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LETTER

Letter to the Editor

A search for meteoritic flashes on the Moon

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Abstract. We present the first results of a search for bright flashes associated to impacts of meteoroids on the surface of the night side of the Moon. We have analysed 13 sets of images of a (2.9±0.3) 10^6-km^2-wide area on the Moon's night side, totaling 4.3 h of observations. No impact events radiating an amount of energy higher than 5×10^6 J have been detected. Five fainter events (E $< 2.5 \times 10^6$ J) have been detected, but they are not confidently identified as impact-related, and might be due to experimental problems. This rate of events would imply an influx of 4800 $\pm$ 500 meteoroids per day onto the Earth, with meteoroid masses of uncertain value, but larger than 0.01 kg. The direct CCD imaging technique that we have used is a potential new tool to asses the population of those meteoroids in the vicinity of the Earth whose masses and velocities are such that the radiated energy upon impact is higher than 5×10^6 J, our threshold for 100% confident detection. The technique can be improved substantially to detect fainter impacts and might provide unique data for the 1999 Leonid meteor shower.

Key words: Moon – solar system: general – meteors, meteoroids

1. Introduction

The physics of meteoritic impacts on the Moon can be considerably different from that of meteors on Earth. This kind of high velocity impacts could have higher luminous efficiency than those on Earth. For violent explosions, the luminous efficiency is higher than what is typical of Earth bolides of the same yield (Nemtchinov et al. 1997). The direct meteoroid impact on the surface of the Moon might be optically detectable from the Earth. A simple order of magnitude estimate for the energy radiated by a 1-kg meteoroid impacting with an average velocity of 20 km s^{-1} (Grün et al. 1985) would be 2×10^7 J (10% luminous efficiency and isotropic radiation). If the energy were radiated in one second of time, the flux at Earth would be 2×10^{-11} W m^{-2}. Such an event would be observable on the night-side of the Moon with current CCD technology and small-sized telescopes.

There are well-documented observations of sudden brightenings on the surface of the Moon (e.g. Cameron 1972; Kolovos et al. 1988). These events, referred to as Lunar transient phenomena could, at least in part, be due to large meteoroid impacts. Hence, we decided to observe the Moon in order to search and count impact events of different energy. Based on our experience gained in the collision of comet Shoemaker-Levy 9 with Jupiter, in which visible radiation from impacting particulates could be observed from the ground despite the large intensity contrast compared to Jupiter itself (e.g. Ortiz et al. 1997; Fitzsimmons et al. 1995; Schleicher et al. 1994), we thought that similar imaging techniques and reduction procedures could be succesfully used to look for impacts on the night side of the Moon.

The rate of infall of solid bodies onto the Earth has been measured in the past in many distinct ways, depending on the size range of the impactors (e.g. Love and Brownlee 1993; Rabinowitz 1993; Ceplecha 1992; Shoemaker et al. 1990; Grün et al. 1985). The technique that we propose here represents another means to derive the current population of large meteoroids in the neighbourhood of Earth and could be used to test models of this population.

2. Observations

The observations were carried out at the Instituto de Astrofísica de Andalucía (Granada, Spain), by means of a newtonian f/6 0.25-m telescope equipped with a 512 $\times$ 256 16-bit Peltier-cooled CCD, based on a Sony ICX027BLA-6 chip. The telescope drives were adjusted to compensate for Lunar drift with respect to the stars. The sets of data were obtained in the dates listed in Table 1. The observations consisted in series of short CCD exposures (5 or 10 sec) of an area on the night side of the Moon, when the Moon's phase was small (see Table 1) in order not to have a strong background caused by the day side of the Moon. The region observed in each run was not always the same, but the total surface area was practically the same in all of them ($\sim 2.9 \times 10^6$ km^2). The images were taken as frequently as possible, but they were separated by uneven intervals

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Table 1. Log of the observations.

UT Date	No Frames	Integ. Time	Lunar Phase	Seeing (arcsec)	5-σ events
24/Oct/97	106	5 s	33%	2–4	0
02/Dec/97	69	10 s	9%	3–5	0
06/Dec/97	430	5 s	47%	3–5	1
24/Dec/97	48	5 s	22%	4–6	0
02/Mar/98	264	10 s	25%	2–4	0
01/Apr/98	99	5 s	31%	3–5	0
28/Jun/98	45	10 s	25%	3–5	0
29/Jun/98	123	5 s	33%	3–5	0
29/Jul/98	128	5 s	36%	3–5	0
27/Aug/98	73	10 s	28%	3–5	0
15/Sep/98	289	10 s	28%	2–4	1
16/Sep/98	249	10 s	19%	2–4	2
15/Oct/98	212	5 s	23%	2–4	1

of no less than some tens of seconds, because of the readout and disk-saving time.

Saturation of the CCD was not a concern since we placed the bright day side of the Moon away from the CCD chip. The noise in our images is overwhelmingly dominated by photon noise from the high background, therefore, dark current noise was negligible (it typically amounted less than 1% of the total noise).

We used integrations of 5 and 10 seconds because they were the highest possible without reaching nonlinearity on the CCD. Ideally, we would have chosen 1-sec integrations (in the assumption that the meteoritic flashes are of very short duration), but if we had done so the amount of observing time compared to the amount of time spent reading the CCD out and saving the files would have been too small. Thus, the best compromise was to use 5 to 10 seconds.

The telescope pixel scale as well as the factor relating ADUs per second to W m^{-2} were derived by means of observations of standard stars. These parameters were 1.72 ± 0.02 arcsec/pixel and 1.85×10^{-16} W m^{-2} per ADU s^{-1}. For the absolute calibration factor, we observed several stars at high and similar airmasses as the Moon. This calibration factor is valid only for airmass $\simeq$3. It decreased as airmass increased due to atmospheric extinction. An estimated fractional error for this calibration factor is 30%.

3. Reductions

The basic idea of the search for flashes in each set of data is to use one image of the Moon as a reference and to subtract it from the next image of the time sequence. The resulting image should be essentially noise except for the bright pixels where an impact ocurred. Then, the idea would be to look for those pixels whose brightness exceeded 5 times the standard deviation of the noise. However, in practice, the procedure to look for flashes is far more complicated than that because of small image motion caused by seeing, wind or tracking problems, because of field stars, cosmic ray hits, hot pixels, and because of changes in atmospheric conditions which cause changes in the background and in the point spread function.

We proceeded, in essence, as follows: 1) Use the first image of the Moon as a reference image. 2) Select a small region of the image. 3) Search for the shift that gives the highest correlation between the reference and the next image of the sequence (using the small region selected in step 2 in order to minimise the computation time). 4) Shift one of the images. 5) Subtract the images. The result of the subtraction is what we call the "subtracted image". 6) Fit a degree-three polynomial to each column of the subtracted image in order to compensate for changes in the background which cause gradients in the subtracted image. 7) Compute an image of residuals of the polynomial fits. The image of residuals is basically noise, except for some minor systematic effects (see Fig. 1). 8) Compute the standard deviation of the residuals. 9) Search for spikes brighter than 5 times the standard deviation of the residuals. 10) Compute the flux of the spikes. 11) Use the second image as reference, load a new image and go to step 3 until all the images are analysed.

This procedure was implemented in a computer code that does all the computations and shows the residual images on the screen, for visual check out. The search for spikes on the residual images was done by using the standard "find" algorithm of the Daophot photometry package. A number of parameters are used by the Daophot routines. These parameters were set to be consistent with the star images we took as calibration frames. Hence, cosmic rays and bad pixels were discarded by the algorithm.

We did this procedure for all the 13 data sets and checked the results by visual inspection. A number of "detected" flashes corresponded in fact to field stars, which showed up as a result of the nonsidereal tracking of the telescope. This differential tracking caused some stars to appear at different pixels in consecutive frames, and therefore, the subtraction shows a negative and positive image of the star (see Fig. 1c). We then added a piece of code to reject detections outside the Moon.

The total area of the Moon observed in each run was computed by fitting an ellipse to the limb of the Moon images. Using the fitted coordinates and the known radius of the Moon, we derived the total area observed in each run. It oscillated between 2.6×10^6 km^2 and 3.2×10^6 km^2 in different runs and therefore we have adopted a value of (2.9 $\pm$ 0.3) 10^6 km^2 for the calculations of meteoroids collision rates.

3.1. *Sensitivity of the search*

The faintest stars detected by our 5-σ algorithm were always above $\sim$ 5000 ADU. Using the absolute calibration factor, this represents (9.3$\pm$2.8) 10^{-13} J m^{-2} and (9.3$\pm$2.8) 10^5 J at the Moon's surface. Therefore, this should be our detection threshold. However, there are reasons to believe that the threshold might be somewhat higher. On many ocassions, changes in atmospheric conditions caused seeing variations that resulted in changes in the spatial resolution. Thus, some Lunar images were sharper than their contiguous images, and the subtraction showed patterns of bright spots located on bright craters

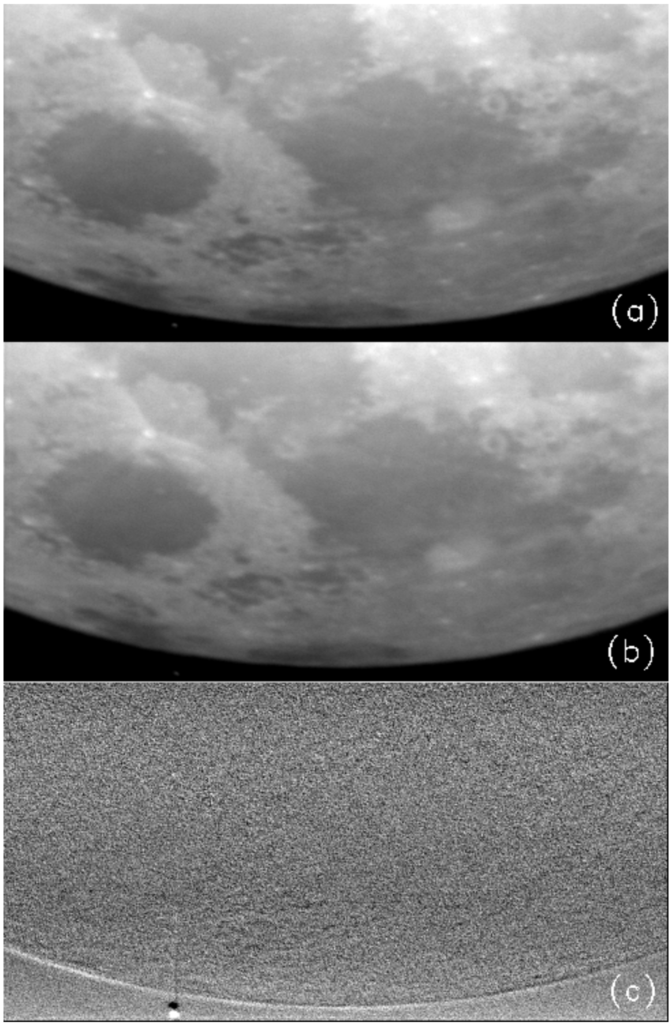

Fig. 1. a Example of reference image of the night side of the Moon taken on September 15th, 1998. The surface features are seen because the Moon is illuminated by the Earth **b** Image separated 20 secs from image **a**. **c** Image b-a after some additional processing (see text). There is a systematic effect at the limb caused by slight differences in seeing from image to image. Note that there is a "positive" and "negative" star, due to the drift of the star with respect to the Moon in consecutive frames.

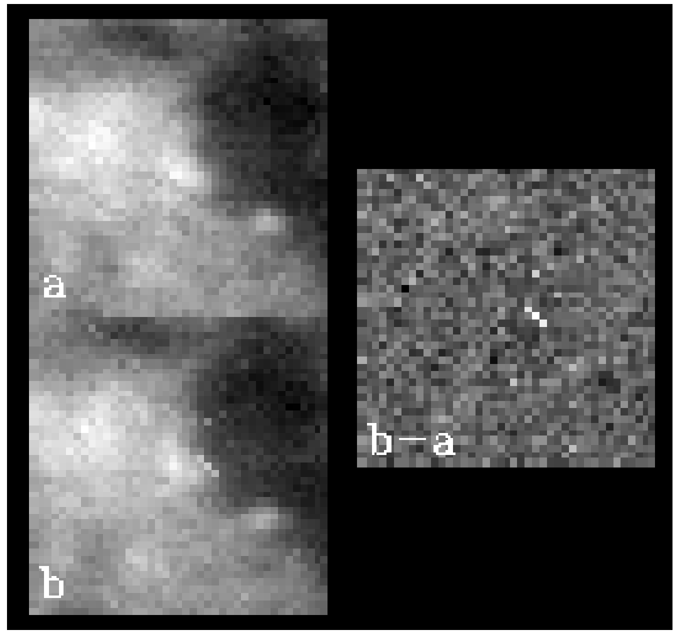

Fig. 2. a Magnified portion of a reference image just before a suspected impact. **b** Magnified portion of the image containing a suspected impact. The rightmost image shows the result of the subtraction **b**-**a**. The total emitted flux is 5200 ADU

or bright features of the Lunar surface. Although some of these spots were above the 5-σ level, they were usually rejected by the Daophot-find algorithm as they did not comply with the star-calibrated sharpness and roundness rejection criteria. On some ocassions a spot happened to have a light distribution compatible with that of the real stars and the algorithm detected it as a possible impact, but visual inspection allowed to reject these detections, since the spots were always located on bright craters or bright Lunar features. We are, however, concerned that we may have misinterpreted true flashes as bright spots and viceversa. Nevertheless, no spots ever reached 5×10^{-12} J m^{-2}. We thus can state that 5×10^{-12} J m^{-2} is our full-confidence sensitivity threshold (Fig. 1 shows a star slightly above 10^{-11} J m^{-2}. Its identification is unambiguous).

4. Results

No single detection has been found above the 5×10^6 J energy level. Had such an impact occurred, we would have detected it very easily. In the energy range below 2.5×10^6 J, only five spikes have the expected characteristics of true impacts and they were not located in Lunar areas of high brightness (see Fig. 2 for an example of detection), but we cannot yet rule out noise of an unknown source or very localized seeing variations as their probable cause. The energies of the suspected impacts (in chronological order) are 1.3×10^6, 0.9×10^6, 1.0×10^6, 1.5×10^6 and 0.9×10^6J.

5. Discussion and conclusions

The lack of detection of impact events of energy $> 5 \times 10^6$J in 4.3 hours, for an area (2.9 $\pm$ 0.3) 10^6 km^2-wide means that the influx of meteoroids of mass m_t must be definitely less than 1000 per day on Earth or $\sim$ 400000 impacts per year. The mass m_t depends on the luminous efficiency adopted (η). If η were 30%, m_t would be 0.08 kg, but m_t is likely much higher, as η is probably much lower than a few percent. If we accept the results in Fig. 1 of Ceplecha (1992) as the ground truth on the rate of impacts on the Earth, we can derive an upper limit on η for those meteoroids whose rate is higher than 400000 per year at Earth. According to Ceplecha (1992), those are meteoroids of less than 0.1 kg in mass and therefore, their η must be $<$ 30% or otherwise an impact would have been detected by our system.

Concerning the possible detection of smaller impacts, our 1.2 impacts per hour represent a flux of 4800 $\pm$ 500 impacts per day onto Earth, or 1.7×10^6 impacts per year, which is close to the flux that can be derived from Fig. 1 of Ceplecha (1992), for masses of 0.01 kg or less. However, the impacts of masses < 0.01 kg cannot reach our 5-σ detection threshold of 9.3×10^{-13} J since their η would have to be close to 100%. This raises additional suspicion on the reality of our detections, but if they were real, it could either mean that the flux of bodies more massive than 0.01 kg is somewhat higher than shown by Ceplecha (1992) or that our detections corresponded to faster-than-average particles. Other more exotic possibilities exist, such as the emission of radiation being highly anisotropic and oriented to the Earth. Our derived collision rate on Earth is similar to that re-proposed by Frank and Sigwarth (1997) for "small comets". Although our result might seem to support Frank and Sigwarth's idea, we should have observed several E$>> 10^7$ J events on the Moon, not E$\sim 10^6$ J events, unless the luminous efficiency of the "small comet impacts" was lower than 0.01%, which could be the case if the "small comets" were swarms of small particles. Some recent papers have been devoted to prove the renewed small-comet theory wrong (Grier and McEwen 1997; Parks et al. 1997; Swindle and Kring 1997; Rizk and Dessler 1997). Our present work would be one more piece of evidence against the theory if one could prove that the luminous efficiency of the small comet impacts is higher than 0.01%.

Other conclusions from our search are: 1) It is feasible to detect impact events such that the emitted energy is higher than 5×10^6 J, but in order to have more sensitivity and total confidence, the background should be reduced as much as possible and the point spread function of the system should be kept as constant as possible. 2) To minimise the background effect, the use of larger telescopes plus specific filters to select line emissions typical of the impacting bodies or typical of the souranding gas might be a good strategy; this would highly enhance the contrast of the flash against the background. These filters could be designed to comprise Mg, Fe, Ca lines or even just the Na D lines, which are typical of bolides on Earth (Borovicka 1993; Borovicka and Spurny 1996). Reducing the integration times would of course lower the background, but very fast read out CCDs are then needed. Also, searches in the infrared or the near infrared might be interesting.

Meteoritic impact volatilisation has been suggested as the dominant source for the Lunar sodium atmosphere by some authors (Sprague et al. 1998), and an overall increase of sodium emission after the 1997 Leonid meteoroid shower has been tentatively identified by Hunten et al. (1998) and Verani et al. (1998). Detailed studies of the rate of impact flashes as well as their spectral properties could help constrain this scenario. An optimized system such as we describe here could be very useful to study the next Leonid meteor shower in 1999, as it is expected to be an intense shower and the Moon will be at an adequate phase.

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