Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon Derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids

D. E. Moser • R. M. Suggs • W. R. Swift • R. J. Suggs • W. J. Cooke • A. M. Diekmann • H. M. Koehler

Abstract Since early 2006, NASA's Marshall Space Flight Center has been routinely monitoring the Moon for impact flashes produced by meteoroids striking the lunar surface. During this time, several meteor showers have produced multiple impact flashes on the Moon. The 2006 Geminids, 2007 Lyrids, and 2008 Taurids were observed with average rates of 5.5, 1.2, and 1.5 meteors/hr, respectively, for a total of 12 Geminid, 12 Lyrid, and 12 Taurid lunar impacts. These showers produced a sufficient, albeit small sample of impact flashes with which to perform a luminous efficiency analysis similar to that outlined in Bellot Rubio et al. (2000a, b) for the 1999 Leonids. An analysis of the Geminid, Lyrid, and Taurid lunar impacts is carried out herein in order to determine the luminous efficiency in the 400-800 nm wavelength range for each shower. Using the luminous efficiency, the kinetic energies and masses of these lunar impactors can be calculated from the observed flash intensity.

Keywords hypervelocity impact · impact flash · luminous efficiency · lunar impact · meteoroid

1 Introduction

When a meteoroid strikes the Moon, a large portion of the impact energy goes into heat and crater production. A small fraction goes into generating visible light, which results in a brilliant flash at the point of impact that can be seen from Earth. The luminous efficiency, η, relates how much of the meteoroid's kinetic energy, KE, is converted into luminous energy, LE, in wavelength range, λ.

$$LE_{\lambda} = \eta_{\lambda} KE \tag{1}$$

The luminous efficiency plays a vital role in understanding observations and constraining models of the near-Earth meteoroid environment. Experiments into lunar regolith simulant at *low velocities* (2 to 6 km/s) have been performed at hypervelocity gun test ranges in order to determine η (Swift et al., 2010), but *high velocities* – meteoroid speeds, 18 to 71 km/s – are impossible to replicate in the laboratory using particle sizes typical of meteoroids. Scaling these low velocity luminous efficiency results to the

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high velocity regime results in luminous efficiencies greater than 1 – a result that is completely unphysical. Numerical hydrocode simulations, like that of Nemtchinov et al. (1999), have mainly focused on particles of asteroidal composition moving at low speeds. There are limited simulations of high speed cometary particles impacting the Moon (e.g. Artem'eva et al., 2001).

Impact flashes have been successfully observed on the Moon by Earth-based telescopes during several showers (e.g. Dunham et al., 2000; Ortiz et al., 2000; Cudnick et al., 2002; Ortiz et al., 2002; Yanagisawa & Kisaichi, 2002; Cooke et al., 2006; Yanagisawa et al., 2006, Cooke et al., 2007; Suggs et al., 2008a,b; Yanagisawa et al., 2008). Observations of lunar impact flashes associated with meteor showers offer an opportunity to measure η at high velocities, since some properties of the impactors, like direction and speed, are known. This was first accomplished by Ortiz et al. (2000) and later detailed in Bellot Rubio et al. (2000a, b) for the 1999 Leonid lunar impact flashes.

The NASA Marshall Space Flight Center (MSFC) has routinely monitored the un-illuminated portion of the Moon for lunar impact flashes in the 400-800 nm range. As the Earth has witnessed several meteor showers in the past few years, so has the Moon. Since the beginning of our monitoring program in 2006, we have captured video of probable Leonid, Geminid, Lyrid, Quadrantid, Orionid, Bootid, Southern Delta-Aquariid, and Taurid meteoroid impacts on the Moon. Multiple lunar impact flashes were detected during the 2006 Geminids, 2007 Lyrids, and 2008 Taurids, allowing for a luminous efficiency analysis like that performed by Bellot Rubio et al. (2000b) for the 1999 Leonids.

This paper is organized as follows: in Section 2, an overview of the lunar impact monitoring program is given, with specifics regarding the data collected during the showers of interest. In Section 3, the luminous efficiency analysis is described, with the results for each shower presented and discussed in Section 4.

2 Observations

2.1 Lunar Impact Monitoring Program Overview

MSFC conducts observations from the Automated Lunar and Meteor Observatory (ALaMO) located in Huntsville, Alabama, USA (34.°66 N, 86.°66 W) and the Walker County Observatory (WCO) near Chickamauga, Georgia, USA (34.°85 N, 85.°31 W). The un-illuminated (earthshine) portion of the Moon is simultaneously observed with two identical Meade RCX-400 0.35 m diameter Cassegrain telescopes, online in June 2006 and September 2007, and one RCOS 0.5 m diameter Ritchey-Chrétien telescope, online in January 2008; two telescopes reside at the ALaMO with the remainder at WCO. The ALaMO telescopes are outfitted with focal reducers resulting in nearly identical 20 arcmin fields of view covering approximately 4×10^6 km^2 or about 10% of the lunar surface. ASTROVID StellaCamEX and Watec 902-H2 Ultimate monochrome CCD cameras (400-800 nm bandwidth) are employed to monitor the Moon. The interleaved, 30 fps video is digitized and recorded straight to hard-drive.

Impact flash detection and analysis is performed by two custom programs: LunarScan (Gural, 2007) and LunaCon (Swift et al., 2008). LunarScan software is used to detect impact flashes in the video. LunaCon determines flash magnitudes, time on target, photometric quality (including sky condition), and lunar area within the field of view. Candidate flash detections are those multi-pixel flashes simultaneously detected in two or more telescopes at the same selenographic location or those that are more than 1 frame (1/30 s), or two video fields (1/60 s each) in duration. Candidate flashes do not exhibit any motion from video field to field but do demonstrate a suitable light curve: a sudden brightness increase followed by a gradual decrease. These criteria rule out cosmic rays, electronic noise, and most sun glints from orbiting satellites. The WCO telescope, located about 125 km from the ALaMO, functions only to eliminate any additional satellite sun glints via parallax. Short flashes observed before the second observatory came online, or flashes not detected by this third telescope due to weather, viewing geometry, or equipment problems, are checked against the unclassified satellite catalog.

Observations of the un-illuminated portion of the Moon are typically conducted when sunlight illuminates between 10 and 50% of the Earth-facing surface. This yields a maximum of 10 observing nights per month. At illuminations greater than 50%, the scattered light overwhelms the video and faint flashes go undetected. Observing at illuminations less than 10% is considered an inefficient use of time and resources since the time between twilight and moon set or moon rise is very limited at these phases. Additional descriptions of the lunar impact monitoring program and analysis techniques are given in Suggs et al. (2008a,b) and Suggs et al. (2010).

2.2 Shower Data

The illumination criterion and weather conditions resulted in several nights of observations at/near the peak of the 2006 Geminids, 2007 Lyrids, and 2008 Taurids. Table 1 lists the observation dates coinciding with the showers, the telescopes employed, and the number of hours of data recorded that were of a consistent photometric quality. The 2006 Geminids, 2007 Lyrids, and 2008 Taurids were observed a total of 2.18 hrs, 10.22 hrs, and 7.93 hrs, respectively. Candidate flashes are associated with a shower if they occur within days of the shower peak and are located in an area on the Moon that is visible to the radiant. Visibility plots for each shower are shown in Figures 1.

Table 1. List of observing times during the 2006 Geminids, 2007 Lyrids, and 2008 Taurids. All times UT.

Date	Shower	Telescopes	Obs Timespan	Obs Time (hr)
14 Dec 2006	Geminids	two 0.35 m	08:30 – 09:29	0.98
15 Dec 2006	Geminids	two 0.35 m	09:12 – 10:24	1.20
20 Apr 2007	Lyrids	two 0.35 m	01:18 – 02:24	1.10
21 Apr 2007	Lyrids	two 0.35 m	01:16 – 03:18	2.03
22 Apr 2007	Lyrids	two 0.35 m	01:12 – 04:29	3.28
23 Apr 2007	Lyrids	two 0.35 m	01:11 – 05:00	3.81
02 Nov 2008	Taurids	0.5 m, two 0.35 m	00:04 – 00:47, 23:46 – 24:00	0.95
03 Nov 2008	Taurids	0.5 m, two 0.35 m	00:00 – 00:13, 00:30 – 01:33, 23:42 – 24:00	1.57
04 Nov 2008	Taurids	0.5 m, two 0.35 m	00:00 – 02:09, 23:42 – 24:00	2.45
05 Nov 2008	Taurids	0.5 m, two 0.35 m	00:00 – 02:58	2.96

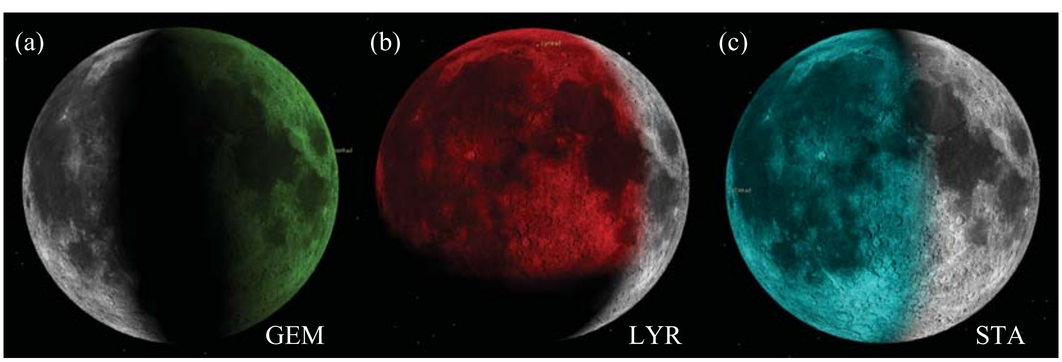

Figure 1. Shower visibility for the (a) 2006 Geminids, (b) 2007 Lyrids, and (c) 2008 Taurids. The colored portion indicates the area of the un-illuminated Moon visible to the radiant.

In all, 12 Geminid, 12 Lyrid, and 12 Taurid impacts were detected during periods of consistent photometric quality. (The data for an additional 8 Geminids, 3 Lyrids, and 2 Taurids detected during the monitoring period was of poor quality and is not considered here.) The details for each flash are given in Table 2.

Table 2. Details of the lunar impact flashes detected during the 2006 Geminds, 2007 Lyrids, and 2008 Taurids.

Shower [*obs time*]	ID	Date	Time (UT) ± 0.02s	Duration (ms)	R Mag	Lum. Energy, LE_{cam} (J)
Geminids	G01	14 Dec 2006	08:32:06.647	33	+9.2	5.6×10^4
[*2.18 hrs*]	G02	14 Dec 2006	08:32:51.993	50	+8.9	7.1×10^4
	G03	14 Dec 2006	08:39:57.155	17	+9.8	3.1×10^4
	G04	14 Dec 2006	08:46:01.957	17	+9.6	3.7×10^4
	G05	14 Dec 2006	08:50:36.200	33	+8.4	1.2×10^5
	G06	14 Dec 2006	08:51:20.562	17	+9.1	6.2×10^4
	G07	14 Dec 2006	08:56:42.837	17	+8.7	8.5×10^4
	G08	14 Dec 2006	09:00:22.142	33	+8.4	1.2×10^5
	G09	14 Dec 2006	09:03:32.851	33	+9.8	3.1×10^4
	G10	15 Dec 2006	09:15:14.040	33	+8.4	1.1×10^5
	G11	15 Dec 2006	09:17:39.336	17	+7.6	2.3×10^5
	G12	15 Dec 2006	09:53:28.464	83	+6.4	7.0×10^5
Lyrids	L01	20 Apr 2007	01:40:04.044	50	+7.8	2.1×10^5
[*10.22 hrs*]	L02	22 Apr 2007	01:15:05.616	67	+8.8	7.9×10^4
	L03	22 Apr 2007	01:15:43.956	33	+10.0	2.6×10^4
	L04[a]	22 Apr 2007	01:38:33.864	33	+8.0	1.6×10^5
	L05[b]	22 Apr 2007	03:12:24.372	67	+6.8	4.9×10^5
	L06	22 Apr 2007	03:52:37.182	17	+9.1	6.0×10^4
	L07	23 Apr 2007	01:15:54.547	17	+8.7	8.5×10^4
	L08	23 Apr 2007	02:23:21.361	50	+8.8	7.7×10^4
	L09	23 Apr 2007	04:08:48.755	50	+8.0	1.7×10^5
	L10	23 Apr 2007	04:40:45.912	33	+9.2	5.6×10^4
	L11	23 Apr 2007	04:42:34.781	83	+6.4	7.1×10^5
	L12	23 Apr 2007	04:59:57.557	50	+7.3	3.3×10^5
Taurids	T01	02 Nov 2008	23:48:39.996	50	+9.4	4.5×10^4
[*7.93 hrs*]	T02	03 Nov 2008	00:11:06.144	50	+7.9	1.9×10^5
	T03	03 Nov 2008	00:33:37.620	50	+9.1	6.0×10^4
	T04	03 Nov 2008	23:59:24.504	50	+8.7	9.0×10^4
	T05	04 Nov 2008	00:04:06.060	50	+8.9	7.2×10^4
	T06	04 Nov 2008	01:10:01.272	67	+8.1	1.5×10^5
	T07	04 Nov 2008	01:39:03.744	67	+6.3	7.8×10^5
	T08	05 Nov 2008	00:38:37.860	117	+7.4	2.9×10^5
	T09	05 Nov 2008	00:53:58.308	67	+8.5	1.1×10^5
	T10	05 Nov 2008	02:05:07.908	100	+7.3	3.0×10^5
	T11	05 Nov 2008	02:09:44.748	50	+9.3	4.9×10^4
	T12	05 Nov 2008	02:32:47.184	67	+8.1	1.5×10^5

[a] Also detected by independent observer Dave Clark in Houston, Texas, USA using a 0.2 m Schmidt Cassegrain telescope.

[b] Also detected by independent observer George Varros in Mt Air, Maryland, USA using a 0.2 m Newtonian telescope.

All of the events had durations between 17 and 117 ms and magnitudes between +10.0 and +6.3. Impact flash locations are shown in Figure 2. Figures 3 and 4 give a sample of impact flashes detected during each shower, shown as video stills of the impact flash on the Moon, and as a sequence of 1/30 s image squares, respectively.

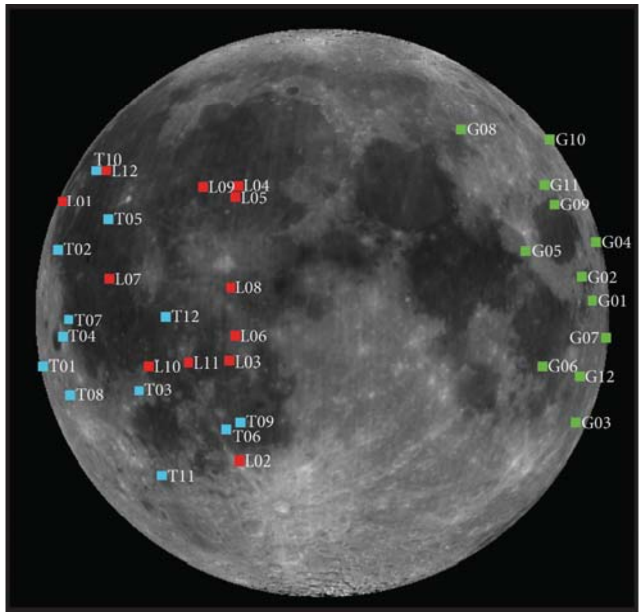

Figure 2. Observed lunar impact locations. Numbering scheme refers to Table 2.

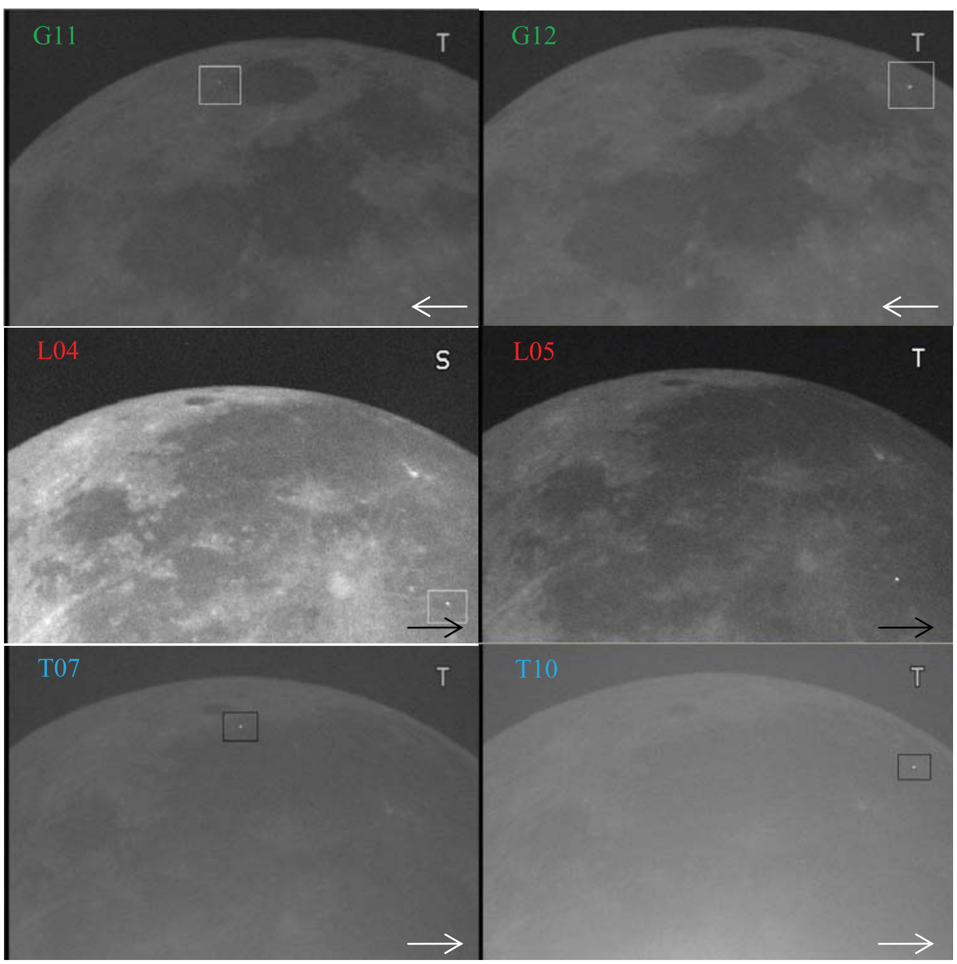

Figure 3. A sample of lunar impact flashes detected during the 2006 Geminids, 2007 Lyrids, and 2008 Taurids. Arrows indicate the direction of selenographic north. The numbering scheme refers to Table 2.

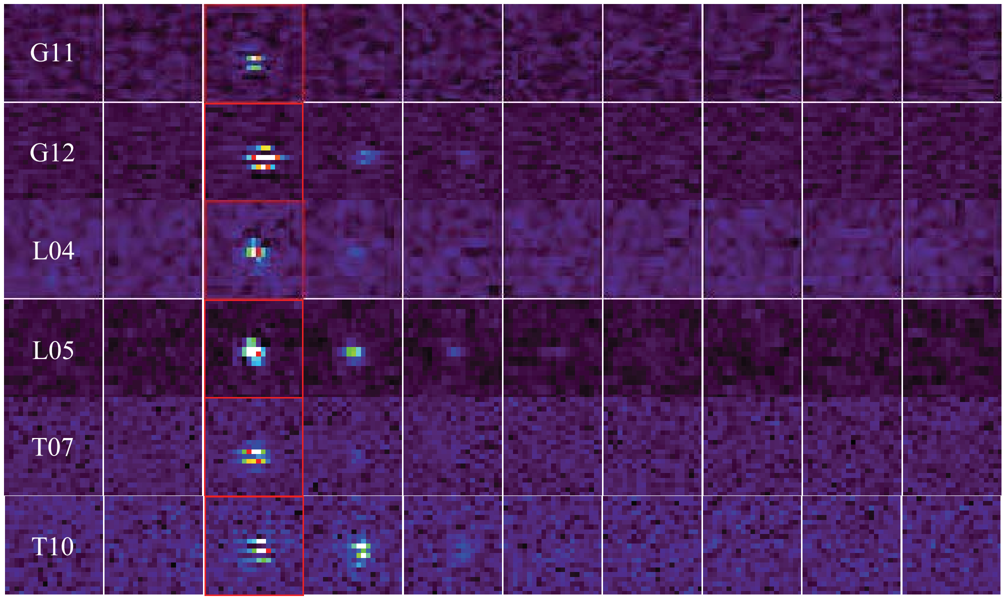

Figure 4. A sample of lunar impact flashes detected during the 2006 Geminids, 2007 Lyrids, and 2008 Taurids. The dimensions of each square in the series are about 35 x 35 arcseconds and each covers 1/30 s. The numbering scheme refers to Table 2.

The amount of sporadic contamination in this sample of meteoroids can be crudely calculated. Using the Grün sporadic flux model (Grün, 1985), and taking lunar shielding into account, it is estimated that roughly 3 of the 36 impact flashes may be caused by sporadic meteoroids as opposed to shower meteoroids. But there is no way to remove this contamination.

3 Luminous Efficiency Analysis

3.1 Theory

The technique for determining luminous efficiency incorporates the method first referenced by Ortiz et al. (2000) and then detailed by Bellot Rubio et al. (2000a, b). Their method is restated in this section and referenced in the text hereafter as BR2000. In addition to this method, an iterative process is used to determine the final luminous efficiency η, and is better suited to discussion alongside a description of the flux parameter inputs in Section 3.2.5.

The number of meteoroids that impact the Moon in time span t_1 to t_2 is

$$N = \int_{t_1}^{t_2} F(t) A_{\perp}(t) dt \tag{2}$$

where $F(t)$ is the flux as a function of time, t, and $A_{\perp}(t)$ is the observed lunar area that is perpendicular to the meteor shower radiant also as a function of time.

The cumulative flux distribution of meteoroids of mass m is given by

$$F(m) = F(m_0)\left(\frac{m}{m_0}\right)^{1-s} \tag{3}$$

where $F(m)$ is the flux of particles having mass greater than m, $F(m_0)$ is the flux of particles of known mass greater than mass m_0, and s is the mass index.

The masses of the meteoroids impacting the Moon are unknown. For an impactor of mass m and velocity V, the kinetic energy is $KE = ½\ m\ V^2$. Substituting this into Eq (3) gives a cumulative flux distribution as a function of kinetic energy.

$$F(KE) = F(m_0)\left(\frac{2KE}{V^2 m_0}\right)^{1-s} \tag{4}$$

Solving Eq (1) for KE and substituting this into Eq (4) gives a cumulative flux distribution as a function of luminous energy, depending on the luminous efficiency η_λ in a particular wavelength range.

$$F(LE_\lambda) = F(m_0)\left(\frac{2LE_\lambda}{\eta_\lambda V^2 m_0}\right)^{1-s} \tag{5}$$

Using Eq (5), Eq (2) becomes the number of lunar meteoroid impacts producing luminous energies greater than LE_λ in the time span t_1 to t_2.

$$N(LE_\lambda) = \left(\frac{2LE_\lambda}{\eta_\lambda V^2 m_0}\right)^{1-s} \int_{t_1}^{t_2} F(m_0, t) A_\perp(t) dt \tag{6}$$

This result is comparable to Eq (4) of BR2000.

In short, the analysis technique involves 'backing out' the luminous efficiency by matching the number of impacts expected on the Moon to that actually observed. One of the difficult problems in using this technique alone derives from uncertainties in the various inputs, namely the flux and mass index. This is discussed in the next section.

3.2 Inputs

The inputs for Eq (6) in the 400-800 nm range are summarized in Table 3 and outlined in the following sub-sections.

Table 3. Input parameters for Eq (6) for the 2006 Geminids, 2007 Lyrids, and 2008 Taurids. The *average* area perpendicular to the radiant in the field of view is given, for illustration purposes.

Shower	V (m/s)	s	$F(m_0,t)$ (#/m^2/hr)	m_0 (kg)	t_1, t_2 (hr)	$A_{\perp ave}$ (km^2)	LE_{cam} (J)
Geminids	35000	1.9	*Suggs*	4.7×10^{-2}	*from*	3.2×10^6	*from*
Lyrids	49000	1.7	*et al.*	8.4×10^{-2}	*Table*	1.1×10^6	*Table*
Taurids	27000	1.8	*(2010)*	2.4×10^{-2}	*1*	3.6×10^6	*2*

3.2.1 Luminous Energy, LE_λ

The energy received at Earth [J/m^2] is calculated using

$$\varepsilon_\oplus = \tau \cdot Flux_{0\lambda} 10^{-0.4 m_\lambda} \tag{7}$$

where τ is the camera exposure time [s], $Flux_{0\lambda}$ is the flux [J/m^2/s] from a zero magnitude star in the camera's wavelength range λ, and m_λ is the measured magnitude of the impact flash. Stellacam and

Watec cameras operate in the 400-800 nm range with a peak response approximated by the R passband. Flash photometry is performed utilizing local background stars in the video as reference and Vega is used as the calibration star with $Flux_{0R} = 3.39\times10^{-9}$ J/m^2/s. The exposure time of the camera is 0.0167 s.

The luminous energy at the Moon [J] is related to the energy received at Earth by

$$LE_{\lambda} = f\ \pi\ d^2 \varepsilon_{\oplus} \tag{8}$$

where f is a factor describing the distribution of the light ($f = 4$ for spherical emission into 4π steradians, $f = 2$ for hemispherical emission into 2π steradians, etc.) and d is the distance in meters between the impact flash on the Moon and the telescope on Earth. It is chosen that $f = 4$, since the radiating plume is most likely above the surface, created from hot meteoroid and regolith materials, and d is assumed a constant 3.84×10^8 m. The resulting luminous energies for each flash, including a correction factor to produce energies in the camera's passband, are seen in Table 2 as LE_{cam}. For more photometry details, see Swift et al. (2008).

This differs from the inputs in the BR2000 method in the choice of f (the compromise $f = 3$) and wavelength range (400-900 nm). In addition, the cameras used in their study peak in the visual range, whereas the cameras we use peak in the red-NIR.

3.2.2 Time Span, t_1 to t_2

Observing sessions typically run from moonrise to twilight (waning phases) or twilight to moonset (waxing phases). Only those times that are of a consistent photometric quality are used in the analysis. For each video, plots of lunar disk brightness and contrast versus time are examined. Any video segments that exhibit obvious cloud attenuation, a loss of contrast due to cirrus haze or fogged optics, a rapid change in extinction during moonrise or moonset, twilight, or obvious obstructions from the observatory dome or trees, are excluded. The time spans $t_1 - t_2$ used in this analysis are listed in Table 1.

3.2.3 Perpendicular Lunar Area, $A_{\perp}(t)$

During each observing session the Moon drifts slightly within the telescope's field of view, thereby changing the amount of lunar surface area detected. The LunaCon analysis software identifies and calculates the lunar area visible in the video. This is accomplished by first detecting the location of the limb within a video frame and solving for the center and radius of the lunar disc in image pixels. From the radius, the lunar area of the center pixel is calculated in square kilometers, and, knowing the radial distance of each pixel in the lunar image, a weight is applied for each pixel to compensate for spherical Moon effects (an image pixel near the limb contains more area than one near the center of the disc); pixels at the lunar limb with *extreme* weights are discarded. Summing over all the lunar pixels in the image with their appropriate weights yields the total lunar area. In this way, the lunar area within the field of view as a function of time is determined (Swift et al., 2008).

To determine the lunar area perpendicular to the shower direction within the field of view, $A_{\perp}(t)$, the area as a function of time determined by LunaCon is modeled as 1 million equal area cells. The area in each cell is multiplied by the cosine of the zenith angle of the radiant. Summing yields the total perpendicular lunar area within the field of view as a function of time. For illustration purposes, the average perpendicular area, $A_{\perp\,ave}$, for each shower is given in Table 3.

In comparison, the BR2000 method calculates $A_{\perp}$ using Monte Carlo simulations and it is considered a constant during the 90 min of Leonid observations they performed in 1999.

3.2.4 Shower Parameters, V and s

The speeds, V, and mass indices, s, for each shower are taken from the annual meteor shower tables compiled by the International Meteor Organization (IMO, 2006, 2007, 2008). Gravitational effects from the Earth and Moon are not considered in the velocity parameter as they are too small to be considered significant. The mass index characterizing the mass distribution of (small) shower meteors in the visual range may not be applicable to large particles. As there are no measurements of the mass index for these shower meteoroids in the lunar impactor size range, it is only possible to estimate s from shower observations; this makes s a rather uncertain parameter input. The speeds and mass indices used are listed in Table 3.

In comparison, the BR2000 method explored the luminous efficiency results from two different mass indices. The first was an extrapolated mass index from the 1999 terrestrial Leonid fireballs of the IMO Visual Meteor Database and the second was a constant $s = 2.0$.

Looking at the effects of varying s has not yet been done for the showers discussed here and is classified as future work.

3.2.5 Flux Parameters, $F(m_0,t)$ and m_0

To determine the flux parameters, the lunar impacts were first considered as an ensemble. The MSFC detected 115 lunar impact flashes in 212 hours of observing between 2006 and 2009, the majority of which are most probably produced by shower meteoroids (Suggs et al., 2010). We calculate an initial limiting magnitude and subsequently an initial limiting kinetic energy based on the ensemble lunar impact data, incorporating previously determined luminous efficiency values based on gun test work (Suggs et al., 2008b) and the 1999 Leonid work by Bellot Rubio et al. (2000). This, in turn, is used to calculate the number of impacts we should have detected, based on observed and historical IMO ZHR data, and given the lunar collecting area in the field of view, observing time, and the shower geometry. Matching the observed and expected number values requires adjustment of the luminous efficiency or limiting magnitude. As there is more uncertainty in the limiting magnitude, this value was adjusted to best fit IMO observations, resulting in a final limiting kinetic energy corresponding to a mass of 100 g moving at a speed of 25 km/s. The final limiting mass, m_0, for each shower yielding the equivalent final limiting kinetic energy is given in Table 3. The flux corresponding to this limiting mass is $F(m_0)$ and the data and time dependence is taken from the observed lunar impact flux, removing any impact flashes that have a magnitude fainter than the corresponding final limiting magnitude . For a more in depth discussion on the flux determination, see Suggs et al. (2010).

The procedure described above is just the first step in an iterative process. Using the 'final' limiting mass determined from the *ensemble* of lunar impacts, which incorporates an initial luminous efficiency estimate, a new luminous efficiency is calculated based on the energies of the *individual* lunar impact flashes using the technique outlined in Section 3.1. The new luminous efficiency is then used to compute a more accurate limiting energy, as in the above paragraph, and the process repeats until convergence.

The determination of the flux at the Moon in the original BR2000 method is quite different. The method scales the terrestrial flux for the 1966 Leonids by a factor of 4 and adopts the timing of the terrestrial 1999 Leonids, shifted to the Moon. Their fluxes are tied to the mass of a Leonid meteoroid producing a meteor of magnitude +6.5 on Earth.

Looking at the ensemble of lunar impacts and comparing it to observations on Earth, we have instead determined a lunar flux for each shower, $F(m_0, t)$, of particles with mass greater than the limiting mass, m_0. Fluxes are discussed in Suggs et al. (2010) and the limiting mass for each shower is listed in Table 3.

4 Results and Discussion

As stated previously, the analysis technique involves 'backing out' the luminous efficiency by matching the number of impacts expected on the Moon to that actually observed. The expected cumulative number of lunar meteoroid impacts, $N(LE_\lambda)$, producing luminous energies greater than LE_λ (as discussed in Section 3) for the 2006 Geminids, 2007 Lyrids, and 2008 Taurids is plotted in Figures 5 alongside the observed cumulative lunar impacts using two different energy binning schemes. Fig 5(a) shows

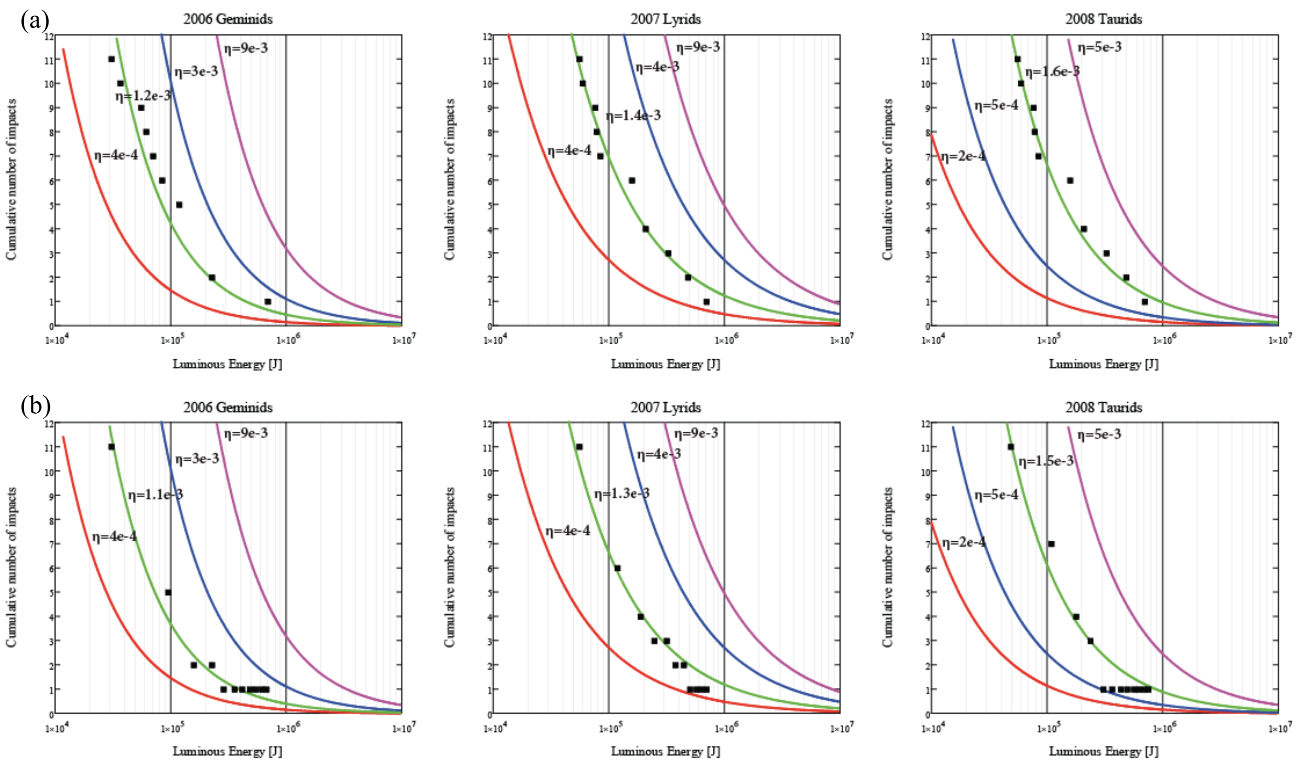

Figure 5. $N(LE_\lambda)$ vs LE_λ, the comparison between expected number of cumulative impacts (colored solid lines) and observed data (black squares) for two different energy binning schemes for the 2006 Geminids, and 2007 Lyrids, and 2008 Taurids. (a) No binning of luminous energy observed during the impact flash, (b) observed luminous energies are binned with bin size = 65,000 J. Wavelength λ is 400-800 nm.

the comparison between expected cumulative number of impacts at various values of luminous efficiency and observed number using almost no binning, since number statistics are poor. Fig 5(b) shows this same comparison with luminous energy bins set at 65,000 J. Binning using the two different schemes yields similar results for luminous efficiency in the 400-800 nm range, η_{cam}, as listed in Table 4 and illustrated in Figures 5.

Table 4 Calculated luminous efficiencies η_{cam} for the 2006 Geminids, 2007 Lyrids, and 2008 Taurids using two different binning schemes (a) and (b); listed in order of increasing velocity. An estimated impactor mass range corresponding to the flashes we detected for each shower is also calculated.

Shower	# Flashes	Obs. Time (hrs)	V (km/s)	s	η_{cam} (a)	η_{cam} (b)	Mass Range (kg)
2008 Taurids	12	7.93	27	1.8	1.6×10^{-3}	1.5×10^{-3}	0.09-1.4
2006 Geminids	12	2.18	35	1.9	1.2×10^{-3}	1.1×10^{-3}	0.04-0.99
2007 Lyrids	12	10.22	49	1.7	1.4×10^{-3}	1.3×10^{-3}	0.03-0.44
*1999 Leonids**	*5*	*1.5*	*72*	*1.83*	2×10^{-3}	*n/a*	*0.12-4.9*

* Bellot Rubio et al. (2000a, b), shown for reference. Results are from a different camera with a different λ range.

Errors in η_{cam} may be on the order of a few percent. The Bellot Rubio et al. (2000a, b) result for the 1999 Leonids is reproduced in Figure 6. A better agreement between the observed number of impacts and the expected number of impacts was found in this work than in Bellot Rubio et al. (2000a, b), as seen by a comparison of Figures 5 and 6, indicating a perhaps more reliable value of luminous efficiency.

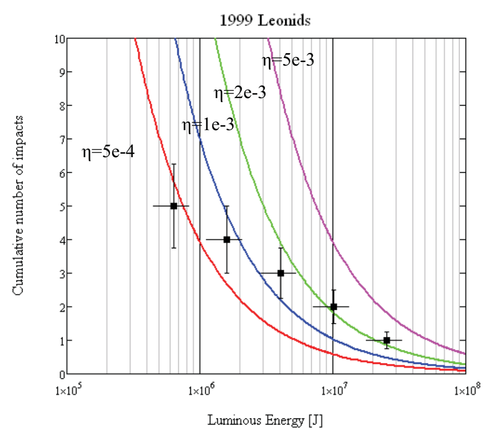

Figure 6. Results of Bellot Rubio et al. (2000b). *N(LE$_\lambda$)* versus *LE$_\lambda$* adapted from Figure 2 of the same reference. Wavelength λ in this case is 400-900 nm. Compared to Figure 5, the observed data points do not fit the curves as well.

The luminous efficiency derived by Bellot Rubio et al. (2000a, b) for the 1999 Leonids is also listed in Table 4 for comparison purposes. It should be noted that this data was observed with cameras having a slightly different spectral response and sensitivity than the cameras in this study and a light distribution coefficient of $f = 3$ instead of 4; other differences in technique are outlined in Section 3.2. Despite these differences, the 1999 Leonid luminous efficiency is consistent with those of the 2006 Geminids, 2007 Lyrids, and 2008.

Luminous efficiency determinations at low speeds into lunar simulant JSC-1a have been made at the NASA Ames Vertical Gun Range employing the same cameras used to monitor the Moon (Swift et al., 2010). These values appear in Figure 7, along with the luminous efficiencies calculated in this paper. Also plotted for reference are previous results found in the literature. A fit to the lunar impact derived data from this paper and the hypervelocity gun test data from Swift et al. (2010) yields the following equation for luminous efficiency in the 400-800 nm wavelength range of our cameras

$$\eta_{cam} = 1.5 \times 10^{-3} e^{-(9.3)^2 / V^2} \tag{9}$$

where V is the speed of the impactor in km/s. The lunar impact data mainly controls the constant scaling factor in Eq (9) while the hypervelocity gun test data largely controls the number in the exponential. Findings from other data sources shown in Figure 7 – Bellot Rubio et al. (2000b) for the 1999 Leonids at 400-900 nm, Ernst & Schultz (2005) considering gun tests into powdered pumice at 340-1000 nm, and numerical hydrocode simulations by Artem'eva et al. (2001) for two different densities, 0.1 g/cm^3 and 1 g/cm^3 – are not considered in the fit, but the results seem to be quite consistent.

The range of estimated impactor masses is computed and given in Table 4, using the luminous efficiencies in binning scheme (a). Simulations by Artem'eva et al. (2001) indicate that luminous efficiency weakly depends (10-20%) on size of the impactor, while luminous efficiencies are twice as high as for low-density impactors. The dependence of luminous efficiency on impactor mass and/or density is left for future work.

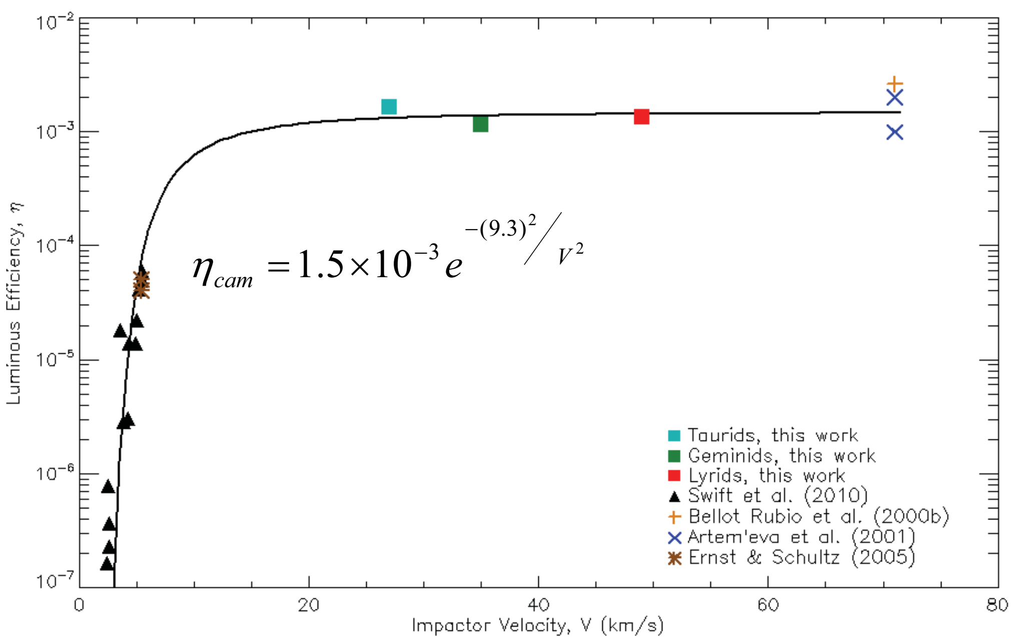

Figure 7. Plot of luminous efficiency versus velocity using several different methods. The data from gun tests into lunar regolith simulant from Swift et al. (2010) populates the low velocity end of the graph. At high meteoroid velocities (this work), the curve is relatively constant. The Bellot Rubio et al. (2000b) point from the 1999 Leonids and Ernst & Schultz (2005) point from gun tests into powdered pumice do not represent the spectral response of the cameras used in this study and were not used in the fit (solid black line); they are shown for comparison purposes only. The results of hydrocode simulations by Artem'eva et al. (2001) are also shown only for comparison purposes. The Bellot Rubio number has a correction applied to convert from the originally assumed f = 3 to f = 4.

5 Summary

Utilizing the technique of Bellot Rubio et al. (2000a,b), the best estimate for the luminous efficiency of lunar impacts involving the 2006 Geminid, 2007 Lyrid, and 2008 Taurid meteoroids is $\eta_{cam} = 1.2 \times 10^{-3}$, 1.4×10^{-3}, and 1.6×10^{-3}, respectively, in the 400-800 nm wavelength range of our cameras. These values are consistent with that found by Bellot Rubio et al. (2000) for the Leonid lunar impacts of 1999 and numerical simulations performed by Artem'eva et al. (2001). Number statistics are poor in all cases, however, and more observations are needed. It must be noted that η is highly dependent on the mass index though how much the determination of η varies with s is left to future work. Mass indices found in the literature and used in this analysis may not apply to the size range considered for lunar impacts. More work to determine mass indices for meteoroids larger than 100 g is needed.

Luminous efficiencies determined from lunar impact flash analyses are fairly constant at meteoroid speeds. Luminous efficiencies calculated as the result of hypervelocity gun tests into lunar simulant has revealed a large variation in η at low velocities. Luminous efficiency values imply impactor masses of roughly 30 to 1400 g. The dependence of luminous efficiency on impactor mass/density is also a topic of future work.

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References

N.A. Artem'eva, I.B. Kosarev, I.V. Nemtchinov, I.A. Trubetskaya, and V.V. Shuvalov, *SoSyR* **35**(3), 177-180 (2001).
L.R. Bellot Rubio, J.L Ortiz, and P.V. Sada, *ApJ* **542**, L65-68 (2000a).
L.R. Bellot Rubio, J.L Ortiz, and P.V. Sada, *Earth Moon Planets* **82-83**, 575-598 (2000b).
W.J. Cooke, R.M. Suggs, W.R. Swift, *LPSC XXXVII*, Paper 1731 (2006).
W.J. Cooke, R.M. Suggs, R.J. Suggs, W.R. Swift, and N.P. Hollon, *LPSC XXXVIII*, Paper 1986 (2007).
B.M. Cudnick, D.W. Dunham, D.M. Palmer, A.C. Cook, R.J. Venable, and P.S. Gural, *LPSC XXXIII*, Paper 1329 (2002).
D.W. Dunham, B. Cudnick, D.M. Palmer, P.V. Sada, H.J. Melosh, M. Beech, R. Frankenberger, L. Pellerin, R. Venable, D. Asher, R. Sterner, B. Gotwols, B. Wun, and D. Stockbauer, *LPSC XXXI*, Paper 1547 (2000).
C.M. Ernst and P.H. Schultz, *LPSC XXXVI*, Paper 1475 (2005).
E. Grün, H.A. Zook, H. Fechtig, and R.H. Giese, *Icarus* **62**, 244-272 (1985).
P.S. Gural, *Meteoroid Environment Workshop*, NASA MSFC, Huntsville, AL (2007).
IMO, Meteor Shower Calendars, http://www.imo.net/calendar/2006 (2006).
IMO, Meteor Shower Calendars, http://www.imo.net/calendar/2007 (2007).
IMO, Meteor Shower Calendars, http://www.imo.net/calendar/2008 (2008).
I.V. Nemtchinov, V.V. Shuvalov, N.A. Artemieva, I.B. Kosarev, and I.A. Trubetskaya, *Int J Impact Eng* **23**, 651-662 (1999).
J.L. Ortiz, P.V. Sada, L.R. Bellot Rubio, F.J. Aceituno, J. Aceituno, P.J. Gutiérrez, and U. Thiele, *Nature* **405**, 921-923 (2000).
J.L Ortiz, J.A. Quesada, J. Aceituno, F.J. Aceituno, and L.R. Bellot Rubio, *ApJ* **576**, 567-573 (2002).
R.M. Suggs, W.J. Cooke, R.J. Suggs, W.R. Swift, and N. Hollon, *Earth Moon Planets* **102**, 293-298 (2008a).
R.M. Suggs, W.J. Cooke, R.J. Suggs, W.R. Swift, D.E. Moser, A.M. Diekmann, and H.A. McNamara, *BAAS* **40**, 455 (2008b).
R.M. Suggs, W.J. Cooke, H.M. Koehler, D.E. Moser, R.J. Suggs, and W.R. Swift, *Meteoroids 2010*, Breckenridge, CO (2010).
W.R. Swift, D.E. Moser, R.M. Suggs, and W.J. Cooke, *Meteoroids 2010*, Breckenridge, CO (2010).
W.R. Swift, R.M. Suggs, and W.J. Cooke, *Earth Moon Planets* **102**, 299-303 (2008).
M. Yanagisawa and N. Kisaichi, *Icarus* **159**(1), 31-38 (2002).
M. Yanagisawa, K. Ohnishi, Y. Takamura, H. Masuda, Y. Sakai, M. Ida, M. Adachi, and M. Ishida, *Icarus* **182**(2), 489-495 (2006).
M. Yanagisawa, H. Ikegami, M. Ishida, H. Karasaki, J. Takahashi, K. Kinoshita, and K. Ohnishi, *M&PSA* **43**, Paper 5169 (2008).