THE OBSERVATION AND CHARACTERIZATION OF LUNAR METEOROID IMPACT PHENOMENA

BRIAN M. CUDNIK[1], DAVID W. DUNHAM[2], DAVID M. PALMER[3], ANTHONY COOK[4], ROGER VENABLE[5] and PETER S. GURAL[6]

[1]*Department of Physics, Prairie View A & M University, Prairie View, TX 77446, USA;* [2]*Johns Hopkins University, Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA;* [3]*D436, Los Alamos National Laboratory, Los Alamos, NM 87544, USA;* [4]*Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington D.C. 20560, USA;* [5]*3405 Woodstone Pl., Augusta, GA 30909, USA;* [6]*Science Applications International Corporation, 4501 Daly Drive, Suite 400, Chantilly, VA 20151, USA*

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Abstract. Confirmed observations of meteoroids from the Leonid stream impacting the Moon in 1999 and 2001 have opened up new opportunities in observational and theoretical astronomy. These opportunities could help bridge the gap between the ground-based (atmospheric) sampling of the smallest meteoroids and the larger objects observable with ground-based telescopes. The Moon provides a laboratory for the study of hypervelocity impacts, with collision velocities not yet possible in ground-based laboratories. Development of automatic detection software removes the time-intensive activity of laboriously reviewing data for impact event signatures, freeing the observer to engage in other activities. The dynamics of professional-amateur astronomer collaboration have the promise of advancing the study of lunar meteoritic phenomenon considerably. These three factors will assist greatly in the development of a systematic, comprehensive program for monitoring the Moon for meteoroid impacts and determining the physical nature of these impacts.

Keywords: Hypervelocity impacts, Leonid meteors, Lunar impact phenomena, Moon, Professional-amateur collaboration, Signal detection technology

1. Introduction

Prior to the confirmed reports of lunar impacts by objects within the Leonid stream, many observers had reported brief flashes of light on the moon and other forms of lunar change, known as Lunar Transient Phenomena (LTP), but none of these had been independently confirmed (Dunham et al., 2000). Historical evidence of such phenomena has been chronicled in Middlehurst (1968) and Gehring (1964). The attempts by several campaigns to obtain scientifically valid LTP observations have been unsuccessful. However, evidence of lunar change, in the form of impacts by kilogram-sized objects, had been recorded by the Apollo Lunar Seismograph program between 1969 and 1978 (Latham, 1973). In addition, a number of impact events during two Leonid storms in 1999 and 2001 have been recorded and confirmed by amateur and professional astronomers. Details about these impacts are provided in a companion paper.

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To recreate impact phenomena and probe the sub-surface composition of the lunar surface, two spacecraft, the Japanese Hiten spacecraft and the American Lunar Prospector, were crashed into the lunar surface. Goldstein (1999) discussed the call for observations of water vapor in the Prospector's ejecta plume via IR detection and the search for dissociated OH molecules using UV detectors. Although the Prospector's impact flash was not seen, a great deal of interest was stirred up in the professional community by the potential information that the encounter would generate – that is, finding large volatile reservoirs of water and other refractory materials on the lunar surface. Because of the evidence revealed by Clementine of the possibility of the existence of water ice in the permanently shadowed regions of the Moon's South Polar Region, scientists were expecting to find spectral signatures of water from these spacecraft impacts. Such a conclusive finding would dramatically aid the human exploration of space. In contrast to the Lunar Prospector impact, the Hiten impact was observed from multiple ground-based stations, including the Siding Spring observatory (Uesugi, 1993), but no conclusive evidence of lunar water was found. In contrast to the relatively "slow" man-made collisions, hyper velocity meteoroid collisions with the Moon are capable of generating far greater energy release than spacecraft impacts. Therefore, meteoroid impacts can serve as a probe for lunar water or other constituents just beneath the lunar surface.

2. The Visibility of Lunar Meteor Impacts from Earth

When an object collides with the Moon, the energy of the impact is suddenly released during the collision, and is re-emitted by the region of the Moon affected during a cooling time period. This cooling time depends on the energy absorbed by the region of the moon affected per unit area of surface, and/or on the radiation of the expanding fireball composed of lunar surface material and the impactor's debris. Due to the very short duration of the impact flash (the actual explosion due to the collision, lasting about $\sim 10^{-3}$ m s), it is unlikely that the flash observed from Earth (typically lasting 30 m s) is governed by an expanding fireball, but rather by the cooling of the affected lunar surface (Latham, et al., 1973). Yanagisawa and Kisaichi (2002) attribute the afterglow of longer duration events (greater than 100 m s) to thermal radiation from a plume of hot droplets ejected from the lunar surface during the high velocity impact event.

With regard to the probability of observing a meteoroid impact event given the high flux density of the 1999 Leonid storms (assuming that all 12 North American observed events of 1999 were real) an average rate of 3.24 observable impacts per hour, or one every 18.5 min was realized during the peak of the storm at the Moon. Assuming the circumstances in 2001 were such that the meteoroid flux at the time of the two confirmed meteor impacts was only 1% that of the 1999 confirmed impacts, it follows that the rate would be one impact every 1850 min, or nearly 31 h between consecutive impacts, on average, assuming a uniform stream of meteoroids. The two confirmed impacts of 2001 occurred within less than 1 h of each other and were each relatively bright. The four events reported by Ortiz et al. (2002) all occurred in a time span of less than 18 min, during elevated background meteor activity.

Considering the observational data from the two Leonid encounters along with the Apollo seismic data discussed earlier, there are several situations available for consideration with regards to the frequency of impacts observable from ground-based instrumentation. However, this frequency remains largely unknown, and the available situations are too limited to make an accurate estimate. Visiting the discussion of the seven confirmed events of the November 1999 impacts during the peak of activity at the Moon, out of a ZHR equivalent of at least 50,000 over an effective 2-h period of observation, it follows that about 715 h of monitoring would be needed before an impact could be detected during non-storm periods (based on expressions in Sigismondi and Imponente, 2000). Estimates from Ortiz (2000) and Ceplecha (1994) place this number closer to 200 h. Considering the impact events of November 2001, the maximum flux at the Moon was predicted to be only 10% that of 1999, so one would have expected to see only 10% of the impacts that were seen two years before. A more thorough discussion of "equivalent Earth ZHR" as experienced on the Moon, and how these values are derived, can be found in Ortiz et al. (2000). On the one hand, the Moon presented a much greater fraction of unilluminated surface to Earth-based observers, coupled with much less glare from the sunlit portion. These circumstances initially made for more favorable observing conditions. On the other hand, significant atmospheric extinction; a short window of observation; severe reduction in signal to noise due to atmospheric scattering from haze, pollution, and aerosols; and generally poor seeing at low elevations (smearing out star-like points) resulted in less-favorable conditions. Nonetheless, two confirmed impacts (comparable in brightness to the 1999 events), occurring within 1 h of each other, were made shortly after the Moon had exited a cluster of meteoroid filaments. If the Leonid level had dropped to one-fifth its peak level for 2001 (that is, about 100 times above the sporadic background level) at the time of the confirmed impacts, the average interval between consecutive events becomes about 50 h, roughly one-third the value obtained from the Apollo seismic data. Based on these considerations, it would seem a reasonable estimate that the rate of impacts observed that are comparable in brightness to the Leonid flashes, is one every 100 h for non-shower periods. Due to a number of factors, however, the rate of detection of these impacts are usually not one-to-one; that is, the event occurs when no one is observing, the event is observed by a single observer (unconfirmed), the event is poorly documented in time (which hinders attempts to confirm it), etc.

3. Improving the Odds of Detection with LunarScan

In order to increase detection rates in the watch for lunar meteors, an automated detection system is needed. Such a system to record short duration flashes in video imagery was a software development challenge that arose after the first confirmed Leonid impacts were made. Immediately after the video recordings were collected in November of 1999, several individuals reviewed their data by eye. That is, they played back their videotapes and carefully reviewed the imagery on a television monitor. Because of the short transient nature of the impact's visual flash, typically of a few tens of milliseconds, relative to the CCD camera frame rate (30 Hz), the flash is visible in only one to two video frames. In addition, due to the large separation between the Earth and Moon, the impacts are small in angular extent and cover only a few pixels, more due to CCD blooming than actual spatial spread. This made it difficult to detect what looks like a brief noise spot on the television screen. Thus only the brightest flashes were discernable by human observers and in many cases because they had been cued from another observer as to time and location from an independent observation. It was under this hit or miss detection scenario that one of the authors undertook the task to develop software capable of reviewing lunar video imagery and automatically search for flashes in a more consistent and reliable fashion.

The use of a personal computer for transient flash detection in video imagery had its roots in a similarly based problem of video meteor detection. Since 1997 software has been developed and interfaced with video frame grabber boards to detect the linear track of a meteor trail in a sequence of just a few video frames, Gural (1997, 1999). Thus the groundwork had already been laid for asynchronous digitizing and image processing at real-time video frame rates as well as high-speed algorithms developed for noise tracking, thresholding, and detection. The PC-based real-time meteor detection software was used as a starting point and modified to suit the unique detection issues associated with transient flash detection. However, the fundamental detection algorithms had to be reformulated since meteor detection involves a linear moving track across multiple frames (spatial-temporal detection with Hough transforms and matched filtering) and impact flash detection has small spatial extent and virtually no temporal component. Nevertheless, a successful detection algorithm was developed and used on David Dunham's Leonid video obtained on 18 November 1999.

At the time of this development effort the hardware components needed for real-time video processing were a digitizing frame grabber that can operate asynchronously with image processing. That is, the CPU is free to access and process a video frame while the frame grabber digitizes the next image. This must be done at 30 frames per second to keep up with the data flow out of the videotape playback unit (note that modern day digital recording cameras and IEEE 1396 interface boards allow one to stream the video data directly to hard disk and then feed the video frames to the computer processor in non-real-time). The real-time system

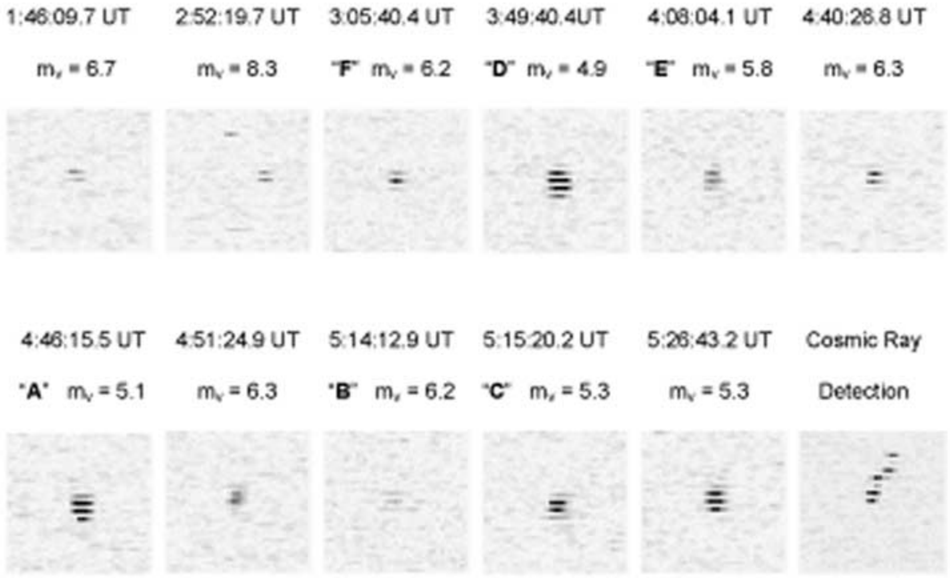

Figure 1. Eleven lunar impact flashes seen between 1:30 to 5:30 UT on November 18, 1999 recorded with David Dunham's 5″ telescope and \$80 CCD video camera. Note the banded appearance of the flash in the odd or even rows of the image due to the flash's short duration (<17 msec), thus showing up only in a single interleave video field. Images identified with letters A-F were independently verified as lunar impacts.

consisted of a Macintosh with a Scion Corporation LG-3 frame grabber. Once the data was digitized into system memory, a noise-tracking filter for each pixel was independently updated using a first order response filter to determine a running mean and standard deviation. For each new frame of imagery, every pixel is tested to see if it crosses above a user defined multiple of the standard deviation added to the mean. Since there is very little temporal extent to the flash phenomena, a spatial-only based algorithm for detection was utilized so processing occurs on each frame uniquely.

The spatial detection algorithm was formulated by first examining impact flashes that had been pre-discovered by human review of the videotapes. Examples of the appearance of the flashes are seen in Figure 1. As is evident from the figure, many of the flashes are of such short duration that they appear in only the odd or even rows of the video (horizontal banding in the flash spot). This is because standard video cameras record first the odd rows of an interleaved frame for the first 16.7 milliseconds (NTSC), followed by the even rows during the next 16.7 milliseconds, alternating between odd and even as it proceeds in time. Since the flash was so short, most of the time only a single interleave frame contains the flash. Thus, the detection algorithm was based on searching for horizontal triplets of threshold exceeding pixels plus an additional exceedance pixel within two rows above or below the center pixel of the triplet. This scheme helped to avoid the numerous false

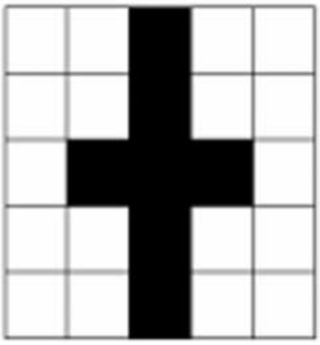

Figure 2. Exceedence criterion of candidate impact flashes.

alarms that occur when single pixels flare with bright noise spikes. The detection mask is shown in Figure 2. The use of this detection algorithm allowed for the discovery of six new flashes in Dunham's 1999 Leonid tapes, doubling the number found from multiple human inspections of the tapes. However only one flash could be confirmed due to lack of coverage by a second telescope system at the time of impact or a potentially confirming video system was pointed at a different region of the lunar surface.

Some discussion on lessons learned is in order for future data collection that is optimal for the automated detection of lunar impacts. One of the most important requirements that grew out of this effort is the desire to have a stable equatorial telescopic mount, properly aligned, and lunar rate motor drive. This is to prevent the bright lunar limb which is always just outside the field of view from "flashing" into or across the field of view causing a cascade of hundreds of detections in the software. In addition, a recorded timing signal, whether WWV on the audio track or a time stamp injected into the video stream prior to the recorder, is necessary for accurate timing of the flashes and confirmation by independent observers. Twin sites should be in operation simultaneously looking at the same lunar region in order to obtain confirmation video. It is also preferable that they are separated by at least 50 kilometers as then parallax rules out that no low earth orbit or geosynchronous satellites or space debris caused a sun glint flash. Having a second observation video also helps to eliminate cosmic rays track detections since they cannot be coincident on two separate CCDs both spatially and temporally. Cosmic ray signatures generally have a different point-spread-function (PSF) than an impact event or star, both of which are essentially point sources as seen from Earth. Atmospheric seeing and diffraction tend to spread out the PSF of a point source over several pixels while a cosmic ray affects discrete pixels. The latter gives a cosmic ray signature a "sharp" appearance in a CCD image compared to the "soft" image of a star or impact event.

The use of high quality digital recording is preferable to VHS, 8mm or other analog videotape media since the digital record/playback is free of the read head noise that can notoriously masquerade as impact flashes. Finally a video sequence of stars near the lunar position is useful for post-detection calibration of the flash magnitudes. Future applications for LunarScan include recording the spectral features of a lunar impact flash event, determining the duration of the flash with high-speed (millisecond resolution) video, and characterization of the frequency of occurrence.

4. On the Value of Amateur–Professional Collaborations in Lunar Impact Observations

Collaborations between professional and amateur astronomers have proven quite useful and mutually beneficial in recent years, especially with an increasing number of amateurs outfitted with equipment traditionally reserved for professional use, such as CCD cameras, low-resolution spectrographs, photoelectric photometers, and filters. While amateurs with this equipment may not have the funds and the assistance of a technician if something goes wrong, they do not have the struggles of the professional: bureaucracy, peer review, budget and funding problems, and lack of facilities for long-term projects (Stickland, 1996). Professional astronomers also face observatory scheduling problems and strong competition for telescope time. Amateurs, unburdened by these formalisms, are free to pursue scientifically useful research of their choosing and do not face the limitations of telescope time. In addition, various astronomical organizations have stepped up to encourage such collaboration, making data collected by the amateur easily accessible to the professional to assist the latter in his or her research. Examples of such organizations including the Association of Lunar and Planetary Observers (ALPO), the International Astronomical Union (IAU), the International Occultation Timing Association (IOTA), the American Association of Variable Star Observers (AAVSO), the International Meteor Organization (IMO), and the American Astronomical Society (AAS) have been, and continue to actively promote such collaboration.

Observations of lunar meteors provide an excellent avenue for professional-amateur collaborations. Since the confirmed observations of the lunar Leonid impacts of November 1999, studies of lunar meteoritic phenomena have gained new interest. However, with great uncertainty as to the frequency of lunar meteor impacts visible to ground-based observers, allocating valuable time on a professional grade instrument is a gamble at best. Nevertheless, a coordinated watch of dedicated amateurs would provide the needed manpower to better determine whether the benefits of a professional effort are worth the risks involved. They have the equipment and the time to dedicate to a meaningful study the Moon's surface for the pinpoint flashes of meteor impacts. The ALPO Lunar Meteoritic Impact Search, coordinated by the lead author of this paper, is one of a handful of groups coordinating observations amongst amateurs with the goal of determining the feasibility of pursuing the study of this phenomenon on a more professional level. The section promotes simultaneous, cooperative observations between two or more amateurs, which are necessary to validate a putative impact flash. Observations of lunar impacts, coupled with ongoing projects to study the flux of meteors entering the Earth's, could help refine the known size spectrum of small bodies in the near-Earth region of the solar system.

5. Discussion: A Comprehensive Program to Characterize Lunar Meteors

To date, all of the scientifically confirmed impact event observations have been derived from the Leonid meteor stream during the 1999 and 2001 storm events. The high number density, coupled with the geometrically favored position of the moon as seen with ground-based telescopes enabled astronomers to document a significant number of events. Similar attempts by groups such as Beech et al. to record meteor impacts from other showers such as the Perseids have yielded nothing conclusive, either due to the absence of significant objects in the stream or the extremely low number density of such objects. These attempts have been isolated but not ongoing and systematic; campaigns of the latter nature stand to have some success in obtaining valuable information about the lunar meteor impact phenomenon. In fact, collaboration between a number of different communities will help to enhance any program to characterize this phenomenon.

Isolated incidents resembling lunar meteoritic impacts have been reported prior to the 1999 lunar Leonid events. In fact, the NASA report R-277 (Middlehurst, 1968), which presents a catalogue of LTP events from 1540 to 1970, has about 12% of these events as appearing impact in nature. Impact events were taken to be events described as short flashes, brief starlike points, and small clouds, which may be the result of impacts kicking dust off the surface that becomes illuminated by sunlight, or may obscure a tiny part of a region. Some ambiguity does exist due to the nature of the reports and the brevity of their description. Many of the reported events, and the confirmed events, were typically pointlike or starlike in appearance and of extremely short duration: from 30 m s up to several seconds in lifetime. Assuming the LTP component of the impact database are legitimate, lunar meteoritic impacts are a fairly regularly occurring phenomenon worthy of attention. Table I contains a brief list of points of justification of establishing a long-term, thorough, and systematic lunar meteor program.

The previous sections discuss different aspects of such a program, from the estimated success rate during background conditions to an automated detection system to amateur-professional collaborations. Small professional observatories working with individual amateurs and advanced amateurs with observatories could produce a multi-wavelength program to study the lunar meteor phenomenon in great physical detail. Observations at specific wavelengths in the Johnson visible (UBVR) and infrared (IJK, 5.0 and 10.0 microns) would provide temperature information of the observed impact events. High-speed, low-light cameras observing

TABLE I

Justification list for Lunar meteor observations

- The Moon as a hypervelocity impact laboratory
- Assess the population of small objects in the Earth–Moon system part of the solar system while bridging the gap between asteroidal surveys and ground-based meteor observations
- Luminosity efficiencies of meteoroids of a range of velocities and sizes
- Impacts as probes to reveal the composition of the lunar subsurface and the impactor
- Unambiguous detection of water in the polar regions of the Moon
- The Moon as an impact detector – impact rates
- An additional chord to probe the structure of annual meteor structure (the Earth being one chord)
- Indirect observations of meteoritic phenomena by monitoring changes in the Moon's Sodium atmosphere (Wilson et al., 1999; Verani et al., 1999)
- Modify, improve, or diversify current models of impact dynamics
- Impacts as sources of other forms of LTP
- Free Oscillations induced by Meteor impacts aid in the study of the lunar interior and core
- Impact processes to include changes in crustal magnetic field and magnetism

the events in multiple wavelengths would provide valuable multi-spectral light-curve data. This data would be invaluable to investigators, such as Ernst and Schultz (2003), who perform laboratory experiments to determine the initial conditions of the impacts based on the actual impact flash decay. Analysis of the measured peak intensity could yield information about velocity and angle, target and projectile type. Complementing the light curve study would be low-light spectroscopes that would enable spectral data to be obtained to complement existing radiometric catalogues and provide additional information about the lunar subsurface and the impacting object. The existing data about the moon's surface can also be used to "subtract" the known lunar features from such spectra, leaving spectral information about the impacting object and /or the lunar sub-surface.

The discussion provided above is not meant to be a rigorous description of an observing program, but is intended to motivate interested workers within the professional community to pursue the study of lunar meteoritic phenomenon vigorously. A much more detailed description of such an ambitious program will be the subject of a future paper; this work provides only an introduction. For such a program to be successful, cooperation from a large number of people will be necessary, and this cooperation will need to be long-term. This cooperation would need support from an infrastructure, which would quickly and efficiently reduce, analyze and store the large amounts of data that would be produced by this endeavor. The results in the form of knowledge gained by an effort such as this would provide lasting benefit to the planetary science and impact community.

References

Ceplecha, Z.: 1994, *Astron. and Astrophys.* **286**, 967–970.

Dunham, D. W., Cudnik, B. M., Palmer, D. M., Sada, P. V., Melosh, J., Frankenberger, M., Beech R., Pellerin, L., Venable, R., Asher, D., Sterner, R., Gotwols, B., Wun, B., and Stockbauer, D.: 2000, *Lunar and Planetary Science Conference XXXI*, Houston, Texas, LPI, Paper 1547.

Ernst, C. M. and Schultz, P. H.: 2003, *Lunar and Planetary Science Conference XXXIV*, Houston, Texas, LPI, Paper 2020.

Gural, P. S.: 1997, *JIMO* **25**(3), 136–140.

Gural, P.: 1999, 'MeteorScan Documentation and User's Guide – Version 2.2', published by P. Gural, Sterling, VA, USA.

Gehring, J. W., Charters, A. C., and Warnica, R. L.: 1964, in Salisbury and Glaser, pp. 215–263.

Goldstein, D. B., Nerem, R. S., Barker, E. S., Austin, J. V., Binder, A. B., and Feldman, W. C.: 1999, *Geophys. Res. Lett.* **26**, 12.

Latham, G., Dorman, J., Duennebier, F., Ewing, M., Lammlein, D., and Nakamura, Y.: 1973, *Proceedings of the Fourth Lunar Science Conference* **3**, 2515–2527.

Middlehurst, B. M., Burley, J. M., Moore, P., and Welther, B. L.: 1968, 'Chronological Catalog of Reported Lunar Events', NASA Technical Report R-277.

Ortiz, J. L., Sada, P. V., Bellot Rubio, L. R., Aceituno, F. J., Aceituno, J., Gutiérrez, P. J., and Thiele, U.: 2000, *Nature* **405**, 921–923.

Ortiz, J. L., Quesada, J. A., Aceituno, J., Aceituno, F. J., and Bellot Rubio, L.R.: 2002, *ApJ* **576**, 567–573.

Sigismondi. C. and Imponente, G.: 2000, *JIMO* **28**(2/3), 54–57.

Stickland, D.: 1996, *Observatory* **116**, 360–364.

Uesugi, K.: 1993, American Astronautical Society Paper, 93–292.

Verani, S., Barbieri, C., Benn, C., Cremonese, G., and Mendillo, M.: 1999, 'Observations of the Lunar Sodium Atmosphere during the 1999 Quadrantids Meteor Shower', American Astronomical Society, DPS Meeting #31, #38.01.

Wilson, J. K., Smith, S. M., Baumgardner, J., and Mendillo, M.: 1999, *Geophys. Res. Lett.* **26**, 1645.

Yanagisawa, M. and Kisaichi, N.: 2002, *Icarus* **159**, 31–38.