Large Meteoroid Impact on the Moon on 17 March 2013

D. E. Moser*
MITS/Dynetics, Meteoroid Environment Office, NASA Marshall Space Flight Center

R. M. Suggs, R. J. Suggs
NASA, Meteoroid Environment Office, NASA Marshall Space Flight Center

*For questions contact: danielle.e.moser@nasa.gov
Overview

On 17 March 2013 at 03:50:54 UTC, NASA detected a bright impact flash on the Moon caused by a meteoroid impacting the lunar surface.

There was enhanced meteor activity in Earth’s atmosphere the same night, and one night following, from the Virginid Meteor Complex.

The impact crater associated with the impact flash was found and imaged by Lunar Reconnaissance Orbiter (LRO).

Luminous efficiency estimates can be made by combining flash and crater measurements. A sanity check of photometric procedures and crater scaling relations is also possible.
Typical impact flashes

15 Dec 2006
09:17:39.336
33 ms
m_R = 7.4
0.09 kg
Geminid (35 km/s)

17 Nov 2006
10:56:34.820
66 ms
m_R = 7.0
0.03 kg
Leonid (71 km/s)

3 Nov 2008
00:11:06.144
100 ms
m_R = 7.7
0.1 kg
S. Taurid (27 km/s)

22 Apr 2007
03:12:24.372
133 ms
m_R = 6.7
0.08 kg
Lyrid (49 km/s)
Atypical flash on 17 March 2013

17 Mar 2013
03:50:54.312
1.03 s
m_R = 3.0
16 kg
Virginid

Flash info
Detected with two 0.35 m telescopes

Watec 209H2 Ult monochrome CCD cameras
  - Manual gain control
  - No integration
  - Γ = 0.45

Interlaced 30 fps video

Saturated → needed saturation correction!
Peak R magnitude saturation correction

Photometry performed using comparison stars (See Suggs et al. 2014)

Saturated
Peak $m_R = 4.9$
UNDERESTIMATED!

CORRECTION:
2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.0 \pm 0.4$
Luminous energy $= 7.1^{+3.9}_{-2.4} \times 10^6$ J

(Similar results for 2D elliptical Moffat fit)
Correlated meteor activity on 17 Mar

All-sky meteor cameras detected a deeply penetrating cluster of 5 fireballs on 17 March.

Radiant and orbital elements consistent with the Virginid Meteor Complex (EVI/NVI).

Significant rates in Canadian Meteor Orbit Radar 1 day later indicating possible outburst.

Assume impact flash was part of Virginid Meteor Complex

\[
\begin{align*}
\therefore \quad v_g &= 25.6 \text{ km/s} \\
\theta_h &= 56^\circ
\end{align*}
\]
GIS tools were used to “georeference” the lunar impact video 3 times, at peak brightness and late impact.

Average crater position
20.60 ± 0.17° N, 23.92 ± 0.30° W
was sent to LRO.
Impact crater found by LRO!

**March 17th Impact**

**Features**
- Fresh, bright ejecta
- Circular crater
- Asymmetrical ray pattern

**Crater info**
- Rim-to-rim diameter = 18 m
- Inner diameter = 15 m
- Depth ≈ 5 m

**Actual crater location**
- 20.7135°N, 24.3302°W
- Δ ≈ 0.399° or 12.1 km
Ejecta in multiple reflectance “zones”

- **High/High** reflectance
- **Low/Low** reflectance

Impact Constraints

- Circular crater, impact angle constrained >15°
  - **HR** zone – impact possible from SE or NW
  - **LR** zone – impact possible from SW
  - ∴ no azimuth constraint

An impact from the SW is consistent with an impactor from the Virginid Meteor Complex.
Transient crater diameter estimates

Assumptions: Virginid $v_{gfo}$=25.7 km/s, $\theta_h = 56^\circ$; $\rho_t = 1500$ kg/m$^3$ (regolith)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\eta$</th>
<th>KE $\times 10^9$ (J)</th>
<th>Mass (kg)</th>
<th>$\rho_p$ (kg/m$^3$)</th>
<th>$D_{calc}$ (m)</th>
<th>$D_{obs}$ (m)</th>
<th>% Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holsapple’s online calculator (Holsapple 1993)</td>
<td>$5 \times 10^{-4}$</td>
<td>14 [9.4,22]</td>
<td>42 [28,66]</td>
<td>1800</td>
<td>12.2 [10.9,13.8]</td>
<td>15</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>$1.3 \times 10^{-3}$</td>
<td>5.4 [3.6,8.4]</td>
<td>16 [11,26]</td>
<td>1800</td>
<td>9.3 [8.3,10.5]</td>
<td>15</td>
<td>38%</td>
</tr>
</tbody>
</table>

Two example values of $\eta$ from the literature yield large ranges for KE and mass. Consequently, model results are highly dependent on luminous efficiency $\eta$.

Assuming a velocity dependent $\eta$ of $1.3 \times 10^{-3}$, these model results are consistent with the observed crater diameters.

$D_{calc} = 8$-18 m transient crater
$D_{calc} = 10$-23 m rim-to-rim
$D_{obs} = 15$ m transient crater
$D_{obs} = 18$ m rim-to-rim
Impact summary

Date of impact: 17 March 2013  3:50:54 UTC
Duration of impact: 1.03 s
Corrected flash peak R magnitude: 3.0 ± 0.4
Luminous energy generated by impact: $7.1^{+3.9}_{-2.4} \times 10^6$ J
Estimated kinetic energy of impactor: $5.4^{+3.0}_{-1.8} \times 10^9$ J = 1.3 tons of TNT (assuming $\eta = 1.3 \times 10^{-3}$)
Estimated mass of impactor: $16^{+10}_{-5}$ kg (assuming $v = 25.6$ km/s)
Estimated diameter of impactor: $22 \pm 3$ cm (assuming $\rho_p = 3$ g/cm$^3$)
Crater diameter: 18 m rim-to-rim, 15 m inner (‘transient’)
Crater location: 20.7135° N, 24.3302° W
Possible meteor shower association: Virginid Meteor Complex
Luminous efficiency: \( LE_\lambda = \eta_\lambda KE \)

\( D_t = 15 \) m from crater measurements
\( LE = 7.1 \times 10^6 \) J from flash measurements

Gault’s crater scaling law (Gault 1974) rearranges to give \( \eta \) vs \( \theta_h \) without assuming impact speed.

\[
KE = (4.0 \ D_t \rho_p^{-0.167} \rho_t^{0.5} \sin^{-1/3} \theta_h)^{1/0.29}
\]

Typical values of \( \eta_\lambda \) derived from lunar regolith range from \( 2 \pm 1 \times 10^{-4} \) to \( 2 \pm 1 \times 10^{-3} \).

Assuming association with the Virginids, \( \theta_h = 56^\circ \) and \( 7.5_{-2.5}^{+4.5} \times 10^{-4} < \eta_\lambda < 1.5_{-0.5}^{+0.8} \times 10^{-3} \).
Backup Slides


Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with:

Virginid Complex
at $\lambda=356.6$

<table>
<thead>
<tr>
<th>meteors</th>
<th>NVI$^1$</th>
<th>EVI$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_g$ (°)</td>
<td>184.1 ± 1.0</td>
<td>183.1</td>
</tr>
<tr>
<td>$\delta_g$ (°)</td>
<td>4.4 ± 0.9</td>
<td>2.3</td>
</tr>
<tr>
<td>$v_g$ (km/s)</td>
<td>25.6 ± 0.8</td>
<td>23.0</td>
</tr>
<tr>
<td>$\lambda_{\text{sun}}$ (°)</td>
<td>356.6</td>
<td>356.6</td>
</tr>
</tbody>
</table>

$^1$Sekanina (1973), $^2$Whipple (1957)

Orbits of the cluster of 5 were very similar with the following average orbital elements:

<table>
<thead>
<tr>
<th>meteoroids</th>
<th>NVI</th>
<th>EVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (AU)</td>
<td>2.25 ± 0.17</td>
<td>1.69</td>
</tr>
<tr>
<td>e</td>
<td>0.79 ± 0.02</td>
<td>0.71</td>
</tr>
<tr>
<td>i (°)</td>
<td>5.26 ± 1.02</td>
<td>3.7</td>
</tr>
<tr>
<td>$\psi$ (°)</td>
<td>280.32 ± 2.11</td>
<td>282.4</td>
</tr>
<tr>
<td>$\Omega$ (°)</td>
<td>356.65 ± 0.07</td>
<td>358.0</td>
</tr>
<tr>
<td>q (AU)</td>
<td>0.48 ± 0.02</td>
<td>0.496</td>
</tr>
<tr>
<td>Q (AU)</td>
<td>4.0 ± 0.3</td>
<td>2.89</td>
</tr>
<tr>
<td>Tj</td>
<td>3.1 ± 0.2</td>
<td>Indicates ~asteroidal body</td>
</tr>
</tbody>
</table>
**Ejecta distribution**

after Robinson et al. (2014)

---

**Ejecta in multiple reflectance “zones”**

- **High reflectance zone**
  - 10-20 m SW, <10 m NE

- **Low reflectance zone**
  - 50 m WSW, 80 m ENE

- **High reflectance zone**
  - ~300 m rough semicircle

- **Low reflectance zone**
  - ~1 km centered in NE

248 splotches within 30 km
- circular/irreg., majority low reflectance

---

**Impact Constraints**

- Circular crater, impact angle constrained >15°

- **HR zone** – impact possible from SE or NW

- **LR zone** – impact possible from SW

∴ no azimuth constraint (Robinson, personal comm.)

---

See Robinson et al. (2014) for more details