Planetary and Space Science ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Characterization and Analysis of Near-Earth Objects via Lunar Impact Observations

J. Jedediah Rembold*, Eileen V. Ryan

New Mexico Institute of Mining and Technology, 801 Leroy Pl, Socorro, NM, 87801, USA

ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form
9 April 2015
Accepted 25 May 2015

Keywords:
Asteroids
Moon
Near-Earth objects

ABSTRACT

Asteroid events such as the air blast above Chelyabinsk, Russia, in the spring of 2013 have highlighted the importance of understanding Earth's local asteroid population and the potential threat they pose. While much observational data exists for larger asteroids (those greater than 50 meters in diameter), comparatively little is known of the very small meteoroid population. This study utilized the non-illuminated part of the near side of the Moon as a detection screen upon which the faint flashes of small meteoroids hitting the lunar surface could be detected. Over 80 hours of observations were conducted between the fall of 2010 and the spring of 2013. The observed lunar area was determined nightly and used alongside the impact count to determine a meteoroid flux rate. Impact flashes were calibrated to extinction and color corrected reference stars to estimate the kinetic energies involved. Analysis indicated an average flux rate of 1.09×10^{-7} km^{-2} h^{-1}, corresponding to 1 impactor larger than 3 centimeters in diameter observed every 30 minutes. Further, the size distribution dependence of small impactors was found to be consistent with the power law governing the larger-size meteoroid distribution. This data helps fix the low-end of the asteroid size distribution for solar system evolution models.

1. Introduction

The dangers of large meteors impacting the Earth have long been the subject of both scientific observation (the Tunguska event in 1908 or the Chelyabinsk air burst in 2013) and popular movie speculation. While much effort has been invested in observing and counting potentially Earth threatening asteroids, less has been devoted to their smaller brethren. This is partly due to the difficulty in observing very small meteoroids through conventional means. In an effort to gain more insight into the small size regime of the near Earth asteroid population, this study has utilized lunar impact observations.

Theorized by Melosh et al., 1993 lunar flashes are caused by collisions between small meteoroids and the lunar surface (Melosh et al., 1993). Light from the resulting impact is detectable against the darker background of the lunar night side. Counting and analyzing these flashes provides both a method of detecting small meteoroids as well as leveraging an immense natural detection screen. Many impacts have been observed to date with initial detections primarily during meteor showers (Ortiz et al., 2000; Dunham et al., November 1999; Ortiz et al., 2002; Yanagisawa et al., 2006) and later extending to include non-shower impacts, commonly called sporadics (Ortiz et al., 2006; Trigo-Rodriguez et al., 2006).

While an initial flux rate can be determined purely from an impact count and measurements of observation area and time, it is desirable to also determine the energy or approximate size of the impacting object. This requires knowledge of the percentage of impact energy that goes into the visible flash, called the luminous efficiency. Methods for determining the luminous efficiency differ, with some comparing models to measurements (Ortiz et al., 2000) and others based on thermodynamics (Sigismondi and Imponente, 2001). More recently, methods utilizing a gas gun firing projectiles into a lunar surface analog have been combined with lunar impact flash observations (Swift et al., 2011; Moser et al., 2011). The work reported in this paper followed the methods of Swift et al. (2011), who determined that the luminous efficiency, η, is a function of the projectile speed:

$$\eta(v) = 1.5 \times 10^{-3}\, e^{-(9.3\ \mathrm{km}\ s^{-1}/v)^2} \quad (1)$$

where v is the impact velocity in km s^{-1}. Typical velocities range from 16.9 km s^{-1} for sporadics (Steel, 1996) to 71 km s^{-1} for the fastest meteor showers, resulting in luminous efficiencies ranging from 0.11% to 0.15%, respectively. These values are slightly lower than the 0.2% estimated by Ortiz et al. (2006), but are bracketed by the 0.05% to 0.5% range used by Bouley et al. (2012).

* Corresponding author. Tel.: +1 503 560 2923.
E-mail address: jedediah.r@gmail.com (J.J. Rembold).

http://dx.doi.org/10.1016/j.pss.2015.05.014

Application of the luminous efficiencies alongside calibrated impact magnitudes result in estimates of impactor kinetic energy, and thus an energy distribution can be inferred. Knowledge of the small-size regime of the asteroid size distribution has important implications both in modeling of solar system evolution (Davis et al., 2002), and well as understanding potential perturbations of asteroids from the main belt to Earth crossing orbits (Morbidelli, 2002). Few academic papers have been published contributing to this small-size regime, with large contributions early by Halliday et al. (1996) and Brown et al. (2002) from fireball studies in the Earth's upper atmosphere. Lunar impact observations by NASA's Marshall Space Flight Center are a large recent contributor to this small-size regime of the asteroid size distribution (Cooke et al., ; Suggs et al., 2014). The primary purpose of this research was to extend the dataset of observed lunar impacts, including the energy distribution. An alternative impact detection process was also investigated, and impact groups were analyzed for relationships between impact speed, impacted terrain, and the observed signal.

2. Observation and Analysis Methodology

2.1. Observational Setup

Observations were conducted on the outskirts of Socorro, NM (34.1° N, 106.9° W) using a 14-inch Meade LX200 telescope with f/3.3 focal reducer to increase the field of view. The Watec 902H2 Ultimate CCD camera was used, recording at 29.97 frames per second, interlaced, and with 720x480 resolution. The camera was operated using manual analog gain control with the gain tuned to the highest sensitivity possible without frequently over-exposing the sensor on impact detection. This setup resulted in a field of view of approximately 30 arcminutes by 22 arcminutes. Camera positioning attempted to maximize the observable portion of the lunar surface while keeping any of the illuminated lunar limb out of the frame, as seen in Fig. 1.

Observations were made when the lunar phase was between 10% to 40%. Below 10% the amount of time the Moon was observable was insignificant, while above 40% glare from the illuminated lunar surface began obscuring the observations. Video files were searched for flash candidates using the software *LunarScan*, developed by Peter Gural[1]. Default *LunarScan* options were used, with the exception of the primary detection threshold, which was lowered for increased sensitivity, and the automatic lunar surface region control, which was disabled to ensure the entire region was always analyzed. *LunarScan* determines impact candidates by searching for clusters of pixels which exceed the set threshold above the lunar background. Candidates are displayed for user confirmation upon completion of the analysis.

Impact flash photometry was done with *LiMovie*, written by Kazuhisa Miyashita[2]. The frameserver *AviSynth*[3] was used to enable direct analysis of the video without requiring extra re-encoding into *LiMovie* readable formats. The open source *Octave* scripting language was used for all other analysis, including impact location determination and lunar area calculations.

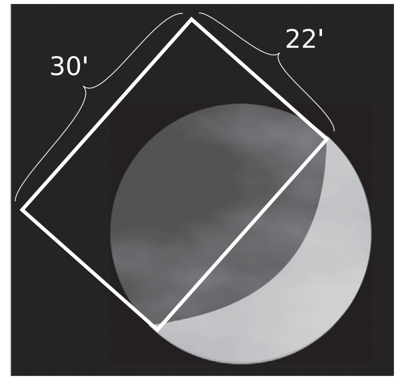

Fig. 1. Typical camera placement and field of view during observations. The field of view measured approximately 30 arcminutes by 22 arcminutes, and was situated to contain as much lunar surface as possible while precluding the brightly lit lunar terminator.

2.2. Calibration

Standard aperture photometry was used for all calibration. Images were flat-field corrected. In several cases impacts were visible over multiple fields. Ernst and Schultz (2005) found that the luminous energy in gun range collisions peaks around 18 μs, much faster than the 17 ms exposure time used in this research. Additionally, Yanagisawa and Kisaichi (2002) proposed radiation from hot droplets ejected during the collision might extend flash duration, while Bouley et al. (2012) suggests flash duration may be dependent on crater size and formation. Syal et al. (2014) have also recently shown that impactor collision angle may play a significant role in perceived flash duration. As such, to limit the effects of regolith composition, plume expansion and impact angle, only the peak flash intensity was used to calculate impactor kinetic energy. This means multi-field impact flashes may slightly underestimate the impactor kinetic energy, but this error is slight in comparison to the luminous efficiency uncertainty. Observations were done without a filter to maximize sensitivity. The Watec CCD spectral response peaks at 600 nm, and thus impacts were calibrated to the Johnson-Cousins R band. It was often the case that no stars were visible at the time of impact. As such, reference stars were measured at the beginning of each night, though stars in the impact field-of-view were utilized when available. Magnitudes were corrected for extinction using October 2012 measurements of reference stars between 1 and 4 airmass. Zero-points were calculated each night. Owing to the spectral response of the Watec camera, impacts were color corrected following the methods of Suggs et al. (2014), where the convolved spectral responses of the Watec with a blackbody and Vega were compared to derive a correction factor. This factor is relatively stable near the estimated temperatures of lunar impacts, and was measured to be -0.65 for this work.

2.3. Converting Magnitudes to Impactor Physical Properties

To estimate the kinetic energy of each impactor, calibrated magnitudes were first converted to observed luminous energy. By Bessell et al. (1998), the flux density can be written:

$$f_\lambda = 10^{-7} \cdot 10^{-(R+21.1+0.555)/2.5} \tag{2}$$

where R is the R magnitude, 21.1 the zero point for Vega in the V band, and 0.555 the R band correction factor. Units are in W/cm^2/Å. The luminous energy observed at Earth (E_{obs}) was determined assuming a hemispherical light emission due to close proximity with the lunar surface, and received at Earth over time Δt. The observed luminous energy was thus written:

[1] LunarScan Version 1.5, Available from http://www.gvarros.com/lunarscan15.zip

[2] LiMovie Version 0.9.29b, Available from http://astro-limovie.info/occultation_observation/limovie_en.html

[3] AviSynth Version 2.6.0 ST, Available from http://avisynth.nl/index.php/Main_Page

Please cite this article as: Rembold, J.J., Ryan, E.V., Characterization and Analysis of Near-Earth Objects via Lunar Impact Observations. Planetary and Space Science (2015), http://dx.doi.org/10.1016/j.pss.2015.05.014