FLUX OF LARGE METEOROIDS FROM LUNAR IMPACT MONITORING AND INFRASOUND

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Meteor - streak of light/ionization produced by a meteoroid ablating in an atmosphere
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Meteor - streak of light/ionization produced by a meteoroid ablating in an atmosphere

Fireball - meteor with a peak brightness greater than the planet Venus (m_V -4). Also called a bolide
Super bolide - a meteor sufficiently energetic to be detected by seismic/other sensors ($m_v \sim -18$)
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Meteorite - any part of a meteoroid/asteroid that makes it to the surface
ASTEROID OR METEOROID?

Size is the discriminator, but no “official” boundary
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Some scientists say meteoroids are smaller than one meter (beach ball size); others place the limit at 10 meters (garage size)
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International Astronomical Union definition: “A meteoroid is a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and considerably larger than an atom.”
How NASA handles meteoroids, asteroids, and space junk

Earth-approaching asteroids

Near Earth Object Office (JPL)
How NASA handles meteoroids, asteroids, and space junk

- Earth-approaching asteroids
  - Near Earth Object Office (JPL)

- Man-made orbital debris
  - Orbital Debris Program Office (JSC)
How NASA handles meteoroids, asteroids, and space junk

- Earth-approaching asteroids
- Meteoroids and meteors
- Man-made orbital debris

- Near Earth Object Office (JPL)
- Meteoroid Environment Office (MSFC)
- Orbital Debris Program Office (JSC)
What does the Meteoroid Environments Office (MEO) do?
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Develop, maintain, and distribute an sporadic meteoroid model suitable for spacecraft engineering/design
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Develop, maintain, and distribute an sporadic meteoroid model suitable for spacecraft engineering/design

Provide meteor shower forecasts to NASA/USG spacecraft operators

Monitor the meteoroid environment in near-Earth space (SSA)

Conduct and manage research to improve sporadic and shower meteoroid models
MAY CAMELOPARDALIDS

On May 24, 2014 Earth will encounter multiple streams of debris laid down by Comet 209P LINEAR
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Models indicate mm size particles in stream, so potential risk to Earth orbiting spacecraft
<table>
<thead>
<tr>
<th>Model</th>
<th>Time on May 24 (UT)</th>
<th>ZHR (#/hr)</th>
<th>RA, Dec (°)</th>
<th>$V_e$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyttinen &amp; Jenniskens (1929)</td>
<td>3:19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyttinen &amp; Jenniskens (1979)</td>
<td>6:04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSFC (peak 1)</td>
<td>6:11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyttinen &amp; Jenniskens (1818, 1853)</td>
<td>6:33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSFC (peak 2)</td>
<td>6:56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyttinen &amp; Jenniskens (1903, max)</td>
<td>6:59</td>
<td>15.86</td>
<td>125, +78</td>
<td>15.86</td>
</tr>
<tr>
<td>Lyttinen &amp; Jenniskens (1909)</td>
<td>7:15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maslov (1898-1919; 1903)</td>
<td>7:18</td>
<td>200-300</td>
<td>122.8, +79.1</td>
<td>16.2</td>
</tr>
<tr>
<td>Maslov (max)</td>
<td>7:21</td>
<td>100</td>
<td>122.8, +79</td>
<td></td>
</tr>
<tr>
<td>Vaubaillon</td>
<td>7:40</td>
<td>100-400</td>
<td>~125, +79</td>
<td></td>
</tr>
<tr>
<td>Lyttinen &amp; Jenniskens (1914)</td>
<td>7:49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maslov (1763-1783)</td>
<td>7:55</td>
<td>50-150</td>
<td>122.8, +79.0</td>
<td>16.2</td>
</tr>
<tr>
<td>MSFC (peak 3)</td>
<td>8:10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jenniskens (general)</td>
<td>123, +79</td>
<td></td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>
7-year observing program

Goal: Monitor the Moon for impact flashes produced by meteoroids striking the lunar surface.

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
- $4 \times 10^6$ km$^2$ on the leading or trailing edge
- Observing when illumination 10-50%
- Maximum 10 observing nights/month
300+ lunar impacts observed
2005-present

For more info:
Suggs et al. (2013) to be submitted
Suggs et al. (2011)
Suggs et al. (2007)
12/15/2006
09:17:39.336
33 ms
m_R = 7.4
0.09 kg
Geminid (35 km/s)

11/17/2006
10:56:34.820
66 ms
m_R = 7.0
0.03 kg
Leonid (71 km/s)

11/03/2008
00:11:06.144
100 ms
m_R = 7.7
0.1 kg
S. Taurid (27 km/s)

04/22/2007
03:12:24.372
133 ms
m_R = 6.7
0.08 kg
Lyrid (49 km/s)
AVGR - Shot 10

Projectile: 0.25" Pyrex
Target: Pumice Powder
Speed: 5.32 km/s
45 deg. impact angle
AVGR - Shot 10

Projectile: 0.25" Pyrex
Target: Pumice Powder
Speed: 5.32 km/s

NASA AVGR
March 17, 2013  3:50:54 UTC

03/17/2013
03:50:54.312
1.03 s

$m_R = ?$
Impactor mass?
Meteor shower association?

The brightest meteoroid impact flash detected in NASA's 7 year lunar observing program.
Estimating the magnitude

Photometry performed using comparison stars

Saturated
Peak $m_R = 4.9$

2D elliptical Gaussian fit to the unsaturated wings
Peak $m_R = 3.0 \pm 0.4$

Similar results for 2D elliptical Moffat fit
Preliminary energy estimate

Luminous efficiency ($\eta_\lambda$) relates how much of the impactor’s kinetic energy (KE) is converted to luminous energy (LE) in a wavelength range $\lambda$

$$\text{LE}_\lambda = \eta_\lambda \text{KE}_\lambda$$

<table>
<thead>
<tr>
<th></th>
<th>Const. $\eta = 2 \times 10^{-4}$</th>
<th>Vel. dep. $\eta = 1.3 \times 10^{-3}$ (Moser et al. 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>Luminous energy (J)</td>
<td>$7.1 \times 10^6$</td>
<td>$4.7 \times 10^6 - 1.1 \times 10^7$</td>
</tr>
<tr>
<td>Kinetic energy of impactor (J)</td>
<td>$3.6 \times 10^{10}$</td>
<td>$2.4 \times 10^{10} - 5.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Impactor mass (kg)</td>
<td>108</td>
<td>72 – 168</td>
</tr>
</tbody>
</table>

Why did we assume $v_g = 25.6$ km/s?
Meteor shower association

19 fireballs seen on Mar 17, 2013

Cluster of 5 seen on Mar 17, 2013

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

<table>
<thead>
<tr>
<th>Virginid Complex</th>
<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>185.7</td>
<td>183.6</td>
</tr>
<tr>
<td>$\delta_g$ (°)</td>
<td>4.4 ± 0.9</td>
<td>2.3</td>
<td>3.7</td>
</tr>
<tr>
<td>$v_g$ (km/s)</td>
<td>25.6 ± 0.8</td>
<td>23.0</td>
<td>28.9</td>
</tr>
<tr>
<td>$\lambda_{sun}$ (°)</td>
<td>356.6</td>
<td>354</td>
<td>354</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>$\omega$ (°)</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>Tj</td>
<td>3.1 ± 0.2</td>
<td>Indicates asteroidal body</td>
</tr>
</tbody>
</table>

Indicates asteroidal body
Mapping the impact location

Flash at peak brightness

Flash 10 frames (333 ms) after the peak

ArcMap (ArcGIS 10) was used to georeference the lunar impact video
Average location: 20.599 ± 0.172° N, 23.922 ± 0.304° W
LROC found the crater!

Actual crater diameter = 18 m

NASA/GSFC/Arizona State University

Monday, March 31, 14
Discovered January 1 at 6:18 UT. 7 images taken over 70 minute interval.
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Magnitude of 19 indicated an object 2-4 meters in diameter
2014 AA

Discovered January 1 at 6:18 UT. 7 images taken over 70 minute interval

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Positions submitted to the MPC, but no one realized object was on an impact course with Earth until just before impact
Projected impact time was Jan 2 2:25 UTC, just off coast of west Africa
Actual impact time was Jan 2 3:30 UTC +/- 30 minutes
Actual impact time was Jan 2 3:30 UTC +/- 30 minutes
Impact energy of about 1 kiloton
### Fireball Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>470 kilotons at altitude of 30 km (19 miles)</td>
</tr>
<tr>
<td></td>
<td>near Chelyabinsk (54.8° N, 61.1° E)</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>19 km/s (42,500 mph)</td>
</tr>
<tr>
<td><strong>Mass/size</strong></td>
<td>~12,000 tons</td>
</tr>
<tr>
<td></td>
<td>19 m (62 ft)</td>
</tr>
<tr>
<td><strong>Composition</strong></td>
<td>Ordinary chondrite (LL5)</td>
</tr>
</tbody>
</table>
Kiloton Airbursts Detected by Infrasound: 2000-2013