The Dust Environment of the Moon

M. Horányi, J. R. Szalay and the LADEE/LDEX Team
U. of Colorado, Boulder, USA
Meteoroid Sources

Meteor Showers

Sporadic Meteoroids

Barensten and Lefevre, 2006

Jones and Brown, 1993
Meteoroid Sources

Meteor Showers

Sporadic Meteoroids

Barensten and Lefevre, 2006

Jones and Brown, 1993
**LDEX Calibration/Test**

**MCP**

- **FPGA Max Value**: 3323 DN
- **Q**: 57.72 fC
- **t_{rise}**: 237.9 µs
- **SNR**: 3.7E+03

**Target**

- **FPGA Max Value**: 229 DN
- **Q**: 75.36 fC
- **t_{rise}**: 494.1 µs
- **SNR**: 1.2E+02

**MCP**

- **FPGA Max Value**: 3003 DN
- **Q**: 51.50 fC
- **t_{rise}**: 119.0 µs
- **SNR**: 3.3E+03

**Target**

- **FPGA Max Value**: 169 DN
- **Q**: 57.91 fC
- **t_{rise}**: 325.9 µs
- **SNR**: 1.9E+02
Impact Rate

a > 0.3 μm

a > 0.7 μm

Horányi et al., Nature, 2015
High Altitude Densities

$n_d = 4.43e^{-h/200.0} \text{ [}10^{-3} \text{ m}^{-3}\text{]}$

Grain Radius [μm]

Density $[10^{-3} \text{ m}^{-3}]$

Altitude [km]

0 50 100 150 200 250

0 1 2 3 4 5 6 7 8 9 10

0.30 0.72 1.73 4.16 10.00
$n(h) = n_0 e^{-h/\lambda}$
\[ M^+ = \sum_s F_s m_s^{\alpha+1} v_\beta^s \cos^3(\varphi - \varphi_s) \]
$$n(h, \varphi, a) = e^{-h/\lambda} \left( \frac{a}{a_{th}} \right)^{-3\alpha}$$

$$n_w \sum_{s} w_s \cos^3(\varphi - \varphi_s) \Theta(\varphi_s - \pi/2)$$
Sporadic Meteoroids

Szalay and Horányi, GRL, 2015a
Annual Variation

Jan. 2014

Feb. 2014

Mar. 2014

Apr. 2014

Density $a > 0.3 \mu m$

0.0 km
20.0 km
40.0 km
60.0 km
80.0 km
100.0 km

To Sun

LADEE
Campbell-Brown and Jones, 2006
Working List of Visual Meteor Showers from the International Meteor Organization (McBeath, 2015) during the LADEE operational period.

<table>
<thead>
<tr>
<th>Name</th>
<th>ID</th>
<th>Start Time [UTC]</th>
<th>Stop Time [UTC]</th>
<th>Peak Time (Moon) [UTC]</th>
<th>$\alpha$ [deg]</th>
<th>$\delta$ [deg]</th>
<th>$\nu$ [km/s]</th>
<th>ZHR [hr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leonids</td>
<td>Leo</td>
<td>06-Nov-2013</td>
<td>30-Nov-2013</td>
<td>17-Nov-2013 15:50</td>
<td>152</td>
<td>22</td>
<td>71</td>
<td>15</td>
</tr>
<tr>
<td>$\alpha$-Monocerotids</td>
<td>aMo</td>
<td>15-Nov-2013</td>
<td>25-Nov-2013</td>
<td>21-Nov-2013 16:11</td>
<td>117</td>
<td>1</td>
<td>65</td>
<td>Var</td>
</tr>
<tr>
<td>Phoenicids</td>
<td>Pho</td>
<td>28-Nov-2013</td>
<td>09-Dec-2013</td>
<td>06-Dec-2013 09:57</td>
<td>18</td>
<td>−53</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>Puppid/Velids</td>
<td>Pup</td>
<td>01-Dec-2013</td>
<td>15-Dec-2013</td>
<td>07-Dec-2013 03:41</td>
<td>123</td>
<td>−45</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Monocerotids</td>
<td>Mon</td>
<td>27-Nov-2013</td>
<td>17-Dec-2013</td>
<td>09-Dec-2013 02:56</td>
<td>100</td>
<td>8</td>
<td>42</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma$-Hydrics</td>
<td>sHy</td>
<td>03-Dec-2013</td>
<td>15-Dec-2013</td>
<td>12-Dec-2013 01:48</td>
<td>127</td>
<td>2</td>
<td>58</td>
<td>3</td>
</tr>
<tr>
<td>Geminids</td>
<td>Gem</td>
<td>04-Dec-2013</td>
<td>17-Dec-2013</td>
<td>14-Dec-2013 05:44</td>
<td>112</td>
<td>33</td>
<td>35</td>
<td>120</td>
</tr>
<tr>
<td>Comae Berenicids</td>
<td>CBe</td>
<td>12-Dec-2013</td>
<td>23-Dec-2013</td>
<td>19-Dec-2013 22:34</td>
<td>175</td>
<td>18</td>
<td>65</td>
<td>3</td>
</tr>
<tr>
<td>Urside</td>
<td>Urs</td>
<td>17-Dec-2013</td>
<td>26-Dec-2013</td>
<td>22-Dec-2013 14:14</td>
<td>217</td>
<td>76</td>
<td>33</td>
<td>10</td>
</tr>
<tr>
<td>Quadrantids</td>
<td>Qua</td>
<td>28-Dec-2013</td>
<td>12-Jan-2014</td>
<td>03-Jan-2014 19:39</td>
<td>230</td>
<td>49</td>
<td>41</td>
<td>120</td>
</tr>
<tr>
<td>$\alpha$-Centaurids</td>
<td>aCe</td>
<td>28-Jan-2014</td>
<td>21-Feb-2014</td>
<td>08-Feb-2014 06:07</td>
<td>210</td>
<td>−59</td>
<td>56</td>
<td>6</td>
</tr>
<tr>
<td>Omicron Centaurids*</td>
<td>oCe</td>
<td>09-Feb-2014</td>
<td>13-Feb-2014</td>
<td>11-Feb-2014 17:07</td>
<td>175</td>
<td>−55</td>
<td>51</td>
<td>2</td>
</tr>
<tr>
<td>$\gamma$-Normids</td>
<td>gNo</td>
<td>25-Feb-2014</td>
<td>22-Mar-2014</td>
<td>14-Mar-2014 20:55</td>
<td>239</td>
<td>−50</td>
<td>56</td>
<td>6</td>
</tr>
</tbody>
</table>

*The Omicron Centaurids (oCe) is a weaker shower and was added to this list due to its temporal correlation with an observed peak. The peak times have been adjusted from the peak times observed at Earth by taking into account the position of the Moon relative to Earth and correcting for the appropriate lead/lag times.
Enhanced Burst Activity Periods. The period corresponds to those labeled in Fig. 1. $a(\gamma_0) = N_{\text{burst}}/N_{\text{sp}}$ gives the ratio of the number of bursts in each period with the average number of sporadic bursts with the exception of the first row of data, which gives the sporadic background burst rates $N_{\text{sp}}$, in day$^{-1}$. The associated stream or complex which is temporally coincident with each period is given in the last column.

<table>
<thead>
<tr>
<th>Period</th>
<th>LDEX Peak Time</th>
<th>$a(3)$</th>
<th>$a(6)$</th>
<th>$a(9)$</th>
<th>$a(12)$</th>
<th>Criteria</th>
<th>Associated Stream or Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12-Nov-2013 22:10</td>
<td>2.6</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
<td></td>
<td>Sporadic Background</td>
</tr>
<tr>
<td>B</td>
<td>06-Dec-2013 00:00</td>
<td>1.3</td>
<td>0.6</td>
<td>1.0</td>
<td>1.3</td>
<td>✓</td>
<td>Taurid Complex</td>
</tr>
<tr>
<td>C</td>
<td>14-Dec-2013 11:34</td>
<td>10.3</td>
<td>13.0</td>
<td>12.1</td>
<td>7.8</td>
<td>✓ ✓</td>
<td>Puppids-Velorids I Complex</td>
</tr>
<tr>
<td>D</td>
<td>03-Jan-2014 14:50</td>
<td>3.1</td>
<td>3.9</td>
<td>3.0</td>
<td>2.6</td>
<td>✓ ✓</td>
<td>Geminids</td>
</tr>
<tr>
<td>E</td>
<td>12-Feb-2014 01:11</td>
<td>0.8</td>
<td>1.3</td>
<td>2.0</td>
<td>2.6</td>
<td>✓</td>
<td>Centaurid I/II Complex</td>
</tr>
<tr>
<td>F</td>
<td>25-Mar-2014 08:54</td>
<td>1.0</td>
<td>1.9</td>
<td>2.0</td>
<td>2.6</td>
<td>✓</td>
<td>?</td>
</tr>
</tbody>
</table>
Density $a > 0.3 \, \mu m$

0.0 km
10.0 km
20.0 km
30.0 km
40.0 km
50.0 km
60.0 km
70.0 km

To Sun

LADEE

Geminids Radiant

Density $[10^{-3} \text{ m}^{-3}]$
Geminids

\[ \gamma_0 = 1 \]

\[ \gamma_0 = 7 \]

\[ \gamma_0 = 16 \]
Extracted Meteoroid Stream Parameters. The established three letter identification code is id, $\lambda$ is the peak time in solar longitude, RA is right ascension, $\delta$ is the declination, and $N(3)$ is the number of bursts with a probability cut of $\gamma_0 = 3$. Earth observed values (McBeath, 2015), propagated in time to the position of the Moon at each peak time. The error on $\lambda$ for LDEX measured values was calculated assuming LDEX could not resolve a maximum in impact rate within three LADEE orbits, corresponding to approximately 6 h or 0.3° in solar longitude. Highlighted in bold are the values for which the estimates are within 1σ.

<table>
<thead>
<tr>
<th>Per.</th>
<th>id</th>
<th>Lat [deg]</th>
<th>$\lambda$ [deg]</th>
<th>$\lambda_{LDEX}$ [deg]</th>
<th>$\alpha$ [deg]</th>
<th>$\alpha_{LDEX}$ [deg]</th>
<th>$\delta$ [deg]</th>
<th>$\delta_{LDEX}$ [deg]</th>
<th>$N(3)$ [day$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>NTa</td>
<td>1</td>
<td>227.7</td>
<td><strong>227.8 ± .3</strong></td>
<td>58</td>
<td>118 ± 38</td>
<td>22</td>
<td>−5 ± 27</td>
<td>3.3</td>
</tr>
<tr>
<td>B</td>
<td>PuV</td>
<td>−64</td>
<td>253.8</td>
<td>252.5 ± .3</td>
<td>123</td>
<td>205 ± 19</td>
<td>−45</td>
<td>−41 ± 14</td>
<td>2.0</td>
</tr>
<tr>
<td>C</td>
<td>Gem</td>
<td>10</td>
<td>261.6</td>
<td><strong>261.8 ± .3</strong></td>
<td>112</td>
<td><strong>92 ± 31</strong></td>
<td>33</td>
<td>27 ± 8</td>
<td>26.7</td>
</tr>
<tr>
<td>D</td>
<td>Qua</td>
<td>63</td>
<td>284.4</td>
<td><strong>284.6 ± .3</strong></td>
<td>230</td>
<td><strong>225 ± 12</strong></td>
<td>49</td>
<td>−25 ± 17</td>
<td>8.0</td>
</tr>
<tr>
<td>E</td>
<td>oCe</td>
<td>−50</td>
<td>325.1</td>
<td><strong>325.4 ± .3</strong></td>
<td>175</td>
<td>273 ± 13</td>
<td>−55</td>
<td>−7 ± 40</td>
<td>2.0</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>4.1 ± .3</td>
<td></td>
<td></td>
<td>275 ± 38</td>
<td></td>
<td>−23 ± 13</td>
<td></td>
<td>2.7</td>
</tr>
</tbody>
</table>
Probing the Structure of the Geminids

![Graph showing the time from Lunar GEM peak in days against the number of meteors per cubic meter.]
Geminids Response

\[ \dot{n} = \alpha M - \frac{n}{\tau} \]

Days of 2013

Normalized

LDEX
UVS (K)
\( \tau = 2.0 \) days
\( \tau = 4.0 \) days
\( \tau = 6.0 \) days
\( \tau = 8.0 \) days
\( \tau = 10.0 \) days

Szalay et al., GRL, (in review)
The image contains four sections labeled "Ongoing Studies," "Geminids as a probe," "Surface Dependence," and "Ejecta Plumes." Each section contains various visual representations, including graphs and images, related to space science research, particularly focusing on the Geminids meteor shower as a probe for studying surface dependence and ejecta plumes.
Conclusions

• The lunar dust cloud responds to changes in meteoroid flux.

• Improved data on the mass distribution of the Geminids can be used to “calibrate the Moon”.

• Lunar dust measurements could be useful complementary data to visual and radar observations.

• Similar impact ejecta processes take place on all airless bodies in the solar system.
Conclusions

• The lunar dust cloud quickly responds to changes in meteoroid flux.

• Improved data on the mass distribution of the Geminids can be used to “calibrate the Moon”.

• Lunar dust measurements could mature into complementary data to visual and radar observations.

• Similar impact ejecta processes take place on all airless bodies in the solar system.
Lunar Dust / LDEX Publications

Gardening Rate

Characteristic Size

\[ \sigma = \int_{a_0}^{a_{\text{max}}} f(a) \pi a^2 \, da \approx \frac{3}{3\alpha - 2} \pi a_0^2 \]

Accumulation Timescale

\[ \tau = \frac{1}{F_0} = \frac{3\alpha - 2}{3\pi F_0 a_{\text{th}}^3 a_0^{3\alpha - 2}} \]

Accumulation Depth

\[ \delta = \frac{\sqrt{\sigma}}{\tau} = F_0 a_{\text{th}}^{3\alpha} \left( \frac{3\pi}{3\alpha - 2} \right)^{\frac{3}{2}} a_0^{3(1-\alpha)} \]

<table>
<thead>
<tr>
<th>(a_0) [μm]</th>
<th>(d) [μm]</th>
<th>(\tau) [10^3 yr]</th>
<th>(\delta) [μm/10^6 yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.2</td>
<td>6 ± 3</td>
<td>30 ± 16</td>
</tr>
<tr>
<td>0.1</td>
<td>0.4</td>
<td>10 ± 6</td>
<td>37 ± 20</td>
</tr>
<tr>
<td>0.3</td>
<td>1.1</td>
<td>22 ± 12</td>
<td>50 ± 28</td>
</tr>
</tbody>
</table>

Szalay and Horányi, *GRL, 2016b*
Lunar Sunrise Terminator

[Graph showing data points and lines for various missions: Apollo (1976), Apollo (2011), Clementine (2014), LRO (2014), LDEX.]

Density Upper Limit [m$^{-3}$] vs. Altitude [km]

Szalay and Horányi, GRL, 2015b