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The flux of kilogram-sized meteoroids from lunar impact monitoring

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ABSTRACT

The flashes from meteoroid impacts on the Moon are useful in determining the flux of impactors with masses as low as a few tens of grams. A routine monitoring program at NASA's Marshall Space Flight Center has recorded over 300 impacts since 2006. A selection of 126 flashes recorded during periods of photometric skies was analyzed, creating the largest and most homogeneous dataset of lunar impact flashes to date. Standard CCD photometric techniques were applied to the video and the luminous energy, kinetic energy, and mass are estimated for each impactor. Shower associations were determined for most of the impactors and a range of luminous efficiencies was considered. The flux to a limiting energy of 2.5×10^{-6} kT TNT or 1.05×10^{7} J is 1.03×10^{-7} km^{-2} h^{-1} and the flux to a limiting mass of 30 g is 6.14×10^{-10} m^{-2} yr^{-1} at the Moon. Comparisons made with measurements and models of the meteoroid population indicate that the flux of objects in this size range is slightly lower (but within the error bars) than flux at this size from the power law distribution determined for the near Earth object and fireball population by Brown et al. (Brown, P.G., Spalding, R., ReVelle, D., Tagliaferri, E., Worden, S. [2002]. Nature 420, 294–296). Size estimates for the crater detected by Lunar Reconnaissance Orbiter from a large impact observed on March 17, 2013 are also briefly discussed.

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1. Introduction

The flux of kilogram-sized meteoroids is ill-determined due to their relatively low flux. Large collecting areas are needed to provide reasonable statistics for flux calculations. All-sky video systems used for fireball detection are limited to the roughly 10,000 km^2 of atmosphere visible from their location and their sensitivity allows them to see down to sub-kilogram particles. Lunar impact monitoring utilizes the roughly 10^6 km^2 collecting area (defined by the camera field of view) of the lunar surface to detect reasonable numbers of meteoroids in the 10s of grams to few kilograms size range. This is accomplished by observing the flash of light produced when a meteoroid impacts the lunar surface, converting a portion of its energy to visible light detectable from Earth.

The possibility of observations of meteoroid impacts on the Moon was discussed almost a century ago by Gordon (1921) and the implications of such observations for the existence of a lunar atmosphere were considered by La Paz (1938). As early as 1966, an attempt to observe lunar impacts during the Leonids yielded promising though unconfirmed results (Carpenter et al., 1967). In 1972, astronaut Harrison Schmitt observed a possible meteoroid impact from lunar orbit during Apollo 17 (NASA, 1972) which may have been produced by a Geminid. The possibility of lunar impact flash detection from Earth was discussed and modeled by Melosh et al. (1993), Clark (1996), Beech and Nikolova (1998), Nemtchinov et al. (1998), and Shuvalov et al. (1999). Ortiz et al. (1999) made single telescope CCD observations of the Moon between 1997 and 1998 but could not conclusively distinguish between noise or seeing variations and a true impact flash. Unambiguous detections of lunar impacts began with video observations during the Leonid storm of 1999 (Bellot Rubio et al., 2000a; Dunham et al., 2000; Ortiz et al., 2000; Yanagisawa and Kisaichi, 2002) and continued with the 2001 Leonids (Cudnik et al., 2002; Ortiz et al., 2002). The collected Leonid data constrained impact models and yielded insight on their thermal properties (Artem'eva et al., 2001). In addition to the Leonids, successful video observations of Geminid, Lyrid, Perseid, and Taurid impacts have been reported (Yanagisawa et al., 2006; Cooke et al., 2006, 2007; Yanagisawa et al., 2008; Moser et al., 2011). Observations made outside shower peak periods have also yielded impact flashes detailed in Ortiz et al. (2006), Cooke et al. (2007), and Suggs et al. (2008, 2011).

NASA's Marshall Space Flight Center (MSFC) implemented a video monitoring program to routinely observe the Moon for impact flashes using multiple telescopes in early 2006. This has

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resulted in the observation of over 300 lunar impacts in roughly 7 years. This paper summarizes the results of the first 5 years of lunar impact monitoring at MSFC and updates previous results presented in Suggs et al. (2008, 2011). Consistent observational practices and careful photometric calibration yield a dataset of 126 impact flashes, the largest and most homogeneous to date. The monitoring technique, photometric calibration, and selection of the best data from the program are described. Calculation of impact kinetic energy, association with meteor showers, and calculation of impactor mass are discussed. The flux to a limiting energy and a limiting mass are compared to measurements and a model for other size ranges.

2. Observations

2.1. Method

The earthshine hemisphere of the Moon is observed between 0.1 (crescent) and 0.5 (first quarter) phase and 0.5 (last quarter) to 0.1. The video field of view is oriented with the equator along the vertical axis and limb in the field of view. This maximizes the lunar surface area observed and minimizes glare from the sunlit hemisphere. Evening observations (waxing phase) cover the western or leading hemisphere while morning observations (waning phase) cover the eastern or trailing hemisphere. Fig. 1 shows a Lyrid impact on 22 April 2007 at 03:12:21 UT (impact #26 in Table 1) and illustrates the video field of view. Lunar surface features are easily visible in earthshine and are used to determine the location of the flash.

Schmidt–Cassegrain telescopes 0.35 m (14 inch) in diameter were used to observe the Moon although some observations were made with a 0.5 m Ritchey Chretien instrument (from 23 January 2008 to 23 January 2010). Focal reducers were used to provide a field of view on the video chip of approximately 20 arcmin along the long axis of the frame. This field of view covers approximately 3.8×10^6 km^2 of the lunar surface. The cameras were "1/2 inch" format NTSC video based on the Sony EXview HAD CCD™ chip. Cameras based on this CCD were chosen because of the high sensitivity of the Hole Accumulation Diode (HAD) and EXview microlens technology. This camera/telescope combination gave a limiting stellar *R* magnitude of approximately 10.5. The frame rate was standard 30 per second with interleaved 1/60 s fields. The video signals were digitized and recorded on PC harddrives for subsequent flash searches and photometric analysis. The digitizers performed mild data compression which did not significantly affect photometry as is evidenced by the near zero average error and 0.2 magnitude standard deviation determined for the ensemble of comparison stars. All photometry was based on the 1/60 s fields by extracting even and odd rows from the video frames.

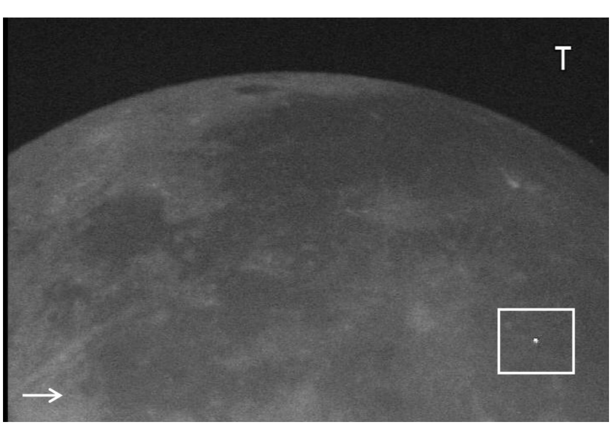

Fig. 1. Lyrid impact flash #26 on 22 April 2007 at 03:12:21 UT. The arrow indicates the direction of selenographic north. The horizontal field of view extent is approximately 20 arcmin.

The cameras were set to manual gain with electronic shutter control off. The cameras and settings used are described in Appendix A. All reported flashes were confirmed using at least 2 telescopes to discriminate against cosmic ray flashes in the CCDs. Two telescopes were operated at MSFC's Automated Lunar and Meteor Observatory (Minor Planet Center designation H58: 34.66°N, 86.66°W). A third 0.35 m telescope was operated near Chickamauga, Georgia (34.85°N, 85.31°W), 125.5 km from MSFC, beginning in September 2007 to eliminate orbital debris sunglints up to geosynchronous altitude. Correlated observations from this telescope showed conclusively that the flashes observed at MSFC could not be from orbital debris. Even without this third telescope, any satellite or debris sunglint lasting more than a few frames shows motion across the field of view unlike the stationary lunar impact flashes.

For some observations in 2009 and 2010 an InGaAs near-infrared (0.9–1.7 μm) video camera was used on one of the telescopes. It proved useful for confirmation but not for photometry due to persistence issues.

2.2. Flash detection and aperture photometry

Impact flash detection was performed using LunarScan (Gural, 2007). The software looks for pixels that exceed the standard deviation over the mean image by a factor of 3.5. The mean and standard deviation are tracked on a frame by frame basis using a first order response filter for each pixel. A spatial correlation filter looks for 3 rows of exceedances which approximates the optical system point spread function. Candidate impact flashes are manually correlated with video recorded from the second and, when available, third telescope to reject any cosmic rays or satellite glints. Fig. 2 shows a false color sequence of video frames of the impact shown in Fig. 1. The LunaCon program (Swift et al., 2008) was used to extract the aperture photometry data for the flashes and for stars near the limb passing through the field of view (the field stars) as well as to display the lunar contrast which was used to exclude periods of clouds and poor photometric quality. This information was used to select the flashes and observation time spans as described in Section 4.1. LunaCon was also used to determine the lunar area within the field of view.

3. Photometric calibration

Standard aperture photometry was applied to the flashes and the field and reference stars used for calibration. Images were flatfielded using skyflats. The impact flash video field (1/60 s) with the largest signal was used in these analyses. Ernst and Schultz (2005) showed that the peak luminous energy in their hypervelocity gun tests occurred on the 10–20 μs time scale. The video exposure time is 1000 times longer even after adjustment for the impactor diameter to velocity ratio they used. Bouley et al. (2012) suggest that luminous efficiencies determined using the entire light curve for Leonids might indicate differences in the impactor or the lunar soil at the impact site. Yanagisawa and Kisaichi (2002) proposed that the prolonged afterglows they observed for impact flashes were due to thermal emission from droplets of lunar soil vaporized and recondensed in flight. Thus the best estimate of impact kinetic energy comes from the shortest exposure time rather than the entire light curve. Subsequent video frames give good information on the rate of cooling of ejecta material (Bouley et al., 2012) but no useful information on the kinetic energy of the impact.