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Results of Lunar Impact Observations During Geminid Meteor Shower Events

R.J Suggs and R.M. Suggs
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May 2015

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Space Administration

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LIST OF ACRONYMS

ALaMO	Automated Lunar and Meteor Observatory
IMO	International Meteor Organization
MEO	Meteoroid Environment Office
MSFC	Marshall Space Flight Center
SD	South Dome
TM	Technical Memorandum
UTC	universal time coordinated
WCO	Walker County Observatory
ZHR	zenith hourly rate (i.e., the number of shower meteors per hour one observer would see if his limiting magnitude is 6.5 magnitudes and the radiant is in his zenith)

TECHNICAL MEMORANDUM

RESULTS OF LUNAR IMPACT OBSERVATIONS DURING GEMINID METEOR SHOWER EVENTS

1. INTRODUCTION

Meteoroids are natural particles with origins from comets, asteroids, and planets from within the solar system. On average, 33 metric tons (73,000 lb) of meteoroids hit Earth everyday with velocities ranging between 20 and 72 km/s. However, the vast majority of these meteoroids disintegrate in the atmosphere and never make it to the ground. The Moon also encounters the same meteoroid flux, but has no atmosphere to stop them from striking the surface. At such speeds even a small meteoroid has incredible energy. A meteoroid with a mass of only 5 kg can excavate a crater over 9 m across, hurling 75 metric tons (165,000 lb) of lunar soil and rock on ballistic trajectories above the lunar surface.

Meteoroids with particle sizes as small as 100 μm (1 μg) can do considerable damage to spacecraft in Earth's orbit and beyond. Impacts can damage thermal protection systems, radiators, windows, and pressurized containers. Secondary effects might include partial penetration or pitting, local deformation, and surface degradation that can cause a failure upon reentry. The speed, mass, density, and flux of meteoroids are important factors for design considerations and mitigation during operations. Lunar operations (unmanned and manned) are also adversely affected by the meteoroid flux. Ejecta from meteoroid impacts is also part of the lunar environment and must be characterized.

Understanding meteoroid fluxes and the associated risk of meteoroids impacting spacecraft traveling in and beyond Earth's orbit is the objective of the Meteoroid Environment Office (MEO) located at Marshall Space Flight Center (MSFC). One of the MEO's programs is meteoroid impact monitoring of the Moon. The large collecting area of the night side of the lunar disk provides statistically significant counts of meteoroids that can provide useful information about the flux of meteoroids in the hundreds of grams to kilograms size range. This information is not only important for characterizing the lunar environment associated with larger lunar impactors, but also provides statistical data for verification and improving meteoroid prediction models.

Current meteoroid models indicate that the Moon is struck by a sporadic meteoroid with a mass >1 kg over 260 times per year. This number is very uncertain since observations for objects in this mass range are few. Factors of several times, higher or lower, are easily possible. Meteor showers are also present to varying degrees at certain times of the year. The Earth experiences meteor showers when encountering the debris left behind by comets, which is also the case with the Moon. During such times, the rate of shower meteoroids can greatly exceed that of the sporadic background rate for larger meteoroids. Looking for meteor shower impacts on the Moon at about the same time as they occur on Earth will yield important data that can be fed into meteor shower forecasting models, which can then be used to predict times of greater meteoroid hazard on the Moon.

The Geminids are one such meteor shower of interest. The Geminids are a major meteor shower that occur in December with a peak intensity occurring usually during the 13th and 14th of the month and appearing to come from a radiant in the constellation Gemini. The Geminids are interesting in that the parent body of the debris stream is an asteroid, which along with the Quadrantids, are the only major meteor showers not originating from a comet. The Geminids parent body, 3200 Phaethon, is about 5 km in diameter and has an orbit that has a 22° inclination which intersects the main asteroid belt and has a perihelion less than half of Mercury's perihelion distance. Thus, its orbit crosses those of Mars, Earth, Venus, and Mercury. The Geminid debris stream is by far the most massive as compared to the others. When the Earth passes through the stream in mid-December, a peak intensity of ≈120 meteors per hour can be seen.

Because of the Geminids' relatively large intensity and unique origin, it is important to monitor and gain information about the Geminids so as to improve their forecasts and understand their contribution to the meteoroid environment in Earth's orbit and at the Moon. It is the purpose of this Technical Memorandum (TM) to document two lunar observing periods coinciding with the Geminid meteor showers that occurred in 2006 and 2010.

2. BACKGROUND

2.1 Lunar Observation Facilities and Methodology

Since March 2006, members of the MEO and the Natural Environments Branch at MSFC have been performing routine video observations of the Moon in order to establish the rates and sizes of large meteoroids (>30 g) striking the lunar surface. Observations are conducted at NASA MSFC in Huntsville, Alabama, at the Automated Lunar and Meteor Observatory (ALaMO). The facility consists of two observatory domes, a 15-m tower with a roll-off roof, and an operations center with laboratory space (fig. 1(a)). Two telescopes are operated at the ALaMO, one in the South Dome (SD) and the other in the Tower. From September 2007 until December 2012, a third telescope located in a facility near Chickamauga, Georgia, in Walker County, was operated remotely from MSFC. The observatory consisted of a ground level building with a roll-off roof and is referred to as the Walker County Observatory (WCO) (fig. 1(b)). The observations from this telesope were used only for flash confirmations.

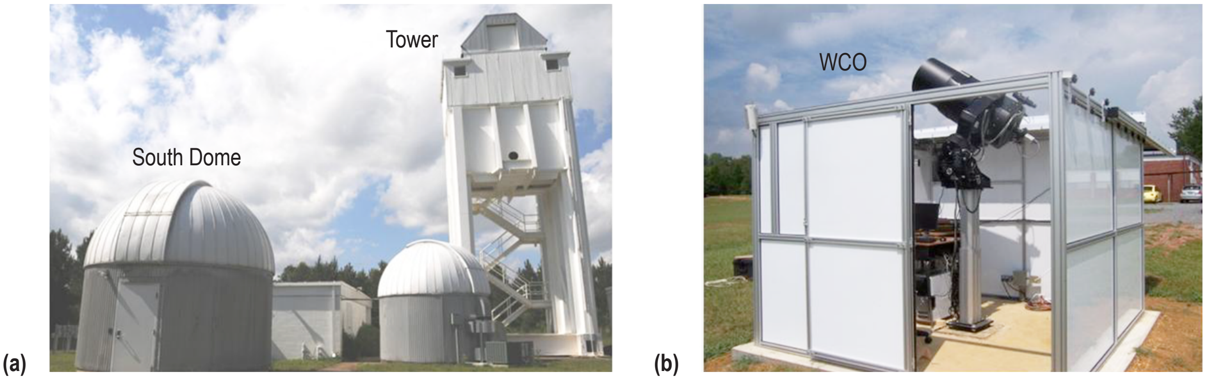


Figure 1. The NASA MEO and Natural Environments Branch's observatories: (a) The ALaMO at MSFC where two telescopes are located, one in the SD and the other in the Tower facility, and (b) the remotely operated telescope located in Walker County, GA.

2.1.1 Instrumentation

Since the start of the observations, the lunar observing instrumentation has changed over time. Beginning in March 2006, initial observations were conducted with one telescope (Orion® 254-mm-diameter) located in the Tower observatory. In July 2006, a second telescope (Meade® RCX400™ 14-in-diameter) was added in the SD. Shortly thereafter (September 2006), the Tower telescope was also replaced with a Meade RCX400 14-in-diameter telescope, both with Optec 0.33X focal reducers. The Tower scope uses a StellaCam-EX monochrome video camera, while the SD scope uses a Watec 902H2 Ultimate monochrome video camera. Both cameras use the same Sony®

HAD EX™ 0.5-in format charge-coupled device. The remote observatory, WCO, has the same equipment as the Tower observatory. The effective focal length is ≈923 mm, giving a horizontal field-of-view of 20 arcmin covering $\approx 4\times 10^6$ km^2, or 12% of the lunar surface. The field-of-view of the telescopes is a balance between resolution, coverage area, and lunar phase constraints discussed in the next section. In 2008, the 14-in telescope in the SD was replaced with a Ritchey-Chrétien Optical Systems 20-in (0.5-m) telescope with the focal reducer adjusted to give approximately the same field-of-view as the 14-in instruments. Then, in August 2010, the 20-in telescope was replaced with a Celestron® 14-in.

The video from the cameras is digitized using a Sony GV-D800 digital tape deck and sent by FireWire® to a personal computer where it is recorded on the hard drive for subsequent analysis. The limiting stellar magnitude at the 1/30-s video frame rate is ≈12.

2.1.2 Observing Methodology

Lunar observations are made of the night portion of the Moon when the sunlit portion is between 10% and 45% illuminated (fig. 2). This occurs on about five evenings from twilight end to moonset when the phase is between New and 1st Quarter, and on five mornings from moonrise to twilight for phases between Last Quarter and New Moon of each month. No observations are attempted during phases less than 10%, since the time between twilight and moonrise or moonset is too short. Observations are not made during phases greater than 45% because the scattered light from the sunlit portion of the Moon is too great and masks the fainter flashes. Large lunar albedo features are easily visible in the earthshine and are used to determine the approximate location of the impacts on the lunar surface. An example of a typical video frame from the two ALaMO scopes is shown in figure 3. This video frame was captured on January 9, 2011 at 1:17:55 UTC. Also shown in the video frame is a confirmed impact. The duration of the flash was for two video frames (video frame rate = 1/30 s) and a flash peak magnitude of 9.

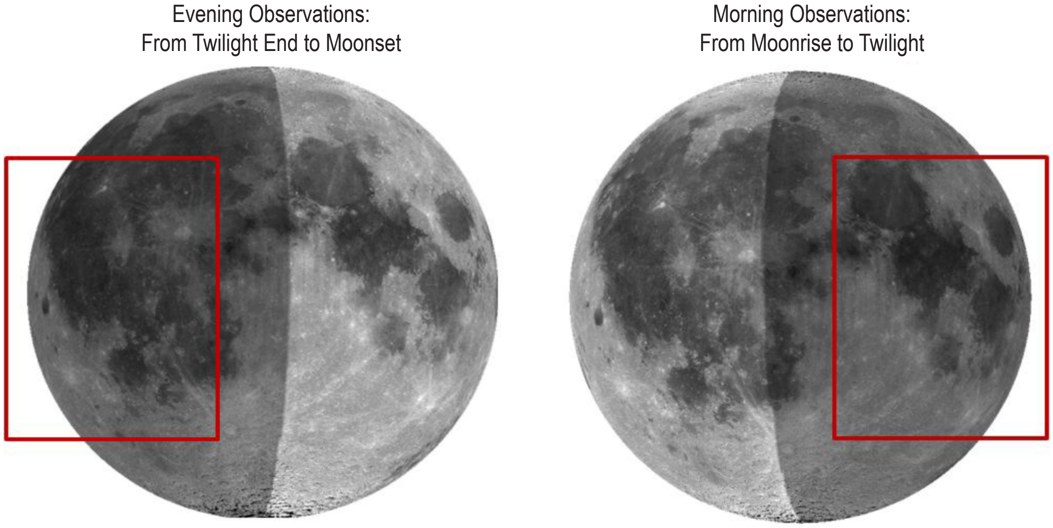


Figure 2. The telescope field-of-view and orientation during the evening and morning observations when the lunar phase is between 10% and 45%.

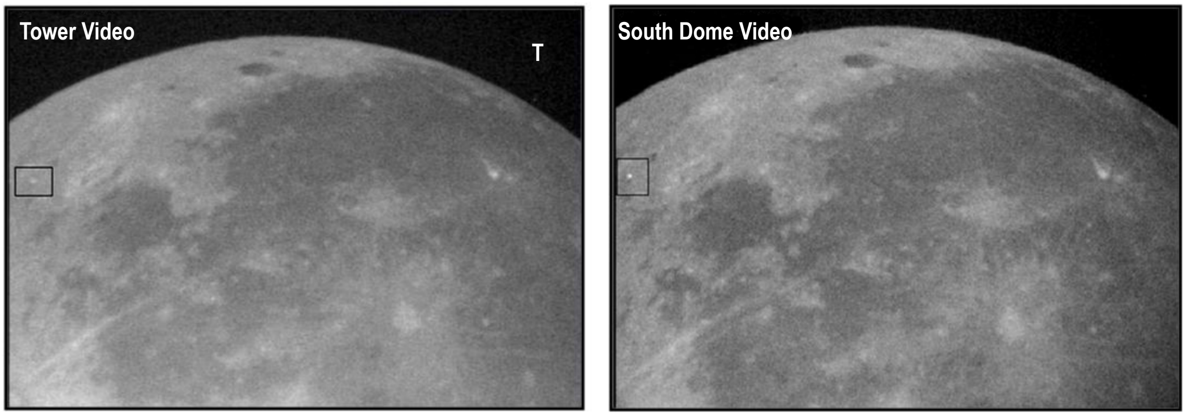
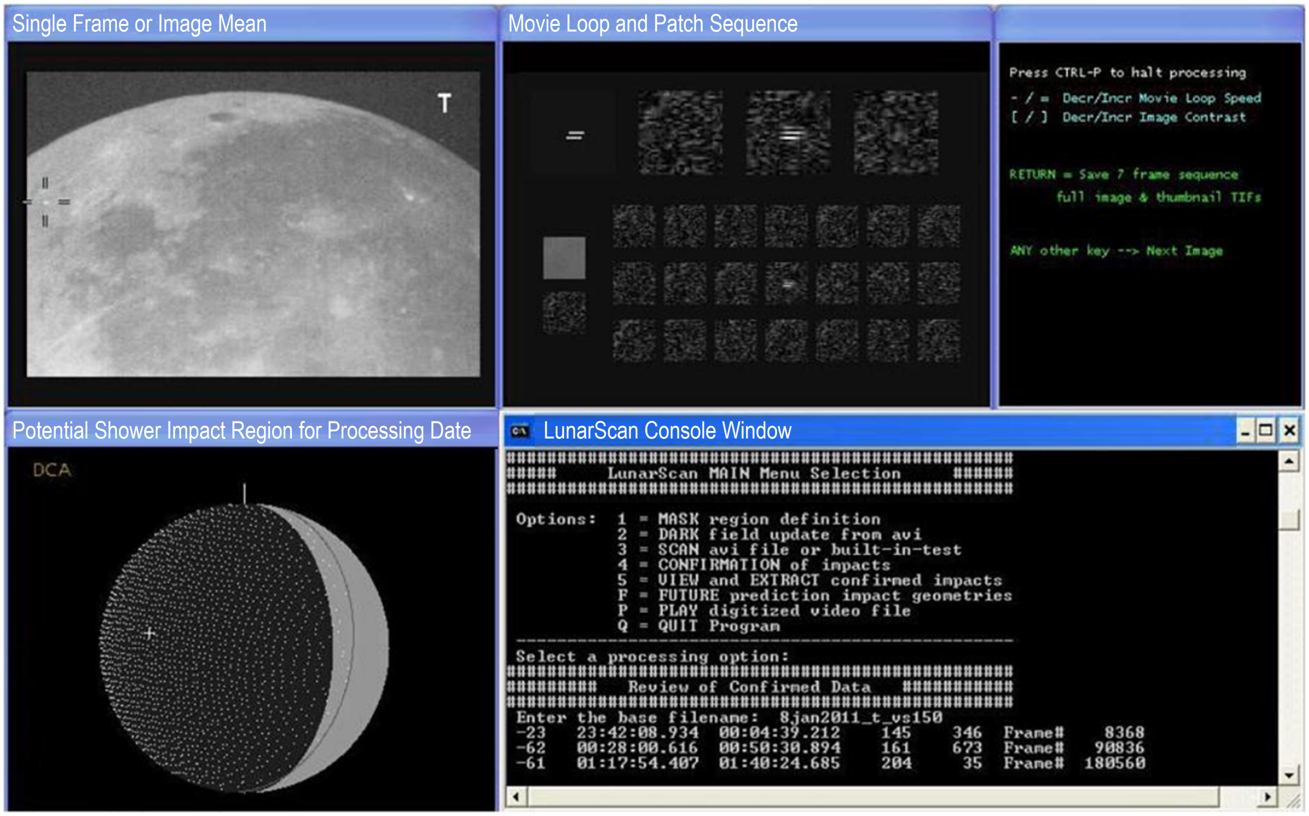


Figure 3. Example video frames from the videos of the ALaMO Tower and SD telescopes recorded on January 9, 2011. Also shown is an impact flash that was simultaneously recorded in both videos.

2.2 Data Analysis

2.2.1 Impact Detection

The recorded video is analyzed using a custom program named LunarScan, which was developed by Peter Gural.[1] The software finds flashes in the video which are statistically significant (as described in ref. 2) and presents them to a user who determines if they are cosmic ray impacts in the detector, sun glints from satellites between the Earth and the Moon, or actual meteoroid impacts. Figure 4 shows the software user interface screen. The video frame containing a detected flash is displayed in the upper-left window of the screen with the flash highlighted. The upper-middle screen shows an enhanced and magnified frame subimage sequence which facilitates motion discrimination and flash duration determination. The lower-left window provides a shower forecast impact geometry associated with the date of the video being analyzed. Candidate impact flashes indentified by LunarScan are then required to be simultaneously detected in two telescopes, thus ruling out cosmic rays and electronic noise.



```
Press CTRL-P to halt processing
- / =  Decr/Incr Movie Loop Speed
[ / ]  Decr/Incr Image Contrast


RETURN = Save 7 frame sequence
        full image & thumbnail TIFs


ANY other key --> Next Image
```

```
##################################################
#####     LunarScan MAIN Menu Selection     ######
##################################################

 Options:  1 = MASK region definition
           2 = DARK field update from avi
           3 = SCAN avi file or built-in-test
           4 = CONFIRMATION of impacts
           5 = VIEW and EXTRACT confirmed impacts
           F = FUTURE prediction impact geometries
           P = PLAY digitized video file
           Q = QUIT Program
 -------------------------------------------------
 Select a processing option:
##################################################
#########   Review of Confirmed Data   ###########
##################################################
 Enter the base filename:  8jan2011_t_vs150
 -23   23:42:08.934  00:04:39.212   145    346  Frame#    8368
 -62   00:28:00.616  00:50:30.894   161    673  Frame#   90836
 -61   01:17:54.407  01:40:24.685   204     35  Frame#  180560
```

Figure 4. LunarScan flash detection software user interface. Each window provides flash detection information: visual location of flash (upper-left), enhanced subimages of video frame sequence containing flash (upper-middle), shower impact geometry and phase visualization (lower-left), and video time and frame information (lower-right).

Early in the lunar observing program, some of the detected impacts were observed with only one telescope. However, only flashes which spanned more than two video frames and showed a proper light curve (abrupt brightness increase followed by gradual decay) were counted as an impact. For short flashes where satellite motion might not have been detectable, custom software was used to check for conjunctions with Earth-orbiting satellites whose orbital elements are available in the unclassified satellite catalog (<www.space-track.org>).

Since there is some probability that orbital debris or a classified satellite not listed in this catalog could cause such a short flash, the video from the WCO was used for confirmation of flashes detected at the ALaMO facility. The spatial separation between the ALaMO and WCO, about 125 km, allows parallax discrimination between impact flashes and sun glints from manmade objects, even at geosynchronous altitude. After five years of operation of the remote observatory, only one candidate flash due to orbital debris has been seen that could have been mistaken for an impact, and that one showed orbital motion upon closer inspection. Whenever the weather does not allow operation of the remote observatory, temporally short flash images are enhanced and closely examined for any sign of motion with respect to the lunar surface.

2.2.2 Flash Analysis

After detection and confirmation, another computer program, LunaCon, is used to perform photometric analysis.[3] LunaCon calculates and displays graphics showing the lunar surface brightness, contrast between the lunar surface and space next to the limb, lunar elevation angle, lunar surface area in the field-of-view, and other data quality diagnostics as a function of time during the night. These displays make it obvious when clouds pass, twilight is contaminating the observations, the Moon drifts in the field-of-view, and when atmospheric extinction is extreme. Using this information allows calculation of time spans of clear weather and good data quality for flux calculations.

LunaCon can also be used for photometry calculations. Background stars in the field-of-view in the lunar videos are used as photometric references to determine the observed luminous energy of the flashes. Since a reference star is unlikely to be in the frame during a flash, the earthshine on the Moon is used as a transfer standard between the reference star and impact flash. Photometric accuracy is estimated to be ±0.5 magnitudes.[2]

Initially, LunaCon was used for flash photometry. However, a more rigorous calibration process is currently used that does not use earthshine as a transfer standard. This technique uses stars observed at different air masses to compute extinction and photometric zero points.[4] When this technique was applied to a quality controlled subset of the observations described in the next section, an average photometric uncertainty of ±0.03 magnitudes was determined.[4]

For the Geminid observations described later, passing clouds during many of the observations made it impossible to use passing stars to determine the extinction coefficients and photometric zero points, so the earthshine reference technique of LunaCon was used for the Geminid magnitudes.

2.3 Overview of Lunar Observation Results

From March 2006 to September 2011, routine lunar observations were scheduled when the lunar phase was within the observing constraints described in the previous section. This resulted in eight to ten scheduled observing sessions per month for the 5½-year period. Beginning September 2011, lunar observations were limited to observing shower events that coincided with the lunar phase observing constraints. Table 1 summarizes the observations for the 5½ years of routine observations. During this period, observational data were collected on 294 out of the 600 nights that were scheduled. Weather conditions greatly reduced the number of observing opportunities. Of the 294 nights of observations, 128 were during the morning (between Last Quarter and New Moon, waning crescent phase) and 166 were during the evening (between New and 1st Quarter Moon, waxing crescent phase). The number of video hours collected totaled 752 hours: 358 and 394 hours during the morning and evening sessions, respectively. Even though a significant number of video hours were collected, the video quality was not consistent from night to night and at times within a night due to sky conditions. Thus, the number of useful video hours containing observed impacts will be smaller. This emphasizes the fact that in order to obtain a statistically large lunar observational dataset for meteoroid analysis, a significantly long observing campaign is needed.

Table 1. Summary of lunar observations.

Year	Nights Scheduled	Nights Observed	Mornings	Evenings	Total Hours	Morning Hours	Evening Hours	Impacts Observed	Morning Impacts	Evening Impacts
2006	100	58	26	32	147	80	67	52	31	21
2007	128	63	28	35	193	92	101	46	7	39
2008	113	65	27	38	155	75	80	63	24	39
2009	103	46	24	22	94	48	46	31	7	24
2010	105	41	17	24	108	50.6	57.05	38	4	34
January–August 2011	51	21	6	15	55	12.3	43	15	3	12
Totals	600	294	128	166	752	358	394	245	76	169

The number of lunar impacts detected in the videos by using LunarScan was 245. Of those impacts, 76 were detected in the morning observations and 169 were detected during the evening observations. Figure 5 shows a plot of the detected impacts, along with their classification as a sporadic minor shower or a major shower source. Two noteworthy impacts that have been observed are the first and second impacts observed at MSFC. The first lunar impact detected was captured on video on November 7, 2005 during a proof-of-concept observation experiment before the ALaMO was established. The impact flash, analyzed and described in reference 5 (see appendix A for press release), was observed in five video frames and was probably a kilogram-size meteoroid from the Taurid meteoroid stream. The second impact observed at MSFC was the first at the ALaMO facility. It also happens to be tied with one other impact observed at the ALaMO facility for the longest duration impact flash observed as of May 2012 by any observer. The flash had a duration of 14 video frames, or ≈0.5 s (see appendix B for press release).[6] Most impact flashes that are observed are on the order of 1 to 2 frames in duration. Results from a detail analysis of a subset of the impact flashes observed during photometric-consistent conditions are given in reference 4.

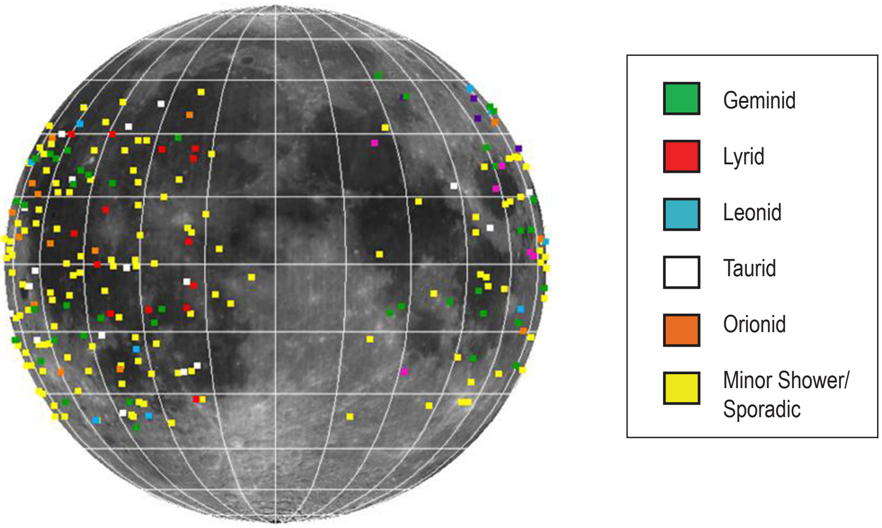


Figure 5. Over five years of observed meteoroid impacts and their shower classifications.

One striking feature of the plot of impacts is the asymmetry in the number of impacts seen between the western and eastern hemispheres. A ratio of 1.45:1 between the evening and morning impacts exists. Suggs et al. has shown that the cause of the asymmetry appears to be due to an overall bias in the impact radiant of the shower meteoroids for the western hemisphere during the periods that observations were made.[7] Though the minor showers are not explicitly separated from the sporadic sources in figure 5, it can be seen that major showers are a significant source of the meteoroid impacts. Suggs et al. shows that shower meteoroids dominate the environment in the observed size range (larger than 100 g) and thus would explain the evening/morning flux asymmetry due to their radiant distribution.[7]

Figure 6 demonstrates the importance of shower meteoroids in the observed meteoroid impact flux. The number of observed impacts is plotted for each year of observations. Also plotted are the number of impacts associated with a major shower event where the peak of the shower occurred during the scheduled lunar observation. It is seen that each of the years of the observations contains one shower event peak, except for 2011, which only includes impact results for the months of January to August. Even though only one major shower event peak was observed for each of the years, impacts associated with the other major showers were observed when the scheduled observation occurred just prior to or after the associated shower peak. When the scheduled observations coincide with the peak of the showers and the lunar impact geometry is favorable for viewing, the observed shower impacts are significant compared to the total observed throughout the year. Also indicated in figure 6 is the lunar phase in which the shower peak occurred. All of the observed peak shower events occurred in the evening, except for 2006. This supports the more detailed analysis performed in reference 7 that the lunar shower impacts observed during the program had an observational bias for the evening sessions (western hemisphere).

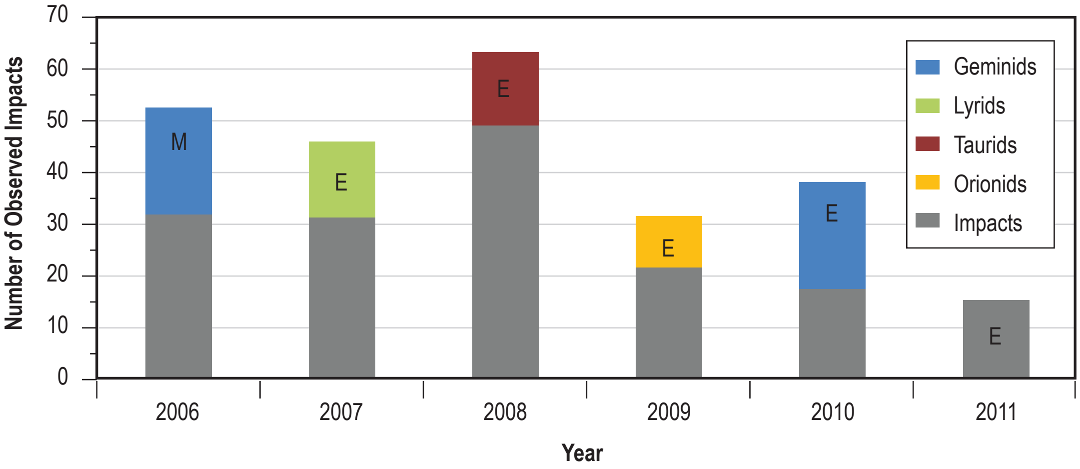


Figure 6. Observed number of impacts associated with major shower events from 2006 to 2011. Also indicated is which lunar observing session the showers were observed, either morning (M) or evening (E).

3. LUNAR OBSERVATIONS DURING THE GEMINID SHOWERS

Since the Geminids are an important component of the meteoroid environment, documenting their observations will aid in monitoring their characteristics and changes that may occur from year to year. From figure 6, the Geminids are seen to be the only shower where their peak activity was observed more than once during the five-year observing campaign. This provides an opportunity to compare the observations between the two periods. Of interest will be a comparison of the impact rate and the energy of the impactors indirectly characterized by the impact flash duration and peak magnitude.

3.1 The 2006 Geminid Shower

The 2006 Geminid shower event fell nicely within the lunar observing scheduled for the early mornings of December 13–16. Also, the meteoroid lunar impact zone as modeled by LunarScan was viewable from Earth and within the field-of-view of the telescopes (fig. 7). Note that the impact geometry shows impacts for the eastern hemisphere consistent with a morning observation of a waning crescent Moon. The first morning of the observing period was cloudy, which was one day before the peak of the shower. The morning during the shower peak was partly cloudy. However, lunar observations were attempted, and 4.6 hours of video were captured, yielding ≈75% of video with clear conditions. The two mornings following the shower peak were mostly clear, allowing 2.3 and 2.5 hours of lunar video to be captured, respectively. The International Meteor Organization (IMO) reported that Earth meteors were seen at a peak zenith hourly rate (ZHR) of 120 per hour on December 14. Figure 8 shows a plot of IMO-reported meteor rates for December 11–16. Also shown are the periods of lunar observations that occurred. On December 14, the ALaMO observed 16 lunar impacts coincident with the shower peak followed by another three impacts on December 15.

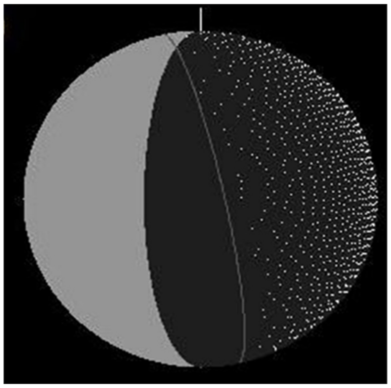


Figure 7. The 2006 Geminid lunar impact geometry showing the predicted impacts (dots) for December 14, 2006. Also shown is the phase of the Moon, which is at 35% illumination.

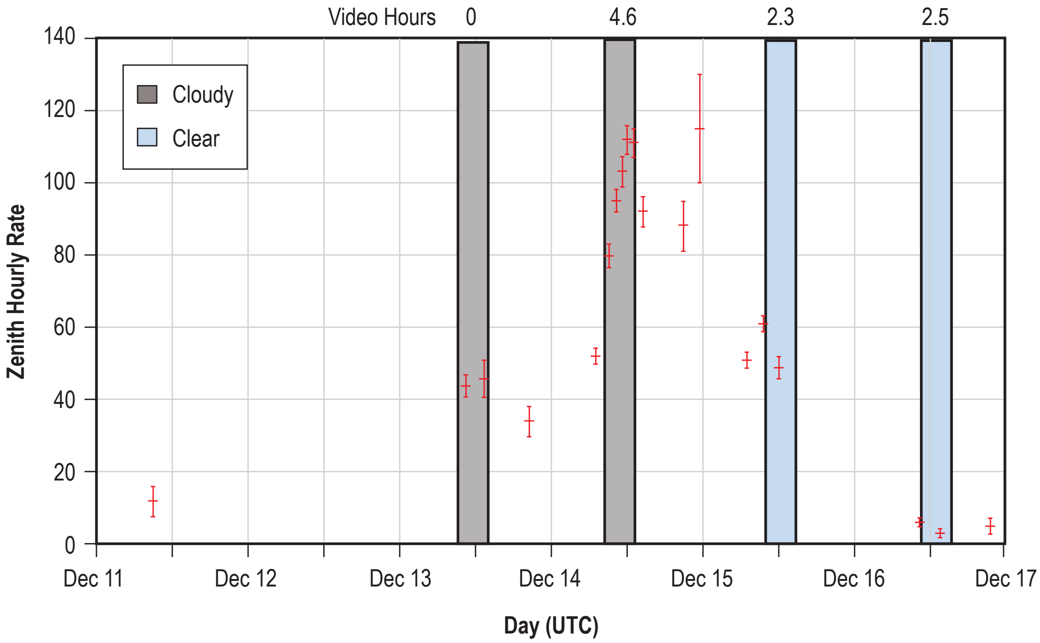


Figure 8. Observed 2006 Geminid meteor shower rates from the IMO data. Overlaid is MSFC lunar observation schedule and observation status.

The detection software was applied to both the ALaMO scopes' videos. However, a few of the impact flashes were not detected in both scopes by the software. For those that were not, visual confirmations of the flashes were made in the videos. Table 2 is a list of the lunar impacts detected in the videos. The table provides the impact location, times, observation status, impact flash duration (number of video frames), and impact flash magnitudes for the observed 2006 Geminids. Table 2 indicates that all of the impacts were observed by the two telescopes at the ALaMO as indicated in the observation status column as either detected (D) or visually confirmed (C). The WCO facility was not operating at the time. The last impact that occurred on December 15 was not confirmed in a second scope due to the impact being just outside the scope's field-of-view. No motion was detected in the three frames where the flash was present, and thus, it was assumed to be an impact.

Table 2. Observed 2006 Geminid lunar impacts.

Impact No.	UTC	Longitude	Latitude	Region	Observation Status		No. of Video Frames		Flash Magnitude
					Tower	SD	Tower	SD	
December 14, 2006 Video Duration = 4.6 hr									
1	08:12:40.0	33.5	46.5	Lacus Somniorum	D	C	1	1	9.5
2	08:14:42.0	72.5	25.0	Plutarch K	C	D	1	1	8.6
3	08:16:46.4	51.5	–21.0	Biot B	D	D	2	1	9.3
4	08:32:06.6	70.5	2.5	Mare Undarum	D	C	1	1	9.6
5	08:32:52.0	66.0	7.5	Mare Undarum	C	D	1	1	10.1
6	08:39:57.2	74.0	–23.0	Phillips B	D	C	1	1	9.8
7	08:46:02.0	80.0	14.5	Hansen B	D	C	1	1	9.9
8	08:50:36.1	46.5	12.5	Palus Somni	D	D	1	1	9.0
9	08:51:20.6	51.5	–11.0	Mare Fecunditatis	C	D	1	1	9.6
10	08:56:43.0	84.0	–5.5	Mare Smythii	D	D	1	1	8.8
11	09:00:22.1	39.0	40.0	Maury P	D	D	2	2	8.9
12	09:03:33.0	61.0	22.0	Mare Crisium	C	D	1	1	10.5
13	10:11:07.3	40.5	–8.5	Gutenberg	D	D	2	2	10.3
14	10:28:51.1	83.5	36.0	Gauss	C	D	1	2	10.2
15	10:56:41.8	71.5	7.5	Mare Undarum	D	D	1	1	9.6
16	11:21:22.6	49.0	–6.0	Mare Fecunditatis	C	D	1	1	10.4
17	11:28:08.4	28.0	–9.5	Theophilus	D	D	3	2	9.4
December 15, 2006 Video Duration = 2.3 hr									
18	09:15:14.0	85.0	37.5	Beals	D	D	1	1	9.5
19	09:17:39.0	60.0	26.5	Delmotte	D	D	1	1	8.0
20	09:53:28.0	67.0	–13.0	Lame N	D	NA	3	NA	6.7

Also seen in table 2 are the flash durations of the impacts in terms of the number of video frames in which they were observed. The flash durations range between 1 and 3 frames, with most of the impacts having a duration of 1 frame. The peak flash magnitudes are also provided and range between 8 and 10.5. The impact rates, flash durations, and flash magnitudes will be compared with the 2010 values in the next section. A plot of the 2006 Geminid impact locations is provided in figure 9, and an example image of one of the impacts (impact no. 11) is seen in figure 10.

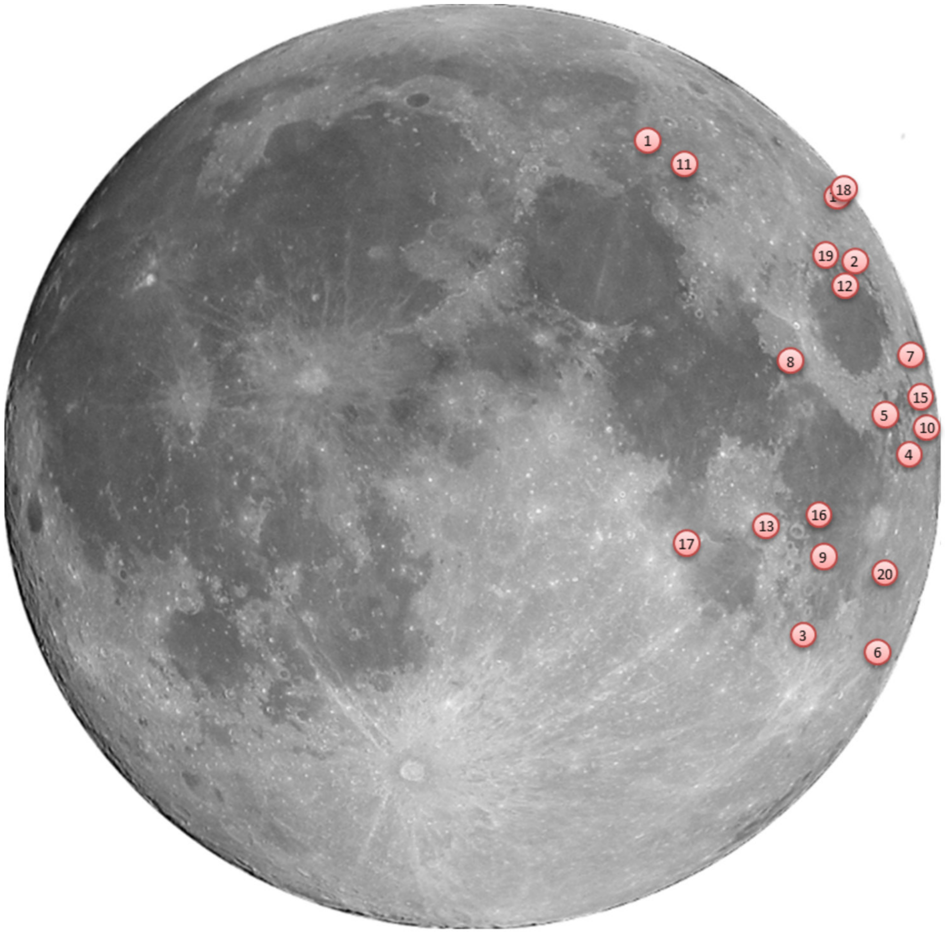


Figure 9. Observed 2006 Geminid lunar impact locations.

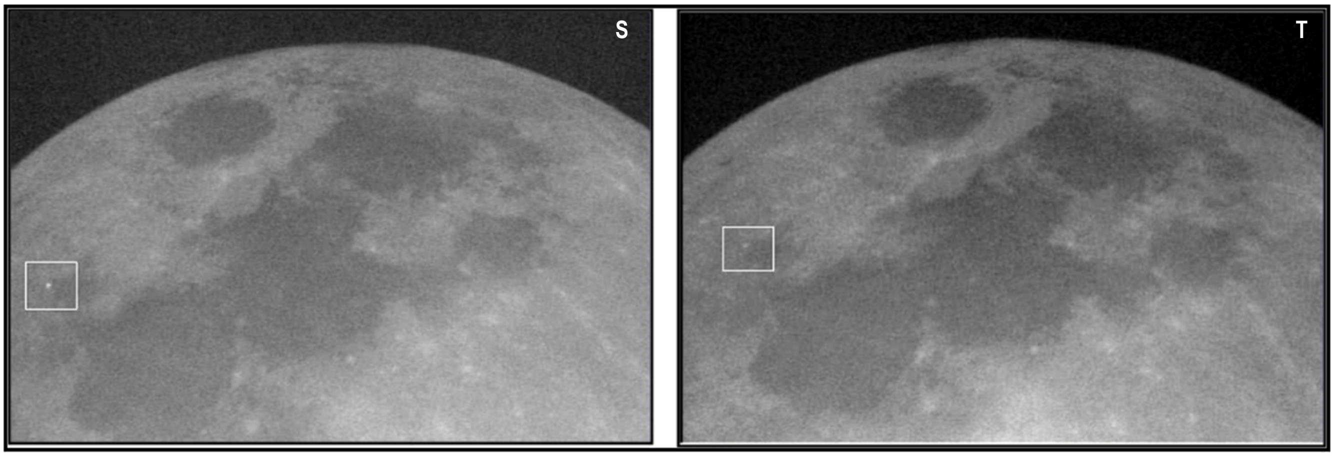


Figure 10. Geminid 2006 impact no. 11 occurring at 9:00:22 UTC. Example of one of the observed impacts detected in both the videos of the ALaMO telescopes.

3.2 The 2010 Geminid Shower

In December 2010, lunar observations of the Geminid meteor shower were favorable. The lunar observing schedule coincided with the run-up to the Geminid shower event. A total of six nights were scheduled (December 9–14), with the sixth night occurring during the peak of the shower but just outside the lunar phase observing constraint. Also, modeling of the Geminid meteoroid stream's encounter with the Moon (Gural's LunarScan software) showed a favorable impact geometry viewable from the Earth during an evening observation of a waxing crescent Moon. The field-of-view of the telescopes was also well within the impact zone of the sunlit region of the Moon (fig. 11).

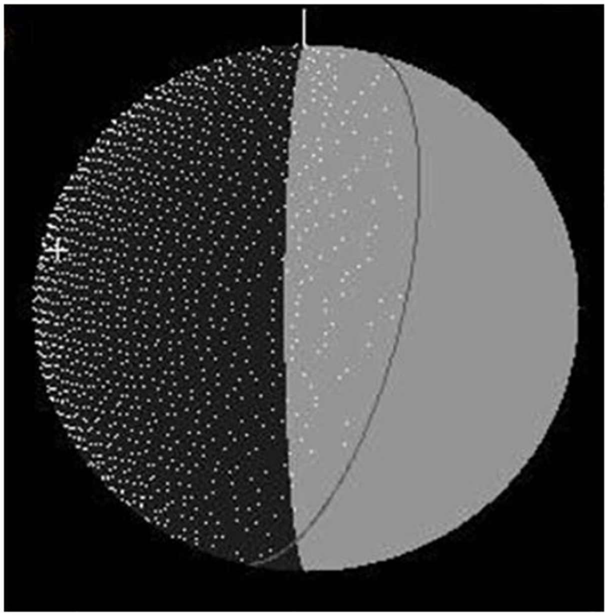


Figure 11. The 2010 Geminid lunar impact geometry showing the predicted impacts (dots) for December 14, 2010. Also shown is the phase of the Moon which is at 54% illumination.

Of the six nights scheduled, only two were clear: the first night and the last night. The first night observations resulted in 2.2 hours of video recorded by the ALaMO cameras with no impacts detected. The last scheduled night of observations during the peak of the shower, resulted in 6.1 hours of video. Even though the sky conditions for this night were clear with high transmittance, the lunar illumination was 54%, which was significantly greater than the observing constraint limit of 45%. The resulting video for that night was thus degraded by glare caused by light from the sunlit portion of the Moon. Even with the glare present in the video, a total of 21 impacts were detected for that night. The IMO reported that Earth observations of the Geminids peaked on December 14 with a ZHR of 120 per hour. Figure 12 shows a plot of the IMO compilation of meteor observation rates during the shower event. Also shown in figure 12 is an overlay of the lunar observations scheduled during the shower event.

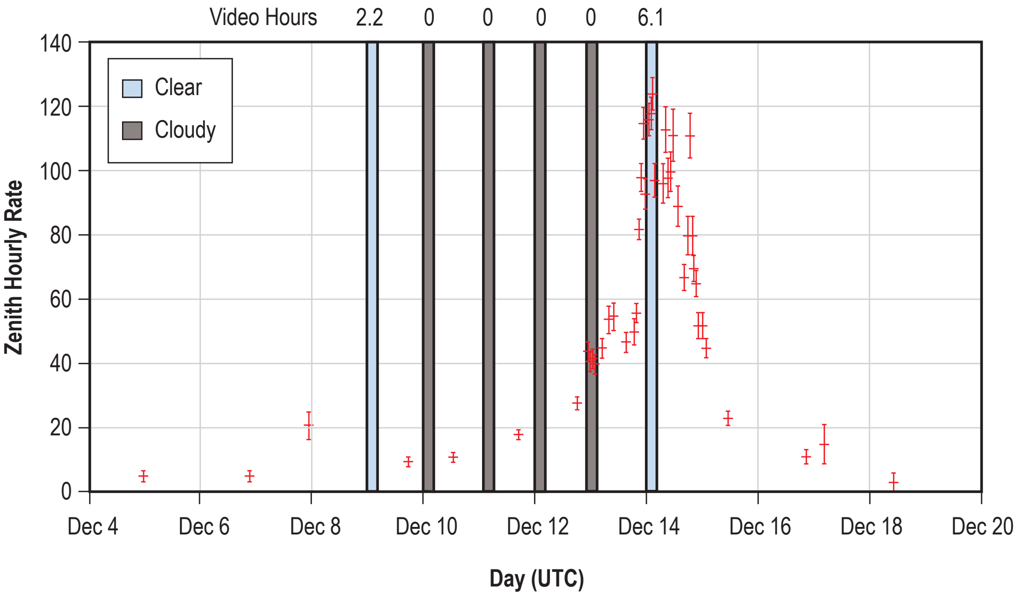


Figure 12. Observed 2010 Geminid meteor shower rates from the IMO data. Overlaid is MSFC lunar observation schedule and observation status.

The detection software was applied to both the ALaMO scopes' videos. However, several of the impact flashes were not detected in both scopes by the software. For those that were not, visual confirmations of the flashes were made in the videos. Table 3 lists the impacts detected during the night of December 13/14, 2010. The table provides the impact location, time, observation status, impact flash duration (number of video frames), and impact flash magnitude. As was the case for the 2006 Geminids, photometric magnitudes were obtained from the LunaCon calculation. A plot of the 2010 Geminid impact locations is provided in figure 13 in the western hemisphere (left). The 2006 Geminids are also plotted for comparison.

Table 3. Observed 2010 Geminid lunar impacts.

Impact No.	UTC	Longitude	Latitude	Region	Observation Status			No. of Video Frames			Flash Magnitude
					Tower	SD	WCO	Tower	SD	WCO	
1	23:53:51.6	–47.0	–16.0	Billy	D	D	O	3	4	NA	9.1
2	23:53:56.9	–58.0	–17.0	Fontana	D	C	O	1	1	NA	10.3
3	00:25:25.5	–75.0	24.0	Eddington	D	C	O	1	1	NA	10.4
4	01:16:14.6	–39.0	–32.0	Lee	D	D	O	2	2	NA	10.1
5	01:16:42.0	–27.0	–13.0	Darney C	O	D	O	NA	2	NA	NA
6	01:17:08.8	–25.0	–10.0	Eppinger	O	D	O	NA	2	NA	NA
7	01:49:31.5	–66.0	25.0	Briggs	D	D	C	2	3	1	9.8
8	01:55:48.1	–41.0	–12.0	Letronne	D	D	O	2	1	NA	10.5
9	01:56:51.5	–64.0	–10.0	Grimaldi	D	C	O	1	2	NA	11.0
10	02:51:00.7	–86.0	–17.0	Kopff B	D	D	O	1	1	NA	9.8

Table 3. Observed 2010 Geminid lunar impacts (Continued).

Impact No.	UTC	Longitude	Latitude	Region	Observation Status			No. of Video Frames			Flash Magnitude
					Tower	SD	WCO	Tower	SD	WCO	
11	02:55:57.6	–41.0	–39.0	Lacus Excellentiae	D	D	O	3	2	NA	9.2
12	03:25:50.9	–58.0	26.0	Zinner	C	D	O	2	1	NA	10.7
13	03:31:47.3	–62.0	24.0	Schiaparelli	D	D	O	1	1	NA	10.2
14	03:33:38.7	–71.0	13.0	Cardanus	D	D	C	2	3	1	9.3
15	03:42:19.7	–39.0	18.0	Bessarion A	C	D	O	1	2	NA	10.8
16	04:08:31.1	–68.0	–22.0	Darwin H	D	D	O	2	3	NA	9.1
17	04:29:48.1	–78.0	14.0	Vasco Da Gama F	D	C	O	1	1	NA	10.0
18	04:35:39.8	–89.0	–17.0	Kopff	C	D	C	1	2	1	10.7
19	04:43:03.5	–47.0	20.0	Aristarchus F	C	D	O	1	1	NA	10.6
20	04:52:12.1	–50.0	21.0	Herodotus	D	D	O	1	2	NA	9.8
21	05:23:56.1	–65.0	–32.0	Lagrange L	D	NA	O	7	NA	NA	NA

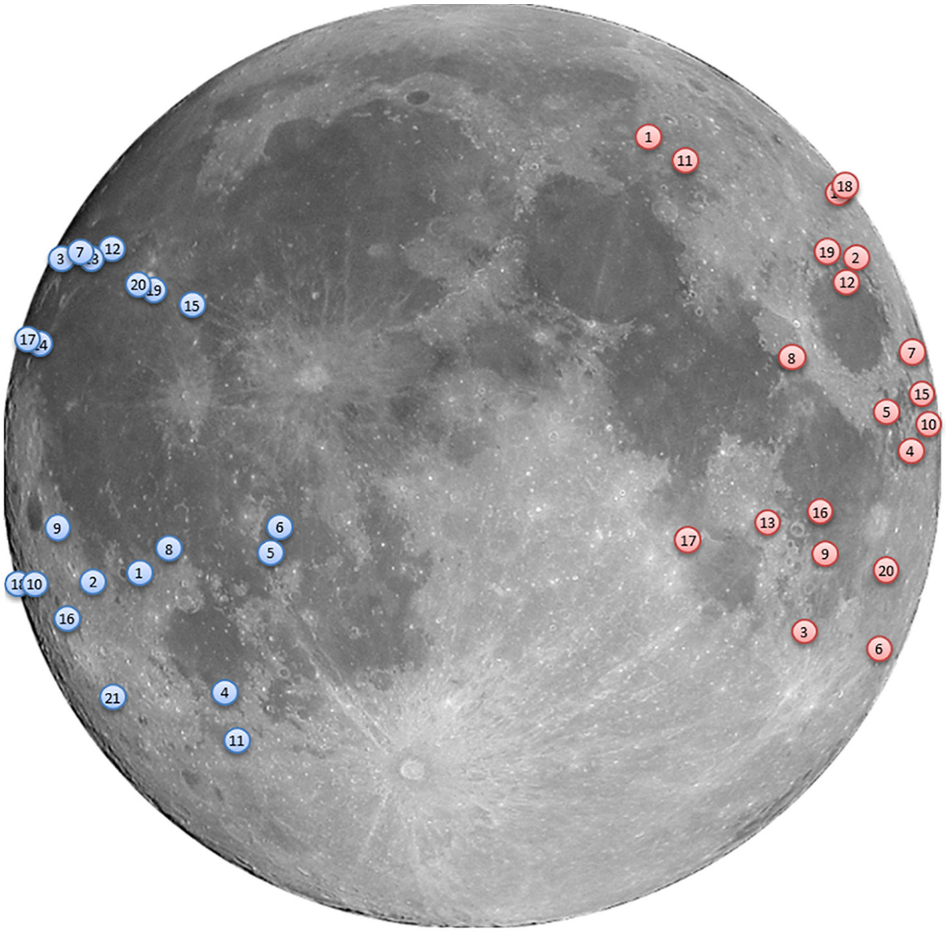


Figure 13. Lunar impact locations of the 2010 Geminids (left) and the 2006 Geminids (right).

Table 3 indicates that each of the impacts, except for three, was seen in at least two videos from the scopes, as indicated in the observation status column as either detected (D) or visually confirmed (C). For the cases where the glare in the video obscured a flash and prevented a confirmation, the letter O is indicated in the table. The three impacts not seen in the videos of two scopes were multiframe flashes, one of which was 7 frames in duration that occurred at the end of the observing session after two of the scopes had been shut down. The WCO video was only used for visual confirmation. The quality of the image in the WCO scope was very poor due to glare, thus it was difficult to confirm the impacts, except in three cases.

An example of a video frame from all scopes is shown in figure 14. This example shows impact no. 19, which was detected in the SD video and visually confirmed in the Tower video. The impact flash was obscured in the WCO video by glare. It is seen that glare was a significant issue in terms of image quality for each of the scopes, with the SD scope exhibiting the best overall quality. Figure 15 shows another example (impact no. 16) of an impact detected in both of the ALaMO scopes' videos. Note the difference in quality between this image and the example image of the 2006 Geminids in figure 10. It is seen that the scattered light issue or glare present during the 2010 Geminids is not present for the 2006 Geminids due to the lunar phase being less than 45%.

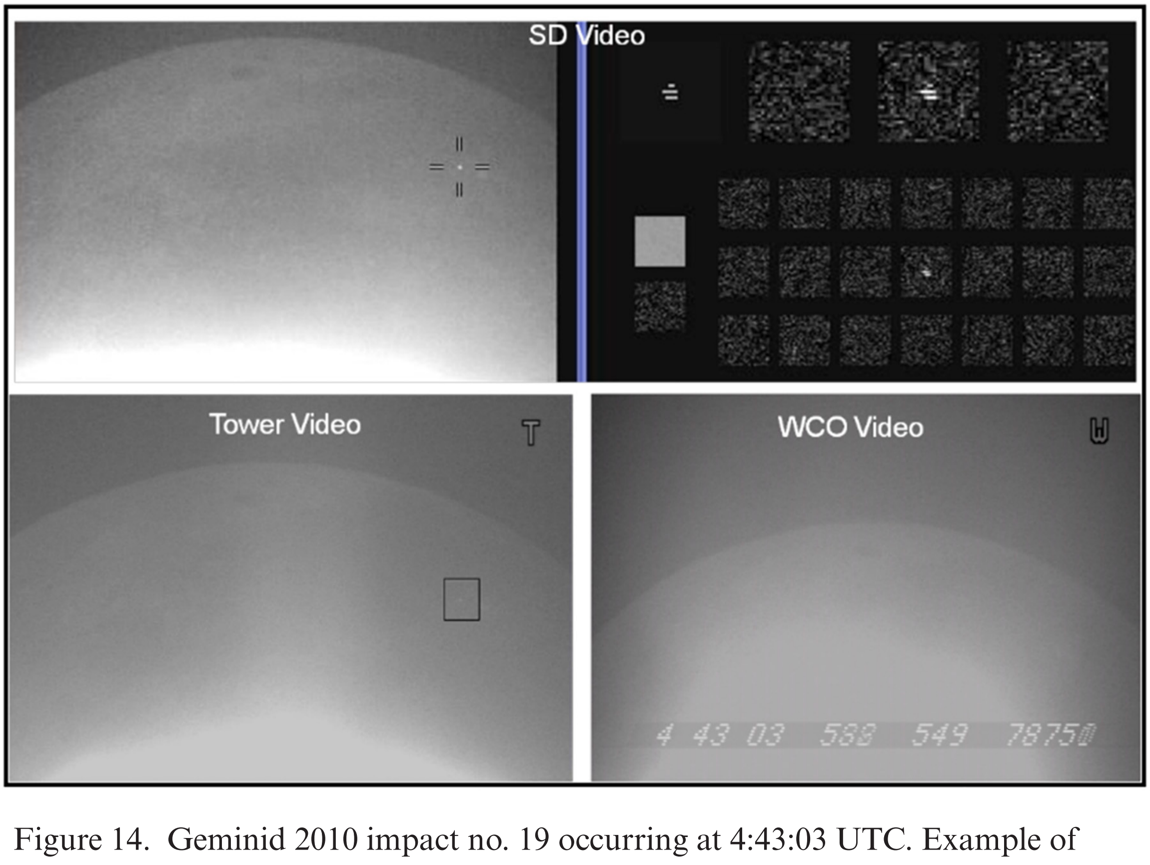


Figure 14. Geminid 2010 impact no. 19 occurring at 4:43:03 UTC. Example of one of the observed impacts detected in the video from the SD telescope. The impact was not detected in the Tower video but was visually confirmed. The impact flash was obscured in the WCO video.

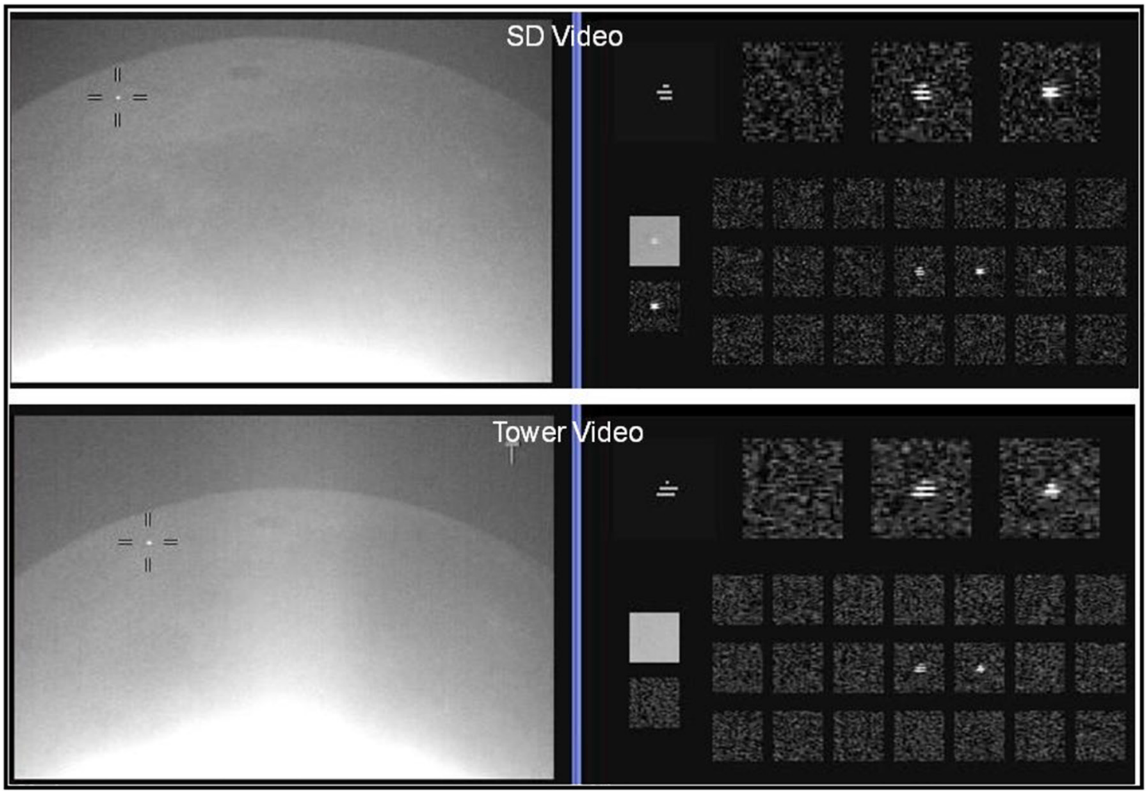


Figure 15. Geminid 2010 impact no. 16 occurring at 4:08:31 UTC. Example of one of the observed impacts detected in both the videos of the ALaMO telescopes.

From table 3, it is seen that the time of the impacts were fairly evenly distributed throughout the 6 hours of lunar videos. All of the impacts had a flash duration ranging from 1 to 7 frames, with most of the impacts having a duration of 1 to 2 frames. Flash visual magnitudes ranged between 9.1 and 11. Three impacts had magnitudes that were undetermined due to the glare present in the video frames.

The impacts observed on December 14 were assumed to be Geminids because of the favorable impact geometry for viewing and the strength of the shower (ZHR = 120). However, minor showers and sporadics could also be a contributor to the observed impacts. The Monocerotids, with a peak ZHR of 3 (December 9), and the Sigma Hydrids, with a peak ZHR of 2 (December 12), both had favorable lunar impact viewing geometries (see fig. 16) that were similar to the Geminids.

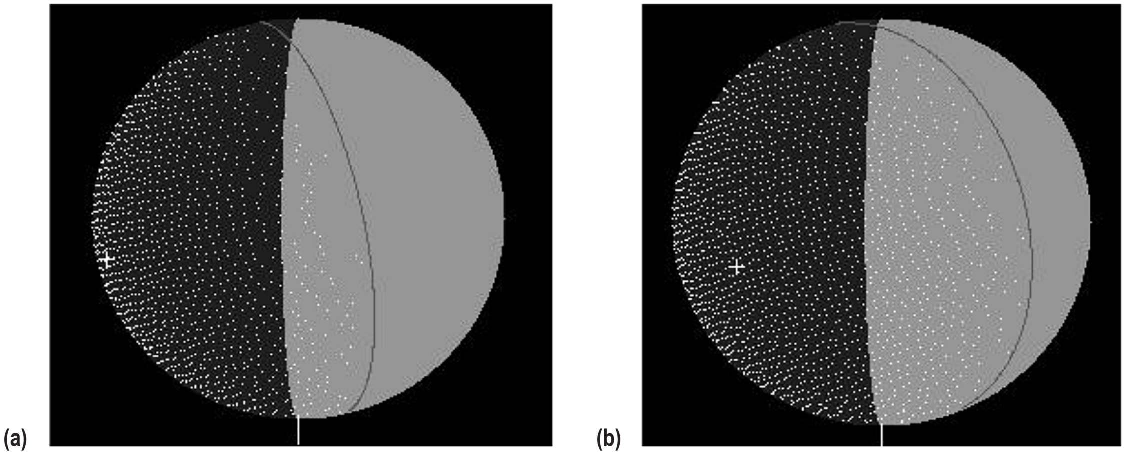


Figure 16. Minor shower impact geometries for December 14, 2010: (a) Monocerotids and (b) Sigma Hydrids. Showers are coincident with the 2010 Geminids.

3.3 Comparison of 2006 and 2010 Geminid Lunar Impacts

Observations of the Geminids over the last 100 years suggest that the Geminid meteor shower has been increasing in intensity (appendix C).[6] It is of interest to compare the 2006 and 2010 lunar observations made at MSFC for any changing characteristics in the Geminid meteoroid stream and to document the impact rate of Geminid meteoroids in the size range of ≈0.1 kg and greater on the Moon. However, it is worthwhile to note that the lunar observing conditions for each of the Geminid shower events that were observed in 2006 and 2010 were not ideal (earlier data do not exist). In 2006, there were intermittent clouds that reduced the observing time, and periods of thin cirrus that reduced the sky transparency and quality of the lunar videos. The photometric quality of the flashes would be greatly affected by any thin cirrus present. For 2010, the sky was clear with moderate transmittance, but because of the lunar phase (54%), significant glare was present in the video, which greatly affected the ability to observe fainter impact flashes and perform accurate flash photometry. Also, the length of the observation in 2010 was almost twice as long as the 2006 observation.

Figure 17 is a plot of the 2006 and 2010 observed Geminid lunar impacts versus time of occurrence during the lunar observation periods. Also shown are the start and end times of the observation videos, periods of significant cloudiness, and the number of video frames of the observed impact flash. The plots provide an overview of the observation periods and observed impact flashes for those two years. Several differences can be seen between the 2006 (fig. 17(a)) and the 2010 (fig. 17(b)) plots. The 2006 period shows that the impacts were not evenly distributed during the observation period as was the case in 2010. For 2006, most of the impacts occurred during the 1-hour period between 8:00 and 9:00 UTC, indicating a relative burst of activity. It is interesting to note that the spatial distribution of the impacts during this 1-hour period was fairly well distributed throughout the viewing region and not concentrated in one area (see fig. 9).

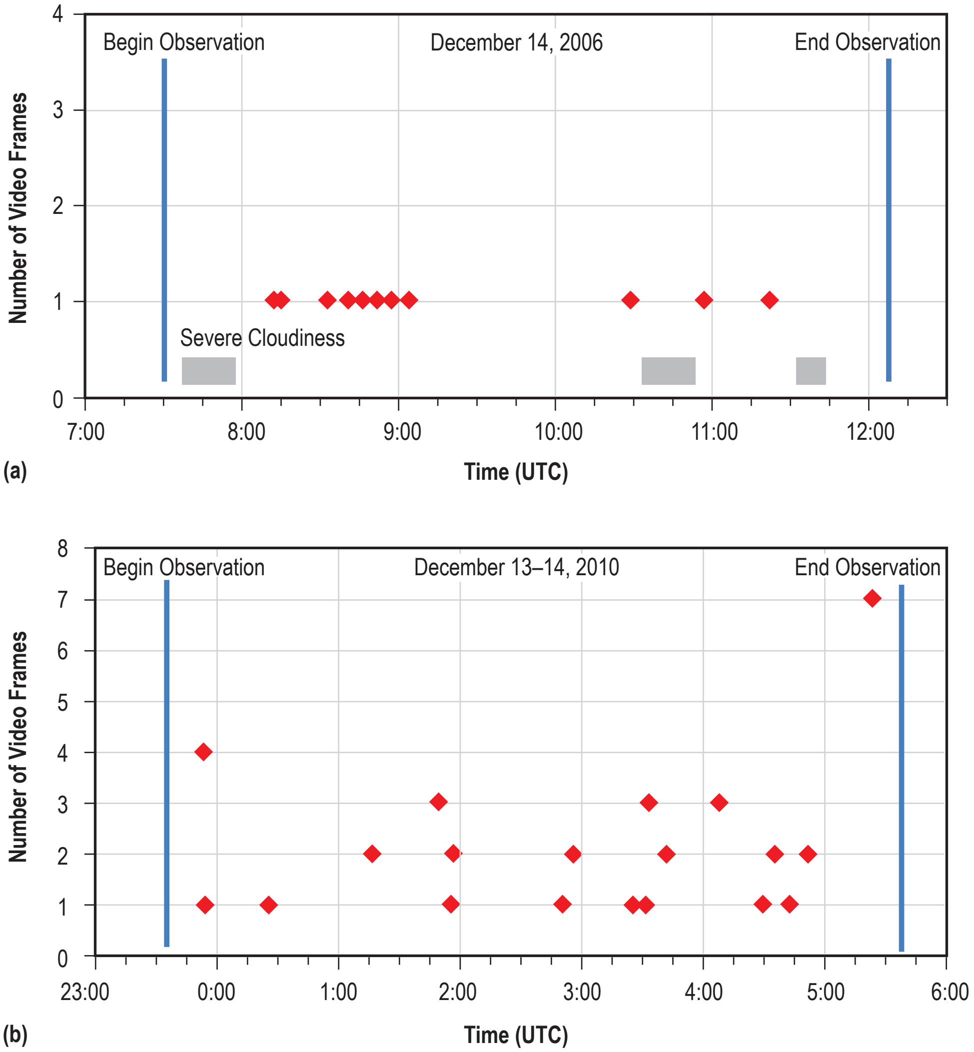


Figure 17. Plot of Geminid lunar impact flash time of occurrence and flash duration for the (a) 2006 and (b) 2010 Geminid showers. Also shown are start and end times of the lunar observations and periods of cloudiness.

For the 2006 shower, a total of 4.6 hours of video were captured, yielding a total of 17 confirmed impacts. For the 2010 shower, the total observation time was 6.1 hours, which yielded 21 observed lunar impacts. The average impact rates over the viewing area using the elapsed video times were 3.7 and 3.5 impacts per hour for 2006 and 2010, respectively. However, if time periods associated with cloudiness are subtracted from the 2006 video, which yields 3.4 hours of observations, the associated impact rate becomes 5 impacts per hour, implying a decrease in the lunar impact rate for 2010.

Finally, from figure 17, the 2006 impacts are also seen to have flash durations on average significantly shorter than those for the 2010 case. In 2006, over 75% of the flashes were of 1-frame-durations, while in 2010, less than half of the impact flashes were of 1-frame-durations.

3.3.1 Impact Rates

For the 2006 and 2010 Geminid meteor showers, the Earth-observed peak rate (ZHR) compiled by the IMO was ≈120 meteors per hour for both years (figs. 8 and 12), thus indicating essentially no change in overall Geminid activity between 2006 and 2010. From lunar observations described above, the average lunar impact rates observed during these periods suggest a decrease in lunar rates in 2010 when the 2006 observing time is adjusted for cloudiness.

A more detailed look at the lunar impact rates is given in figure 18. The plots show the cumulative number of impacts versus elapsed observation time for 2006 (fig. 18(a)) and 2010 (fig. l8(b)). For each half-hour of elapsed time, the cumulative number of impacts observed to that point was plotted. The plot illustrates the changes in impact rate over time, as compared to an average rate provided by a least-squares fit through the data points, where the slope of the line is the average impact rate. For 2006, the impact rate varies significantly from the average rate during the first 1.5 hours of elapsed time. Between 1 and 2 hours of elapsed time, the impact rate spikes to 9 per hour, mostly occurring in a half-hour time span. Thus, a cluster of impactors were encountered, driving impact rates significantly from the average. For 2006, the average impact rate from the slope of the fit line is 3.9 impacts per hour. This value is most likely depressed because of the cloudy periods present. However, an impact rate of 5 per hour indicted above, obtained by subtracting out the cloudy periods, is probably an overstatement of the rate because of the spike in impactors early in the observing period.

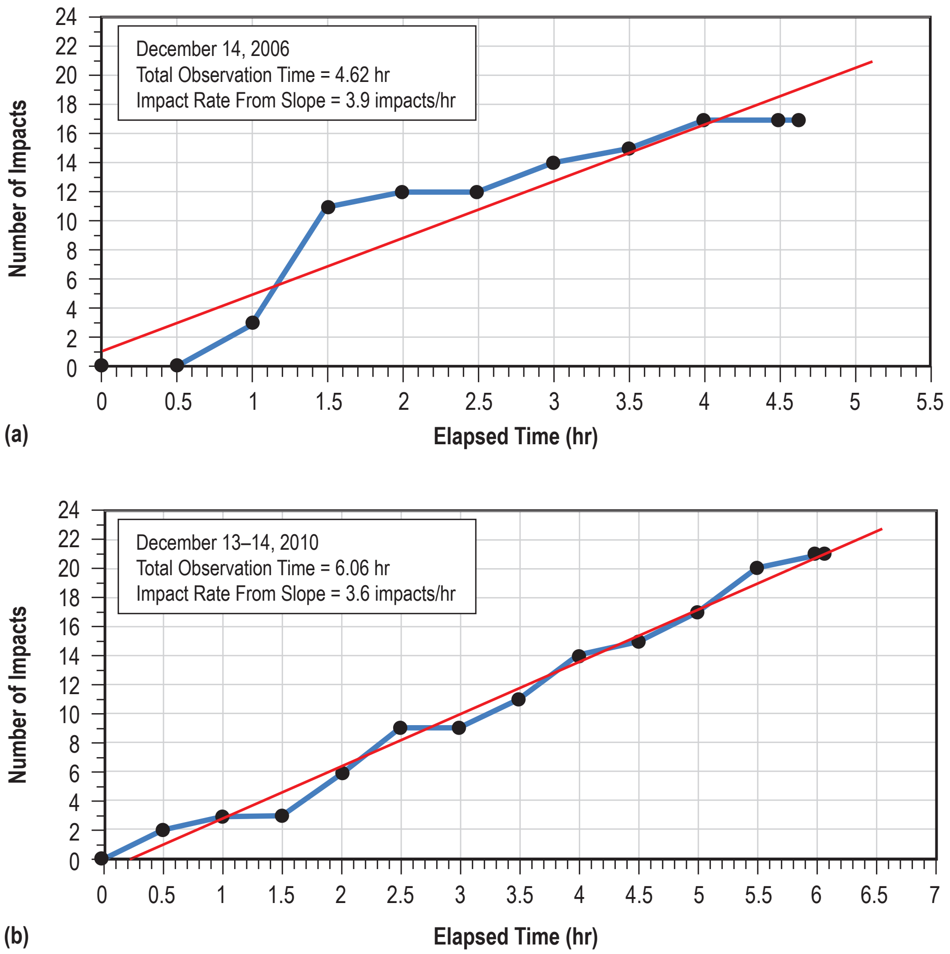


Figure 18. Plot of the cumulative number of lunar impacts versus elapsed observation time during the (a) 2006 and (b) 2010 Geminid showers. Also shown is a least-squares fit of the data points where the slope represents the average lunar impact rate observed for each shower.

In 2010, the observed impact rate as seen from figure 18 is fairly constant during the observation period, as indicated by the relative small variations about the fit line. The slope of the fit line is 3.6 impacts per hour, which is close to that observed in 2006. Similarly, as in the case for 2006, the 2010 impact rate is most likely depressed as well but for different reasons. As mentioned previously, poor observing conditions for the night of the 2010 shower were present due to glare in the telescope caused by the sunlit portion of the Moon. The glare reduced the effective field-of-view and reduced the ability to detect the fainter flashes that may have been present. If the 2010 rates were indeed depressed because of glare, then one would expect that a lower relative number of faint, short-duration impact flashes, on the order of 1 frame, would be observed. As mentioned previously and in more detail in the next section, this was the case.

Thus, the lunar impact rates for 2006 and 2010 of 3.9 and 3.6, respectively, are considered consistent and imply that no change in the lunar impact rates between 2006 and 2010 was observed. However, both of these rates are considered to be depressed for different reasons. In 2006, clouds were an issue, and in 2010, glare was a limiting issue. As discussed previously, an impact rate of 5 is most likely an upper-bound, and a rate of 3.6 is a lower-bound. Thus, this analysis suggests that the actual Geminid lunar impact during the peak of the showers was probably between 3.6 and 5, or ≈4.3 impactors per hour.

3.3.2 Flash Duration and Photometric Magnitude

A second parameter that is useful to compare is the flash duration. The flash duration is directly related to the energy of the object on impact. However, flash duration can also be affected by the characteristics of the impact. The location of the impact such as terrain features that could mask some of the light radiated from the impact, lunar curvature with respect to the line of sight of the observer, and impact angle with the surface are just a few effects. For comparison purposes between the 2006 and 2010 shower events, these effects are expected to be present in both impact samples from the two events. However, sky photometric quality can affect the determination of the duration and needs to be considered.

A plot of the impact flash durations for the two events is shown in figure 19. For comparison purposes, the relative number of impacts per duration interval (number of video frames) is given. Two features in the plot stand out. One is that the 2006 Geminids have a bias towards a shorter duration as compared to the 2010 event. The overall average flash duration for each event is 1.3 and 2.1 frames for 2006 and 2010, respectively. In 2010, the relative number of 2-frame impactors was approximately double that for 2006. Moreover, in 2010, there were five flashes where the flash duration was 3 frames or greater, while in 2006 there was only one flash that was of 3 frames in duration.

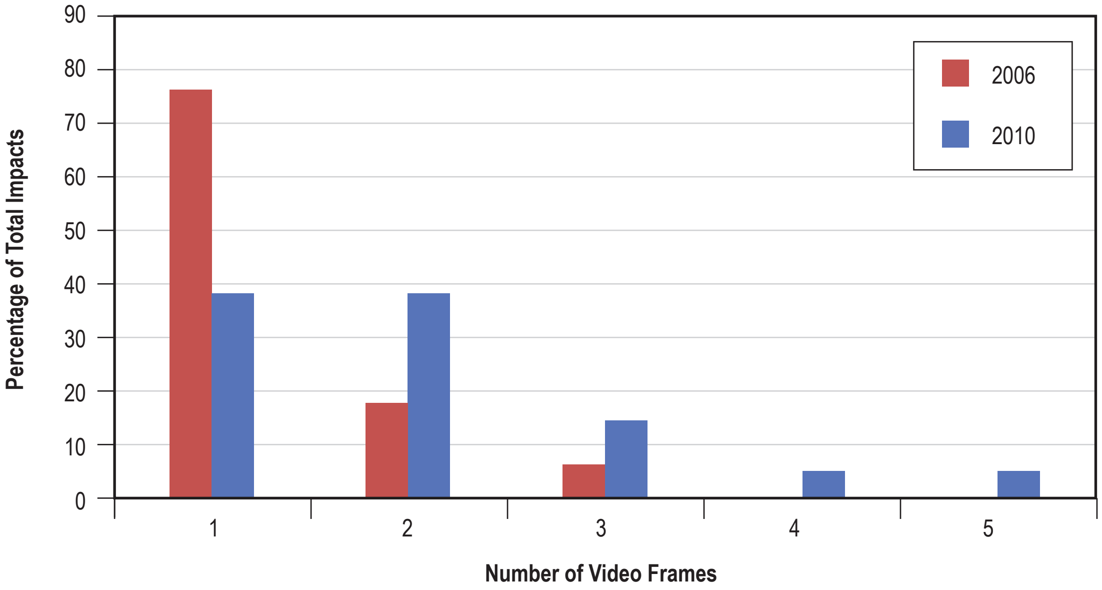


Figure 19. Comparison of impact flash durations between the 2006 and 2010 Geminids.

The second feature in figure 19 that stands out is that the relative number of 1-frame-durations for 2010 seems depressed. In 2006, 75% of the impactors had a duration of 1 frame, while only 38% of the observed population in 2010 had a duration of 1 frame. Moreover, the number of impactors in 2010 having a duration of 2 frames was equal to those with 1 frame. Over the 5½ years of lunar observations, the 1-frame impacts completely dominate the impacts that have been observed. The significant reduction of the relative number of 1-frame impacts in 2010 strongly suggests that telescope glare was a factor in observing the fainter and thus single-frame flash impacts, causing a reduced number to be observed.

The bias in flash duration would imply that the 2010 lunar impactors could have been more energetic or more massive than the 2006 lunar impactors. However, a number of factors could explain the bias in the observations. Since the larger impactors are less frequent, the shorter observing time in 2006 could be a factor. Also, the glare issue in the 2010 observations could cause the fainter 1-frame-duration impacts not to be seen, and thus bias the observations to the larger impactors.

If the 2010 observed Geminid impactors are on average more energetic than those observed in 2006, as implied by the flash durations, then a comparison of the flash magnitudes should provide further evidence for this result. One would expect that the 2010 impact flashes to be biased to brighter magnitudes (lower numbers) than the 2006 impact flashes. Figure 20 is a plot of the relative frequency of the peak magnitudes of the impact flashes for 2006 and 2010 Geminids. The plot does not include three 2010 impact flash magnitudes due to glare issues. One of the missing magnitudes is from the 7-frame-duration flash (see table 3). The other two missing flash magnitudes are from flashes with durations of 2 frames.

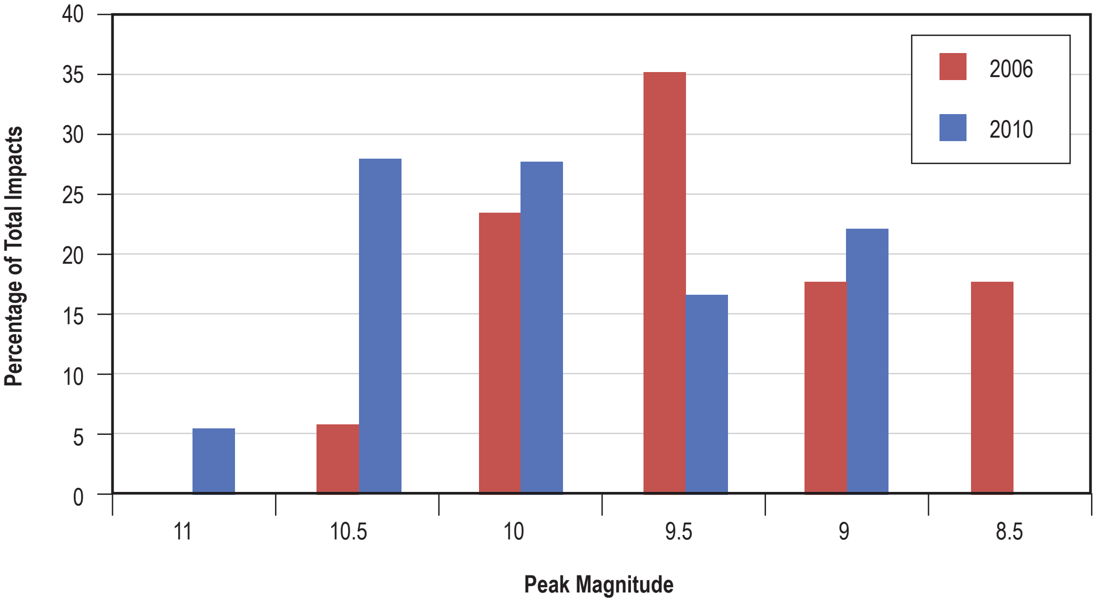


Figure 20. Comparison of impact flash peak magnitudes between the 2006 and 2010 Geminids.

The plot reveals that the 2006 impact flash magnitudes appear to have a shift to lower values or larger magnitudes than the 2010 flashes. Indeed, the average magnitude for the 2006 and 2010 impact flashes is 9.6 and 10.1, respectively. The accuracy of the magnitude calculations is estimated to be ±0.5 magnitudes. Thus, the flash magnitude results do not provide conclusive evidence that the 2010 shower lunar impacts are larger or more energetic on average than the 2006 shower sample.

For the 2010 observations, the effect of glare on the magnitude calculation is significant. As seen in figures 14 and 15, the glare originates from the sunlit region of the Moon and diminishes across the lunar field-of-view. Thus, the glare is not uniform and distorts the visibility of the earthshine on the lunar surface. Since the magnitude calculation uses the earthshine on the Moon as a transfer standard between background stars that are not coincident with the impact flash, the calculation may be suspect. The nonuniform nature of the glare across the field-of-view causes the lunar surface to be brighter and the impacts to be relatively fainter than actual. Since the reference stars are at the edge of the field-of-view away from the source of the glare, they are affected less than that of the lunar surface. The brighter lunar surface thus has an effect of biasing the flash magnitude calculation to fainter values.

4. SUMMARY AND CONCLUSIONS

During the five years of routine lunar observations, several shower events were observed during their peak activity. The peak activity of the Geminids was observed twice, the first event in 2006 and the second event in 2010. For both years, a significant number of Geminid lunar impacts were observed. In 2006, a total of 19 Geminid impacts were observed, which made up 37% of the impacts observed for all of 2006. In 2010, a total of 21 Geminid impacts were observed, which made up 55% of all the impacts observed for that year.

A comparison of the two events is made difficult due to the observing conditions present during the events. In 2006, observations were hampered by passing clouds with some persistent thin cirrus. This impacted the quality and duration of lunar observations. The observation duration for the peak activity was 3.4 hours. For the 2010 Geminid event, 6.2 hours of lunar observation took place, but the conditions were also an issue. The lunar illumination for that night was 54%, which caused considerable glare in the image and thus hampered detection of the fainter impacts. However, the two events do show different characteristics.

The shower impact rate for 2006 was not as constant over the observing period as was the case in 2010. During the 2006 event, a temporal grouping of impactors was observed yielding 9 impacts in 1 hour. The average impact rate observed for the 2006 event was 3.9 impacts per hour. The impact rate for the 2010 event was seen to be consistent over the observing period with an average rate of 3.6 impacts per hour. These rates are most likely lower than actual due to the poor observing conditions for both the 2006 and 2010 events. It is estimated that the actual rate was between 3.6 and 5, or ≈4.3 impactors per hour.

A comparison of flash durations between the 2006 and 2010 events indicates that the 2010 event had on average longer flash durations. The overall average flash duration for each event is 1.3 and 2.1 frames for 2006 and 2010, respectively. It would appear that the 2010 event may have been comprised of larger impactors. However, observing conditions could be a factor. There were relatively fewer 1-frame-duration flashes for the 2010 event. This is most likely due to glare obscuring the fainter flashes and thus biasing the average flash duration to a larger value. Likewise, there were relatively fewer longer duration flashes for the 2006 event, which could be due to the shorter observation time than in the 2010 case.

A comparison of the impact flash magnitudes shows that the 2010 impact sample was slightly biased toward fainter flashes as compared to the 2006 flash magnitudes. This is not consistent with the flash duration comparison, implying larger impactors in 2010. The average magnitude for the 2006 and 2010 impact flashes is 9.6 and 10.1, respectively. The accuracy of the magnitude calculations is estimated to be ±0.5 magnitudes. Thus, the flash magnitude results do not provide conclusive evidence that the 2010 shower lunar impacts are larger on average than the 2006 shower sample. Again, the glare present in the 2010 observation could significantly compromise the magnitude calculations.

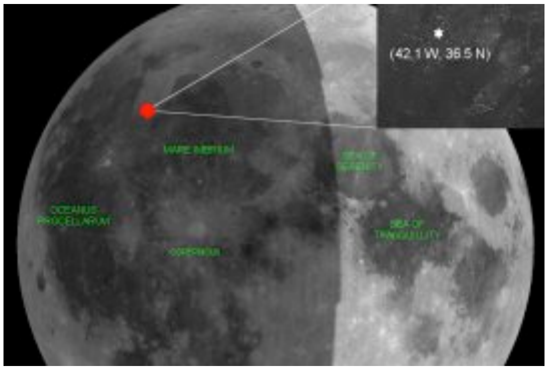
Though a comparison of the 2006 and 2010 Geminid lunar impacts is hampered by the observing conditions and prevents providing additional information about the Geminids themselves, it is seen from the results documented in this TM that the lunar meteoroid environment is greatly affected by major shower events such as the Geminids.

APPENDIX A—AN EXPLOSION ON THE MOON (WEB PAGE ARTICLE)

A copy of the web page article, “An Explosion on the Moon” by Dr. Tony Phillips, is shown in appendix A.

So you thought nothing ever happens on the moon?

NASA scientists have observed an explosion on the moon. The blast, equal in energy to about 70 kg of TNT, occurred near the edge of Mare Imbrium (the Sea of Rains) on Nov. 7, 2005, when a 12-centimeter-wide meteoroid slammed into the ground traveling 27 km/s.



Above: The red dot marks the location of the Nov. 7, 2005, meteoroid impact. Credit: NASA/MSFC/Bill Cooke.

"What a surprise," says Marshall Space Flight Center (MSFC) researcher Rob Suggs, who recorded the impact's flash. He and colleague Wes Swift were testing a new telescope and video camera they assembled to monitor the moon for meteor strikes. On their first night out, "we caught one," says Suggs.

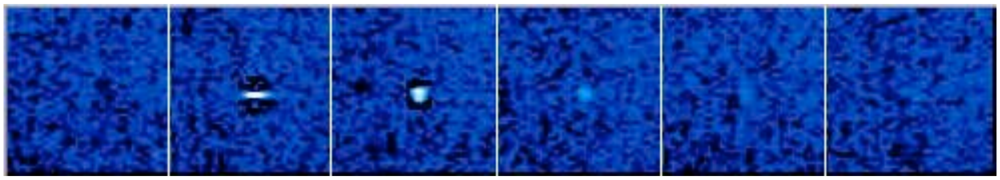
The object that hit the moon was "probably a Taurid," says MSFC meteor expert Bill Cooke. In other words, it was part of the same meteor shower that peppered Earth with fireballs in late October and early November 2005. (See "Fireball Sightings" from Science@NASA.)

The moon was peppered, too, but unlike Earth, the moon has no atmosphere to intercept meteoroids and turn them into harmless streaks of light. On the moon, meteoroids hit the ground--and explode.

"The flash we saw," says Suggs, "was about as bright as a 7th magnitude star." That's two and a half times dimmer than the faintest star a person can see with their unaided eye, but it was an easy catch for the group's 10-inch telescope.

Cooke estimates that the impact gouged a crater in the moon's surface "about 3 meters wide and 0.4 meters deep." As moon craters go, that's small. "Even the Hubble Space Telescope couldn't see it," notes Cooke. The moon is 384,400 km away. At that distance, the smallest things Hubble can distinguish are about 60 meters wide.

This isn't the first time meteoroids have been seen hitting the moon. During the Leonid meteor storms of 1999 and 2001, amateur and professional astronomers witnessed at least half-a-dozen flashes ranging in brightness from 7th to 3rd magnitude. Many of the explosions were photographed simultaneously by widely separated observers.



Above: The Nov. 7th lunar Taurid explosion, shown as a sequence of 6 false-color video frames. Credit: Wes Swift/NASA.

Since the Leonids of 2001, astronomers have not spent much time hunting for lunar meteors. "It's gone out of fashion," says Suggs. But with NASA planning to return to the moon by 2018, he says, it's time to start watching again.

There are many questions that need answering: "How often do big meteoroids strike the moon? Does this happen only during meteor showers like the Leonids and Taurids? Or can we expect strikes throughout the year from 'sporadic meteors?'" asks Suggs. Explorers on the moon are going to want to know.

"The chance of an astronaut being directly hit by a big meteoroid is miniscule," says Cooke. Although, he allows, the odds are not well known "because we haven't done enough observing to gather the data we need to calculate the odds." Furthermore, while the danger of a direct hit is almost nil for an individual astronaut, it might add up to something appreciable for an entire lunar outpost.

Of greater concern, believes Suggs, is the spray—"the secondary meteoroids produced by the blast." No one knows how far the spray reaches and exactly what form it takes.

Right: An artist's concept of the Nov. 7, 2005, explosion. Credit: NASA/MSFC. [Larger image]

Also, ground-shaking impacts could kick up moondust, possibly over a wide area. Moondust is electrostatically charged and notoriously clingy. (See "Mesmerized by Moondust" from Science@NASA.) Even a small amount of moondust can be a great nuisance: it gets into spacesuit joints and seals, clings to faceplates, and even makes the air smell when it is tramped indoors by moonwalkers. Could meteoroid impacts be a source of lunar "dust storms?" Another question for the future....

Suggs and his team plan to make more observations. "We're contemplating a long-term monitoring program active not only during major meteor showers, but also at times in between. We need to develop software to find these flashes automatically," he continues. "Staring at 4 hours of tape to find a split-second flash can get boring; this is a job for a computer."

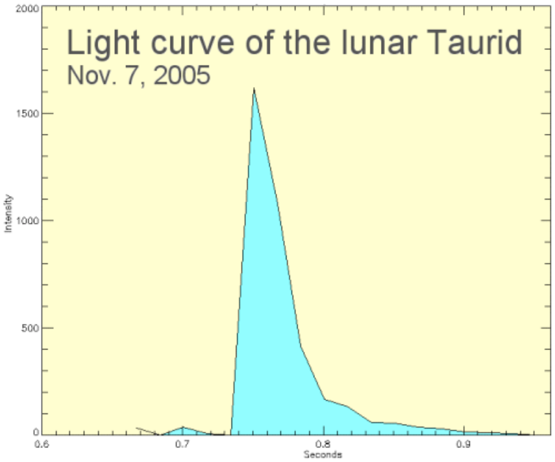
With improvements, their system might catch lots of lunar meteors. Says Suggs, "I'm ready for more surprises."

As far as they know, Suggs and Swift were the only ones who recorded the impact of Nov. 7th–"probably because we were the only ones looking," says Suggs. So, unlike the lunar Leonids of 1999 and 2001, the lunar Taurid of 2005 was not confirmed by a second or third observer.

Nevertheless, "we are 99% sure it was real," says Suggs.

Other possibilities include: a satellite passing in front of the moon, glinting in sunlight; a cosmic ray hitting the video camera's CCD chip;
a meteor in Earth's atmosphere, directly between Earth and the Moon.
"We don't believe it was a satellite," says Cooke who, together with aerospace engineer Heather McNamara, searched through NORAD's catalogue of 8363 "trackable objects" in Earth orbit. "There was no unclassified satellite or piece of space debris in the right place at the right time to cause the flash."

It couldn't have been a cosmic ray. "We observed the lunar explosion in five consecutive video frames (total time span: 150 msec). A cosmic ray would have caused a flash in only one frame," explains Suggs.



Above: The light curve of the flash observed by Suggs and Swift on Nov. 7, 2005. Credit: NASA/MSFC

And finally, it almost certainly couldn't have been a meteor in Earth's atmosphere. "To masquerade as a lunar impact, a meteor in Earth's atmosphere would have to be heading directly toward our observing site at the Marshall Space Flight Center, head on, so that it looked like a point rather than a streak of light," says Suggs. "A meteoroid hitting the moon is more plausible. Furthermore," he says, "the light curve of our Nov. 7th Taurid has the same shape as light curves of lunar Leonids observed in 1999 and 2001. Also, it doesn't match the light curve of a 'point meteor."

APPENDIX B—A METEOROID HITS THE MOON (WEB PAGE ARTICLE)

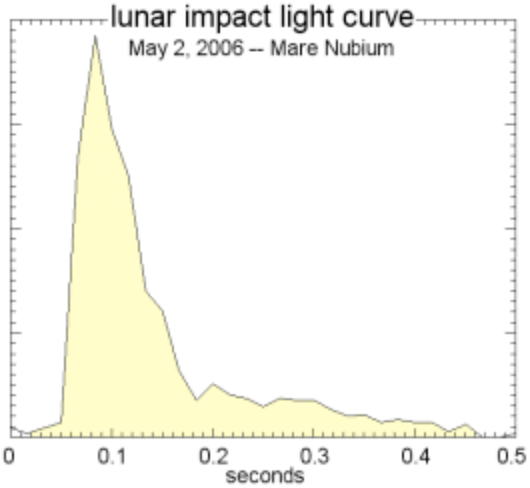
A copy of the web page article, “A Meteoroid Hits the Moon” by Dr. Tony Phillips, is shown in appendix B.

There's a new crater on the Moon. It's about 14 meters wide, 3 meters deep and precisely one month, eleven days old.

NASA astronomers watched it form: "On May 2, 2006, a meteoroid hit the Moon's Sea of Clouds (Mare Nubium) with 17 billion joules of kinetic energy that's about the same as 4 tons of TNT," says Bill Cooke, the head of NASA's Meteoroid Environment Office in Huntsville, AL. "The impact created a bright fireball which we video-recorded using a 10-inch telescope."

Lunar impacts have been seen before--"stuff hits the Moon all the time," notes Cooke--but this is the best-ever recording of an explosion in progress:

“The duration of the fireball was only four-tenths of a second,” says Cooke. "A student member of our team, Nick Hollon of Villanova University, spotted the flash.”



Taking into account the duration of the flash and its brightness (7th magnitude), Cooke was able to estimate the energy of impact, the dimensions of the crater, and the size and speed of the meteoroid. "It was a space rock about 10 inches (25 cm) wide traveling 85,000 mph (38 km/s)," he says.

If a rock like that hit Earth, it would never reach the ground. "Earth's atmosphere protects us," Cooke explains. "A 10-inch meteoroid would disintegrate in mid-air, making a spectacular fireball in the sky but no crater." The Moon is different. Having no atmosphere, it is totally exposed to meteoroids. Even small ones can cause spectacular explosions, spraying debris far and wide.

According to the Vision for Space Exploration, NASA is sending astronauts back to the Moon. Are these meteoroids going to cause a problem?

"That's what we're trying to find out," says Cooke. "No one knows exactly how many meteoroids hit the Moon every day. By monitoring the flashes, we can learn how often and how hard the Moon gets hit."

The work is underway. Using a computerized telescope built by Rob Suggs and Wesley Swift of the Marshall Space Flight Center, Cooke's group is monitoring the night side of the Moon "as often as ten times a month, whenever the lunar phase is between 15% and 50%."

During a telescope test last November 7th, Suggs and Swift recorded an explosion on their very first night of observing. A piece of debris from Comet Encke struck the plains of Mare Imbrium, making a crater about 3 meters wide.

Now that regular monitoring has begun, Cooke's group has already found a second impact, the May 2nd event, in only 20 hours of watching. This time, they believe, the impactor was a random meteoroid, "a sporadic," from no particular comet or asteroid.

"We've made a good beginning," says Cooke, but much work remains. He would like to observe all year long, watching the Moon as it passes in and out of known meteoroid streams. "This would establish a good statistical basis for planning [activities on the Moon]."

Is it safe to go moon walking during a meteor shower? How much shielding does a lunar habitat need? Does the Moon have its own meteor showers, unknown on Earth?

Expect the answers in a flash.

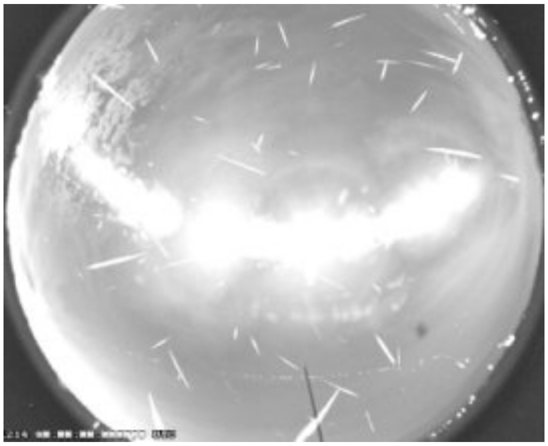
APPENDIX C—THE 2009 GEMINID METEOR SHOWER (WEB PAGE ARTICLE)

A copy of the web page article, "The 2009 Geminid Meteor Shower" by Dr. Tony Phillips, is shown in appendix C.

Make hot cocoa. Bundle up. Tell your friends. The best meteor shower of 2009 is about to fall over North America on a long, cold December night.

"It's the Geminid meteor shower," says Bill Cooke of NASA's Meteoroid Environment Office "and it will peak on Dec. 13th and 14th under ideal viewing conditions."

A new Moon will keep skies dark for a display that Cooke and others say could top 140 meteors per hour. According to the International Meteor Organization, maximum activity should occur around 12:10 a.m. EST (0510 UT) on Dec. 14th. The peak is broad, however, and the night sky will be rich with Geminids for many hours and perhaps even days around the maximum.



Right: A flurry of Geminids in Dec. 2008 recorded by an all-sky camera at the Marshall Space Flight Center.

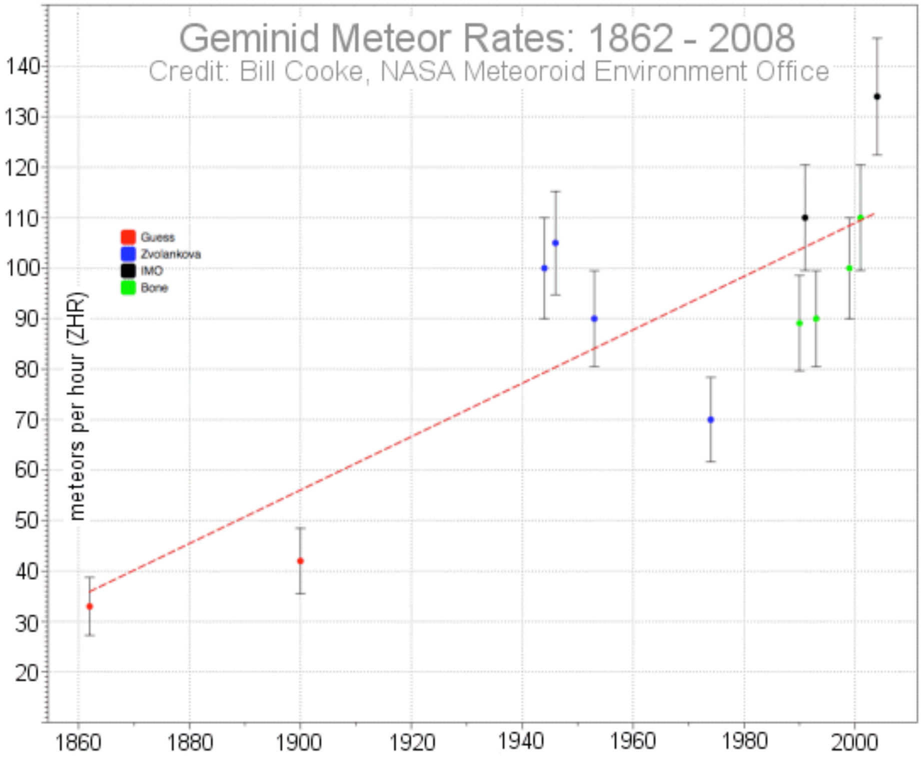
Cooke offers this advice: "Watch the sky during the hours around local midnight. For North Americans, this means Sunday night to Monday morning."

Researchers are interested to see what the Geminids do in 2009. The shower has been intensifying in recent decades and they wonder if the trend will continue.

Geminids are pieces of debris from a strange object called 3200 Phaethon. Long thought to be an asteroid, Phaethon is now classified as an extinct comet. It is, basically, the rocky skeleton of a comet that lost its ice after too many close encounters with the sun. Earth runs into a stream of debris from 3200 Phaethon every year in mid-December, causing meteors to fly from the constellation.

When the Geminids first appeared in the late 19th century, shortly before the US Civil War, the shower was weak and attracted little attention. There was no hint that it would ever become a major display.

But now it has. "The Geminids are stronger" and getting stronger," says Cooke, who has prepared a plot showing how the shower has intensified since its discovery:



What's going on? Jupiter's gravity has been acting on Phaethon's debris stream, causing it to shift more and more toward Earth's orbit. Each December brings a deeper plunge into the debris stream.

Meteor expert Peter Brown of the University of Western Ontario (UWO) says the trend could continue for some time to come. "Based on modeling of the debris done by Jim Jones in the UWO meteor group back in the 1980s, it is likely that Geminid activity will increase for the next few decades, perhaps getting 20% to 50% higher than current rates."

A 50% increase would boost the Geminids to 200 or more meteors per hour, year in and year out. "That would be an amazing annual display," says Cooke.

Moreover, says Brown, "the proportion of large, bright Geminids should also increase in the next few decades, according to Jones' model." So the Geminids could turn into a "fireball shower."

Brown cautions that "other models of the debris stream come to different conclusions, in some cases suggesting that Geminids will decrease in intensity in the coming decades. We understand little about the details of the formation and evolution of Phaethon's debris despite many years of efforts."

Recent trends favor a good show. Enjoy the Geminids!

REFERENCES

1. Gural, P.: "Automated Detection of Lunar Impact Flashes," Paper Presented at 2007 Meteoroid Environments Workshop, NASA Marshall Space Flight Center, Huntsville, AL, January 31–February 1, 2007.

2. Suggs, R.M.; Cooke, W.J.; Suggs, R.J.; et al.: "The NASA Lunar Impact Monitoring Program," *Earth Moon Planets*, Vol. 102, Nos. 1–4, pp. 293–298, doi:10.1007/s11038-007-9184-0, June 2008.

3. Swift, W.R.; Suggs, R.M.; and Cooke, W.J.: "Algorithms for Lunar Flash Video Search, Measurement, and Archiving," *Earth Moon Planets*, Vol. 102, Nos. 1–4, pp. 299–303, doi:10.1007/s11038-007-9226-7, June 2008.

4. Suggs, R.M.; Moser, D.E.; Cooke, W.J.; and Suggs, R.J.: "The Flux of Kilogram-sized Meteoroids from Lunar Monitoring," *Icarus*, Vol. 238, pp. 23–26, doi:10.1016/j.icarus.2014.04.032, August 2014.

5. Cooke, W.J.; Suggs, R.M.; and Swift, W.R.: "A Probable Taurid Impact On The Moon," Paper Presented at 37th Lunar and Planetary Science Conference, League City, TX, No. 1731, March 14–17, 2006.

6. Cooke, W.J.; Suggs, R.M.; Suggs, R.J.; et al.: "Rate And Distribution Of Kilogram Lunar Impactors," Paper Presented at 38th Lunar and Planetary Science Conference, League City, TX, No. 1986, March 12–16, 2007.

7. Suggs, R.M.; Cooke, W.J.; Koehler, H.M.; et al.: "Lunar Meteoroid Impact Observations and the Flux of Kilogram-sized Meteoroids," Paper Presented at Meteoroids 2010 Conference, Breckenridge, CO, May 24–28, 2010.

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Monitoring meteoroid fluxes provides an understanding of the associated risk of meteoroids impacting spacecraft traveling in and beyond Earth's orbit. The large collecting area of the night side of the lunar disk provides statistically significant counts of meteoroids that can provide useful information about the flux of meteoroids in the hundreds of grams size range. The purpose of this Technical Memorandum is to document two lunar observing periods coinciding with the Geminid meteor showers that occured in 2006 and 2010 to improve their forecasts and to understand their contribution to the meteoroid environment in Earth's orbit and at the Moon.

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