GROUND-BASED OBSERVATIONS OF LUNAR METEORITIC PHENOMENA

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Abstract. The occurrence and visibility of meteoroid impacts on the moon as seen from the earth were little more than speculation prior to November 1999. The best evidence of present-day impact activity came from the seismic experiments left on the Moon during the Apollo era. Past systematic attempts at earth-based observations to document lunar impacts revealed nothing conclusive. However, during the Leonid storms of 1999 and 2001, lunar impact events were for the first time confirmed by multiple independent observers. A total of 15 meteoritic impact flash events have been verified during these storms, with an additional 12 unconfirmed but likely events awaiting confirmation. Estimates of the mass of these meteoroids range from less than one gram for the faintest flashes to more than 10 kg for the brightest observed flash. The fraction of visible light to total energy produced by these events, a quantity known as luminous efficiency, averages about 0.001 for the established events. The confirmation of lunar meteoritic events on the Moon opens a new avenue in lunar and planetary research, one which could help bridge the gap between atmospheric sampling of the smallest components of meteoroid streams and interplanetary debris to the larger scale objects accessible to ground-based telescopes.

Keywords: Hypervelocity impacts, Leonid meteors, Lunar impact phenomena, Moon, Transient lunar phenomena

1. Introduction

The visible occurrence of impacts on the Moon's surface seems to be a rare phenomenon, with only sparse observational evidence currently available. Prior to 1999, many observers had reported brief flashes of light on the moon, presumably from meteor impacts, but none were independently confirmed (Dunham et al., 2000). This was despite the historical evidence of the visibility of lunar impacts as had been chronicled in Middlehurst (1968) and Gehring (1964). Several campaigns have been attempted to obtain scientifically valid lunar impact observations without much success. One of the most notable of these was by Association of Lunar and Planetary Observers (ALPO), who attempted a systematic program in the 1960s

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to observe lunar meteoritic impacts. Although ALPO observers recorded many candidate events, none of the sightings were independently confirmed with two or more widely separated observers (Westfall, 1997, 1998; Dunham et al., 1999, 2000).

In 1994, the collision of comet Shoemaker-Levy 9 with Jupiter provided an opportunity to observe multiple planetary impact events in a more remote part of our solar system. These impacts were observed by the photopolarimeter radiometer of the Galileo spacecraft en route to Jupiter. Martin (1995) was able to deduce the light profile, energy of the impactor, duration of the flash, and extent of the plume. As a result of this work, both spatial and temporal resolution of the visible impact flash provided much needed characterization of the impact dynamics and placed boundaries on the parameters involved in the modeling of high-speed collisions in space.

In addition, seismometers left on the lunar surface during the Apollo missions provided further indirect evidence of lunar impact phenomena. The results published by Latham (1973) indicate that a given Apollo landing site recorded an average of 70–150 events per year from meteoroids in the 100-gram to 1000-kilogram range over the entire Moon's surface. Using Latham's flux estimate, the frequency of meteoroid impacts greater than 1 kg in mass is one event for every 140 h of observation. This assumes that at least a 1 kg mass object is needed to produce a visible flash and a ground-based observer is able to see one-half of the Moon's near side area (not illuminated by the Sun) on average. It is not yet known what the smallest mass is that is capable of producing an observable flash and thus the frequency of observable events is hard to establish. Later analysis of the lunar seismic data by Duennebier (1975) and Oberst (1989) produce fluxes of one impact every 35 and 7 h respectively for objects over one kilogram. Each of these three estimates is for the sporadic meteor background and would be significantly higher during strong meteor showers.

In the present paper, we deal with the observations of the Leonid meteor impacts of 1999 and 2001 as recorded by several teams of observers. The physical nature of the impact events and impactors, the validation of the events, and the overall structure of the Leonid stream are considered in this paper. A companion paper deals with the process of observing lunar meteor impacts in general, including automated attempts at detection of Lunar Leonid impacts which have great potential for future lunar meteor detections.

2. Data Acquisition and Reduction

The productive Leonid meteor stream associated with comet Tempel-Tuttle, provided excellent opportunities to observe impacts of meteoroids on the lunar surface on 18 November 1999 and 18/19 November 2001. The Leonid shower had been expected to reach storm-like conditions of over 1000 meteors per hour

TABLE Ia

Observer and instrument information, 1999 Lunar Leonid observations

Name	Location	East Long.	North Lat.	Telescope Aper. (cm)	Video Instrumentation
B. Cudnik	Columbus, TX	–96.664	29.618	36	Audio tape (vis.)
D. Dunham	Mount Airy, MD	–77.206	39.342	13	PC-23C videocam
R. Frankenberger	San Antonio, TX	–98.653	29.486	20	PC-23C videocam
D. Palmer	Greenbelt, MD	–76.859	38.988	13	PC-23C videocam
P. Sada	Monterrey, Mex.	–100.143	25.915	20	PC-23C videocam
Yanagisawa and Kisaichi (2002)	Tokyo, Japan	139.75	35.67	20 28	Ikegami ICD-2DC, Watec 902H

visible in the Earth's atmosphere for a ground-based observer. The Moon was also predicted to pass through streams of higher meteoroid densities fed by comet dust ejected decades before. For 1999 and 2001, the Moon was favorably placed so that ground-based observers could see the un-illuminated (but faintly earthlit) portion of the Moon as it faced into the meteoroid stream. To successfully observe the impacts, the highest contrast was required and thus the dark face of the Moon was monitored for flashes. The approach to this observing program consisted of a network of amateur and professional astronomers equipped with unfiltered, low-light video cameras and telescopes with apertures ranging from 13 to 40 cm in diameter. These observers monitored the Moon during the times of maximum flux for visible signs of a lunar Leonid impact. A team observed from the United States and Mexico for both Leonid events, with a pair of observers in Japan observing the 1999 (Yanagisawa and Kisaichi, 2002) events, and other teams in Spain and India (Ortiz et al., 2002; Shah, 2001, private communication) observing the 2001 events. A total of fifteen such events have been confirmed so far, with at least an additional twelve probable events awaiting confirmation. The names of the observers, their locations, instrumentation, and recording methods for both 1999 and 2001 are presented in Tables Ia and Ib.

For both the 1999 and the 2001 confirmed events, each was assigned a letter designation in order of discovery. The unconfirmed, probable events were given a designation F1, F2 . . . (1999) and P1, P2 . . . (2001), also in order of discovery. Observations made by Ortiz et al. (2002) and Yanagisawa and Kisaichi (2002) retain the designations given in their respective papers; that is, lower case alphabetic in order of discovery in the former paper, upper case alphabetic prime (A′, B′, C′, etc.) in order of discovery for the latter paper. The acquisition and reduction of the data apply to that obtained by the North American observers; corresponding details for the Japanese and Spanish teams can be found in their respective papers. More

TABLE Ib

Same as Table Ia, 2001 Lunar Leonid observations

Name	Location	East Long.	North Lat.	Telescope Aper. (cm)	Video Instrumentation
Roger Venable	Augusta, GA	–82.525	33.160	41	PC-23A videocam
David Dunham	Laurel, MD	–76.895	39.084	20	Watec 902H camera
Tony Cook	Alexandria, VA	–77.138	38.810	20	Watec 902H camera
David Palmer	Whiterock, NM	–106.211	35.818	13	PC-23C videocam
Ortiz et al. (2002)	Granada, Spain (several locations)	–3.4	37.1	40 20 25	Watec-100N CCD, B&W PAL video cameras

information about Table II and these events are given in the next section. Once the flashes were discovered and several video frames before and after the event were digitized, an estimate of the apparent magnitude was made for each event. These events were each of such short duration (typically from 30 to 50 ms) that they were only visible on one or two video frames. Several notable exceptions to this "typical" behavior are mentioned in the following section.

In order to obtain a measurement of the magnitude of each impact flash, Dr. Dunham compared each event's visual intensity to that of nearby 4th and 8th magnitude stars, which were recorded during the course of his observations. Mr. Gural later refined the magnitude estimates after digitizing the video stream around each impact flash as well as each available star (Psi 1 Aquarii, Psi 2 Aquarii, SAO 146570, SAO 146578, and SAO 146577). To calibrate the apparent magnitude versus log intensity for the video camera system response, a region around and including each star was integrated for several video frames and an equivalently sized background region (near the star but not including it) was subtracted off. It has been found in video meteor work that for non-saturated pixels the log intensity versus V-magnitude plot is close to linear. The resulting fit yielded a calibration curve of:

$$\mathrm{m_V} = 13.6 - 2.9 \log_{10} I.$$

Mr. Venable used a similar approach when estimating the magnitude of the 2001 "B" impact flash, but used the following expression for the diameter of a star (at FWHM) on his monitor showing the video of the flash:

$$D = -0.13\mathrm{m_V} + 29,$$

where D is the image diameter in millimeters and $\mathrm{m_V}$ is the visual magnitude. The term "V-magnitude" is used here for convenience; in reality these are unfiltered images, made without the use of the Johnson-V filter or any other filter.

TABLE IIa

Impact times and magnitudes for the 1999 Lunar Leonid events

Event name	Quality[a]	UTC (18 Nov.) hh:mm:ss	Mag.	Selenographic (±1) Long.	Lat.	Comments[b]
F1	P	1:46:09.67	6.7	58 W	16 N	
F2	P	2:52:19.68	8.3	66 W	46 N	
F	C	3:05:44.89 ± 0.02	6.2	65 W	40 N	#1 of Bellot Rubio et al (2000)
D	C	3:49:40.40 ± 0.02	4.9	68 W	03 N	#2 of Bellot Rubio et al (2000)
E	C	4:08:04.10 ± 0.03	5.8	78 W	15 S	#3 of Bellot Rubio et al (2000)
G	C	4:12:27.83 ± 0.05	5.5	90 W	40 S	
F6	P	4:32:50.79	4	51 ±3 W	21 ±3 N	#4 of Bellot Rubio et al (2000)
F7	P	4:34:49.52	7	38 ±3 W	21 ±3 N	#5 of Bellot Rubio et al (2000)
F3	P	4:40:26.75	6.3	58 W	17 N	
A	C	4:46:15.52 ± 0.05	5.1	71 W	14 N	#6 of Bellot Rubio et al (2000)
F4	P	4:51:24.92	6.3	74 W	49 N	
B	C	5:14:12.92 ± 0.02	6.2	58 W	12 N	#7 of Bellot Rubio et al (2000)
C	C	5:15:20.22 ± 0.02	5.3	58 W	20 N	#8 of Bellot Rubio et al (2000)
F5	P	5:26:43.25	5.3	54 W	03 S	
A′	TC	11:07:46.2	6	62 W	21 N	Entry angle 31°
B′	TC	11:18:05.9	7	59 W	28 N	Entry angle 30°
C′	TC	12:11:45.5	7	46 W	04 S	Entry angle 20°
D′	P	13:54:26.0	4?	68 W	32 S	Mag. uncertain, CCD saturated, entry angle 54°, lasted 140 ms
E′	P	14:14:31.0	3?	42 W	17 N	Mag. uncertain, CCD saturated, entry angle 11°, lasted 250 ms

[a] With regards to "quality", a full description is found in the text.

[b] Entry angle as given by Yanagisawa and Kisacichi (2002), with respect to the vertical.

Determination of the flash magnitude was carried out by first integrating the flash image over a finite region (typically 25 × 25 pixels) and then finding the average background from integrating exactly the same region in several frames before and after the flash. This assures that the same lunar background dark limb features are removed from the flash intensity. A computation of log intensity and use of the calibration curve yields the final value for the flash magnitude. It should be noted that this is a spatial and temporally integrated magnitude over 33 ms and if the flash duration is shorter than the video frame rate, then the actual magnitude

TABLE IIb

Impact times and magnitudes for the 2001 Lunar Leonid events

Event name	Quality[a]	UTC, 18 Nov. (19 Nov. in bold)	Mag.	Selenographic Long.	Lat.	Comments (entry angles ±3°)[c]
a	P[b]	18:27:46	5.2	16 W	23 S	Lasted 0.6 sec., entry angle 76°
b	C[b]	18:10:36	7.5	15 E	39 N	Entry angle 63°
c	C[b]	18:12:21	7.9	11 E	05 N	Entry angle 43°
d	C[b]	18:19:55	8.2	E00	04 N	Entry angle 53°
B	C	23:19:15.21 ± 0.02	6.4	11 E	03 S	
A	C	**00:18:58.20 ± 0.02**	5.0	06 E	15 N	

[a] In addition to these, three probable events were recorded by Kiran Shah of Pune, India with a Watec 902S and a 0.2-m telescope. However, no magnitude or positional data are available at this time. The times of the events (to the nearest minute) are 13:02, 13:47, and 13:53, 18 November. A second, independent observer reported an impact to the nearest second – 13:53:14 18 November – but the uncertainty in time for the first 13:53 event remains too large to render this a confirmed impact event.

[b] Flashes termed as "Confident" by Ortiz et al. (2002).

[c] Entry angle as given by Ortiz et al. (2002), with respect to the vertical.

is underestimated. No extinction correction was applied to the derived magnitudes, but the fact that the stars and moon were located in roughly the same part of the sky somewhat decreases the error associated with not correcting for atmospheric extinction. This method provided a first order estimate of the magnitudes of the impact flashes, but is limited by a lack of calibration stars (of magnitudes other than 4th and 8th) near the moon. A discussion of the estimated size of the impactors based on these magnitudes follows in a later section. Note that the lettered impacts were those discovered by human review of the videotapes and that several automated computer scanned discoveries are on average fainter, thus extending the detection potential for this type of work.

To find the selenographic coordinates of each impact, Dr. Dunham integrated several full frames of video around the time of each flash. This helped to pull out lunar features that were of very low contrast on the dark limb of the imaged lunar surface. After alignment with the moon's edge, computation of the libration, and overlay of the rotated Moon's surface matching the imagery, a coordinate map was superimposed on the flash image. The coordinates for each flash could then be obtained to within 30 kilometers (or 1 degree of latitude and longitude) and are shown in the map of Figure 1a. All of these events, except D, E, and G, occurred in the western part of Oceanus Procellarum (Ocean of Storms). The events D, E, and G, happened in the highlands area a short distance west of the western shore of Oceanus Procellarum. Mr. Cudnik used a similar approach to determine the locations of the confirmed impacts from the November 2001 images. Don Stockbauer

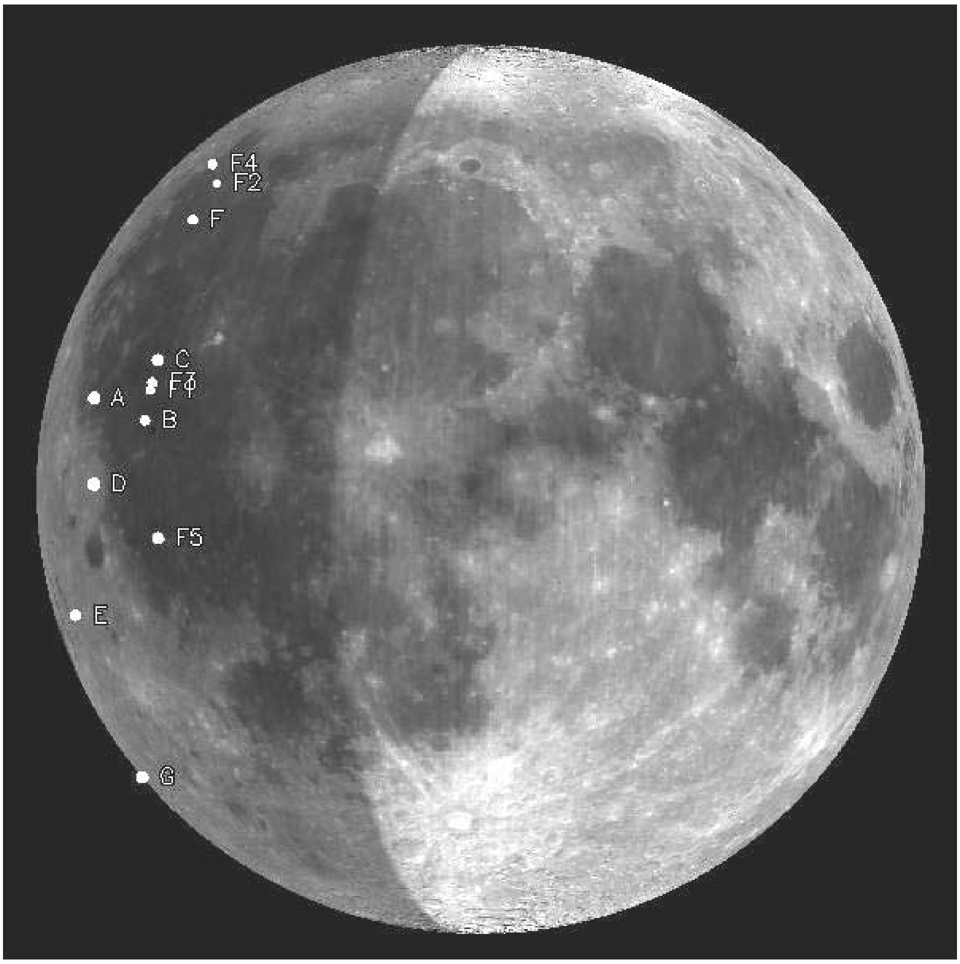

Figure 1a. 1999 November 18 Lunar meteor impact locations, confirmed and likely (unconfirmed but probable).

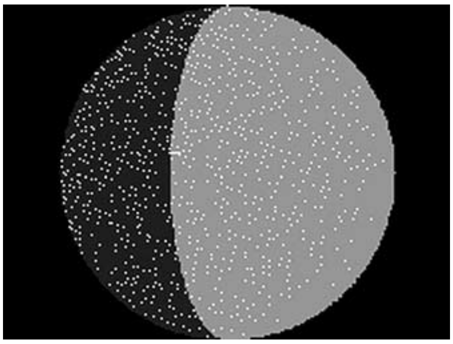

Figure 1b. 1999 November 18 Lunar Meteor Impact Prediction. See text for details.

derived the event times to within 0.05-s accuracy by creating an accurately time-inserted copy of the videotape with an IOTA-Manly video time inserter (the small rate and light propagation time correction of the WWV signal from Ft. Collins, CO, USA, was not applied to any of these times).

3. Summary of Recorded Events and the Duration of the Impact Flashes

We provide, in Tables IIa and IIb, and Figures 1a, 1b, and 2, a summary of the details of the November 1999 and November 2001 Leonid meteor impact observations. Tables 2a and 2b give the event times, apparent magnitude (uncorrected for atmospheric extinction) at the maximum observed intensity, and selenographic position. Figure 1a shows the location of the 12 events of 1999 observed by the North American astronomers, and Figure 2 readily shows the location of the 18 November 2001 impact "B" due to the brightness of the earthshine rendering the lunar features easy to locate. Figure 1b is a plot of the expected Leonid meteoroid impact flux as the Moon crosses the densest part of the meteoroid stream. The plot assumes a uniform distribution of meteoroids in the stream and is plotted for 2-h UT. Since the sub-radiant point of the moon is located near the left edge (east in terms of celestial coordinates) of the figure, within the dark part of the moon, the concentration of dots is higher. Lower radiant elevation on the opposite side results in the dots appearing more spaced out, resulting in a lower impact flux. A brief comparison between Figures 1a and 1b shows that the confirmed and probable lunar impact observations are almost certainly derived from Leonid meteoroids. The locations of the impacts lie within the region of highest impact flux density, near the sub-radiant point on the moon.

The criteria of the inclusion of the events of Tables II included three qualifiers, at least two of which were used for inclusion in the table. If the event was independently confirmed by a second observer, the event appears on more than one CCD video frame, and the event signature, at minimum, resembled that shown in Figure 3 (or covered more pixels than this in a symmetric fashion, such as to resemble the image of a star or other natural point source), they were included in the table. In several cases, only the second and third conditions were used for inclusion in the table. The criteria for determining the validity of the events reported in Bellot Rubio et al. (2000), Ortiz et al. (2002), and Yanagisawa and Kisaichi (2002) are described in each paper. The observations of these particular authors were chosen owing to their availability in the literature coupled with the likelihood of their observed events being genuine impact events (again, the reader is referred to their respective works for more detail of the validity of their respective events).

All of the observed events, including those made by Ortiz et al. (2002) and Yanagisawa and Kisaichi (2002), are listed in the table, and can be grouped into three sets (i.e., the "quality" of the event): confirmed impact events (designated in the table by the abbreviation "C"), unconfirmed, but probable events (P), and

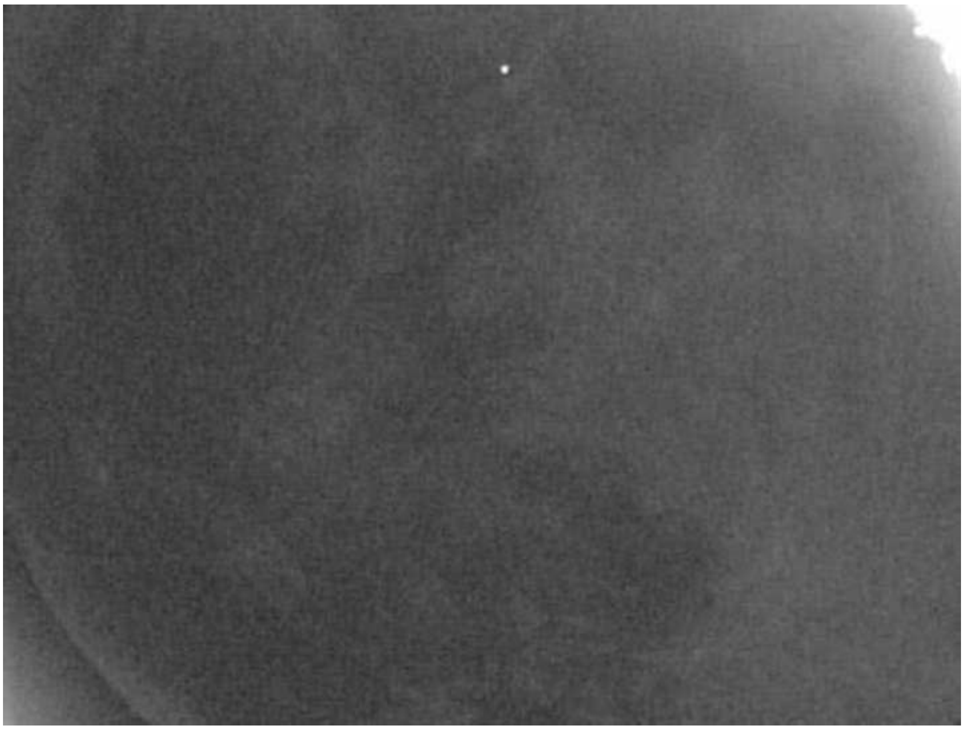

Figure 2. Impact Flash B, imaged at maximum flux output, by David Dunham.

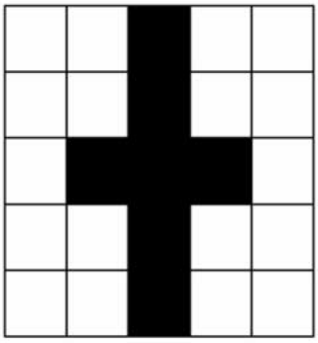

Figure 3. Exceedence criterion of candidate impact flashes. This pixel pattern was used to determine which event signatures are likely impact events and which are cosmic ray signatures (see text for a more detailed description).

tentatively confirmed events (TC). An impact event is defined as “confirmed” if two or more observers, separated by at least 50 km, have independently recorded the event within 1 s of each other. An event is defined as “probable” if the signal has a point spread function similar to a confirmed event or star of similar brightness, and/or the event is visible on at least two consecutive video frames. A “tentative

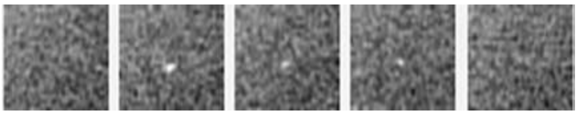

Figure 4. Image Sequence of 2001 Flash 1 at 1/60-sec intervals, recorded by David Dunham.

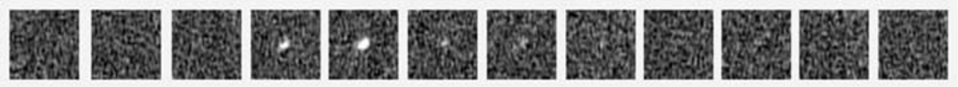

Figure 5. Image Sequence of 2001 Flash 2, (2001 November 18 UTC 00:18:58) recorded at 1/60th second time intervals by Tony Cook.

confirmation" will be used to describe an event with the same characteristics as the "probable" event, with the additional criterion of having been observed in two independent telescopes separated by less than 50 km. For the purposes of this paper, we will treat the "tentative confirmations" as "confirmed", but the reader should note the lack of corroboration by a distant second observer makes these events somewhat less certain than the ones unambiguously corroborated, but considerably more certain than the probable events.

In each of the 1999 confirmed cases observed from North America, Dr. Dunham verified the existence of the events, along with the times of impacts obtained from his tapes. In November 2001 two confirmed impacts were each independently recorded by three widely separated observers. A number of additional events await confirmation (only confirmed events listed by the authors, and events observed by Ortiz et al., 2002 are discussed in any detail in this paper). Figures 4 and 5 are sequences of images separated by 1/60 s, which show the overall evolution of the two verified 2001 Leonid impacts. A typical event was observed in two to three video frames, lasting no more than about 35 ms. Several exceptions to this typical duration were recorded, including two flashes observed in 1999 by Yanagisawa and Kisaichi (2002) lasting 140 and 250 ms, longer than what current impact models predict. An event during the 2001 Leonids was recorded lasting more than 600 ms, with oscillations in brightness as it fades (Ortiz et al., 2002). One possibility that Ortiz raises is that this particular impactor, with an almost grazing incidence angle, may have had very different properties than the rest of the stream, or it encountered a region on the Moon with different properties. A second, which is unlikely given the long duration of this event, is the possibility that tidal disruption from the Moon's gravity caused this meteoroid to fragment into several pieces, which successively impacted the surface producing the long event. If this were the case, the chain would impact in considerably less time than was observed. A chain of fragments would explain the oscillations observed in the afterglow of the event, but this is far from certain. Regardless, the authors determined that it is likely the grazing incidence of the impactor had something to do with its long duration.

4. Validation of the Leonid Impact Events and Comparison with Background Rates

When the 1999 Lunar Leonid impacts were first reported, much skepticism was raised concerning the nature of the events. One of the first possible explanations proposed for the flash observations was the occurrence of sun glints caused by sunlight briefly reflecting off of artificial satellites or space debris. This is very unlikely, given the fact that the observations were made late at night local time when most orbiting space objects were deep in the Earth's shadow. However, geosynchronous satellites are high enough to be outside of the Earth's shadow, but none of these appeared close enough to the Moon as seen from the east coast of the United States at the time of the A-impact to masquerade as a lunar flash (Sam Herchak, personal communication). Another strong argument against sun glints is the short duration of most of the lunar flashes. While most sun glints from rotating satellites last anywhere from a few tenths to several seconds, the typical lunar flash was only 1/30 s in duration. For a sun glint to be only 1/30 s, since the Sun's angular diameter is 1/2 degrees, this would mean that the satellite must be rotating a full revolution every 12 s (this may need to be even faster, since solar panels are not perfectly flat – cells can easily have individual tilts of ±1 degrees). For a satellite outside of the Earth's shadow as seen from ground-based locations, the viewing geometry could not change significantly in 12 s, so there would be another similar flash 12 s after the first one, and probably several more. But the tapes were scrutinized for over a minute from the times of the observed flash events, and no other flashes were seen. Also, sun glints vary in time with location on the Earth, while the flashes that we observed occurred at the same time at the different observing locations, therefore they must be lunar or near lunar in origin. For both years' observations, all the groups verified that satellites were not present near or at the location of the Moon during all intervals of observations.

In addition to the arguments against these flashes being sun glints off of satellites or space debris, the fact that seven flashes in 1999 were simultaneously recorded at two or more well separated locations, two in 2001 from three well separated stations, and the convincing evidence provided by the Japanese and Spanish astronomers leads to a much greater probability that the flashes are lunar phenomena rather than something nearer to Earth. Comparing the locations on the Moon's disk derived from the separate video records reveals agreement within the measurement accuracy of about 2 degrees in location and 1 s in time. For example, from David Palmer's video images, the selenographic longitude and latitude of the 1999 "D" impact were 68.5 degrees west and 2 degrees north, respectively, while for the 1999 "E" impact, these values were 79 degrees west and 17 degrees south, respectively. These are in good agreement with David Dunham's video images to within two degrees in longitude and latitude (compare to the values listed in Table IIa).

Another argument in favor of the impact origins of the flashes is the number of background events (i.e., when the Moon is away from any significant annual meteoroid stream) that have been detected. From September 2000 to June 2003 Cook monitored the Earthlit part of the Moon for impact flashes outside major shower times in order to obtain a set of control measurements for background impact flash rates. The telescope was an undriven 20 cm f/5 Newtonian with a CCD video camera placed at the Newtonian focus. The majority of observations, until late 2002, were made from Alexandria, VA. Observations after this date were acquired from Long Eaton, Nottingham, UK. It is difficult to quantify the effective sensitivity of the camera during each observing session as this varied with the changing transparency of the atmosphere, atmospheric seeing conditions, glare from the illuminated Moon, and the camera instrumentation used. The CCD camera most commonly used was a Watec 902 HS camera, which was capable of recording stars as faint as $M_V = 10$. However a less sensitive PC23C video camera was used in the first few months, and also at other times when too much glare prevented the operation of the Watec 902 CCD camera. The PC23C could record stars as faint as magnitude $M_V = 7.5$. However for R and I magnitudes the sensitivity was likely to be 1–2 magnitudes greater due to the near IR sensitivity of the CCD cameras. This greater IR sensitivity favored the detection of impact flashes, which are expected to yield more energy in the red and near IR part of the spectrum. It is important to note though that the detection sensitivity for flashes in a single TV field, against background noise was probably 1–1.5 magnitudes brighter than these limits.

On some occasions optical devices were placed in front of the CCD camera such as a narrow wedge prism, a low resolution blazed diffraction grating, a near infrared or a 589 nm narrow band filter. The first two were used in the hope that they would yield spectra and discriminate true impact flashes from cosmic rays. The latter two filters were used in the hope that these would enhance detectability of flashes when glare was a problem. Video from both CCD cameras was archived to digital tape on a camcorder and an audio time signal recorded to the sound track. After the first year of observing, it was decided to observe to no less than 15 degrees in local elevation; to observe any lower greatly increased atmospheric absorption, reducing the visibility of the Moon's surface in Earthshine. Also it was decided, that although Earthshine was still visible in the CCD after 80% phase (waxing Gibbous), observing would only take place up to 1st quarter due to glare problems.

The total observing time exceeded 100 h and numerous flashes were detected ($\sim$1 per 15 min with the Watec 902HS CCD camera). The majority of these were obviously cosmic ray detections. This was deduced because they either occurred off the lunar limb, were split into two or more points across the screen, were too sharp compared to the seeing disk, a 2nd observer did not record them, or they did not produce a spectrum when a diffraction grating was placed in the optical path. Of the remaining flashes that were clearly not cosmic rays or satellites/aircraft, none were present in more than 1 TV field as were seen with the Leonid impact flashes. Therefore, none of the events that Dr. Cook observed were convincing impact candidates. In addition, based on comparisons of the atmospheric background (sporadic) hourly rate to that of annual showers in the atmosphere (i.e., shower times versus non-shower times) the background rate of lunar meteoritic flashes would be expected to be much lower than the rate during showers. For the Leonid shower events detected by only one instrument in Table II, no reports of a confirming observation were received. Also, for several additional events, the two instruments were relatively near to one another (less than 10 km ground separation). In these cases, the latter two conditions described above (appearance on multiple CCD video frames and stellar-like signature) were used to validate the events. Although one cannot say for sure whether these events were true impact events, the probability of these being impact in nature are rather high, due to the number of actual confirmed events and the presence of large numbers of Leonid meteors at the location of the moon. Once the lunar impact nature of these events was established beyond a reasonable doubt, the next item of concern was the size of the impacting objects.

5. Initial Mass Estimates and Luminous Efficiencies of the Impactors

Jay Melosh, at the University of Arizona's Lunar and Planetary Laboratory, provided early calculations showing the mass of the impacting meteoroids to range from several tens of kilograms to a few hundred kilograms, with a diameter of about one-half meter (Melosh, 1999, personal communication). Craters resulting from such objects would likely be 10–15 m in diameter. However, such large bodies in the Leonid meteor stream were thought to be far fewer in number than what the new lunar impact data seemed to imply. Artificial satellite collision tests showed that much more energy was converted to light than was expected from standard collision theories, according to Mark Matney, of Lockheed Martin Space Operations in the Orbital Debris Program Office at NASA Johnson Space Flight Center (Matney, 1999, personal communication). Matney believes that hypervelocity collisions may produce some non-equilibrium phenomena resulting in the output of "extra" light. Thus the meteoroids that caused the observed lunar impacts may be smaller than what Melosh indicates by one to two orders of magnitude, making them more compatible with the expected Leonid stream size/mass distribution.

Several different models appear to confirm the higher luminous efficiency of these hypervelocity impacts. Examples include work by Artemieva, Shuvalov, and Trubetskaya who, with numerical simulations, have determined that a magnitude 3 flash could be produced by an object 3kg in mass traveling at the Leonid impact velocity of 72 km/sec. One of the smallest reported impacts, at magnitude 7, may have resulted from a 25 g meteor (Artemieva et al., 2000; hereafter AST). AST derived a luminous efficiency of about 1/1000 of the kinetic energy for the Leonid lunar impact velocity. In addition, AST found that the density of the impacting

TABLE III

Calculated masses of Leonid impactors producing optical flashes of magnitude 3 and 7

Mag.	Diameter	La Paz (1938)	Gehring et al. (1964)	Beech & Nikolova (1999a, b)	Aretmieva et al. (2000)
3	20 cm	0.5 kg	12 kg	10 g	3 kg
7	4 cm	12 g	40 g	0.2 g	25 g

meteors must be at least 1 g/cm^3 in order for the flashes to have appeared on two half-frames of our videotapes.

The results of these and other authors are summarized in Table III. The mass estimates of Beech and Nikolova are much lower than the others. They assumed an efficiency of roughly 1/10, which is probably unrealistically large. There is still considerable uncertainty in the actual luminous efficiency of these impacts that occurred at much higher velocities than any existing experimental data, and therefore in the sizes and masses of the impacting meteoroids. But the meteoroids are likely to range in size from about 4 to 20 cm in diameter. In any case, the craters on the Moon produced by these meteors will be very hard to find since they are likely only a few to several meters in diameter, while the uncertainty in their locations is many kilometers. Although these calculations were made for the 1999 Leonids, the 2001 objects appeared to be of similar apparent magnitude and, since they are also likely from the Leonid stream, the parameters given in Table III apply to them as well.

6. Structure and Nature of the Leonid Meteor Streams

During the 1999 passage of the Moon through the Leonid meteoroid streams, the maximum flux at the moon was the equivalent of a localized region on the Earth experiencing a Zenithal Hourly Rate (ZHR) of 50,000. These were the conditions when the twelve observations of impact flashes were collected. The 2001 encounter, in contrast, saw the maximum lunar "ZHR" equivalent to one order of magnitude less. That value had decreased by another order of magnitude, only 1% of the 1999 flux level, by the time the Moon became observable to the four American observers who confirmed two of the impact events (D. Asher, 2001, personal communication). In 1999, the Moon passed through a ribbon of debris shed by the comet Tempel-Tuttle during its passage through the inner solar system in 1899. In 2001, the Moon encountered several filaments of meteoroids during the 17–18 November period, including streams of debris shed by the comet in 1965, 1866 and 1833.

Each of the nine unambiguously confirmed events from both years was bright, with no faint corroborated event observations. If we assume the "tentatively confirmed" events to be real, all but two are of magnitude 7.5 or brighter. The apparent bias toward brighter events, with the mean magnitude of the sample being 5.4, is likely the result of a selection effect arising from the low signal to noise ratio of the fainter events, coupled with the confusion provided by frequent cosmic ray events, resulting in few faint events recorded with confidence. Beech, Hughes, and Murray (2001) raise the intriguing possibility that the fireballs observed from Earth in the 1998 meteor storm may have been derived from fragments of the mantle of Comet 55P/Tempel-Tuttle. They raise the possibility that the outbursts of comet 55P/Tempel-Tuttle during its 1699 and 1866 perihelion returns may have been mantle loss events, the former resulting in the great Leonid meteor storm of 1833. Such events would inject a population of larger meteoroids into a stream consisting of otherwise mainly small objects. The Moon, in 2001 encountered debris shed by the comet in 1866, assuming Asher's calculations are correct. If this is the case, it is possible that the two confirmed impacts were fragments of mantle material. However, given the small number of confirmed events, lack of confidence in the fainter impact candidates, and uncertainty as to whether there were mantle fragments present at all in the stream encountered by the Moon renders this argument as little more than speculation. However, careful observations of future lunar passages through meteor streams may provide more conclusive information concerning the presence of a separate, distinct population of large objects within a given meteoroid stream.

7. Conclusions

While it is too early to reliably determine the frequency of lunar meteoritic impacts observable from the Earth, the fifteen confirmed impact events from the 1999 and 2001 Leonid storms provide a starting point. In addition to the confirmed events, twelve probable events were considered and compared with the confirmed events; under the assumption the latter are genuine impact events. Systematic study into the lunar meteor phenomena could lead to a better understanding of the structure of meteoroid streams, the composition of the lunar sub-surface, and the size spectrum of the near-Earth environment, to name a few examples. The discovery and confirmation of these phenomena underscores the importance of amateur-professional collaboration, and will continue to do so as investigations into the frequency of observable lunar meteoroid impacts continue. The uncertainty of the occurrence of these events makes it difficult to justify allocating precious time on large telescopes for the study of lunar meteors. Smaller observatories and amateurs can make a serious contribution in this area by determining not only the frequency of occurrence, but also the energy output and spectra of these events.

Work by Beech et al. (Beech et al., 2001; Beech and Nikolova, 1999a, b; Beech, 1998) suggests that several prominent annual meteoroid streams have a distinct class of large members, bifurcating the size spectrum of the stream. They suggest this discontinuity likely exists in the size spectrum of large objects within a particular meteoroid stream, and as a result, what is observed as lunar impact flashes from the ground is the result of the more massive component of the stream (Beech, 2002, personal communication). Beech and Nikolova (1999a) attempted to verify this assertion with the Perseid meteors by counting atmospheric and lunar meteor events, but did not observe any lunar impact events. The result suggested a lack of such a distinct population, with meter-sized and larger objects being sparsely distributed in the Perseid stream at best. Two possible impacts events were observed by others at the time of the peak Perseid flux, but these cannot be verified as either being Perseid in origin or real impact events. While the existence of a distinct population of large meteoroids within the Leonid (or Perseid) meteoroid stream is possible, it is far from conclusive. Uncertainties in the detection of faint lunar impacts, caused by the noise introduced by the earthlit lunar surface and instrument electronics and the regular occurrence of impact-mimicking cosmic ray events, leave the question open as to the size spectrum of the meteoroids. The selection effects inherent in the observations of lunar meteors further complicate this – only the largest objects are detected from ground-based instruments. It is likely that, as observed in the Solar System on large scales, and with the meteors entering the Earth's atmosphere on a small scale, the size spectrum of the Leonid stream is generally continuous, with no bifurcation in terms of size.

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