Muon vision for planetary geology: A look inside asteroids, comets and surface features

15th Small Bodies Assessment Group

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Image credit: ESA/Rosetta
Small Solar System Bodies

Asteroids, meteoroids, comets, moons of Mars, less than a few 10s of km in scale.

- Phobos by Curiosity
- Tempel 1 by Deep Impact
- Asteroid Toutatis by Goldstone Radar (Potentially hazardous object)

Note Halloween flyby of “skyscraper-sized” asteroid 2015 TB145.

Accessible near-Earth asteroids (NHATS) - Image credit: S. Kortenkamp, PSI
Interior structure of asteroids and comets?

Voids on the order of the size of the constituent fragments comprising the asteroid – possibly larger depending upon the role of friction and van der Waals forces.

Density contrasts: \(\sim 3 \, \text{g/cm}^3\) (component rock) and \(0 \, \text{g/cm}^3\) (voids).

Heterogeneous / collisionally - processed.

Density discontinuities between compressed and uncompressed comet material, perhaps manifested as sheets of high-density within low-density material.

Density contrast: \(0.5 \, \text{g/cm}^3\) (uncompressed) and \(2 \, \text{g/cm}^3\) (compressed).
Collisional processing

Itokawa as a gravitational aggregate
Brazil nut effect - Are the larger pieces on the outside?
Deep Mapping

Significance:

**Interior structure, composition & properties**
- Density & macroporosity
- Rubble-pile v. homogeneous
- Volatile content
- Strength of materials

**Planetary defense**
Kinetic impactor vs. nuclear burst

**Planetary science**
Origins and evolution

**NASA initiatives**
Asteroid Mission
Strategic knowledge gaps (SBAG, e.g. Abel & Rivkin, AstroRecon 2015)

**Resources & exploration**
Mining, capture, in situ resource utilization (ISRU), radiation environment

Plesko et al., AstroRecon 2015
## Prospective Deep Mapping Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Physical Parameter</th>
<th>Object Size/depth</th>
<th>Resolution limit</th>
<th>Issues</th>
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<tbody>
<tr>
<td>Radar</td>
<td>Dielectric constant, conductivity</td>
<td>kilometers</td>
<td>meters</td>
<td>Contrast detection, ambiguous</td>
</tr>
<tr>
<td>Gravimetry &amp; Radio Science</td>
<td>Gravity field</td>
<td>Whole-body, regional mass anomaly</td>
<td>?</td>
<td>Model based</td>
</tr>
<tr>
<td>Seismic</td>
<td>Seismic velocity, density</td>
<td>kilometers</td>
<td>Thin structures challenging</td>
<td>Contrast detection, ambiguous</td>
</tr>
<tr>
<td>Muon imaging</td>
<td>Density (electron)</td>
<td>&lt; 3 km</td>
<td>meters</td>
<td>Long integration times</td>
</tr>
</tbody>
</table>

Some combination of these methods may be required!
Radar measurements indicate CG-76P is homogeneous on scales of several meters, but cannot rule out larger blocks (Kofman et al., *Science*, 2016)

- Constrained volumetric dust/ice ratio (0.4 to 2.6) and porosity of (75 to 85%)

- Gravity measurements confirm high porosity, absence of large voids (Patzold et al., *Nature*, 2016)
Muon fundamentals

Muons are elementary charged particles (leptons), like electrons, but 200× more massive.

Muons are produced primarily by the decay of pions and kaons, e.g.

\[ K^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]

Muons subsequently decay, e.g.

\[ \mu^- \rightarrow e^- + \bar{\nu}_e \]

Muons undergo weak interactions:

- Energy loss by ionization, radiative & nuclear processes
- Destruction is dominated by decay (2.2 µs mean lifetime)
- High-energy muons can penetrate kilometers of rock
Muon range and transmission
(total muon flux as a gage of thickness)

Spectrum of muons at Earth’s surface

How many muons arrive at depth?

Standard rock: \( \rho = 2.65 \text{ g/cm}^3 \)
Muon imaging

- Application of muons to radiography and tomography
- About 10,000 muons per square meter at Earth’s surface
  - A uniform source for radiography
  - Atmospheric muons are **far** more penetrating than any other particle used for radiography
- Atmospheric muons used to measure tunnel overburden in the 1950’s for civil engineering and today for geology!
- The first reported radiographs were by Alvarez et al. (1970) of the Pyramid of Chepren (Khafre)
- Muons are used today to study damaged Fukushima-Daiiichi reactor cores, homeland security, architecture, civil engineering, and geophysics.

*Compared images measured with a hodoscope to simulated images with “hidden” chamber.*
Muon imaging in geophysics

Muons produced in extended air showers have been used to map the interior of large structures on Earth.

Internal structure of Satsuma-Iojima volcano using a 1 m² muon telescope (Tanaka et al., 2010) – “Muography”

Image by University of Chicago & Kavli Institute for Cosmological Physics & the Pierre Auger Observatory (CC-BY-2.5)
Muon imaging in geophysics

Internal structure of Satsuma-Iojima volcano using a 1 m² muon telescope (Tanaka et al., 2010) – “Muography”

Hodoscope: Tracking planes determine particle trajectory.

hodos + scopos = path + observer
Application to asteroids?

Steps for 3D filtered backprojection

- Acquisition of hodoscope data
- Ray-sorting/binning → projection geometry
- Conversion of counts to density integrals
- Tomographic reconstruction

*Ideal* projection data for a small asteroid with a dense inclusion

Animation progression:
Asteroid exterior → Projected density → Filtered projection
Steps for 3D filtered backprojection

Acquisition of hodoscope data

Ray-sorting/binning → projection geometry

Conversion of counts to density integrals

Tomographic reconstruction

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In practice, months in close proximity could be required to acquire data for 3D interior mapping.

Integration time depends on inclusion scale and contrast, hodoscope design, and concept of operations.
Challenges for asteroids & comets:

Are there enough muons?
• Yes – Integration times "typical" for mapping missions with 1 m² hodoscope

Can interior structures be separated from surface features?
• Yes – Radar measurements of surface density constrain muon production

Can muons be separately measured from other particles by a practical imaging system?
• Probably – however, electrons may pose a challenge

Muon production in solid surfaces and Earth’s atmosphere

Regolith materials

Muon production in solid surfaces and Earth’s atmosphere

0.1 g/cm³

5 g/cm³

$E^2 \Phi_\mu$ (cm⁻² s⁻¹ sr⁻¹ GeV⁻²)

$E_\mu$ (GeV)
Regolith shower: Signal

- **Target:**
  - Itokawa shape (500 m length)
  - Low density (0.5 g/cm³)

- **Projectile**
  - 10 TeV proton

- **Secondaries**
  - High-energy muon penetrates interior
  - Co-linear with source

- **Details:**
  - Logarithmic time steps
  - Event generator: MCNPX
  - All particles sans electrons
  - 1 GeV cutoff
Regolith shower: Spatter

- **Target:**
  - Itokawa shape (500 m length)
  - Low density (0.5 g/cm³)

- **Projectile:**
  - 6 TeV proton

- **Secondaries:**
  - Low-energy muons emitted on the same side as the projectile

- **Details:**
  - Logarithmic time steps
  - Event generator: MCNPX
  - All particles sans electrons
  - 1 GeV cutoff
Can we separate transmitted muons from the spatter?

Detailed simulations of particle production and transport were carried out for a spherical asteroid:
- Isotropic GCR protons
- 50 m radius asteroid;
- Uniform, 0.5 g/cm³ standard rock
- Monte Carlo (FLUKA) simulations highlighted
- *We are exploring the sensitivity of results to model assumptions*

**Special case:** \( R_0 = R \) (on the surface)

\[
l(w) = 2R_0 w
\]
Muon chord lengths (FLUKA)

Signal: These traversed the sphere in a straight line.

\[ l(w) \propto w \]

All muons, detector on the surface
Muon chord lengths (FLUKA)

Muons escaping with kinetic energy > 600 MeV

Restrict the FOV (look towards center)
Particle energy distributions

Emission angles less than 30°, detector on the surface

spatter

transmitted muons

kinetic energy (GeV)

per cosmic ray proton per GeV

all
muon +/-
electron +/-
pion +/- or kaon +/-
Cerenkov Radiation – Velocity Filter

• Passage of a swift charged particle through a dielectric medium produces EM radiation
  • Radiation emitted when \( v/c = \beta > 1/n \)
  • Conical wave front, \( \cos \theta = 1/n\beta \)
  • Threshold kinetic energy:

\[
\frac{E}{m_0} > \left( \frac{1}{\sqrt{1 - 1/n^2}} - 1 \right)
\]

• Amount of EM radiation emitted at a given wavelength range is given by the Frank-Tamm formula:

\[
N = 2\pi \alpha Z^2 L \sin^2 \theta \times \left( \frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}} \right)
\]

<table>
<thead>
<tr>
<th></th>
<th>Quartz</th>
<th>Water</th>
<th>Aerogel</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>1.46</td>
<td>1.33</td>
<td>1.01</td>
</tr>
<tr>
<td>( E/m_0 ) thresh.</td>
<td>0.37</td>
<td>0.52</td>
<td>6.1</td>
</tr>
<tr>
<td>( \theta^\dagger )</td>
<td>47°</td>
<td>41°</td>
<td>8.1°</td>
</tr>
<tr>
<td>( \sin^2 \theta^\dagger )</td>
<td>0.53</td>
<td>0.43</td>
<td>0.02</td>
</tr>
<tr>
<td>( N/L ) (cm(^{-1}))( ^\ddagger )</td>
<td>320</td>
<td>260</td>
<td>12</td>
</tr>
</tbody>
</table>

\(^\dagger \beta=1 \quad ^\ddagger 300-500 \text{ nm for } \beta=1\)
Candidate materials

- Gas or aerogel provide required threshold $\beta$
  - Could be incorporated into tracking planes
  - Up-down discrimination may be limited by Rayleigh scattering

- Fused silica (quartz)
  - Easy to work with
  - Good candidate for tracking planes
  - Up-down discrimination
  - Rejects low velocity particles

Aerogel tile
- $1.010 < n < 1.012$
- Aspen Aerogels

Quartz
- $n = 1.46$

$n = 1.46$
Particle velocity distributions

Emission angles less than 30°

$n = 1.01 \times 10^4$

Electrons cannot be suppressed using a velocity filter.
Coarse requirements:
- High $\beta$ filter
- Up-down discrimination
  - Direction of Cerenkov light
  - Timing
- Scattering medium for electrons
  - # of radiation lengths TBD
  - At least three tracking planes
- Wide area
  - A few $m^2$-steradian etendue
Beyond NIAC

A prototype hodoscope could be tested on the International Space Station (ISS) or on balloon flights.

AMS-1 image of the MIR space station using secondary $\pi^-$ and $\mu^-$ emissions
Pilot Mission

• Target: < 1 km asteroid observable by ground-based radar

• Payload
  • Muon telescope, up to 1 m²
  • Shape data from camera or laser altimetry
  • Optional radar system
  • 3-6 months in close proximity to target

Radar observations constrain surface density and, consequently, muon production

The Fresnel reflectivity is a measure of the bulk density (relative) in the top about $2\pi$ wavelengths.

Spacecraft-based 12-cm wavelength systems have been flight-tested (Mini-RF on LRO).
Pilot Mission

- Target: < 1 km asteroid observable by ground-based radar
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JAXA/Hayabusa
Phobos via Mars’ atmosphere?

• High angular flux of atmospheric muons expected at Phobos
• May enable characterization/imaging of large surface features

Miyamoto, H. et al. (2016), LPSC #1684.
Deep mapping summary

• Muon imaging is a promising method for probing asteroid & comet interiors:
  • Sensitive to bulk density & macroporosity
  • Spatial resolution depends on integration time and contrast

• Potentially powerful tool for planetary science, defense, and in situ resource utilization

• We have identified potential limiting factors & strategies for mitigation

• We will identify prospective targets and document science goals & requirements for instruments and operations for future missions