The Lunar Dust EXperiment (LDEX) for LADEE

or

How to design a dust detector

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&

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LASP:
Laboratory for Atmospheric and Space Physics
The LDEX instrument
Outline

• The LADEE mission
  – Instruments

• The lunar dust environment:
  – Human and robotic activity
  – Impact ejecta
  – Electrostatic lofting

• LDEX instrument
  – Design
  – Optimization
  – Performance in the UV environment

• Summary
LADEE mission
(Lunar Atmosphere and Dust Environment Explorer)

- NASA mission
- ~ $100M for the mission (100 days of operation)
- ~$6M for LDEX
- Started in ~2008
- Launch in late 2012
- ~40 – 100 km elliptical orbit
- 3 axis stabilized

Science goals:

- Measure atmospheric composition and variability (before disturbed by future lunar exploration)
- Measure dust component and its variability in the exosphere
Lunar Dust EXperiment (LDEX)
Impact ionization dust detector

In situ measurement of exospheric species

P. Mahaffy
NASA GSFC
(Directed – SMD)

300 Dalton range/unit mass resolution

Neutral Mass Spectrometer (NMS)
MSL/SAM Heritage

In situ measurement of exospheric species

P. Mahaffy
NASA GSFC
(Directed – SMD)

UV Spectrometer (UVS)
LCROSS heritage

Dust and exosphere measurements

A. Colaprete
NASA ARC
(Directed – SMD)

Lunar Laser Com Demo (LLCD)
Technology demonstration

High Data Rate Optical Comm

D. Boroson
MIT-LL
(Directed – SOMD)

300 Dalton range/unit mass resolution

SMD - Directed instrument

SMD - Directed instrument

SMD - Competed instrument

51-622 Mbps
The Moon is a dusty place!
Dust is a problem for future exploration

- Dust is a hazard for humans and mission
- Dust stirred up by human and robotic activity
- Micrometeoroid bombardment
- Emission of secondary ejecta
- Dust lofting due to plasma effects (maybe)
Impact ejecta cloud

The dust detector instrument on the Galileo spacecraft was the fits to observe the dust ejecta cloud around the Ganymede and other Jovian satellites.


The number density of dust as a function of altitude above the surface of Ganymede.
Impact ejecta – around the Moon

The cumulative density of dust grains as function of particle radii at an altitude of 50 km.

*Calculation by M. Horanyi.*

**Parameters:**

1) $F = 2 \times 10^{-15} \text{ kg/m}^2/\text{s}$  
   (Interplanetary micrometeoroid flux)

2) $Y = 10^3 - 10^4$  
   (mass yield – cratering)

3) $\Psi(\langle u \rangle) = (u/\langle u \rangle)^\gamma$  
   (velocity distribution)
LCROSS notes

LCROSS kicked up much less dust than expected

Possible explanation:
- Hollow cylindrical impactor is difficult to model
- “Soft landing” on loose regolith
• Water in gaseous phase detected
• Approx 5% in mass
The charging of the lunar surface
Lunar Horizon Glow I.

Surveyor 5: 1967-267T11:10:56

Surveyor 6: 1967-328T14:15:26

Surveyor 6: 1967-328T14:36:41

Surveyor 7: 1968-023T06:21:37

Surveyor 7: 1968-023T06:36:02

Surveyor 7: 1968-023T06:51:44

Surveyor 7: 1968-023T07:32:09
Lunar Horizon Glow II.

Composite picture

Horizon glow

Sun position
Lunar Horizon Glow III.

Startracker image by the Clementine spacecraft
Lunar Horizon Glow IV.

- Apollo 17 astronauts’ sketch of the Lunar horizon glow.
- Analysis suggest submicron sized dust
  - $n \sim \exp(H/H_S)$, $H_S = 5 - 20$ km
  - $n \sim 100 \text{ m}^{-3}$, 0.1 micron dust at 50 km

Analyzed by Zook and McCoy, GRL, 1991.
LEAM Apollo 17 measurements

LEAM: Lunar Ejecta and Meteorites (O. Berg)
Dust lofting

Electrons, protons

Solar UV

E-field

Lunar surface

Surface potential $\varphi \approx 5 \text{ V}$
Electric field $E \approx 5 - 10 \text{ V/m}$
Surface charge density $\sigma \approx 10^{-10} \text{ C/m}^2$
Charge in 1 $\mu$m dust $Q << 1 \text{ e}^-$

Difficult to explain dust lofting to high altitudes:

Energy balance $Mgh = Q \varphi$
$r = 0.1 \text{ micron, dust potential } = 5 \text{ V} \Rightarrow h = 20 \text{ m} << 50 \text{ km}$
Dust “ponds” on Eros
The effect of UV variability

Variability of the VUV emission spectrum with solar activity measured at 1 AU from the Flare Irradiance Spectral Model (FISM) (Chamberlin et al. 2008).

The photoelectric yield measured on the samples returned by the Apollo missions (after Willis et al., 1973).
The effect of UV variability

Photoelectron current from the Moon

The cumulative photoelectron current from 5 eV to 22 eV photon energy.

\[ J_{ph} = q \int_{\lambda}^{\infty} Y(E) S(\lambda) \frac{d\lambda}{dE} dE \]

E² is the proxy for dust mobilization

Sternovsky et al., 2008

Simple model:

\[ F_D \sim E\sigma \sim E^2 \]

Conclusion: dust mobilization should correlate with solar activity (flares)
Expected dust environment

Lofted dust

Secondary ejecta
Temporal Variability

1) Spherically symmetric continually present ejecta cloud

2) Temporal & spatial variability due to meteor showers on time scales of days

3) Variability with solar activity (flares, 11 year cycle)

4) Density enhancements of small grains over the terminators due to plasma effects, expected to be correlated with solar wind conditions
Instrument
Heritage
LDEX instrument development

Prototype → Model → Instrument
LDEX Instrument

- Deployable door
- Biased grid
- Biased hemispherical grid
- MCP detector
- Hemispherical Target (GND)
- E-field
- Electronics box
- Faraday shield
- ~15 cm
Operation Principle - Impact Ionization

Hypervelocity impact (> 1 km/s)

Dust particle

Total impact charge:

\[ Q[C] \approx 0.5 \, m \, v^{3.5} \]

\( Q[C], \, m[\text{kg}], \, v[\text{km/s}] \)

Velocity determined from signal rise-time

\( v = 1.7 \, \text{km/s} \)

(LADEE)

Mass determined from impact charge

\( Q \approx 2 \, \text{C/kg} \)

\( (v = 1.7 \, \text{km/s}) \)

Dietzel et al., J Phys E (1973)
Individual Dust Impact Detection

MCP detector for ions (high sensitivity)

Impact signal from prototype instrument

Incoming dust

Hemispherical target

Target collects electrons (low sensitivity)
Individual Dust Impact Detection II

What size dust particles can be detected?
Requirement: <1 µm to 5 µm

Total impact charge:
\[ Q[C] \approx 0.5 \text{ mV}^{3.5} \]

<table>
<thead>
<tr>
<th>( r \ [\mu m] )</th>
<th>( Q \ [e^+] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>240</td>
</tr>
<tr>
<td>0.25</td>
<td>3,700</td>
</tr>
<tr>
<td>1</td>
<td>2.4 \times 10^5</td>
</tr>
<tr>
<td>5</td>
<td>3 \times 10^7</td>
</tr>
</tbody>
</table>

Lofted dust

Expected performance

Impact ejecta
Small Particles – Collective Mass

Integrated (100 ms) charge from small dust particle impacts

Incoming dust
(~1000/s)
(~0.1 micron)

Simulated signal over the terminator region
Collective mass – background removal

MCP signal → 100 ms integrated signal for collective mass

1-9 sec. normal mode

10th sec background measurement

(10 S/s) time

The noise background is measured by reversing the bias on the ion focusing grid and prevent ions from being collected.

Bias changed from -200 V to +28 V
LDEX: Ion Optics Design

MCP detector housing

- MCP -1100 V
- Target at Gnd
- Ion Paths
- -1600 V Grid
- -1100 V Plate
- Hemi Grid -200 V

SIMION simulations
Ion Collection Efficiency vs. Ion Thermal Energy, for Various Impact Positions (theta=0, 30, 55, and 80 degrees)

Ion Collection Efficiency

Ion Thermal Energy (eV): P(E) ~ exp(-E/E_{th})^2
UV Environment

- Sunlit lunar surface in FOV
- UV reflection from Moon
- Low UV background
- No science
- In Moon’s shadow
- Sun in FOV
UV reflected back from the lunar surface
UV reflected back from the lunar surface

\[
\begin{align*}
\text{df} \ i, \varepsilon, \alpha & := I_0 \cdot \frac{a \cdot b \cdot \cos(i) \cdot \cos \varepsilon}{R^2} \cdot \frac{\cos(i)}{\cos(i) + \cos \varepsilon} \cdot \Sigma \alpha \cdot B \alpha, \ g \cdot \text{dA}
\end{align*}
\]

(See also picture on right):
\begin{itemize}
  \item \( \phi \) = angle between surface normal and direction of incidence
  \item \( \psi \) = angle between surface normal and direction to detector
\end{itemize}

**Scattering angle for UV**

- **Sigma (alpha)**
- Phase angle alpha [rad]

**Retrodirective function**

- **B(alpha)**
- Phase angle alpha [rad]
UV reflected from the lunar surface

UV photon influx as a function of altitude

Variation with position on orbit

Angle from local noon [deg]
• LDEX is designed to reject UV light (specular reflection)
• Only scattered light can reach the MCP detector

**Target:**
- Rh coating
- highly polished
Wavelength dependence

Solar spectrum (solar max – 2012 launch)

MCP quantum efficiency of detection (QE)

Cumulative contribution (SS x QE)

Lunar reflectivity:
The geometric albedo of ~5% applies over a wide range of wavelengths (58 – 184 nm).

Experimental data published:
• 120 - 165 nm (Lucke et al, 1976)
• Lyman alpha (Taguchi et al, 2000)
• 58 - 166 nm (Wu et al. 1977)
• 82 - 184 nm (Henry et al, 1995)
(increasing of albedo with decreasing wavelength)
UV reflectance of materials

The numbers below are the reflectance of materials at normal (0 deg) and grazing incidence for Lyman alpha wavelength (1216 Å). The number are from the figures presented in Samson (Vacuum Ultraviolet Spectroscopy). The cutoff is a number where the reflectance drops below 1% (roughly) for normal incidence.

<table>
<thead>
<tr>
<th>Material</th>
<th>0 deg</th>
<th>89 deg</th>
<th>Cutoff at 0 deg (~1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>0.17</td>
<td>0.97</td>
<td>15 nm</td>
</tr>
<tr>
<td>Silver</td>
<td>0.08</td>
<td>0.96</td>
<td>15 nm</td>
</tr>
<tr>
<td>Platinum</td>
<td>0.21</td>
<td>0.97</td>
<td>15 nm</td>
</tr>
<tr>
<td>Iridium</td>
<td>~ 0.2</td>
<td>0.97</td>
<td>20 nm</td>
</tr>
<tr>
<td><strong>Rhodium</strong></td>
<td>~ 0.1</td>
<td>0.97</td>
<td>15 nm</td>
</tr>
<tr>
<td>Tungsten</td>
<td>~ 0.3</td>
<td>0.98</td>
<td>20 nm</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.15</td>
<td>0.97</td>
<td>20 nm</td>
</tr>
</tbody>
</table>

* Rhodium has minimum in the reflectance for Lyman alpha (0.1) but increases to 0.2 around 600 Å.
Target surface roughness

Total integrated scatter

\[ TIS \Delta n, \sigma := \left( \frac{4\pi \sigma \Delta n}{\lambda} \right)^2 \]

- \( \sigma \) – rms surface roughness
- \( \Delta n \) – refractive index difference
- \( \lambda \) – wavelength (Ly alpha)

Polished surfaces
- 100 nm  common polish
- 10 nm  good polish
- 1 nm  super polish
Zemax modeling of LDEX

• Description of scattering:

• Scattering ratios used:
  – Rh (0.25), Au (0.5), Ag (0.5)

• Distribution of scattered light (Gaussian dist.)
  – \( \sigma = 0.01 \) or 0.1
Angle dependence of UV flux
And the critical place is....
Dust accelerator facilities

HV generator

Experimental chamber

Dust particles

Heidelberg facility
CCLDAS dust accelerator facility

- 3 MV Pelletron
- 1 - 100 km/s dust velocity
- Commissioning: spring 2011

Science:
- Impact physics
- Generation of secondary particles (particulates, ions, neutral)
- Instrument development and testing

Webcam: http://dustcam.colorado.edu
Calibration Measurements

Dust samples
Material: Fe
Velocity range: ~1-40km/s
Size range: <1 to 5µm radius
Calibration results

-The calibration curve measured
-The ratio of the MCP and Target signals is constant (same charge is measured)

\[ Q \approx 0.3 \, m v^{3.5} \]

[Q] in Coulombs
[m] in kg
[v] in km/s
LDEX instrument

- LDEX is designed to minimize UV noise
- Individual impact detection range 0.3 – 5 micron
- Integrated signal to measure 0.1 micron particles
- Calibrated at the Heidelberg dust accelerator facility
Summary

• **Planetary science:** LDEX will be the first instrument to measure secondary ejecta particles from a rocky planetary object

• **Lunar & plasma science:** LDEX and LADEE will resolve dust lofting issue

• **LDEX instrument science requires:**
  – UV optics & modeling
  – Ion optics & modeling
  – Planetary science
  – Material science
  – Engineering
  – ….& lots more
My colleagues:
Jianfeng Xie
Mihaly Horanyi
Eberhard Gruen
George Lawrence
Mark Lankton
David Gathright
Keegan Amyx