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Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon

Derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids

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Abstract

Since early 2006 the Meteoroid Environment Office (MEO) at NASA's Marshall Space Flight Center has been consistently 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. (2000) 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.

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 a particular wavelength range (λ).

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

The luminous efficiency plays a vital role in understanding observations and constraining models. Experiments into lunar regolith simulant at low velocities (<10 km/s) have been performed at hypervelocity gun test ranges in order to determine η (Swift et al., 2010), but high velocities – meteoroid speeds – are impossible to replicate in the laboratory. Since the properties of shower meteoroids are often known better than that of sporadic meteoroids, observations of lunar impact flashes associated with showers offer an opportunity to estimate η at high velocities.

The MEO made Earth-based observations of the Moon in the 400-800 nm wavelength range during the 2006 Geminids, 2007 Lyrids, and 2008 Taurids. Multiple lunar impact flashes were detected, allowing for a luminous efficiency analysis like that presented in Bellot Rubio et al. (2000) for the 1999 Leonids. η is estimated from a comparison of the total number of events detected to the total number expected given the shower's spatial density and mass distribution index. Using the derived luminous efficiency and velocity, the masses of the lunar impactors are estimated.

Setup

Observing Facilities » Automated Lunar and Meteor Observatory (ALaMO) in Huntsville, Alabama (34.°7 N, 86.°7 W)
» Walker County Observatory (WCO) near Chickamauga, Georgia (34.°9 N, 85.°3 W), ~125 km away

Telescopes Simultaneous observations with
» Two identical Meade RCX-400 0.35m (14") Cassegrain telescopes
» One RCOS 0.5m (20") diameter Ritchey-Chrétien telescope

FOV With focal reducers, 20 arcmin horizontal fields of view (FOV), covering ~4 × 10^6 km² on the lunar surface

Cameras » ASTROVID StellaCamEX
» Watec 902-H2 Ultimate monochrome CCD cameras
Video is digitized and recorded straight to hard-drive.
30 frames per second, interlaced; FWHM = 400-800 nm

Detection LunarScan software is used to detect impact flashes in the video (Gural, 2007)

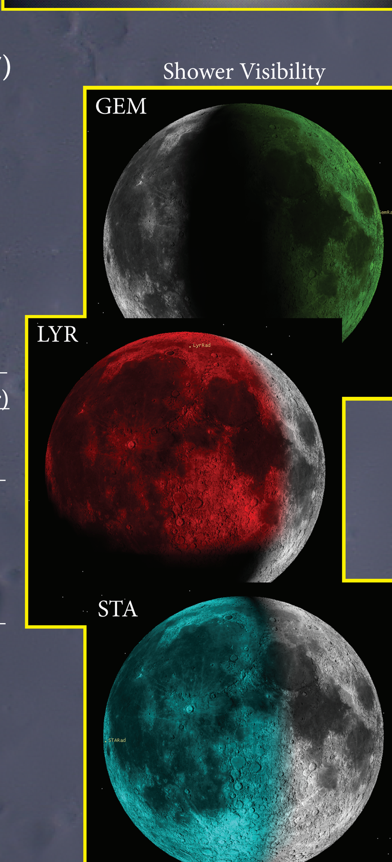
Analysis LunaCon is used to determine flash magnitudes, time on target, photometric quality, and lunar area within the FOV (Swift et al., 2008)

Observation Periods 2.18 hrs of '06 Geminids, 10.22 hrs of '07 Lyrids, 7.93 of '08 Taurids were of a consistent photometric quality

Table 1

Date	Shower	Telescopes	Obs Timespan (UT)	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	0.72
			23:46-24:00	0.23
03 Nov 2008	Taurids	0.5 m, two 0.35 m	00:00-00:13	0.22
			00:30-01:33	1.05
			23:42-24:00	0.30
04 Nov 2008	Taurids	0.5 m, two 0.35 m	00:00-02:09	2.15
			23:42-24:00	0.30
05 Nov 2008	Taurids	0.5 m, two 0.35 m	00:00-02:58	2.96

Shower Visibility



Theory

The technique for determining luminous efficiency incorporates the method of Bellot Rubio et al. (2000), restated here. 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 and $A_\perp$ 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 $KE = \frac{1}{2} m V^2$. Substituting this into Eq (2) gives a cumulative flux distribution as a function of kinetic energy.

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

Solving Eq (1) for *KE* and substituting this into Eq (4) gives a cumulative flux distribution as a function of luminous energy.

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

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

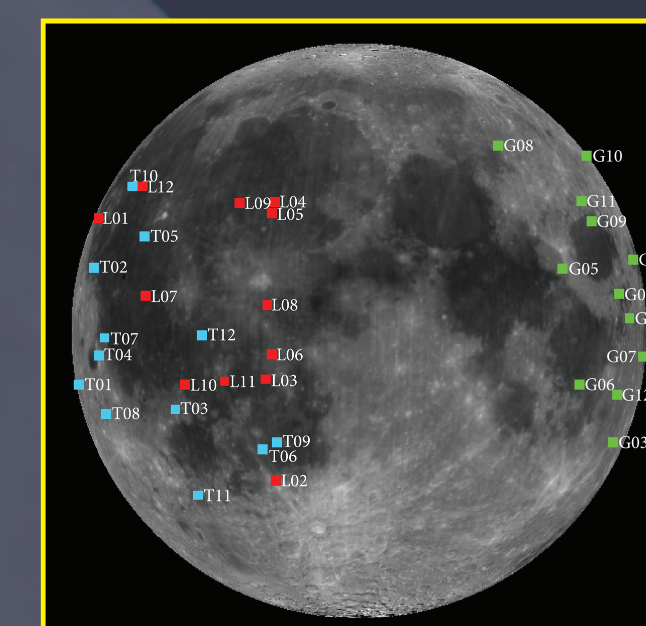
$$N(LE_\lambda) = \left(\frac{2\,LE_\lambda}{\eta_\lambda V^2\, m_0}\right)^{1-s} \int_{t_1}^{t_2} F(m_0, t) A_\perp(t)\, dt \tag{6}$$

This result is comparable to Eq (4) of Bellot Rubio et al. (2000).

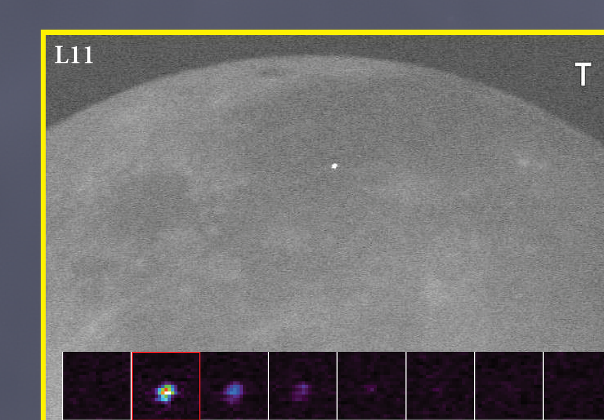
Observations

Table 2

Shower	ID	Date	Time (UT)	Dur (ms)	R Mag	LE_{cam} (J)
Geminids	G01	12/14/06	08:32:06.647	33	+9.2	5.6×10^4
[2.18 hrs]	G02	12/14/06	08:32:51.993	50	+8.9	7.1×10^4
	G03	12/14/06	08:39:57.155	17	+9.8	3.1×10^4
	G04	12/14/06	08:46:01.957	17	+9.6	3.7×10^4
	G05	12/14/06	08:50:36.200	33	+8.4	1.2×10^5
	G06	12/14/06	08:51:20.562	17	+9.1	6.2×10^4
	G07	12/14/06	08:56:42.837	17	+8.7	8.5×10^4
	G08	12/14/06	09:00:22.142	33	+8.4	1.2×10^5
	G09	12/14/06	09:03:32.851	33	+9.8	3.1×10^4
	G10	12/15/06	09:15:14.040	33	+8.4	1.1×10^5
	G11	12/15/06	09:17:39.336	17	+7.6	2.3×10^5
	G12	12/15/06	09:53:28.464	83	+6.4	7.0×10^5
Lyrids	L01	04/20/07	01:40:04.044	50	+7.8	2.1×10^5
[10.22 hrs]	L02	04/22/07	01:15:05.616	67	+8.8	7.9×10^4
	L03	04/22/07	01:15:43.956	33	+10.0	2.6×10^4
	L04	04/22/07	01:38:33.864	33	+8.0	1.6×10^5
	L05	04/22/07	03:12:24.372	67	+6.8	4.9×10^5
	L06	04/22/07	03:52:37.182	17	+9.1	6.0×10^4
	L07	04/23/07	01:15:54.547	17	+8.7	8.5×10^4
	L08	04/23/07	02:23:21.361	50	+8.8	7.7×10^4
	L09	04/23/07	04:08:48.755	50	+8.0	1.7×10^5
	L10	04/23/07	04:40:45.912	33	+9.2	5.6×10^4
	L11	04/23/07	04:42:34.781	83	+6.4	7.1×10^5
	L12	04/23/07	04:59:57.557	50	+7.3	3.3×10^5
Taurids	T01	11/02/08	23:48:39.996	50	+9.4	4.5×10^4
[7.93 hrs]	T02	11/03/08	00:11:06.144	50	+7.9	1.9×10^5
	T03	11/03/08	00:33:37.620	50	+9.1	6.0×10^4
	T04	11/03/08	23:59:24.504	50	+8.7	9.0×10^4
	T05	11/04/08	00:04:06.060	50	+8.9	7.2×10^4
	T06	11/04/08	01:10:01.272	67	+8.1	1.5×10^5
	T07	11/04/08	01:39:03.744	67	+6.3	7.8×10^5
	T08	11/05/08	00:38:37.860	117	+7.4	2.9×10^5
	T09	11/05/08	00:53:58.308	67	+8.5	1.1×10^5
	T10	11/05/08	02:05:07.908	100	+7.3	3.0×10^5
	T11	11/05/08	02:09:44.748	50	+9.3	4.9×10^4
	T12	11/05/08	02:32:47.184	67	+8.1	1.5×10^5



Observed lunar impact flash locations



Observed lunar impact flash(es)

The energy received at Earth [J/m²] is calculated using $\mathcal{E}_\oplus = \tau\, Flux_{0\lambda}\, 10^{-0.4 m_\lambda}$ where τ is the camera exposure time [s], $Flux_{0\lambda}$ is the flux [J/m²/s] from a 0 mag star in the camera's wavelength range λ, and m is the measured magnitude of the impact flash. Stellacam and Watec cameras operate in the 400-800 nm range approximated by the R passband. Vega is used as the calibration star; $Flux_{0R} = 3.39 \times 10^{-9}$ J/m²/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 [J/m²] by $LE_\lambda = f \pi d^2 \mathcal{E}_\oplus$ where *f* is a factor describing the distribution of the light (spherical, hemispherical, etc), and *d* is the distance between the impact flash on the Moon and the telescope on Earth. It is chosen that *f* = 4 and *d* is assumed a constant 3.84399 × 10^8 m. Photometry is initially done in R-band; a simple correction has been applied to obtain energies in the camera passband, as given in Table 2.

Luminous Efficiency

Parameters for Eq (6) in the 400-800 nm range are given in Table 3, as well as the resulting luminous efficiency, η_{cam}. The fits to the data are shown below, for two different binning schemes.

Bellot Rubio et al. (2000) derived $\eta = 2 \times 10^{-3}$ in the 400-900 nm wavelength range for the 1999 Leonids. Their results are shown at right.

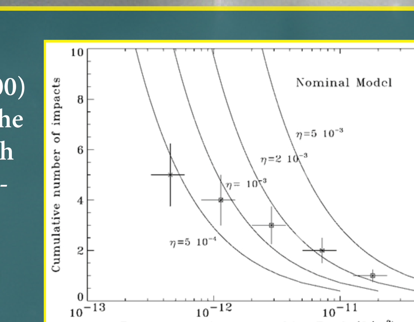
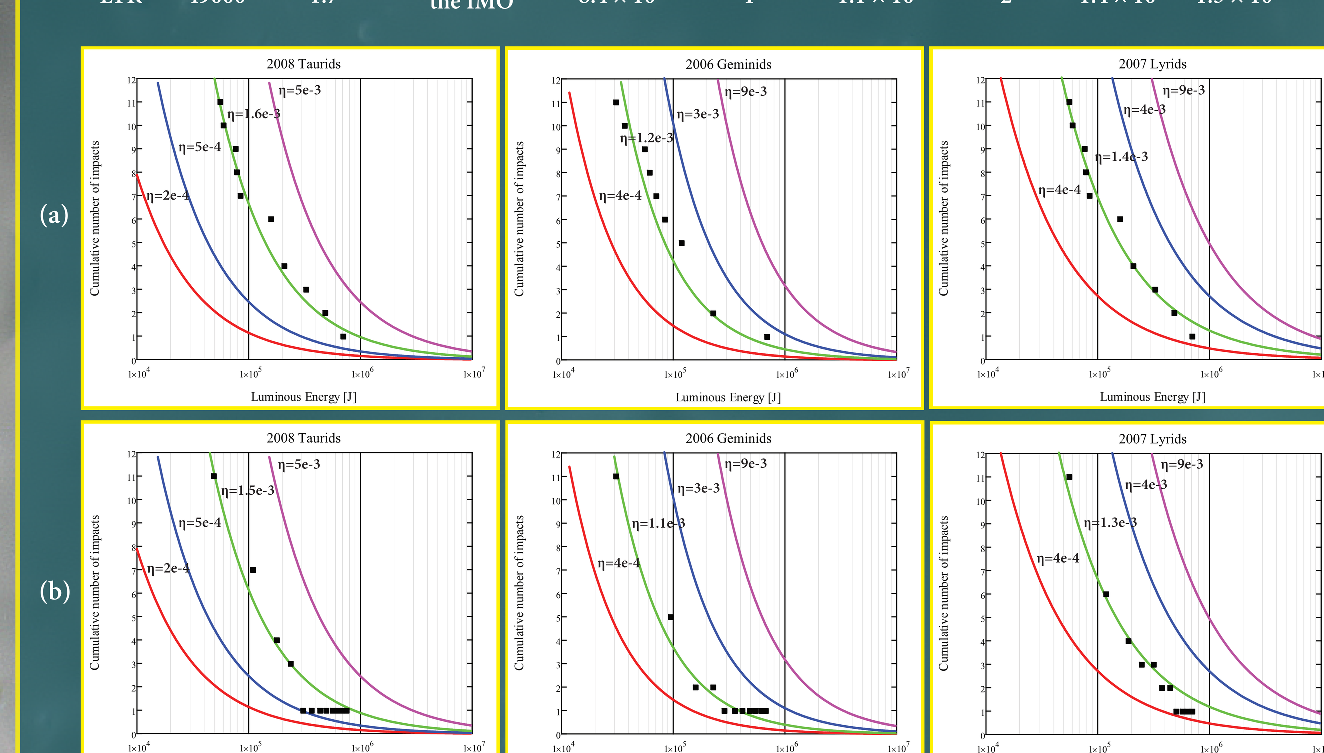


Table 3

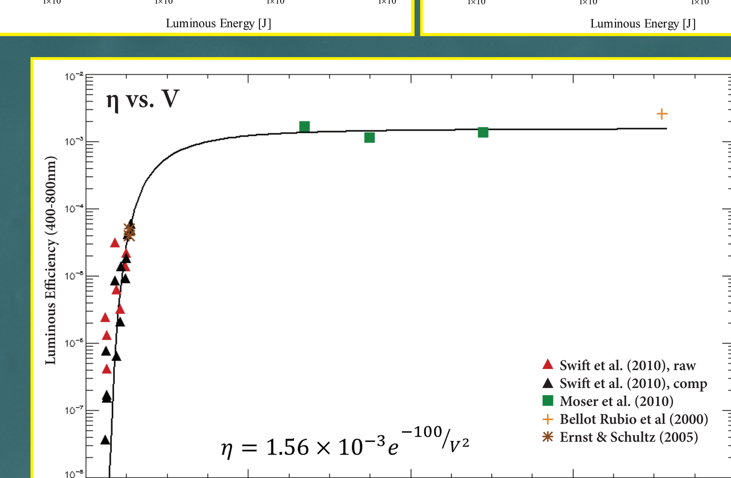
Shower	*V* (m/s)	*s (IMO)*	$F(m_0,t)$ (#/m²/hr)	m_0 (kg)	t_1, t_2 (hr)	$A_\perp$ (km²)	LE_{cam} (J)	η_{cam} (a)	η_{cam} (b)
STA	27000	1.8	Suggs et al.	2.4×10^{-2}	*see*	3.6×10^6	*see*	1.6×10^{-3}	1.5×10^{-3}
GEM	35000	1.9	(2010) and	4.7×10^{-2}	*Table*	3.2×10^6	*Table*	1.2×10^{-3}	1.1×10^{-3}
LYR	49000	1.7	the IMO	8.4×10^{-2}	*1*	1.1×10^6	*2*	1.4×10^{-3}	1.3×10^{-3}



The number statistics are rather poor, but binning using two different schemes, (a) and (b), yields similar results for η. Data points - LE_{cam} - match the predicted curves better than Bellot Rubio et al. (2000) (at top right).

The luminous efficiency is highly dependent on the mass index, *s*; it dictates the shape of the curve. Mass indices taken from the literature may not apply to this size range. A calculation of *s* from the would be possible if more data was available.

The derived luminous efficiencies yield the following mass ranges (assuming η has no dependence on mass):
STA 0.09 - 1.4 kg
GEM 0.04 - 0.99 kg
LYR 0.03 - 0.44 kg



Luminous efficiency determinations at low speeds into lunar simulant JSC-1a have been made at the NASA Ames Vertical Gun Range with the same cameras used to monitor the Moon (Swift et al., 2010). These values appear at left, along with the luminous efficiencies calculated in this paper, that given in Bellot Rubio et al. (2000), and those derived in the laboratory by Ernst & Schultz (2005). The B-R point and E&S point do not represent the spectral response of the cameras used in this study and were not used in the fit; they are shown for comparison purposes only.

Summary

Utilizing the technique of Bellot Rubio et al. (2000), the best estimate for the luminous efficiency of lunar impacts involving Geminid, Lyrid, and Taurid meteoroids is $\eta_{cam} = 1.2 \times 10^{-3}$, 1.4×10^{-3}, and 1.6×10^{-3}, respectively. These values are in good agreement with that found by Bellot Rubio et al. (2000) for the Leonid lunar impacts of 1999. Number statistics are poor in all cases; more observations are needed. η values imply impactor masses of roughly 30 to 1400 g. It must be noted that luminous efficiency is highly dependent on mass index. Mass indices found in the literature 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.

References

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