

Lunar Meteoroid Impact Observations and the Flux of Kilogram-sized Meteoroids

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Abstract Lunar impact monitoring provides useful information about the flux of meteoroids in the hundreds of grams to kilograms size range. The large collecting area of the night side of the lunar disk, approximately 3.8×10^6 km² in our camera field-of-view, provides statistically significant counts of the meteoroids striking the lunar surface. Over 200 lunar impacts have been observed by our program in roughly 4 years. Photometric calibration of the flashes observed in the first 3 years along with the luminous efficiency determined using meteor showers and hypervelocity impact tests (Bellot Rubio et al. 2000; Ortiz et al. 2006; Moser et al. 2010; Swift et al. 2010) provide their impact kinetic energies. The asymmetry in the flux on the evening and morning hemispheres of the Moon is compared with sporadic and shower sources to determine their most likely origin. These measurements are consistent with other observations of large meteoroid fluxes.

Keywords impact flash • lunar impact • meteoroid flux

1 Introduction

Video observations of the Moon during the Leonid storms in 1999 and 2001 (Dunham et al. 2000; Ortiz et al. 2000, 2002) confirmed that lunar meteoroid impacts are observable from the Earth. One probable Geminid impact was observed from lunar orbit by Apollo 17 astronaut Dr. Harrison Schmitt (NASA 1972). NASA's Marshall Space Flight Center (MSFC) began routine monitoring of the Moon in June 2006 with multiple telescopes following our first detection in November 2005 (Cooke et al. 2006 and 2007). Of the more than 175 impacts observed in the first 3 years, 115 of them have been used to determine the flux of impactors in the 0.1 to 10s of kilogram size range. This flux is compared with other measurements in section 5 and the correlation of the observations with meteor showers and sporadic is examined in section 4.

2 Observation and Analysis Process

The observations are carried out at the Automated Lunar and Meteor Observatory located on-site at the

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MSFC near Huntsville, Alabama (latitude 34.66 north, longitude 86.66 west) and at a remotely controlled observatory near Chickamauga, Georgia (34.85 north, 85.31 west). The instrument complement has changed somewhat over time beginning with a 10 inch (254 mm) diameter Newtonian reflector for the initial observations then two Meade RCX400 14 inch (355mm) diameter telescopes with Optec 0.33x focal reducers and StellaCam EX or Watec 902H2 Ultimate monochrome video cameras. Both cameras use the same Sony HAD EX ½ inch format CCD. The effective focal length is approximately 923mm giving a horizontal field of view of 20 arc minutes covering approximately 4×10^6 square km or 12% of the lunar surface (see Figure 1). In 2008, one of the 14 inch telescopes was replaced with a Ritchey Chretien Optical Systems 20 inch (0.5 m) telescope with the focal reducer adjusted to give approximately the same field of view as the 14 inch instruments. The limiting stellar magnitude at the 1/30 second frame rate is approximately 12. The video from the cameras is digitized using a Sony GV-D800 digital tape deck and sent by Firewire to a personal computer where it is recorded on the hard drive for subsequent analysis.



Figure 1. Camera field of view and orientation.

The observations of the night portion of the Moon are made when the sunlit portion is between 10% and 50% illuminated. This occurs on about five nights and five mornings per month. No observations are attempted during phases less than 10% since the time between twilight and moon rise or set is too short. Observations are not made during phases greater than 45 - 50% because the scattered light from the sunlit portion of the Moon is too great and masks the fainter flashes. Large lunar albedo features are easily visible in the earthshine and are used to determine the approximate location of the impacts on the lunar surface.

The recorded video is analyzed using two custom programs. LunarScan (available at <http://www.gvarros.com>) was developed by Peter Gural (Gural 2007). The software finds flashes in the video which are statistically significant (as described in Suggs et al. 2008) and presents them to a user who determines if they are cosmic ray impacts in the detector, sun glints from satellites between the Earth and the Moon, or actual meteoroid impacts. By requiring that a flash be simultaneously detected in two telescopes, cosmic rays and electronic noise can be ruled out. Five of the detected impacts were observed with only one telescope early in the program but only flashes which spanned more than two video frames and showed a proper light curve (abrupt brightness increase followed by gradual decay) were counted. There have also been a few impacts independently observed by amateur astronomers using 8 inch (200 mm) telescopes (Varros 2007; Clark 2007). For short flashes where satellite motion might not have been detectable, custom software was used to check for conjunctions with Earth orbiting

satellites whose orbital elements are available in the unclassified satellite catalog (www.space-track.org). Since there is some probability that orbital debris or a classified satellite not listed in this catalog could cause such a short flash, a remotely controlled observing station was constructed in northern Georgia about 125 km from MSFC. This allows parallax discrimination between impact flashes and sun glints from manmade objects, even at geosynchronous altitude. After 3 years of operation of the remote observatory only one candidate flash due to orbital debris has been seen that could have been mistaken for an impact and that one showed orbital motion upon closer inspection. Whenever the weather doesn't allow operation of the remote observatory, temporally short flash images are enhanced and closely examined for any sign of motion with respect to the lunar surface.

After detection and confirmation, another computer program, LunaCon, is used to perform photometric analysis (Swift et al. 2007). Background stars are used as photometric references to determine the observed luminous energy of the flashes. Since a reference star is unlikely to be in the frame during a flash, the earthshine on the Moon is used as a transfer standard thereby correcting for first order extinction. LunaCon also displays graphics showing the lunar surface brightness, contrast between the lunar surface and space next to the limb, lunar elevation angle, lunar surface area in the field of view, and other data quality diagnostics as a function of time during the night. These displays make it obvious when clouds pass, twilight is contaminating the observations, the Moon drifts in the field of view, and atmospheric extinction is extreme. Using this information, time spans of clear weather and good data quality were determined for use in the calculations of observation time necessary for flux calculations. Flashes outside of these time spans were not used in the analysis reported here. Photometric accuracy is estimated to be approximately ± 0.5 magnitudes.

3 Observational Results

Using the photometric quality criteria described above, 115 impacts were observed during periods of consistent photometric quality. By plotting the histogram of number of flashes per magnitude bin (Figure 2), we determined that our completeness limit was approximately 10th magnitude (Johnson-Cousins R band) and there were 108 flashes brighter than that. These were included in the dataset for further analysis.

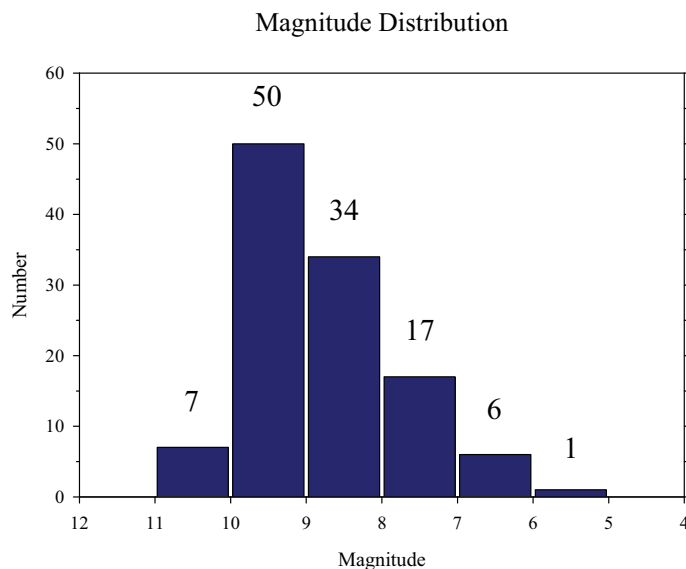


Figure 2. Histogram of flash magnitudes showing completeness to approximately magnitude 10

Calculating the flux to this completeness limit:

$$\text{Flux} = 108 \text{ impacts} / (212.4 \text{ hours} * 3.8 \times 10^6 \text{ km}^2) = 1.34 \times 10^{-7} \text{ km}^{-2} \text{ hr}^{-1}$$

To compare with other estimates of meteoroid fluxes, the limiting kinetic energy corresponding to the limiting magnitude of our observations must be determined. We observe the intensity of the impact flash in our camera passband. The ratio of the optical energy and the impact kinetic energy is the luminous efficiency η .

$$\eta = \frac{\text{optical energy in passband}}{\frac{1}{2} m v^2}$$

where m is the mass of the impactor and v is its velocity. The luminous efficiency is a function of velocity and has been determined using laboratory measurements at low velocities (Swift et al. 2010) and using several meteor showers (Bellot Rubio et al. 2000 for Leonids and Moser et al. 2010 for Geminids, Lyrids and Taurids). The luminous efficiencies determined from laboratory and shower observations have been assimilated into a single expression by Swift et al. (2010) for the passband of the cameras used in our observations

$$\eta_{cam} = 1.5 \times 10^{-3} e^{-\left(\frac{9.3}{v}\right)^2}$$

Using this expression and the velocities of the various showers associated with the observations we estimated the mass at our completeness limit to be approximately 100 grams.

The impact asymmetry between the western (left, leading) and eastern (right, trailing) hemispheres evident in Figure 3 is real and when corrected for hours of observation amounts to a ratio of 1.45:1. The explanation for this asymmetry is addressed in the next section.

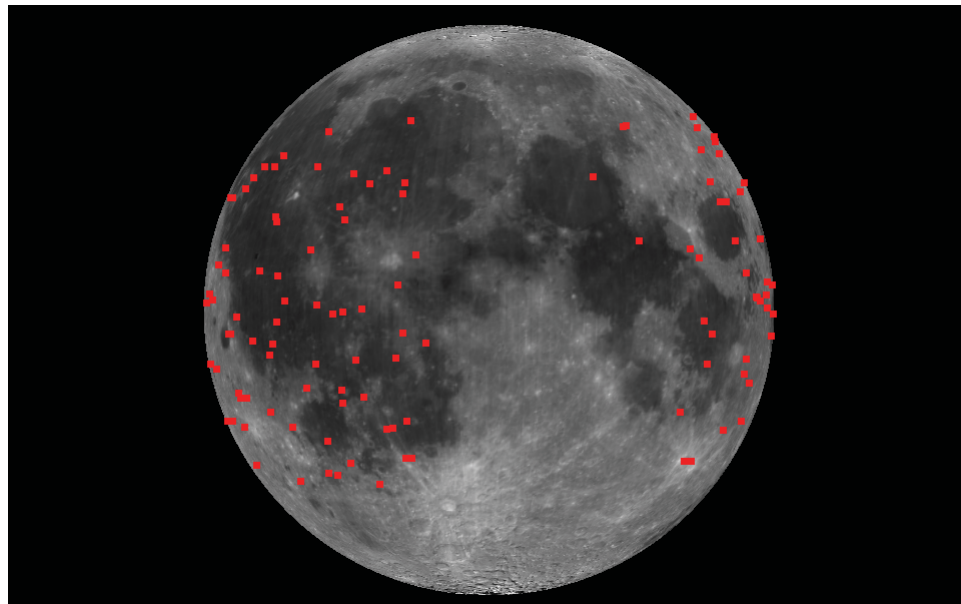


Figure 3. Impact flashes observed between June 2006 and June 2009 and culled for use in this analysis. Continuous monitoring was from April 2006 to the present.

4 Modeling

Our initial explanation for the asymmetry was this: observations of the western hemisphere occur leading up to first quarter phase when the observed portion of the Moon is exposed to both the Apex and Antihelion sporadic meteoroid sources. The eastern hemisphere is observed following last quarter phase when the Apex source is only visible from the farside of the Moon thus no Apex meteoroids can impact the portion of the Moon we are observing. The Apex source's flux is lower than the Antihelion's but the velocities are higher so the impact kinetic energy at a given mass would be higher. Thus the limiting mass would be lower and more meteoroid impacts would be visible. This seemed like a reasonable explanation but modeling of the asymmetry using the Meteoroid Engineering Model (McNamara et al. 2004) showed that the ratio would be 1.02:1 rather than the observed 1.45:1 so sporadics could not be the dominant source of the impacts. This result was confirmed by similar calculations by Wiegert (private communication).

Shower meteoroids then were a more likely explanation for the observed impacts and the expected rates and hemispheric asymmetry were calculated to test this hypothesis. Figure 4 shows the temporal variation of impacts compared with shower peaks.

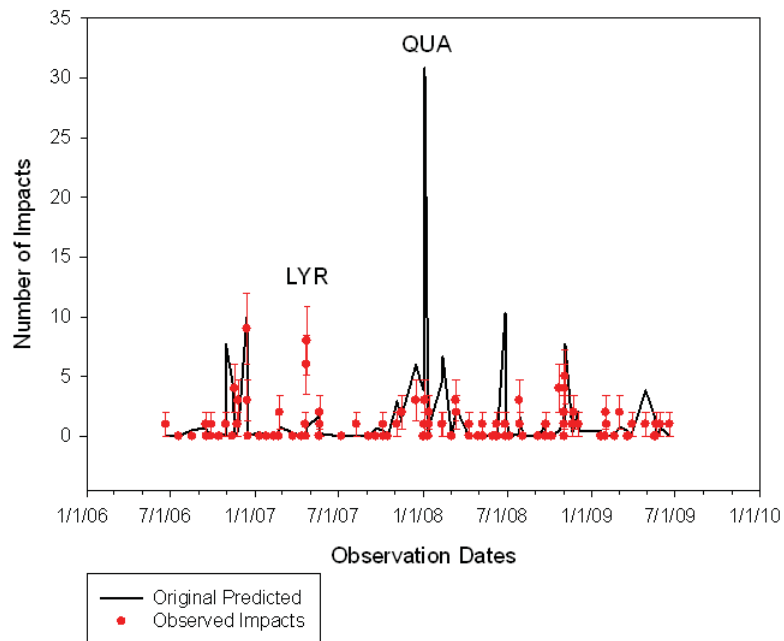


Figure 4. Impact flash distribution versus time compared with meteor showers. The red points are the observed rates with error bars representing the square root of the number of impacts per bin. The black curve is the impact rate calculated from observed values of zenithal hourly rate at the Earth. See text for discussion of this calculation.

The predicted flash rate was calculated using the reported shower zenithal hourly rates (ZHR), speed, and population/mass index. Knowledge of the camera energy threshold, combined with the shower speed and the luminous efficiency (Swift et al. 2010), enables the computation of the limiting mass for each shower. This may then be used with the ZHR (corrected for the lunar location) and the population and mass indices to obtain a flux. The predicted rate is obtained by multiplying this flux by the fraction of the observed lunar surface visible from the shower radiant. There are obviously

uncertainties in the photometry and other quantities, so these were used to constrain the adjustment of the energy threshold, which was varied until a best fit with the observed Geminid rate was achieved. The Geminids were chosen because 1) they are the strongest annual shower in terms of rates, and thus 2) they have the best determined mass and population indices. The resulting impact rate was plotted for comparison with the observed rates (Figure 4).

There is a clear correlation between the observed and predicted rates. Some of the weaker showers, such as the June Bootids, JBO, do not correlate as well due to their small zenithal hourly rate and poorly determined mass index. The shallow mass indices for showers relative to the steeper one for sporadics means that there are relatively more large particles in the showers. This fact alone argues that observed lunar impacts are dominated by shower meteoroids. Sporadic source populations are less likely to contain larger particles but they do contribute to the overall observed rate. Since we are observing impacts from meteoroids larger than 10^{-1} kg and visual and video observers (from which the population indices and ZHRs are derived) have limiting masses around 10^{-7} to 10^{-5} kg, we are extrapolating over several decades in mass to estimate the impact rate we observe. It is remarkable that the rates match as closely as seen in Figure 4. The mass indices for two showers had to be adjusted to get a better match. Figure 5 shows that the calculated impact rate for the Quadrantids (QUA) was too high and for the Lyrids (LYR) was too low. A better fit was obtained for the 2007 Lyrids when its population index was changed from 2.9 to values of 2.5, 2.3, and 2.6 for the dates of April 21, 22, and 23, respectively. This shallower distribution increased the number of larger meteoroids to better match those impacts we observed. The 2008 Quadrantids had a reported population index of 2.1 which overestimated the number of large meteoroids by a factor of 10. When the population index was adjusted to 2.6, a better match with our observations was obtained. Figure 4 has these adjustments included while Figure 5 does not.

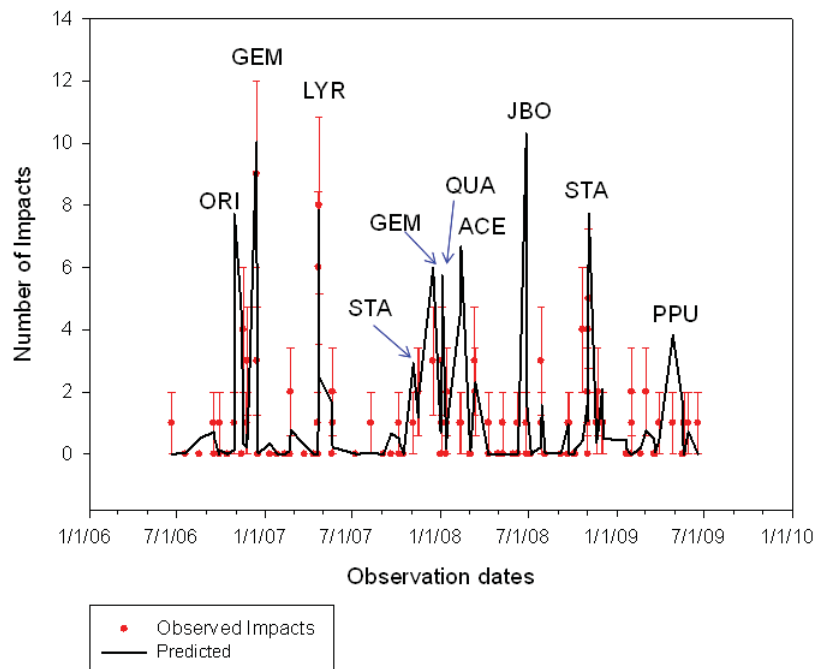
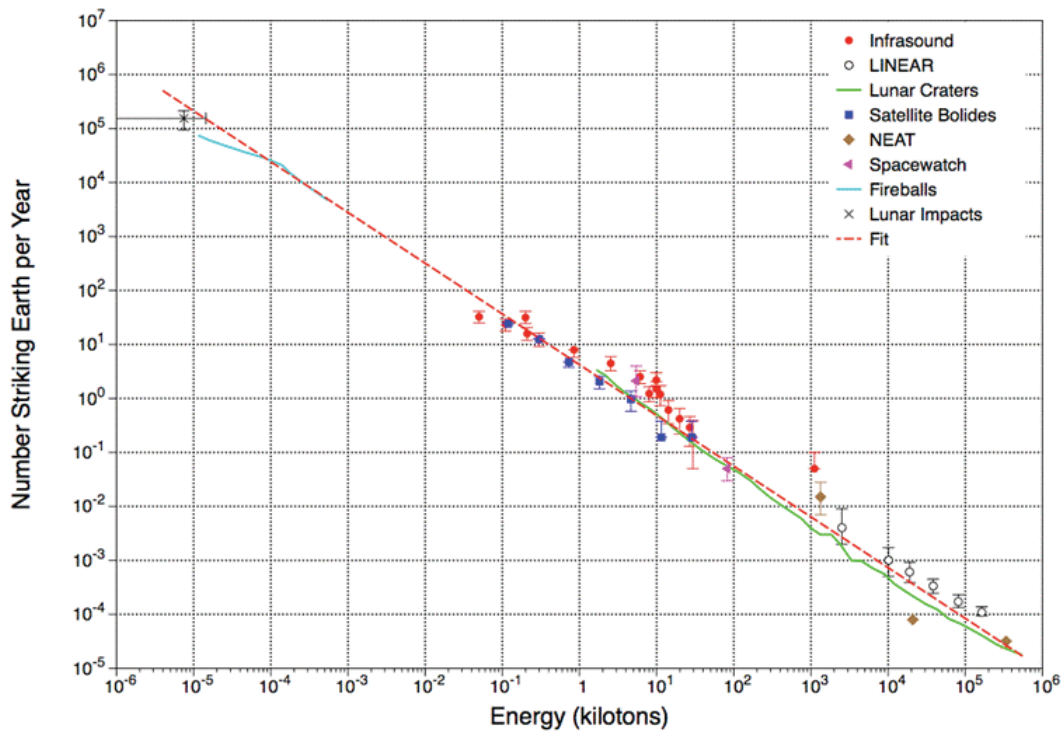


Figure 5. Impact flash distribution versus time compared with meteor showers using observed ZHRs and population indices from the International Meteor Organization (<http://www.imo.net/data/visual>). The symbols are similar to those in figure 4. Adjustment of the population indices for the Quadrantids (2.1 to 2.6) and Lyrids (2.9 to ~2.5) yielded the better fit seen in Figure 4.

Using these adjusted rates for the meteor showers gives a predicted hemispheric asymmetry during our observation periods of 1.57 compared to the observed ratio of 1.45:1. This is compelling evidence that shower meteoroids, including those from minor showers, dominate the observed impacts.

5 Flux Comparison

The observed flux of meteoroids with impact energies greater than our completeness limit was compared with fluxes determined by other techniques for larger objects. Figure 6 plots the flux determined using impact observations with those determined by all-sky fireball cameras, infrasound of meteor entries, lunar craters, satellite observations of fireballs, and telescopic observations of near-earth asteroids (Silber et al. 2009). The comparison is very favorable including the slight downturn from the power-law fit observed by the fireball network.



After Silber, ReVelle, Brown, and Edwards, 2009, JGR, 114, E08006

Figure 6. Number of meteoroids striking the Earth each year versus the impact energy in kilotons of TNT. Our measurement is to the extreme upper left. The cyan curve closest to our measurement is determined from all-sky camera observations of fireball meteors in the Earth’s atmosphere.

6 Conclusions

MSFC’s 4 years of routine lunar impact monitoring has captured over 200 impacts. Data from the first 3 years of operation were analyzed to investigate the source of the meteoroids, their flux, and the observed hemispheric asymmetry. It was found that shower meteoroids dominate the environment in this size range and explain the evening/morning flux asymmetry of 1.45:1. The observed flux of meteoroids

larger than 100 g impacting the Moon is consistent with fluxes determined by all-sky fireball meteor cameras. With sufficient numbers of impacts, this technique can potentially help determine the population index for some showers in a size range not normally measured.

Future plans include performing detailed calculations to investigate the observed concentration of impacts on the trailing hemisphere limb. Observations will be continued to build up number statistics to improve our understanding of meteoroids in this size range. A dichroic beamsplitter system is under construction to allow simultaneous observations with visible and near-infrared cameras with our 20 inch (0.5 m) telescope now located in southern New Mexico. This arrangement allows 1 telescope to be used to detect and confirm impacts and allows temperature measurements of the impact flash. Observations supporting robotic lunar seismic and dust investigation missions are also planned.

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