A Bright Lunar Impact Flash Linked to the Virginid Meteor Complex

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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 meteor activity in Earth’s atmosphere the same night from the Virginid Meteor Complex.

The impact crater associated with the impact flash was found and imaged by Lunar Reconnaissance Orbiter (LRO).
9-year observing program

Goal: Monitor the Moon for impact flashes produced by meteoroids striking the lunar surface. Determine meteoroid flux in 10’s g – kg size range.

Observation from MSFC
- Two 0.35m telescopes simultaneously
- Black & white CCD video cameras
- Interleaved 30fps video digitized, recorded
- Video analyzed with custom software

Field of View
- FOV covers approx. 20 arcmin
- 4×10^6 km^2 on the leading or trailing edge
- Observing when illumination 10-50%
- Maximum 10 observing nights/month
330+ Lunar impacts observed

For more info:
Suggs et al. (2014)
Suggs et al. (2011)
Suggs et al. (2007)
Typical impact flashes

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

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

17 Nov 2006
10:56:34.820
66 ms
m_R = 7.0
0.03 kg
Leonid (71 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
$m_R = 3.0 \pm 0.4$
16 $^{+10}_{-5}$ kg
Virginid

Flash info

Detected with two 0.35 m telescopes

Watec 902H2 Ultimate monochrome CCD cameras
- Manual gain control
- $\gamma = 0.45$

Saturated $\rightarrow$ needed saturation correction!
- Photometry performed using comparison stars (Suggs et al. 2014)
- 2D elliptical Gaussian fit to unsaturated wings of PSF

Peak $m_R = 3.0 \pm 0.4$
Lum energy $= 7.1^{+3.9}_{-2.4} \times 10^6$ J
Increased lunar activity on 17 Mar 2013

Observed by A. Kingery & R.M. Suggs; detected by R.J. Suggs
19 meteors were observed by NASA & SOMN all-sky meteor cameras on 17 Mar 2013
Meteors seen on 17 Mar 2013

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

- \( \alpha_g \) (°) = 184.1 ± 1.0
- \( \delta_g \) (°) = 4.4 ± 0.9
- \( v_g \) (km/s) = 25.6 ± 0.8
- \( \lambda_{\text{sun}} \) (°) = 356.6

Cluster of 5 seen on 17 Mar 2013

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

<table>
<thead>
<tr>
<th>meteoroids</th>
<th>a (AU)</th>
<th>2.25 ± 0.17</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.79 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>i (°)</td>
<td>5.26 ± 1.02</td>
<td></td>
</tr>
<tr>
<td>( \omega ) (°)</td>
<td>280.32 ± 2.11</td>
<td></td>
</tr>
<tr>
<td>( \Omega ) (°)</td>
<td>356.65 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>q (AU)</td>
<td>0.48 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>Q (AU)</td>
<td>4.0 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>Tj</td>
<td>3.1 ± 0.2</td>
<td></td>
</tr>
</tbody>
</table>

Indicates ~asteroidal body
Meteors on 17 Mar 2013

19 meteors seen on 17 Mar 2013

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

### Virginid Complex (rad 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>$\lambda_{Sun}$ (°)</td>
<td>356.6</td>
<td>354</td>
</tr>
</tbody>
</table>

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

Cluster of 5 seen on 17 Mar 2013

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

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</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>$\omega$ (°)</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>$T_j$</td>
<td>3.1 ± 0.2</td>
<td>Indicates ~asteroidal body</td>
</tr>
</tbody>
</table>

Indicates ~asteroidal body
Pink indicates the portion of the moon visible to the radiant.
Impact angle ~56° from horizontal.
All-sky meteor cameras detected a deeply penetrating cluster of 5 meteors on 17 March.

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

Impact flash rate increased to 1 every 0.87 hours on 17 March. (4 impacts in 3.5 hours)

**Impact Constraints**

Assume impact flash was part of Virginid Meteor Complex

- $v_g = 25.6 \text{ km/s}$
- $\theta_h = 56^\circ$
- Asteroidal? ($T_j = 3.1 \pm 0.2$)
Mapping the impact location

ArcMap was used to selenoreference the lunar impact following a newly developed selenolocation workflow.

Using the intensity-weighted center of the flash

Final predicted crater position

20°.684 ± 0.258 N, 24°.228 ± 0.288 W
Impact crater found by LRO!  
Robinson et al. (2014)

**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

**Impact Constraints**
- Circular crater, impact angle constrained $\theta_h > 15^\circ$
- Ejecta gives no azimuth constraint (Robinson, personal comm. 2014a)
### Comparison of geolocation results to obs crater location

<table>
<thead>
<tr>
<th>Method</th>
<th>Longitude ($^\circ$ W)</th>
<th>Latitude ($^\circ$ N)</th>
<th>Angular distance from observed ($^\circ$)</th>
<th>Surface distance from observed (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workflow</td>
<td>24.228 ± 0.288</td>
<td>20.684 ± 0.258</td>
<td>0.10026</td>
<td>3.041</td>
</tr>
<tr>
<td>LRO observed</td>
<td>24.3302</td>
<td>20.7135</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Transient crater diameter estimates

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Lum eff. $\eta$</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></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20.2 [18.0,23.0]</td>
<td>15</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>$1.3\times10^{-3}$</td>
<td>5.4 [3.6,8.4]</td>
<td>16 [11,26]</td>
<td>1800</td>
<td>14.1 [12.5,16.0]</td>
<td>15</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.3 [13.6,17.4]</td>
<td>15</td>
<td>2%</td>
</tr>
<tr>
<td>Holsapple’s online calculator (Holsapple 1993)</td>
<td>$5\times10^{-4}$</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></td>
<td></td>
<td></td>
<td></td>
<td>12.5 [11.1,14.2]</td>
<td>15</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>$1.3\times10^{-3}$</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>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.5 [8.5,10.8]</td>
<td>15</td>
<td>37%</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 $\eta = 1.3\times10^{-3}$, 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 inner (‘transient’)
$D_{obs} = 18$ 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: $3.0 \pm 0.4$

Luminous energy generated by impact: $7.1_{-2.4}^{+3.9} \times 10^6$ J

Estimated kinetic energy of impactor: $5.4_{-1.8}^{+3.0} \times 10^9$ J = 1.3 tons of TNT (assuming $\eta = 1.3 \times 10^{-3}$)

Estimated mass of impactor: $16_{-5}^{+10}$ kg (assuming $v = 25.7$ km/s)

Estimated diameter of impactor: $22 \pm 3$ cm (assuming $\rho_p = 3000$ kg/m$^3$)

Crater diameter: 18 m rim-to-rim, 15 m inner (‘transient’)

Crater location: $20.7135^\circ$ N, $24.3302^\circ$ W

Possible meteor shower association: Virginid Meteor Complex
Backup Slides
Luminous efficiency: $\text{LE}_\lambda = \eta_\lambda \text{KE}$

$D_t = 15$ m from crater measurements
$\text{LE}_\lambda = 7.1 \times 10^6$ J from flash measurements

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

$\eta_\lambda = \text{LE}_\lambda / \text{KE} = \text{LE}_\lambda / (4.0 \, D_t \rho_p^{-0.167} \rho_t^{0.5} \sin^{-1/3} \theta_h)^{1/0.29}$

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 $7.5^{+4.5}_{-2.5} \times 10^{-4} < \eta_\lambda < 1.5^{+0.8}_{-0.5} \times 10^{-3}$. 
Crater scaling laws

Gault’s scaling law (Gault 1974) for $D < 100$ m

$$D = 0.25 \rho_p^{0.167} \rho_t^{-0.5} E^{0.29} (\sin \theta_h)^{1/3}$$

- $D$ = transient crater diameter
- $\rho_p$ = projectile density
- $\rho_t$ = target density
- $E$ = kinetic energy of projectile
- $\theta_h$ = impact angle measured wrt horizontal

Holsapple crater calculator
(http://keith.aa.washington.edu/craterdata/scaling/index.htm)
Crater scaling laws

- **D**
  - Transient crater diameter
  - Measured at the height of the pre-existing surface
  - Aka inner diameter, apparent diameter

- **D_{rim}**
  - Crater rim diameter
  - Measured from rim to rim
  - Aka outer diameter

Holsapple assumes $D_{rim} = 1.3D$ similar to Melosh (1989)
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 circ/irreg splotches within 30 km

See Robinson et al. (2014) for more details

**Impact Constraints**

- Circular crater, impact angle constrained >15°
- **HRZ** – impact possible from SE or NW
- **LRZ** – impact possible from SW
  - no azimuth constraint  
  (Robinson, personal comm. 2014a)

An impact from the SW is consistent with an impactor from the Virginid Meteor Complex.
Peak Impact Flash Magnitudes

Mar 17 impact
Cluster of 5 penetrated fairly deeply into the atmosphere.
Moderately large, 0.003 kg to 0.1 kg masses
Crater associated with Spanish flash on 11 Sep 2013

Crater info
• Rim-to-rim diameter = 34 m
• Ejecta effects extend more than 500 m from the crater in all directions
References


Holsapple, K.A. “Crater sizes from explosions or impacts.”


Robinson, M.S. (2014a) Personal communication.


