Microgravity Geology: A New Challenge for Human and Robotic Space Exploration

February 20th, 2013
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Near Earth Objects: Itokawa vs. 1999 JU3 at a Glance

(162723) 1999 JU3 (C)

(25143) Itokawa (S)

~870 m

Earth Crossing Orbits

Mars

Earth

1999 JU3

International Space Station

(Collage Courtesy: P. Lee, 2006)

(Model Courtesy: Kaasalainen, et al., 2008)
What You Need for Asteroid Mining: A Typical Case Proposed by Planetary Resources Corp.

1. Survey
2. In-situ Remote Sensing
3. **Internal Structure** (e.g., Interceptor)
4. **Landing and Mining**
5. Transportation
Asteroid Interior Investigation Techniques Sorted by Depths & Resolutions

- Vesta Crater Exploration
- Family Asteroid Exploration
  - Radar Sounder /Tomography
  - Seismic Network
  - Boulder & Groove Rover *In-situ*
  - Fixed Lander *In-situ*
  - Sample Return (Core Boring)
  - Sample Return (Regolith)
  - In-Situ Microscopic Camera
  - Micro-tomography

To better-understand internal structure of undifferentiated minor body
Key Questions for Technology and Operation for Small Body Mining

How to Reach
How to Descend
How to Land
How to Anchor
How to Excavate
How to Contain
How to Examine
How to Ascend
How to Return

“Know Your Enemy”
= Microgravity Geology
“Chicks” of Hayabusa:
Sample Return Missions to sub-km~km Sized Bodies

Hayabusa
Itokawa = S type
(1996~/2003-10)

Hayabusa-2
1999 JU3 = C type
Lessons Learned from Hayabusa
(2010~/2014-20)

Hayabusa Mk-II
D type, Dormant comet
Advanced, Full Model-change
(Mid 2010’s~/Early 2020’s)

Post Hayabusa Series

OSIRIS-REx
1999 RQ36 = B type
New Frontier Class
(2016-23)

Marco Polo-R
1999 FG3 = C type
Cosmic Vision-M
(2022-29)

Main Asteroid Belt

S type
C type
D type

Ordinary Chondrites
Carbonaceous Chondrites

IDP, AMMs, Tagish Lake?
Microgravity Geology, a New Research Field of Solar System Science and Engineering

• Current planetary system formation theory has a “black box” in the intermediate state between dust-to-dust aggregation (e.g., Mukai, et al., Blum, et al.,) and planetesimal growth/disruption (e.g., Kokubo, et al., Michel, et al.) that are never able to learn from exploration of large, differentiated bodies.

• Yet, no one had witnessed geological evolution of small planetesimals or equivalent, until Hayabusa’s in-depth exploration of Itokawa, a sub-km rubble pile asteroid.

• Geological features of Itokawa surprised us about both similarities and differences from larger asteroids like Eros and much larger satellites/planets.
Microgravity Geology, a New Research Field of Solar System Science and Engineering

• Apparent similarities between Itokawa and the Earth (and Mars) are not necessarily due to the same geological processes as the terrestrial geology largely affected by the presence of water in atmosphere, surface and underground, let alone five orders of magnitude difference of G-levels.

➤ Thus, a need to create a new research field of “Microgravity Geology” is clear, in order to understand the missing link of the planetary evolution processes, as well as better preparation for future robotic and human exploration of such microgravity bodies, such as off-earth mining.

➤ Such knowledge can also be beneficial to natural disaster management on the Earth for better understanding of their triggering mechanisms.
Research Theme Flow of “Microgravity Geology”

Theme-1: Geological Data Analysis on Microgravity Body

Theme-2: 1G Impact Tests/ Elastic Wave Measurements

Theme-3: Microgravity Impact Tests

Theme-4: Microgravity Granular Convection

Theme-5: Microgravity Geological Activity Simulation

Theme-6: Physical Models of Microgravity Geology

“Microgravity Geology”
(New Research Field of Solar System Science and Engineering)
Main Focuses of Microgravity Geology Experimental Research

<Understanding Physical Processes>

(1) Impacts (Gravity-strength regime scaling, Ejecta redistribution, Low density/weak strength monolithic targets vs. granular targets, etc.)

(2) Vibration (Wave propagation, seismic efficiency, diffusivity, quality factor, etc. in regolith and low density targets)

(3) Granular Mobility (Brazil Nuts effect, granular convection, dust levitation, surface mobility, non-gravitational activities such as cometary gas release, etc.)

Also investigate other internal/external forces than impacts such as Centrifugal force, YORP, tides, etc.)

<Applications to Small Body Exploration>

- Development of sampling system and landers for Hayabusa follow-on missions
Understand Geological Features in Microgravity
Terrestrial Geological Features: 
Governed by Gravity, Heat, Air and Water

- Boulder Terrain
- Landslides
- Sand Pond
- Gravel Field
- Breccia
Asteroidal Geological Features:Mainly due to Impacts and Vibrations in Vacuum and Microgravity

- Boulder Terrain (Itokawa)
- Landslides (Eros)
- Fine Regolith Pond (Eros)
- Breccia (Itokawa)
- Gravel Field (Itokawa)

⇒ How to form apparently similar geological features to the Earth?
⇒ What these similarities and differences tell us about asteroid evolution?
Internal Structure Implied by Rotational Periods and Sizes

Barrier at the rotation rate where a strengthless body would fling itself apart

(Pravec et al. 2002)
## Thermal Inertia vs. Surface Condition

<table>
<thead>
<tr>
<th>Thermal Inertia: G [J m(^{-2}) s(^{-0.5}) K(^{-1})]</th>
<th>Surface Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 10</td>
<td>Very fluffy, high porosity (~80%), Ceres, Martian soils</td>
</tr>
<tr>
<td>~ 50</td>
<td>Fine sand: Lunar regolith (d ~ 100 mm or less)</td>
</tr>
<tr>
<td>100 ~ 200</td>
<td>Sandy regolith (d ~mm): Eros’ Pond</td>
</tr>
<tr>
<td>200 ~ 400</td>
<td>Pebbles (d ~cm): Itokawa’s Muses-Sea Regio</td>
</tr>
<tr>
<td>400 ~ 1000</td>
<td>Boulders, Rock fragments (d &lt; m): Itokawa’s rough terrain</td>
</tr>
<tr>
<td>1000 ~ 2000</td>
<td>Rocks with high porosity</td>
</tr>
<tr>
<td>2000 ~</td>
<td>Monolithic rocks</td>
</tr>
</tbody>
</table>

Thermal inertia gives information about the presence (or absence), depth and thickness of regolith, and the presence of exposed rocks on the surface of atmosphere-less bodies (\(\Gamma\) in SI units: J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\)).

![Diagram showing thermal inertia for different bodies](image)
Compressive Strength Measurement of Sub-mm Meteorite Powders

5×10 mm Compressive Strength

TL: Tagish Lake
carb -r: carbonate-rich
carb -p: carbonate-poor

(Miura, Tsuchiyama, Noguchi and Yano, 2008)
C-type Asteroid Analog Targets Based upon Meteorite Measurements

Monolith  Gravels (Coarse Regolith)  Fine Regolith
# Grain Target Comparison with Asteroids

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Itokawa (S-type)</th>
<th>Eros (S-type)</th>
<th>Mathilde (C-type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
<td>1.9 g/cm³</td>
<td>2.4 g/cm³</td>
<td>1.3 g/cm³</td>
</tr>
<tr>
<td>Porosity</td>
<td>~40 %</td>
<td>~20 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fujiwara et al.</td>
<td>Yeomans et al.</td>
<td>Yeomans et al.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>This study</th>
<th>Glass beads f5 mm</th>
<th>Glass beads f0.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
<td>1.6 g/cm³</td>
<td>1.6 g/cm³</td>
</tr>
<tr>
<td>Porosity</td>
<td>36 %</td>
<td>36 %</td>
</tr>
</tbody>
</table>

(Makabe and Yano, 2008)
X-ray Tomography of 3D Internal Structure of Asteroid Regolith
(Tsuchiyama, et al., Science, 2011)
Gravity-Duration Diagram
The Gravity-Duration Diagram:
Solar System Bodies in Different Gravity Level

Gravity Level (G)

Long

Short

Day-Year

Min.

Sec.

Earth

Mars

Moon

Enceladus

Ceres, Vesta

1999JU3

Gravity Level (G)
Typical Duration of Low Gravity Geological Processes

Gravity Level (G)

- Gardening, Granular Mobility
- Convection, Re-accumulation of Ejecta
- Brazil Nuts Effect, Dust Aggregate
- Granular Surface
- Mobility
- Non-G Effect, Dust Levitation
- Hypervelocity Impacts

Typical Duration of Low Gravity Geological Processes

- Earth
- Mars
- Enceladus, Ceres, Vesta
- Itohika

(Micro-G Geological Phenomena)
Human-tended Test Facilities for Microgravity

- **Sub-Orbital**
  - 3~5 min.
  - $10^{-3} \sim 10^{-4}$
  - 2 wk~1 yr
    - $(10^{-3} \sim 10^{-5})$
  - 1~2 wks
    - $(10^{-3} \sim 10^{-3})$
- **Parabolic Flights**
  - 20~30 sec.
    - $(1/4 \sim 10^{-2})$
- **ISS**
- **Soyuz**

**Gravity Level (G)**
- Long
  - Gardening,
  - Granular
  - Convection,
  - Re-accumulation of Ejecta
- Short
  - Brazil Nuts Effect
  - Dust Aggregate
  - Granular Surface
  - Mobility
  - Non-G Effect,
  - Dust Levitation
  - Hypervelocity Impacts

**Human-Tended Test Facilities for Microgravity**

- Earth
- Mars
- Ceres, Vesta
- 1999JU3
- **ISS**
- **Soyuz**
- Sub-Orbital
  - 3.5 min.
    - $(10^{-3} \sim 10^{-3})$

**Human-Tended**
Unmanned Test Facilities for Microgravity

- **Expendable Sounding Rockets**: 5-10 min. ($10^{-3}$ to $10^{-5}$)
- **Reusable Sounding Rockets**: 1 wk-1 yr ($10^{-4}$ to $10^{-6}$)
- **Retrievable Free Flyers**: 1 wk-1 yr ($10^{-4}$ to $10^{-6}$)
- **Sub-Orbital**: 3-5 min. ($10^{-3}$ to $10^{-2}$)
- **Catapult-mode Drop Tower**: 4.5-9 sec ($10^{-5}$)
- **Small Tower**: 2 sec ($10^{-3}$)
- **Balloon Capsule**: ~30 sec ($10^{-4}$)
- **Parabolic Flights**: 20-30 sec. (1/4 to $10^{-2}$)
- **Gravity Level (G)**: Long, Short
- **Gardening, Granular Convection, Re-accumulation of Ejecta**
- **Brazil Nuts Effect, Dust Aggregate Mobility**
- **Non-G Effect, Dust Levitation Hypervelocity Impacts**
- **ISS, Soyuz, Re entries, Voyagers, 1999JU3, Balloon Capsule**
**Summary of the Microgravity Geology Experiments**

- **Expendable Reusable Sounding Rockets**
  - 5-10 min.
  - $(10^{-4} - 10^{-5})$

- **Sub-Orbital Sounding Rockets**
  - 3-5 min.
  - $(10^{-4} - 10^{-5})$

- **Balloon Capsule**
  - 20-30 sec.
  - $(1/4 - 10^{-2})$

- **Catapult-mode Drop Tower**
  - 4.5-9 sec.
  - $(10^{-5})$

- **Retrievable Free Flyers**
  - 1 wk-1 yr
  - $(10^{-5} - 10^{-6})$

- **Small Tower**
  - 2 sec.
  - $(10^{-3})$

- **ISS**
  - 2 wk-1 yr
  - $(10^{-3} - 10^{-5})$

- **Soyuz**
  - 1-2 wks
  - $(10^{-3} - 10^{-2})$

- **Parabolic Flights**
  - ~30 sec.
  - $(10^{-4})$

- **Gravitational Level (G)**
  - **Human-Tended**
  - **Unmanned**

- **Gravity Level (G)**
  - **Micro-G**
  - **Geological Phenomena**

*Plus counter-mass/low friction stages and underwater analog sites for longer duration*
Examples of Past and Current Efforts:
Science
High and Slow Velocity Impacts

- Smaller and slower impacts studied by Blum, Colwell, etc.
- Hypergravity impact experiments extrapolated to microgravity ranges by Housen & Holsapple

<Major Issues>

• **Disruption ~ Re-accumulation?**
  > Ejecta Behavior
  > Compaction Effect

• **Strength Regime vs. Gravity Regime for Cratering**
  > Revisit the Impact Scaling Laws
  > New Dominant Forces in Microgravity?

• **Computer Simulation** (Hydrocodes, DEM)

• **Improve Impact Experiment Apparatus**
  > Vacuum Level, Dry Powders/Grains
  > Microgravity Level and Duration
  > High Speed Imagery

• **Sampling Device Development**
Simulations of asteroid disruptions suggest that objects >100 m are rubble piles
Michel et al., *Science* (2001)

Impact energies and outcome depend strongly on internal structure of asteroids

“What Is the Boundary between Impact Disruption and Aggregation?: Structure, Size, Material

“Survival of the Weakest”: Asphaug, Scientific American
MGLAB at Toki, Japan
(4.5 sec. of $10^{-5}$ G…. until 2010.)
Inside the Microgravity Vacuum Chamber
High-speed Imagery of Projectile Impacts onto Glass Beads of 500 μm

Cone (90deg., 4.7g, ~11m/s)
$t = 0$ msec

Cone (150deg., 4.7g, ~11m/s)

$t = 10$ msec

$t = 20$ msec
Examples of Impact Cratering on 100-500 Micron Glass Beads in Vacuum Microgravity

Gravity-strength regime formula predicts a long expansion of a large crater in microgravity
Crater formation mostly ends in the first second during a 4.5-seconds free fall in MGLAB drop tower.
Granular Impacts in Gravity Regime without Gravity?

- How to grow an impact crater on grains in microgravity, presumably in strength regime?
- Frictional / VdW force may play an important role to determine crater size in microgravity

Micro-G crater trend matches with 1G’s, unlike the prediction of strength regime dominated cratering.

(Takagi and Yano, 2006)
Gravels on Itokawa were reallocated after depositions → *shaken globally*  
(Miyamoto et al., 2007)

No small gravels are on the surfaces of boulders  
Orientations of (larger) gravels appear to be gravitationally stable
Gravel migrations in rough terrains are evidenced by a range of morphological characteristics similar to terrestrial landslides:
- Piles of gravels exclusively on the uphill sides
- Boulder alignments / Imbrications of boulders

(Miyamoto, Yano, et al., Science, 2007)
Image-Model Comparison of Granular Flow and Surface Potential on Itokawa

* Images indicating directions of surface mobility

* Potential vectors match with granular flow images
How the Interior Might Affect Surface Morphology

Boulders Inside

Powder Inside

(Modified from Miyamoto et al., 2007)

Fractured Monolith

Grains
The only suspicious case: a boulder might be missing

(Miyamoto et al., 2009)
Experimental Work on Wave Attenuation inside Regolith and Porous Materials

- How effectively can impact energy contribute to global and local mobility of surface materials?
- What can we learn about sub-surface, internal structure of rubble piles and regolith layers?

(Teramoto & Yano, 2005)
Brazil Nuts Experimental Work: Granular Behaviors in Variable Gravity

- Parabolic flight by GS-II (1G=> 2G=> micro-G=> 2G=>1G) proved that granular convection speed greatly varied with gravity level

- Currently following up in 1G, 1-axis vibration experiments with computer simulation

(Yano and Makabe, 2007, Miwa, 2009)
Dust Levitation

- A few lunar studies
- Recently revisited by Lee et al. for asteroids and Martian satellites
- Chou et al. started vacuum chamber plasma sputtering to lunar regolith

<Major Issues>
- Discover the Evidences
- Understanding Its Mechanism and Conditions
- Simulate in Laboratories
- Evaluate Macro-scale, Geological Effects
- Spacecraft / Lander Safety Assessment
Numerical Simulation of Levitation Dust

(Scheeres, et al., 2010)

Test Particle Size (micron)

FBS Detection Height

Initial Launch Velocity (m/s)

Equilibrium Height (m)

3-13 m

1 micron

10 micron

3 micron at 0-1.2 cm/s

(Hartzell and Scheeres, 2011b)

(Colwell, et al., 2005, Senshu, et al., 2012)
Landing or Tough & Go or Blast?

Harpoon and Anchoring Legs

AMOR Concept
(T.Jones, et al.)
Phobos-Grunt :
Martian Satellite Landing & Sample Return (2011X)

Descent Firing Landing to Flat Places (Well Mapped Area)
Hayabusa-2’s Landers and Other Elements to Be Left at 1999 JU3

<Robotic Landers>
* MASCOT (to be provided by DLR) (x1)
• MINERVA-II1, 2 (x2) and their covers (x1)
⇒ Bouncing and Hopping

<Sampling Instruments>
• Target Markers (x up to 5)
⇒ Non-bouncing
• 5-g, Ta Projectiles (x up to 3)
⇒ 1-second Touch & Go

<Artificial Impact Experiments>
* Deployable Camera (DCAM) (x1)
• Small Carry-on Impactor (SCI): Metal projectile and fragments of exploded module (x1)
⇒ Self Explosive
Hayabusa’s Tough & Go

Gate Position (2005/09/12~09/27)
Home Position (09/27~10/05)
Science Tour (10/05~10/21)
Site Selection (10/28)
Touch Downs (2 Rehearsals, 1 Image Navigation Test & 2 TDs) (11/04, 09, 12, 19, 25)
Solar System Exploration
by Physical Interactions, i.e.
Impacts, Excavations, Blasts
Hayabusa-2’s New Challenge: Observe and Sample Excavated, Sub-Surface Materials by a Small Carry-on Impactor

- ~2 kg Copper Projectile
- Impact Velocity ~ 2 km/s
- Spin separation

Expected Crater Size:
D~2-3m: Autodyne Simulation
D~4 m: Takagi et al.
D~7.4 m: Housen & Holsapple
Conclusion
Microgravity Research Is a Critical Element of Small Body Research, Missions and Future Mining

< Spacecraft Data >
* Sub-km Asteroids: Itokawa, 1999 JU3, 1999 RQ36
* Large Asteroids: Eros, Phobos, Deimos, Vesta, Ceres, etc.
  • Cometary Nuclei: Halley, Tempel-1, Wild-2, Hartley-2, C-G, etc.
  • Small Satellites: Jovian Retrograde Satellites, Enceladus, etc.
  ➞ Comparative Data (High-G Bodies): Earth, Moon, Mars

< Experimental Facilities >
* Drop Tower (ZARM): 4.5-9.0 sec., 10-5 G
* Vacuum Drop Capsule (ISAS): 2 sec., 10-3 G
* Parabolic Airplane (DAS, Nove Space, Zer-G Corp, etc.): 20-30 sec., 10-2 G
* High-Altitude Balloon (ISAS): ~30 sec., 10-3~4 G
* Sounding Rocket (Reusable/Expendable) (ISAS): ~180 sec., 10-5 G
* Suborbital Flight (NASA Suborbital EX): ~180 sec., 10-5 G

< Modeling >
* Shape Model ➞ Gravitational Potential Simulation
* Micro-G Impact Hydrocodes (Autodyn 3-D, DEM), etc.