Deep Mapping of Small Solar System Bodies with Galactic Cosmic Ray Secondary Particle Showers

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Large

Planets, dwarf planets, large moons and asteroids

Jupiter by Cassini
Earthrise by Apollo 8
Vesta by Dawn

Solar system graphics by T. Prettyman; Images courtesy NASA.
Asteroids, meteoroids, comets, moons of Mars, less than a few tens of km in scale.

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

Solar system graphics by T. Prettyman; Images courtesy NASA.
Delivery mechanism for achondritic (HED) meteorites

Vesta
Vestoids

3:1
e.g., Binzel and Xu 1993; Vilas et al. 2000; Burbine et al. 2001; Moskovitz et al. 2010

Rheasilvia
(e.g. Jaumann et al. 2012)

A recent basin-forming impact (~1 Ga) launched many km-sized objects from Vesta, forming the Vesta dynamical family.

Chips off these “Vestoids” migrate to nearby resonances (e.g. 3:1) and are deflected into Earth-crossing orbits.
Meteors and Meteorites

Chelyabinsk ~20 m diameter, 500 kT (low end of Torino Scale)
Beauty is only skin deep

• What if we could peer inside a small asteroid or comet?

• At present, internal structure of small bodies must be inferred from surface morphology and other observations.
  – Methods to directly image the interior of these objects are sought.

• Information on the porosity, density distribution and internal structure of comets and small asteroids would provide powerful constraints on their formation, evolution and impact history.
  – For example, physical processes within cometary nuclei (venting mechanisms & transport of volatiles within their interiors) are poorly understood.

• This information would also be useful in developing planetary defense strategies and for in situ resource utilization (ISRU) (e.g. OH/H₂O, Fe-Ni).
Comets

81P/Wild 2 (NASA/Stardust, 2004)

Rubble-pile: One of several hypotheses for the structure of cometary nuclei. Artist’s conception from Weissman & Lowry (2008).

Tidal disruption of Shoemaker-Levy 9 (NASA/HST) supports the “rubble pile” hypothesis (Weissman & Lowry, 2008).
Our Concept

• Planetary surfaces and atmospheres are exposed to a steady rain of high energy particles (baryons), known as Galactic Cosmic Rays (GCRs).

• A shower of secondary particles (hadrons and leptons) is produced when GCRs interact with nuclei near the surface.

• Muons, leptons produced in hadronic showers, can penetrate km-scale structures.

• The interiors of small bodies and surface structures could be mapped with high spatial resolution using a muon telescope (hodoscope) deployed in close proximity (in situ or from orbit).
\( \gamma \) continuum \((Z, A)\)

Galactic Cosmic Ray

Discrete \( \gamma \)-rays (O, Mg, Si, Fe) and \( \gamma \) continuum \((Z, A)\)

\( \gamma \) continuum

\( (n,n' \gamma) \)

Radioelements

\( \Sigma_{\text{eff}} \)

H, A, \( \Sigma_{\text{eff}} \)

Radioelements

H, A, \( \Sigma_{\text{eff}} \)

Electromagnetic

Mesonic

Nucleonic \( \rightarrow \) Electromagnetic

\( \mu^\pm \) (muons) can penetrate to km depths

Samples decimeter to meter depths
Project sub-theme: Have we overlooked any signatures that would inform us of the composition and subsurface structure of planetary surfaces?
Muon radiography & tomography

“Muonography”

Asteroid Itokawa (JAXA/Hyabusa)

1. Galactic cosmic ray primary
2. Initial direction of high-energy muon (μ⁻)
3. Exit direction
4. Detection by orbiting particle telescope

Muons can penetrate large distances through rock, while undergoing minimal deflection by multiple coulomb scattering.

Graph showing range and θ₀ versus muon kinetic energy.
Muons produced in extended air showers have been used to map the interior of large structures on Earth.

**Challenges for space applications:**

- Is the production rate of muons in solid surfaces and thin atmospheres sufficient to meet imaging requirements?

- Can muons be separately measured from other particles in the space environment by a telescope that can be deployed on a planetary mission?

- For airless bodies, can interior structures be separated from surface features?

Internal structure of Satsuma-Iojima volcano using a 1 m² muon telescope (Tanaka et al., 2010) – “Muonography”
Tanaka et al. (2010) demonstrated a transportable muonography system for geology on Earth.
AMS-1 image of the MIR space station using secondary $\pi^-$ and $\mu^-$ emissions

Alpha Magnetic Spectrometer 1
From Aguilar et al. (2008) NIM-B.
Technical Approach

• Use high energy physics codes (e.g. FLUKA & MCNPX), analytical models and scaling relationships to estimate the production rate of secondary particles, such as muons, in regolith materials.
  ➢ Validate the codes against experimental data for extended air showers.

• Investigate concepts for space-based muon hodoscopes.

• Simulate muon radiographic imaging and tomography of small airless bodies.
Muon flux at sea level

Vertical intensity (cm$^2$ s sr GeV/c)$^{-1}$

- Experiment - Allkofer et al. (1971)
- Analytic calculation - Lipari (1993)

Muon momentum (GeV/c)
Muon flux at sea level

Vertical intensity (cm² s sr GeV/c⁻¹)

Muon momentum (GeV/c)
Muons subsequently decay, e.g.
\[ \mu^- \rightarrow e^- + \bar{\nu}_e \]
Prompt muons are also made by short-lived, charmed hadrons: \( D^\pm, D^0, \bar{D}^0, \Lambda_c^+ \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Decay length ( c\tau ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^\pm )</td>
<td>( 6.6 \times 10^4 )</td>
</tr>
<tr>
<td>( \pi^\pm )</td>
<td>780</td>
</tr>
<tr>
<td>( K^\pm )</td>
<td>371</td>
</tr>
<tr>
<td>( D^\pm )</td>
<td>0.028</td>
</tr>
</tbody>
</table>
Muon flux at sea level

Muon production is a balance between meson collisional losses and decay.

$\phi(E) = aE^k \left[ \frac{A_{\pi}}{1 + B_{\pi} E/\varepsilon_\pi} + \ldots \right]$  

$E/\varepsilon_\pi \propto d_\pi = \rho \gamma c \tau_\pi$

Density scaling

Decay length (g/cm²)
Muon flux at sea level and in rock

$\pi, K$ muon flux at $\sim 1000 \text{ g/cm}^2$ depth in a solid ($\rho = 1.6 \text{ g/cm}^3$)

4000×

Vertical intensity (cm$^2$ s sr GeV/c)$^{-1}$

Muon momentum (GeV/c)
Muon flux at sea level and in rock

Prompt muons from the decay of charmed mesons (isotropic flux)

- Experiment - Allkofer et al. (1971)
- Analytic calculation - Lipari (1993)
- Gaisser cascade model (1990)
- Gaisser's model scaled to rock - this study
- Prompt muons - Bugaev et al. (1998)
A. Muons > 0.1 TeV punch through (muons in this range are insensitive to density variations; other particles are “filtered out”)

B. The muon leakage current is sensitive to intervening materials
Contrast Sensitivity

1 m² hodoscope (1.8 sr)

800 m diameter asteroid with a 400 m diameter inclusion

\[ \mu_{\text{out}} \]

\[ \mu_{\text{in}} \]

\[ \rho \]

\[ \rho_i = 0.5 \text{ g/cm}^3 \]

\[ \rho_i = 3.6 \text{ g/cm}^3 \]

\[ \cos \theta \]

Counts/m²/day

Bulk asteroid

Inclusion

\[ \cos \theta \]

Incident cos \( \theta \)
The signal is the change in counts in the ROI relative to that expected for a homogeneous asteroid:

\[ \text{Signal} = \frac{\text{Counts}_{\text{ROI}} - \text{Counts}_{\text{Ref}}}{\text{Counts}_{\text{Ref}}} \]

The 3\(\sigma\) Poisson detection limit can be expressed in terms of mean counting rates:

\[ Time > \frac{9 \times \text{Rate}_{\text{ROI}}}{(\text{Rate}_{\text{ROI}} - \text{Rate}_{\text{Ref}})^2} \]

Bulk asteroid

Inclusion

\(\rho_i = 0.5 \text{ g/cm}^3\)

\(\rho_i = 3.6 \text{ g/cm}^3\)

Region of interest (ROI)
An comet or asteroid may have high density contrast:

- Silicate regolith surrounding a icy interior (comet)
- Fe-rich region within in a rubble-pile asteroid
How about a very small body?

- 50 m diameter
- $\pi$, K muons greater than 10 GeV are comparatively abundant and can penetrate the asteroid
- Detection limit decreases
Conclusions

- **Estimates of muon production in solids indicate long integration times for muonography of asteroids and comets; however,**
  - A search for *high contrast* interior regions might be feasible for objects with 100 m to 1 km diameters using muons produced by charmed mesons (>100 GeV)
  - Very small bodies (10- to 100-m) or surface features would likely be accessible by K, π muons, which are more abundant at low energies (10- to 100-GeV)
  - An assessment of muon production as a function of regolith density and composition is in progress

- **The complexity of the hodoscope would depend on deployment**
  - A magnetic spectrometer with active shielding is probably needed for measurements in space
  - A sub-surface spectrometer might be similar to those used on Earth

- **Prospective applications are numerous, but include determining the macroporosity of small asteroids for planetary defense and searching for hydrous inclusions in asteroids for ISRU**

- **Prompt production by charmed mesons may dominate the high-energy muon flux in solid surfaces**
  - The absence of π, K muons on asteroids may enable the detection of this so far elusive, charmed component
  - A cosmic ray observatory on a small asteroid could provide additional data needed to advance our knowledge of cosmic rays and fundamental nuclear physics