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Estimating the number of impact flashes visible on the Moon from an orbiting camera

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Abstract–Using a dust flux model and experimental data on the efficiency of light emission upon impact, the number of impact flashes visible on the Moon by a camera on a lunar orbiter is estimated.

INTRODUCTION

While preparing for the predicted storm activities of the Leonid meteor stream at the end of the 1990s, it was realized that it should be possible to see the impact flash which a meteoroid produces when hitting the lunar surface. The Moon is far away, thus only very bright events generated by large and fast particles would be detectable. On the other hand, the collecting area is very large—the un-illuminated area of the three-day old Moon is more than 15 million km^2. Thus, the chances for an impact visible from the Earth are not negligible.

Indeed, visual observations of impact flashes were recorded in 1998, performed by independent observers, thus confirming that they are real. Very soon, video cameras were used to record the Moon and started giving results in 1999 (see e.g., Cudnik et al. 2002). When recording from two different stations independently to exclude camera artifacts (e.g., a cosmic ray hitting the sensor) or satellite flashes, these provide conclusive evidence for impacts on the Moon. NASA's Meteoroid Environment Office has used such a setup using 0.25, 0.36, and 0.5 m telescopes and low-light-level video cameras to record the night side of the Moon. In 2 years of observations, they recorded about 110 impacts (Suggs et al. 2008a).

Recently, a camera was proposed to observe impact flashes from a low-flying lunar orbiter called Lunar Exploration Orbiter (LEO) (see, e.g., Jaumann et al. 2008). This camera would be based on a camera breadboard called Smart Panoramic Optical Camera Head (SPOSH) developed under a contract from the European Space Agency to Jena Optronic and DLR in Germany (Koschny et al. 2004). It has a 120° field of view and can record light flashes as short as 40 ms with an equivalent visible magnitude $M_v < 5$ mag.

This paper is intended to predict the detection capabilities of this camera by modeling the incoming particle flux onto the lunar surface and using experimental results on the emitted light intensity. We will show that several impact flashes can be observed per hour with such a camera from lunar orbit.

OVERVIEW OF THE MODELLING PROCESS

To find the number of impact flashes visible on the Moon for a given camera, we use the following approach:

1. We estimate the number of particles larger than a given size impacting the Moon using the dust model of Grün et al. (1985). This results in a number per area per unit time.
2. From the mass and assuming an average velocity of the particle, we estimate the energy emitted as light by using data from Eichhorn (1976) and Burchell (1994, 1996).
3. The produced energy is converted to numbers of photons per area, time, and wavelength, at the average distance between camera and for the observed surface area on the Moon.

The following sections expand on these points in more detail.

SIMULATING THE INCOMING DUST FLUX

Several detailed meteoroid models are currently available, e.g., Dikarev et al. (2005) or McNamara et al. (2004). However, for a first assessment of the dust flux, the simple model of Grün et al. (1985) is sufficient. Grün et al. use in situ dust measurements, zodiacal light observations, and the distribution of lunar micro craters to derive a model for the cumulative number of meteoroids larger than a given size. They arrive at the following functional relationship:

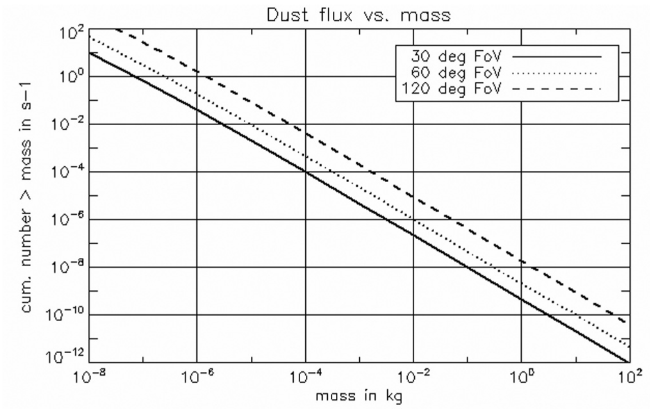

Fig. 1. Number of particles impacting the lunar surface larger than a given size, for different field of views of cameras in 100 km orbit over the Moon.

$$F(\geq m) = (2.2 \cdot 10^3 * m^{0.306} + 15)^{-4.38} + 1.3 \cdot 10^{-9} (m + 10^{11} m^2 + 10^{27} m^4)^{-0.36} + 1.3 \cdot 10^{-16} * (m + 10^6 m^2)^{-0.85} \quad (1)$$

where $F(\geq m)$ is the number of particles per unit area (i.e., the flux) larger than mass m. Note that the Grün formula as written above does not assume any gravitational focusing. For the Moon, we assume that none should be taken into account as its mass is small compared to the Earth's and the distance to the Earth is large.

We assume a camera with 120° square field of view at a distance of 100 km to the lunar surface. Neglecting the curvature of the Moon, the area A which the camera covers is:

$$A = (2 * 100 \text{ km} * \tan(60°))^2 = 120000 \text{ km}^2 = 1.2 \cdot 10^5 \text{ km}^2 \quad (2)$$

The flux as given by Equation 1 is the flux for a rotating plate with a size of the unit area. On the Moon's surface, only particles from one half sphere can impact the surface. Thus, the number of particles hitting the surface area visible by our camera is computed by

$$F_{cam} = F(\geq m) * A * 0.5 \quad (3)$$

We compute the number of particles impacting the area visible by the camera for different values of the field of view (30°, 60°, and 120° full angle). The result can be seen in Fig. 1.

ESTIMATING THE GENERATED LIGHT INTENSITY

During a hypervelocity impact, the kinetic energy of the impactor is used to heat up the target area and the projectile. Depending on the energy, material is molten and possibly vaporized. Part of the energy generates shock waves and mechanical fracturing. A crater is excavated and liquid and solid ejecta material is thrown away, i.e., taking away kinetic energy.

The fraction of energy converted to light is commonly referred to as "luminous efficiency." We here circumvent the use of luminous efficiency by taking empirical relationships from experimental impact work done by Eichhorn (1976) and Burchell (1994, 1996). Note that both authors were mainly concerned with performing impacts on technical material rather than planetary surface representatives. However, no more relevant experiments were found to be published.

Eichhorn used an electrostatic accelerator of the Max-Planck Institute for Nuclear Physics in Heidelberg, Germany, to shoot metallic particles in the mass range of 10^{-12} kg to 10^{-19} kg and velocities between 0.5 km s^{-1} and 35 km s^{-1} into different technical targets, e.g., iron, copper, tungsten, gold, but also for basalt. He placed witness plates around the targets and observed the interaction of the ejecta particles with the witness plates using image-intensified cameras. He also gave results for the light flash of the primary impact, which is what we use here.

He states that the total energy E can be described by

$$E = c_2 m v^{3.2} \quad (4)$$

The light energy varies from 2×10^{-6} to 1×10^{-2} of the projectile energy, depending on the materials of target and projectile. Values for the constant c_2 are not given.

To estimate c_2, we use Fig. 6 in Eichhorn 1976. From there, we take a typical value of $10^{5.2}$ for the light energy divided by mass of the projectile for an impact of iron into Basalt at 3 km s^{-1}. With this, we get $c_2 = 1.18 \times 10^{-6}$ for v in m s^{-1}.

So

$$E = 1.18 \cdot 10^{-6} m v^{3.2} \quad (5)$$

with E in erg, m in g, v in m s^{-1}. In SI units and replacing $1/2 mv^2$ with kinetic energy KE, (5) can be written as

$$E = 2.46 \cdot 10^{-10} v^{1.2} \cdot KE \quad (6)$$

Burchell (1994, 1996) performed impact experiments using the light-gas gun at the light-gas gun facility of the University of Kent, UK. He measured the emitted light using a calibrated photodiode. He provides the following two empirical relations for the emitted light energy:

$$E_{1994} = 4.6 \cdot 10^{-7} v^2 \cdot KE \quad (7)$$

$$E_{1996} = 5.35 \cdot 10^{-7} v^{1.65} \cdot KE \quad (8)$$

with v the velocity in km s^{-1}, KE the kinetic energy of the projectile in J.

The energy arriving at an observer in distance r can be computed via

$$E_r = \frac{E}{4\pi r^2} \quad (9)$$

We assume that the energy dependencies derived in Equations 6, 7, and 8 are panchromatic, i.e., that they give the complete energy emitted. The sensor is assumed to be sensitive roughly in the Johnson V band, i.e., in the wavelength range from approximately 500 to 700 nm. To estimate the energy visible in this wavelength range only, we assume that the emitted energy follows a blackbody curve:

$$\frac{dE_r}{d\lambda} = 2\pi \cdot \frac{hc^2}{\lambda^5\left(e^{\left(\frac{hc}{\lambda kT}\right)} - 1\right)} \tag{10}$$

This formula is the Planck distribution, with $dE_r/d\lambda$ the energy at one given wavelength λ, h the Planck constant ($h = 6.626{\cdot}10^{-34}$ Js), c the speed of light ($c = 299.792 \times 10^6$ m/s), k the Boltzmann constant ($k = 1.380 \times 10\ ^{23}$ J/K). The complete integral E_r is set to the energy obtained via Equations 6, 7, or 8. The energy visible by the detector is then obtained by assuming a blackbody temperature, in our case 5000 K. Then we integrate from 500 to 700 nm to obtain the energy which is visible by the detector. Note that we neglect the fact that the Johnson V band is not constant over the wavelength.

To make the emitted light energy more intuitive, we convert it to stellar magnitudes. We can do this by noting that the visual magnitude M_v of the Sun is -26.74 mag at the Earth's distance and the energy per unit area (called the solar constant) is $I_{sun} = 1380$ W/m^2. We use the relation between intensity and magnitude

$$m_v - m_{v,0} = 2.5\log\left(\frac{I_0}{I}\right) \tag{11}$$

m_v, m_0 are stellar magnitudes, and I, I_0 are intensities. The intensity can be computed from the total emitted energy by assuming a duration Δt of the light flash, $I = E/\Delta t$.

Solving Equation 9 for m_v and substituting the intensity with energy over duration, we get

$$m_v = 2.5\log\left(\frac{1380\,W/m^2}{E/\Delta t}\right) - 26.74 \tag{12}$$

In summary, we perform the following steps:

1. Derive the total emitted energy generated by the impact using formulae 6, 7, 8;
2. Reduce the emitted energy due to the distance using Equation 9;
3. Determine the fraction of the energy in the Johnson V band using Equation 10;
4. Convert to stellar magnitude using Equation 12.

In Fig. 2 we show the result: the emitted light intensity, converted to stellar magnitudes in the visible (V) band, as a function of mass for a projectile at 16 km s^{-1} and from a typical distance of 120 km. This value was chosen as representative for a 100 km altitude orbit. The duration of the energy emission was assumed to be 10 ms (Burchell 1996).

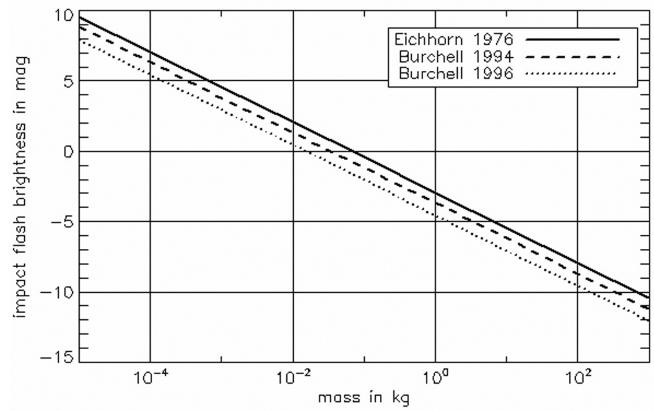

Fig. 2. Emitted light energy by an impact as a function of mass for $v = 16$ km s^{-1}, seen from 120 km distance.

Table 1. Number of detectable impact flashes. 50% vis. means that only half of the actual impact flashes are visible from the camera due to shading by mountains.

Lim. mag	Mass	Time between impacts	No/hour (50% vis.)
6 mag	$1.5.0^{-4}$ kg	200 s	9
5 mag	$3.5.10^{-4}$ kg	670 s	2.7
4 mag	$7.9.10^{-4}$ kg	1920 s	0.9

COMBINING THE ITEMS

Figures 1 and 2 can now be used to determine the number of impact light flashes which would be expected to be seen with a camera at 100 km altitude over the Moon and a certain limiting magnitude *lm*. Assume the camera sensitivity allows the detection of light flashes with magnitude $mag = 5$. From Fig. 2 we derive that, depending on the experimental results used, impact flashes generated by particles with a mass of 10^{-4} to 10^{-3} kg will be visible. Using Fig. 1, one can derive the flux of particles with smaller than or equal this mass, for different field of views. As an example, for 1.5×10^{-4} kg and with 120 deg field of view, one can expect 5×10^{-3} impacts per second or about 200 s between impacts.

A summary of the results for different camera sensitivities is given in Table 1. Here we assume that only 50% of all impacts are really visible due to shadowing effects of mountains. We also assume the relation between impact flash magnitude versus mass from Fig. 2 as given by Eichhorn, i.e., the faintest magnitude. Using Burchell's data would result in more detectable events. In the table, we give a time between impact which is the average occurrence time between two particles with mass m hitting the Moon. The last column gives the number per hour, assuming that only 50% of the particles are observable to account for effects like impacts hitting inside a crater or behind a mountain and thus not visible from our camera.

Table 2. Constants for Equation 14 for the three different laboratory papers and resulting luminous efficiency η.

Reference	c	N	η
Eichhorn 1976	$2.46.10^{-10}$	1.2	2.10^{-4}
Burchell 1994	$4.6.10^{-7}$	2	6.10^{-4}
Burchell 1996	$5.35.10^{-7}$	1.65	2.10^{-3}

DISCUSSION

In the previous sections, we derive a predicted number of observable impact flashes from a camera orbiting the Moon (based on the design of the SPOSH camera, see Koschny 2004). The mass of the smallest detectable particles is in the order of 10^{-4} kg, corresponding to a particle size in the order of millimeters. The flux of particles in this size range is well constrained from ground-based observations using meteor radar systems and optical cameras recording meteors and fireballs entering the Earth's atmosphere. Thus, these observations would complement the flux measurements done on Earth. They can be used to better constrain the light emission process during an impact.

Our model for the light emission from impacts is based on three papers by Eichhorn (1976) and Burchell (1994, 1996). Several constraints have to be considered when using these measurements.

Most of the targets Eichhorn and Burchell used were technically relevant materials, as aluminium, copper, and gold. Only Burchell 1996 uses basalt targets in a few of his experiments. Thus, the relevance of the large part of the measurements for the lunar surface is arguable. Also, the experimental work was done mainly with micron-sized particles—the few data with millimeter-sized particles were at velocities below 7 km s^{-1}. Any velocity effects on the light emission process could change the result dramatically.

A totally different approach of estimating the emitted light energy was taken by Bellot Rubio et al. (2000). He observed the cumulative number of impact flashes versus magnitude during the Leonid meteor storm in 1999. Assuming different "luminous efficiencies" η (defined as the ratio of emitted light energy versus kinetic energy of the impactor) and noting that the Leonids have a known impact velocity of 72 km s^{-1}, he models the expected cumulative flux distribution. Comparing observation with model and using additional constraints, he arrives at $\eta = \sim 2 \times 10^{-3}$. We can compare these with Equations 6, 7, and 8. To do this, we write these formulae more generic as

$$E = c \cdot v^n \cdot KE \tag{13}$$

with c and n being constants. Then, the luminous efficiency can be computed by

$$\eta = \frac{E}{KE} = c \cdot v^n \tag{14}$$

Table 2 lists the constants c and n for the different papers and the resulting value for η, using a velocity of 72 km s^{-1}. Note that in the formula for Eichhorn (1976), the velocity has to be entered into Equation 14 in km s^{-1}, for the two papers by Burchell in m s^{-1}.

Thus, the resulting luminous efficiencies are in the order of 6×10^{-4} to 2×10^{-3}. This is consistent with the value of 2×10^{-3} derived by Bellot Rubio and gives confidence in the assumption that the experimental work in the laboratory is representative for real lunar impacts.

To convert the emitted energy to the number of photons in the V band, we assumed a black-body temperature of the impact of 5000 K. For lower temperatures, the peak of the light emission will be shifted towards the Infrared wavelength range and the detectable light would be reduced.

The duration of the impact flash is also entering into the computation of the peak intensity. We here assume 10 ms. Ground-based telescopic observations of impact flashes on the Moon have recorded flashes as long as 500 ms (Cooke 2008). The peak intensity would then be reduced by up to a factor of 50, reducing the detectable number of events.

CONCLUSION

We show that using currently available camera technology, one should expect a number of impact flashes of one to several per hour to be observable from a camera in Lunar orbit, which would make it well worth to send a camera like this to the Moon. These observations would contribute to better understanding the light emission process during an impact for millimeter- to centimeter-sized objects hitting the lunar regolith and to the flux determination of this size range.

These observations would complement ground-based observations of lunar impact flashes. Since the ground-based observations are done from a larger distance, the particle mass needs to be much higher (in the order of kg) to generate a detectable effect. However, the detector area is basically the complete un-illuminated part of the Moon, still resulting in a useful number of observable events (the typical time between impacts for the sporadic background is 5 to 14 hours, Suggs et al. 2008b). These observations are thus very relevant to cover a size/mass range of meteoroids which is currently not well observed. The flux of smaller-sized particles (millimeter and smaller) is well constrained by ground-based radar meteor observations and by in-situ dust detectors. For millimeter- to decimeter-sized objects reasonable statistics are obtained by photographic observations of fireballs. Objects of tens of meters and larger can be observed when they orbit the sun with ground-based telescopes. Objects in the range of meters, however, are too small for observing when still orbiting the Sun, but not numerous enough to produce reasonable statistics when observed as fireballs. Impact light flash observations with ground-based telescopes cover just this part, thus these observations contribute significantly to constraining the flux in this size range—if the light emission process is understood properly, which is what can be done with the orbiting camera.

In addition, more experimental work on the light emission process is urgently needed. In particular, experiments should be done in all possible size—and velocity regimes, using geologically relevant targets (basalt, granite, regolith). The light emission should be measured in absolute flux, over a large spectral region from the infrared to the visible wavelength bands, and with high time resolution.

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