10 m size range, but are in agreement in the lower energy range. Also plotted in this figure is the Ivanov et al. (2003) impactors' relative size distribution translated into energy distribution and scaled to match the 1-km impact rate adopted here. The size distribution is translated into energy distribution by using an average impact speed of 20.2 km/s and average density of 2700 $\mathrm{kg/m^3}$. The Ivanov et al. (2003) data are derived from the crater size distribution on the Moon. Our best estimate implies that objects with masses larger than 1 kg impact at least 80,000 times per year on Earth, and blasts larger than 15 kton could be more frequent than 1 per year.

## 4. Conclusions and implications

In summary, as expected, our terrestrial impact flux estimates based on sporadic flashes on the Moon are highly dependent on the luminous efficiency used. A value of 0.02 would provide results consistent with the terrestrial impact flashes by Brown et al. (2002) but incompatible with the upper limit from previous Leonid impact flashes (which took place at much higher speed), and orders of magnitude higher than what is derived from laboratory experiments and numerical models. Besides, a recent work (Yanagisawa et al., 2006) on the detection and analysis of a Perseid lunar impact flash seems to be inconsistent with a 0.02 luminous efficiency because the size distribution of the Perseid stream would have to be too steep. For those reasons we suggest that the latest impact hazard estimates may be somewhat too low. We have found that our best fit requires an enhancement of at least a factor 2 in the terrestrial impact rate.

A continuous lunar impact flash monitoring and subsequent cross-calibrations of the luminous efficiency against well-known meteoroid showers other than the Leonids may allow a more accurate sporadic impact flux evaluation in the future (because the meteor showers are essentially monovelocity and permit a good determination of the luminous efficiency at the shower speed). Also, the exact magnitude of the flash from the hypervelocity impact of the 290 kg ESA SMART-1 spacecraft on the Moon, scheduled for September 2006, may provide an additional opportunity to derive luminous efficiency constraints under well-known velocity and geometry conditions. This could perhaps be an adequate proxy for the lunar sporadic impact case, although the 2 km/s spacecraft speed would require some scaling compared to the sporadic impact speed. There are different estimates of the effect of impactor speed ($v$) on the luminous efficiency. A $v^3$ dependence of the total intensity (as shown by Ernst and Schultz, 2004) implies a linear dependence of the luminous efficiency with speed. This is because the luminous efficiency is the ratio of the total emitted luminous energy (proportional to $v^3$) to the kinetic energy (proportional to $v^2$). Therefore, the result of the division is a linear dependence on $v$. Our own fit to the data from Fig. 3b of another experimental work at higher speeds (Eichhorn, 1976) indicates that the luminous efficiency has a $v^{1.2}$ dependence. Our nominal estimate of the SMART-1 impact flash visual magnitude is in the range of 7.7–8.9 (in the most optimistic and pesimistic cases, respectively), well within the reach of a large number of telescopes. Spectroscopic observations would also be feasible by large telescopes. These estimates are made for 0.04 s flashes, which is the typical duration of most lunar flashes recorded so far, but some flashes from meteoroid streams lasted more than 10 times longer than that (Yanagisawa et al., 2006; Ortiz et al., 2002). In the event that the SMART-1 spacecraft caused a long duration flash, the peak brightness of the flash would be decreased, making it harder to detect. In this scenario, a 0.4 s flash would result in an integrated visual magnitude of 10.2–12.4, which would be difficult to observe within a typical $\sim$10 mag/arcsec$^2$ background (caused by the glare of the bright sunlit part of the Moon). At the lightcurve maximum the magnitude would lie somewhere in the middle of the values stated above (from 9 to 10.5). Thus, the flash would be more easily detectable at peak brightness and this requires the use of fast imaging cameras. In any scenario, the use of fast imaging devices is important to record this kind of event.

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