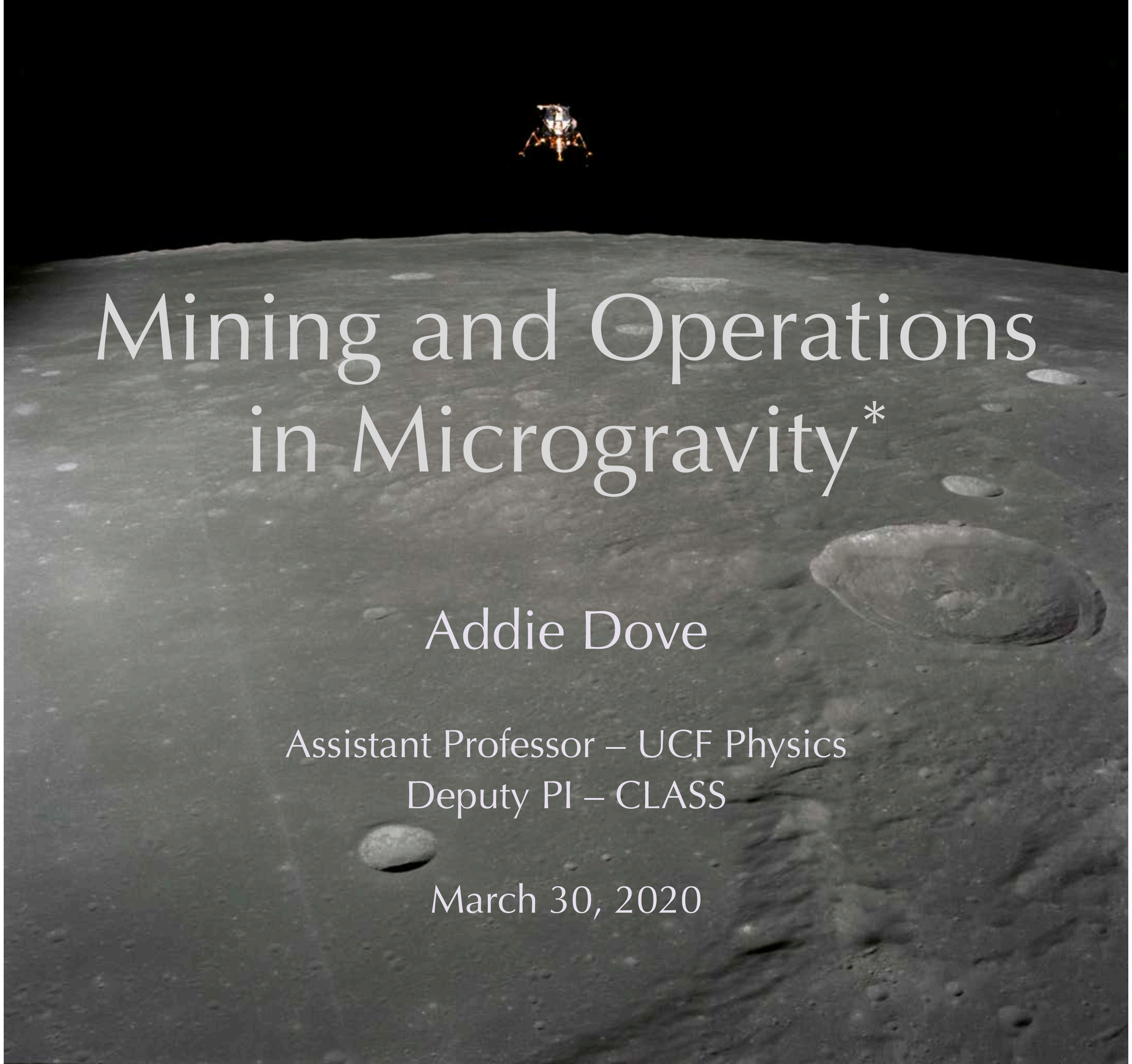


Mining and Operations in Microgravity*

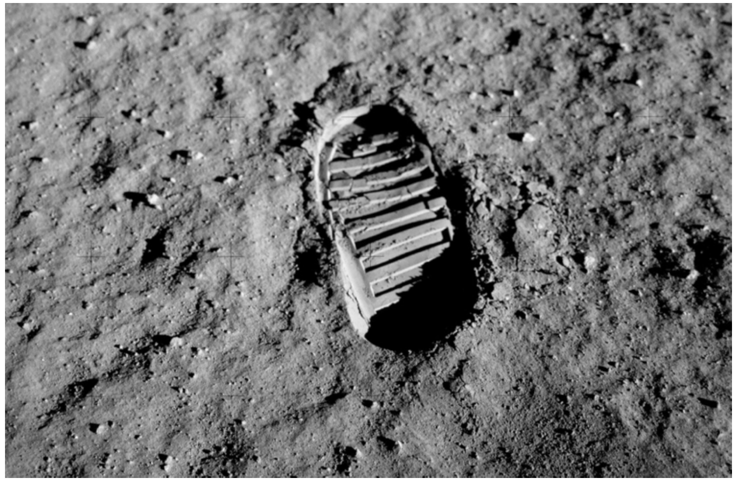
Addie Dove

Assistant Professor – UCF Physics
Deputy PI – CLASS

March 30, 2020

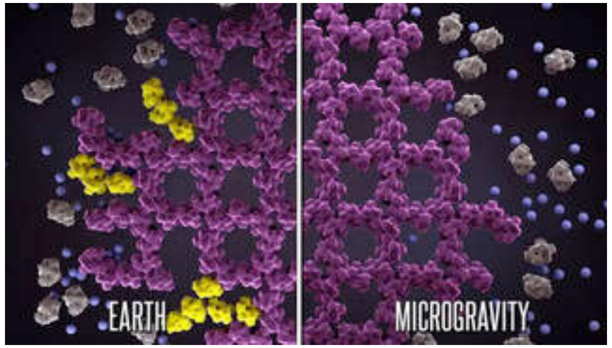
Operations in Microgravity

- What are microgravity environments?
- How does microgravity shape natural surface processes?
- How will it affect operations?
- How can we simulate microgravity, or develop realistic models to drive down risk for future operations?

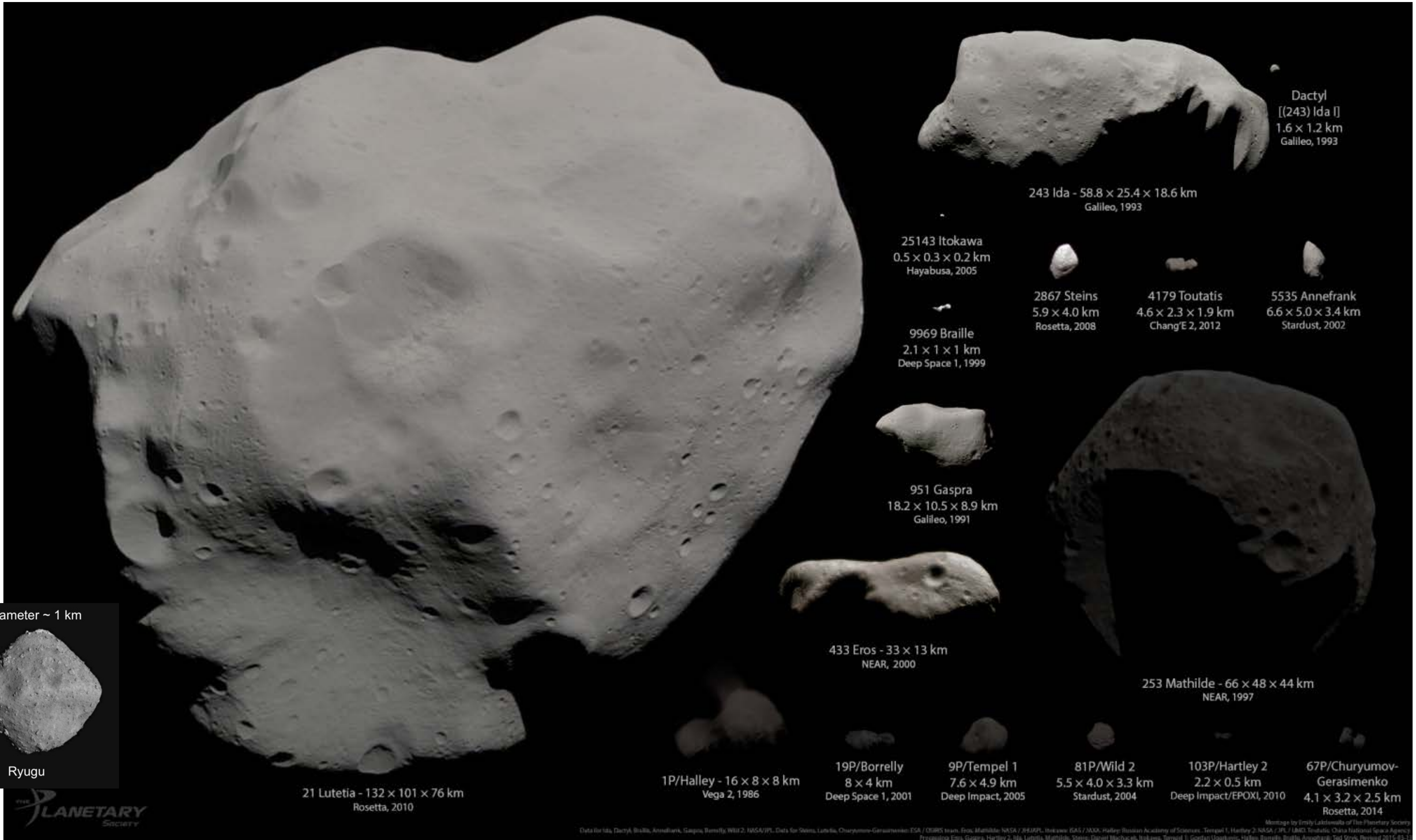


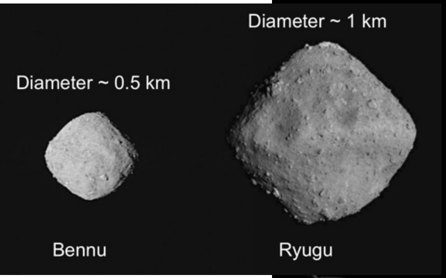
What is "microgravity"?

- Gravity levels on a planetary surface are defined by the body's physical properties, including ***size (radius/diameter)***, ***mass***, ***and density***
- "Microgravity" is often used to refer to the regime of near-weightlessness
  - Can technically refer to the gravity levels on small asteroids
  - Other low-gravity regimes are sometimes lumped in



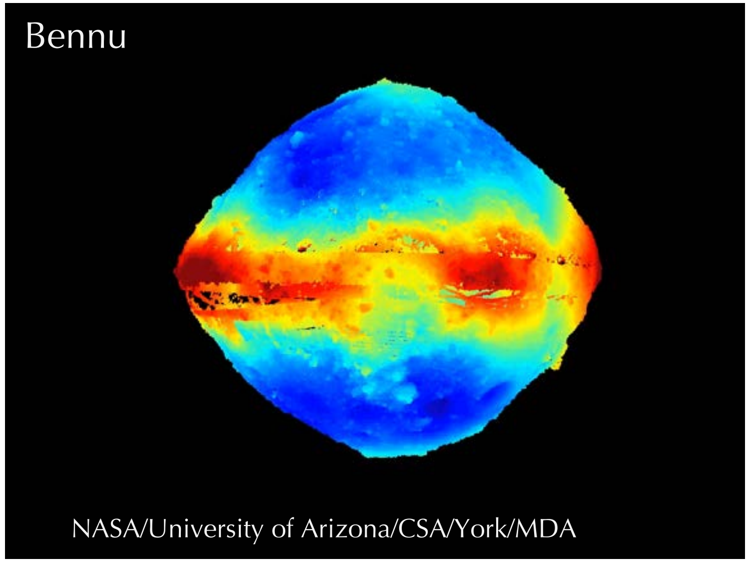
Ranges of gravity regimes



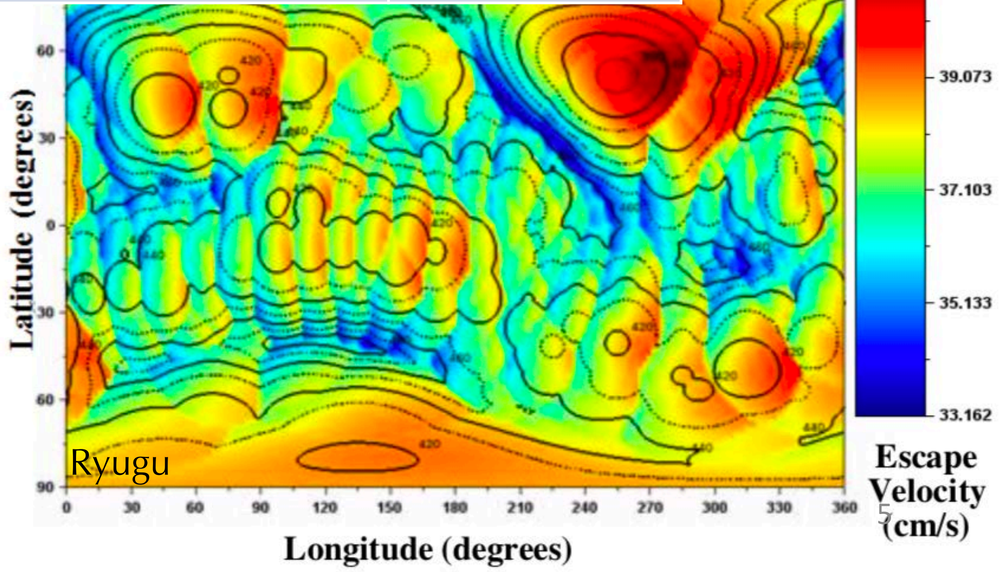


Ranges of low-gravity regimes

	Mean diameter (km)	Gravity Level (g)	Surface gravitational acceleration (m/s^2)	Escape speed
Earth	13,000 km	1 g	9.8 m/s^2	11.2 km/s
Mars	6,800 km	1/3 g	3.7 m/s^2	5.0 km/s
Moon	3500 km	1/6 g	1.6 m/s^2	2.4 km/s
(433) Eros	17 km	1/1700	0.0059 m/s^2	~10 m/s
(162173) Ryugu	.87 km	1/80,000 g	1.2×10^{-4} m/s^2	~.4 m/s
(101955) Bennu	0.5 m	1/100,000 g	~9.8×10^{-5} m/s^2	~.2 m/s
(25143) Itokawa	0.32 km	1/114,000 g	8.6×10^{-5} m/s^2	~.2 m/s



Lorda *et al.*, 2017



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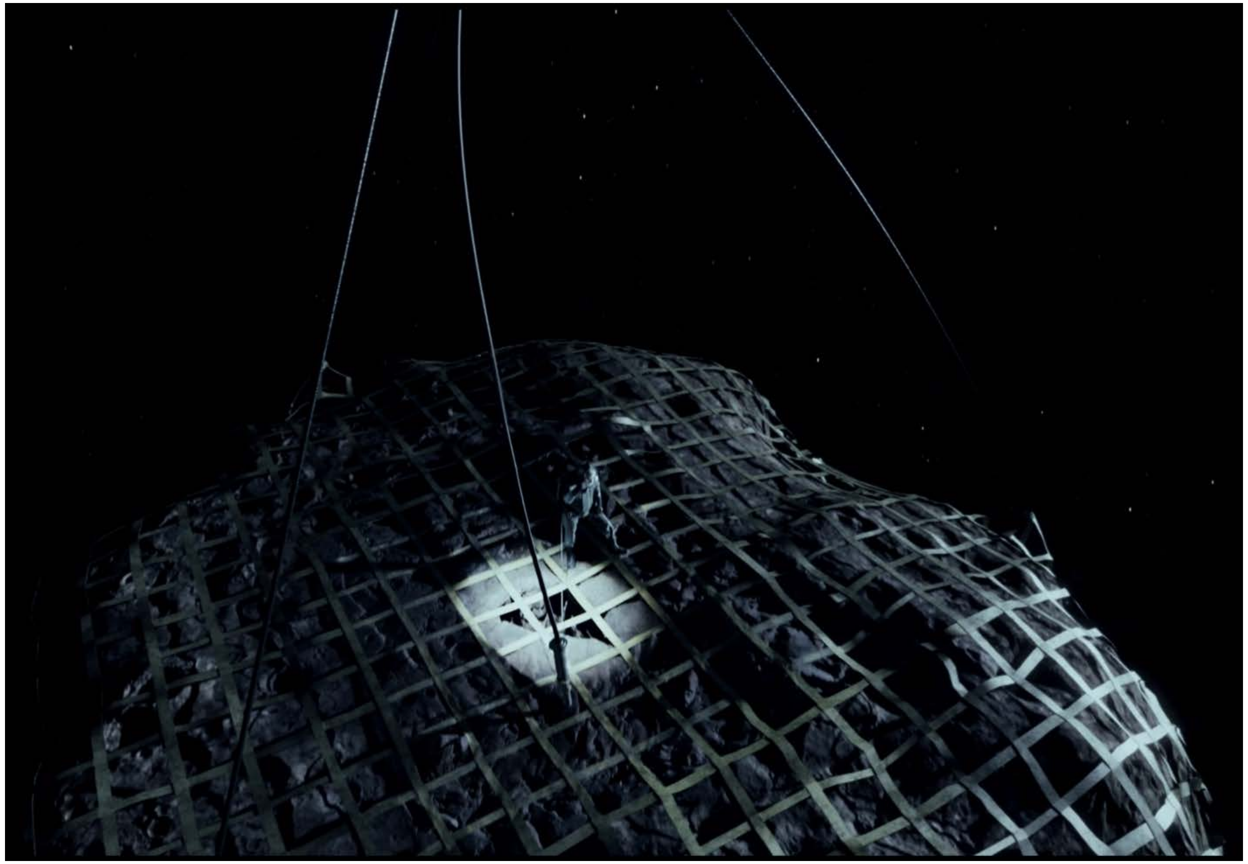
- Gravity regimes define the behavior of objects on the surface – determines the relative importance of different forces

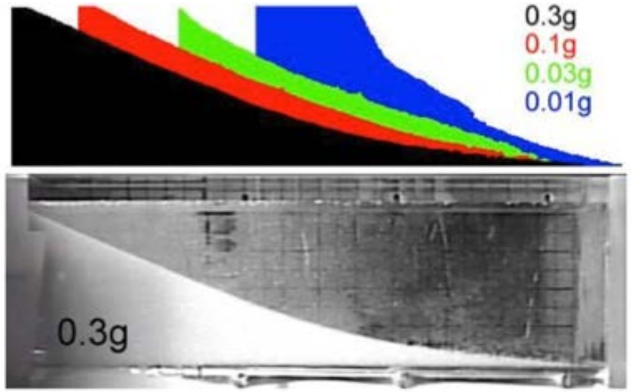
Granular mechanics and microgravity

- Low-gravity operations and granular mechanics complications are interlaced
- Develop novel anchoring/ off-loading techniques to enable surface operations
- Granular materials present and additional challenge – can also try to use these to our advantage

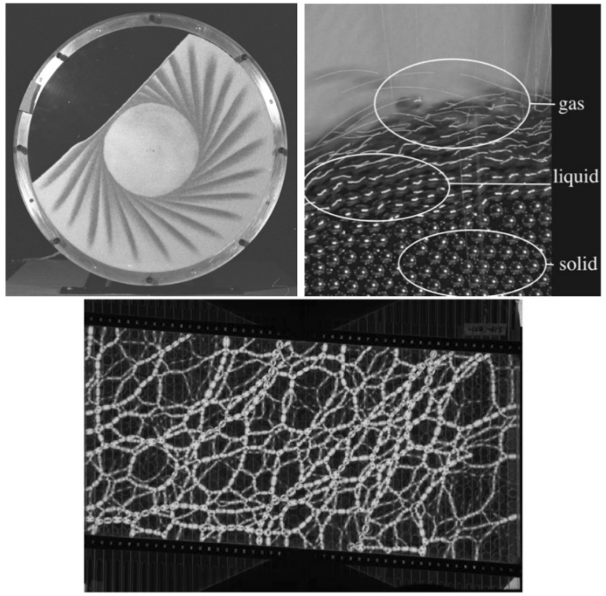


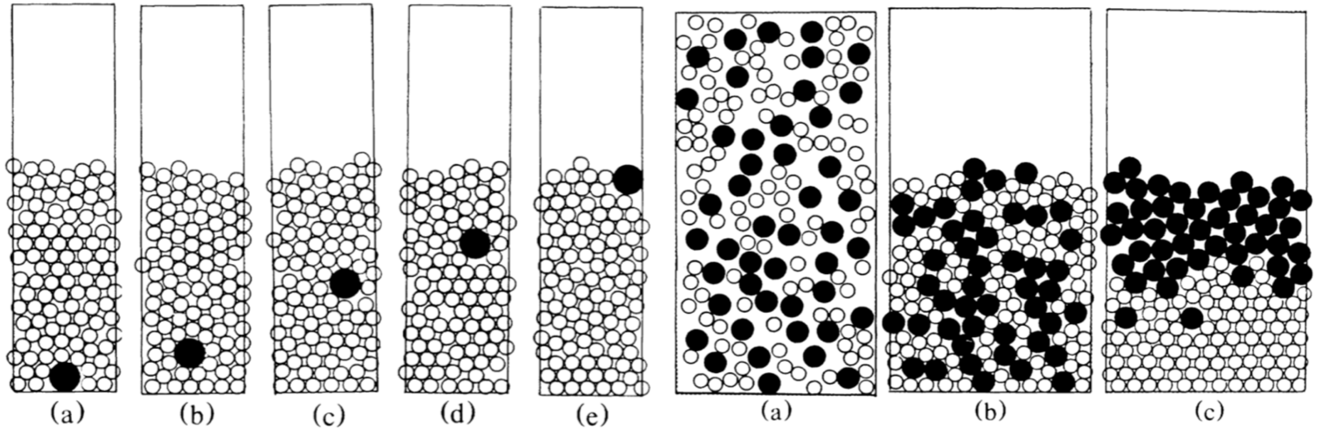
Granular mechanics in variable-g

- Consider both bulk motion and individual particle behavior
- Granular flow can transition through classical solid-liquid-gas regimes
- Scaling laws are difficult to establish
  – However, there are discrepancies between theoretical predictions, numerical simulations, and experiments
  – i.e. the dependence of avalanche behavior (timing, slopes, failure mechanisms) on gravity level



Hofmeister *et al.*, 2009



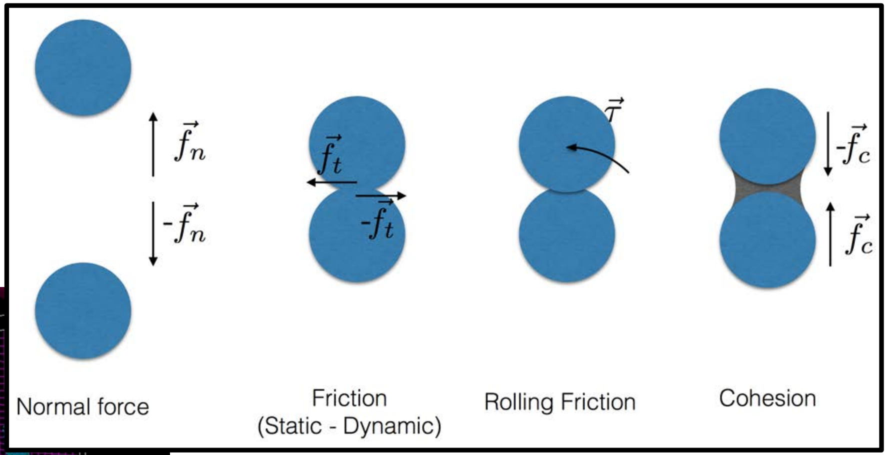


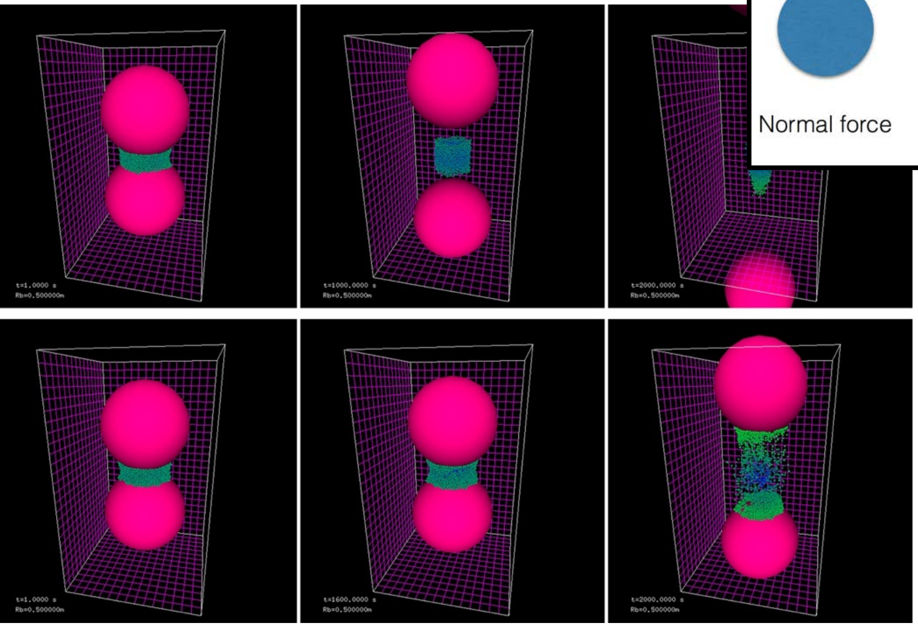
Rosato, 1987

From Murdoch *et al.*, 2015

Granular material behavior in variable-g

- Consider both bulk motion and individual particle behavior
- Different relative effects of forces in the extreme environments of other planetary surfaces
- Granular

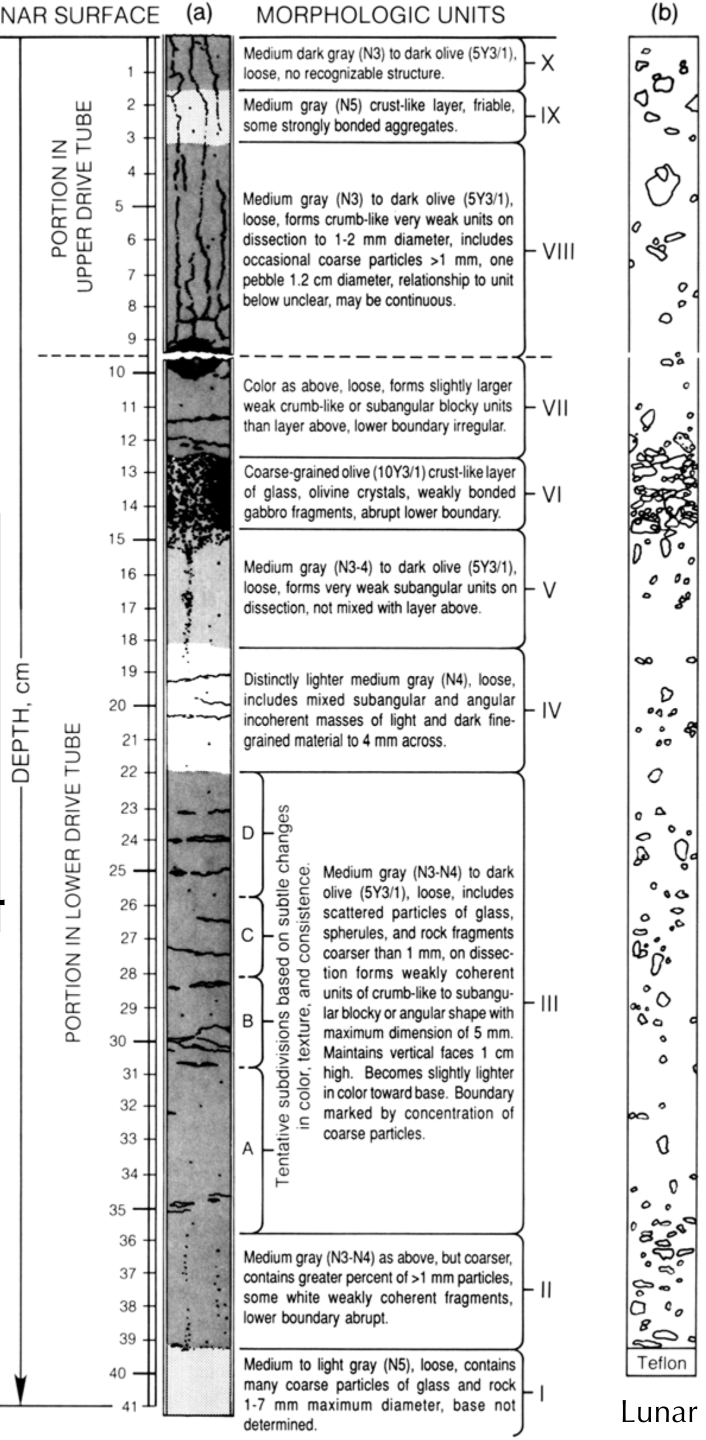




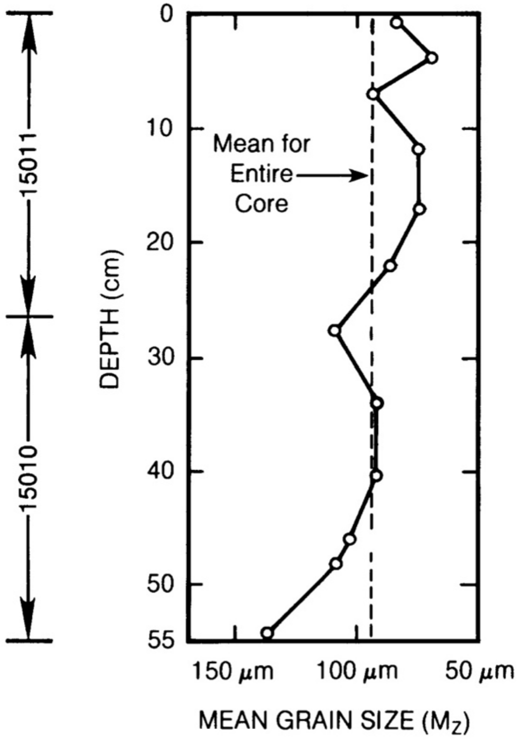
Sanchez and Scheeres

Lunar Regolith Distributions

Apollo 12 drive-tube core

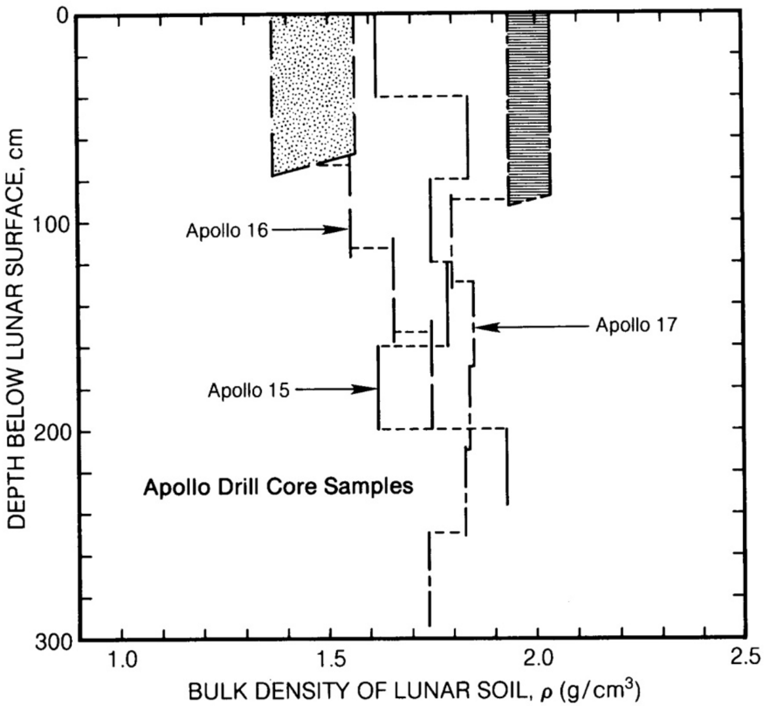


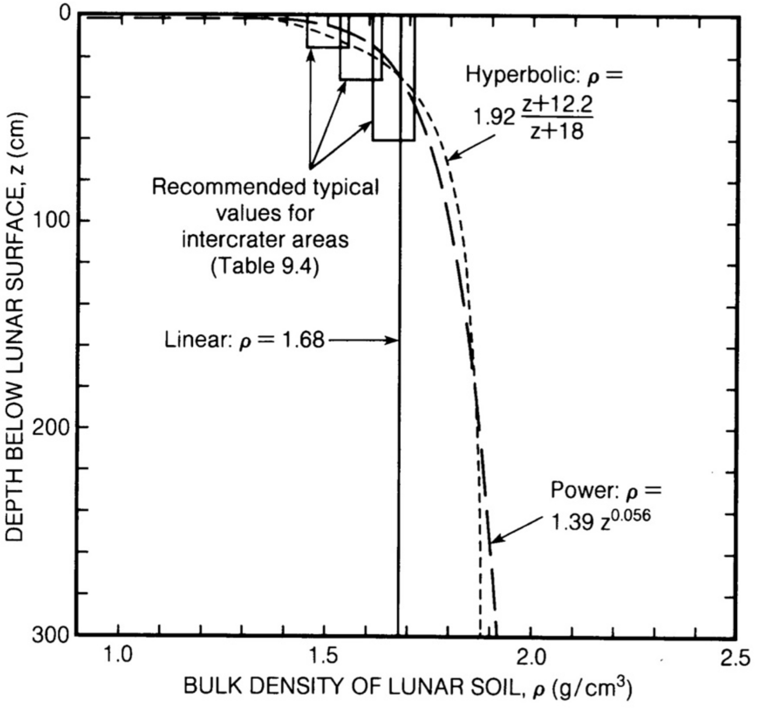
Apollo 15 drive-tube core



- Discrete layers ID-ed in all drive-tube cores, with some variation from site-to-site
- Tubes have been analyzed to determine mean* grain size with depth

Lunar Sourcebook, Ch 7



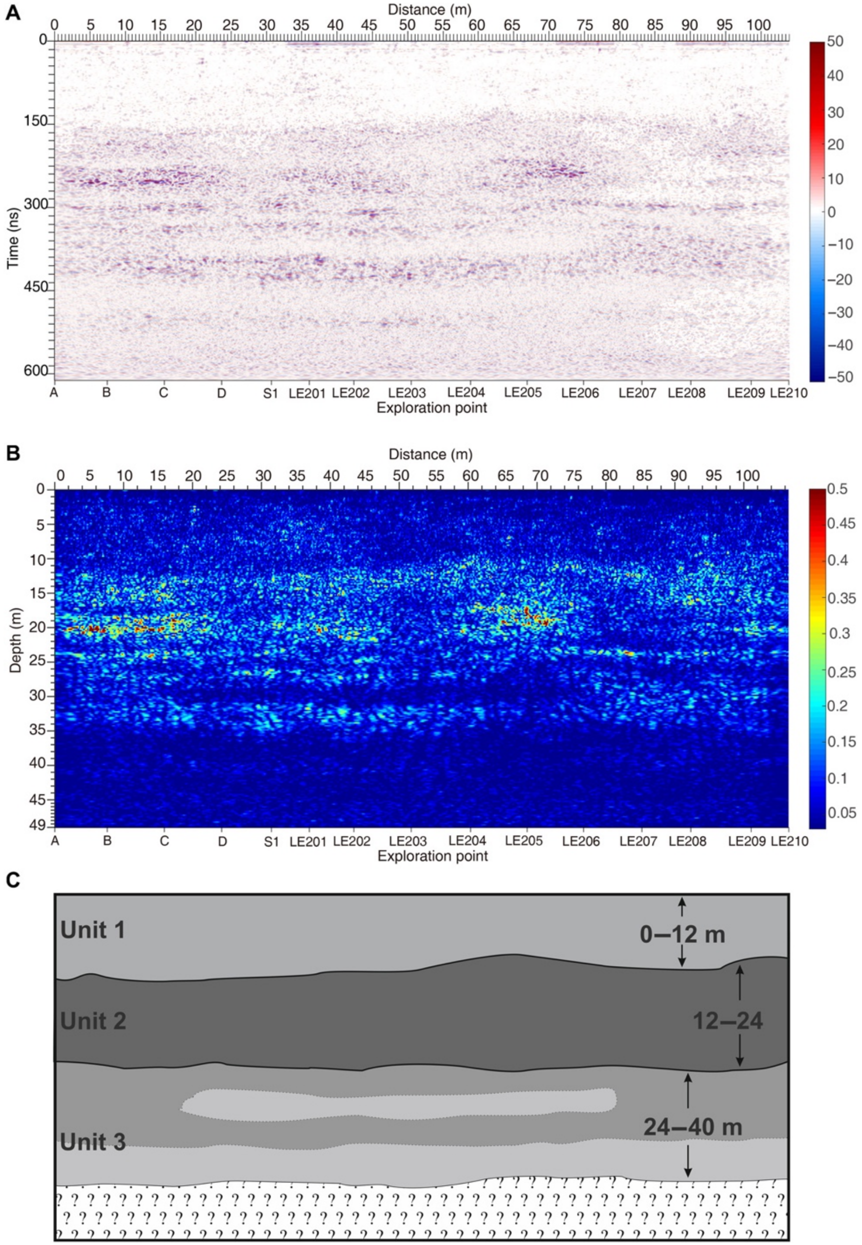


Lunar Sourcebook, Ch 9

Lunar Regolith Distributions

- Discrete layers ID-ed in all drive-tube cores, showing variation from site-to-site
- Tubes have been analyzed to determine mean* grain size with depth

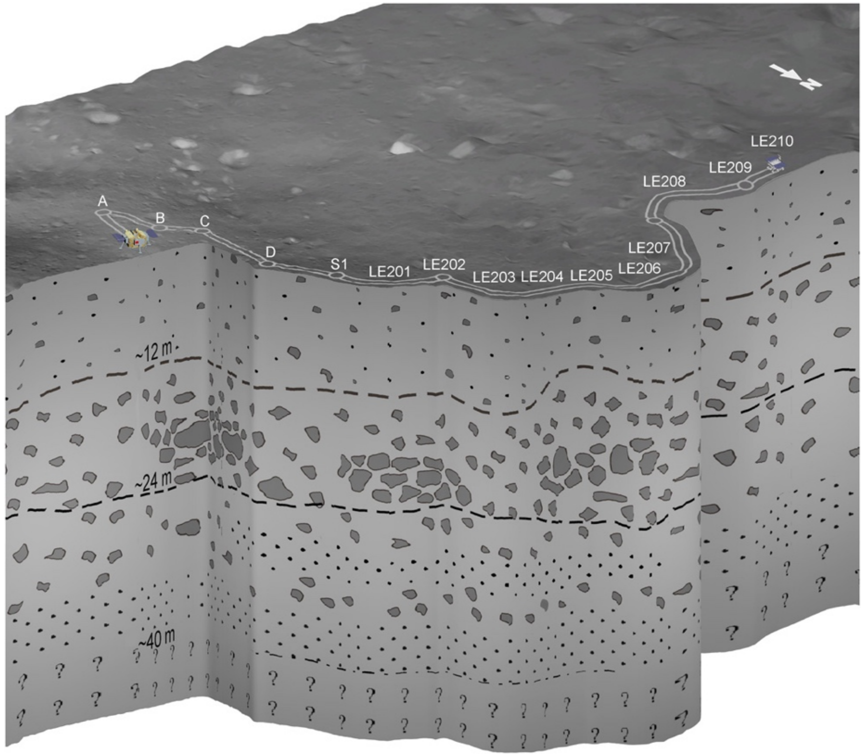
- Can try to predict the general behavior of the bulk density of lunar soil w/ depth
  - But appears to be more striated, so simple smooth model not perfect
- Even understanding this distribution doesn't guarantee performance of drill, penetration device



Li *et al.*, 2020

Lunar Regolith Distributions

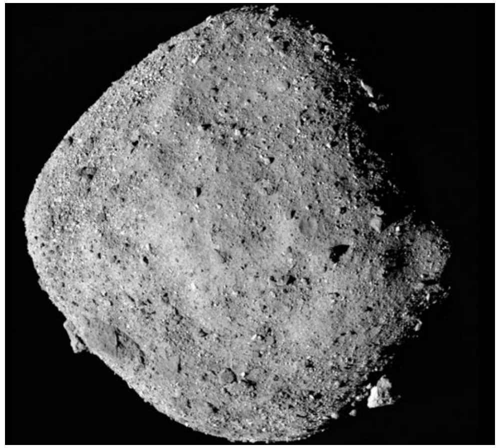
- New results from the Chang'e-4 rover on the lunar farside, in an ejecta deposit

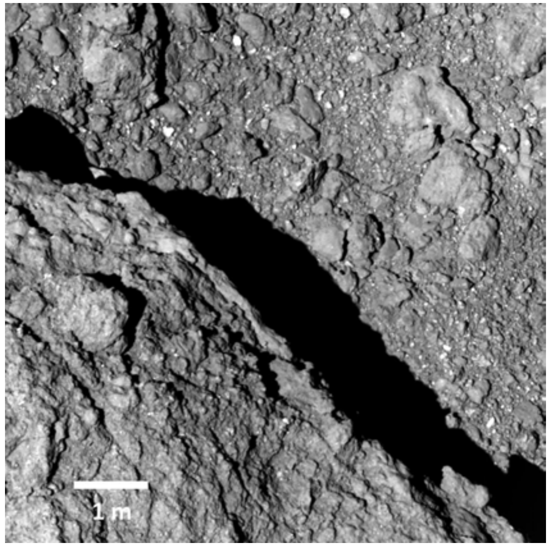


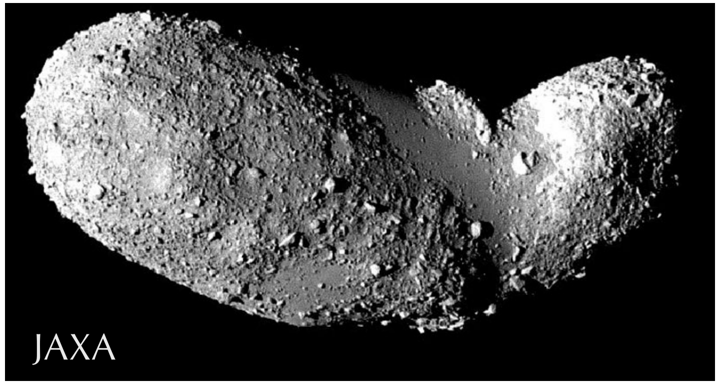
- Radar data shows subsurface structure, although challenging on the Moon!
- Provides general structure, large structures, but not much information about particle sizes, distributions

Asteroid Regolith Distributions

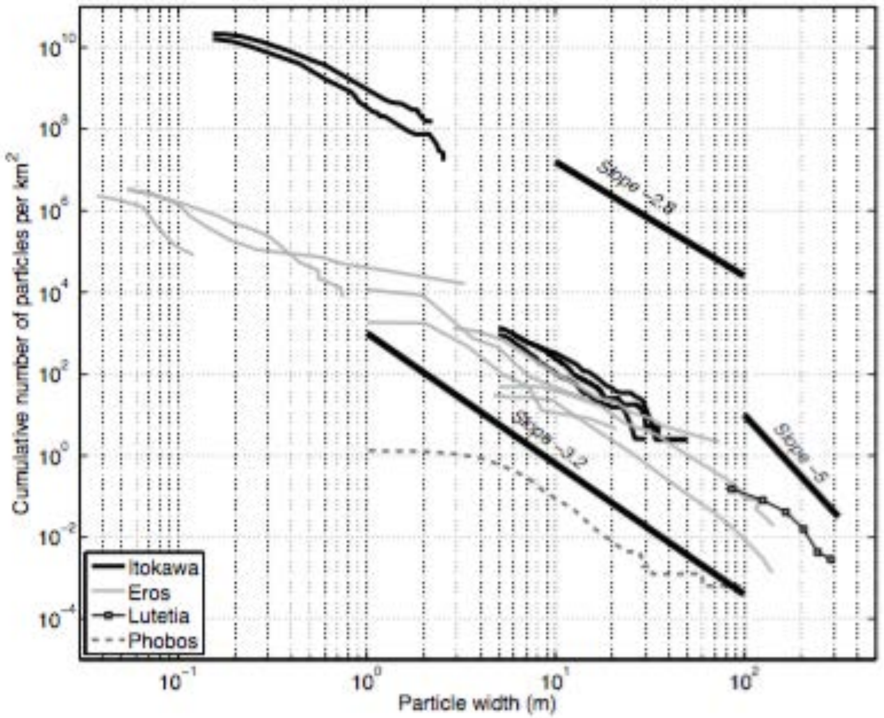
NASA/
OSIRIS-REx







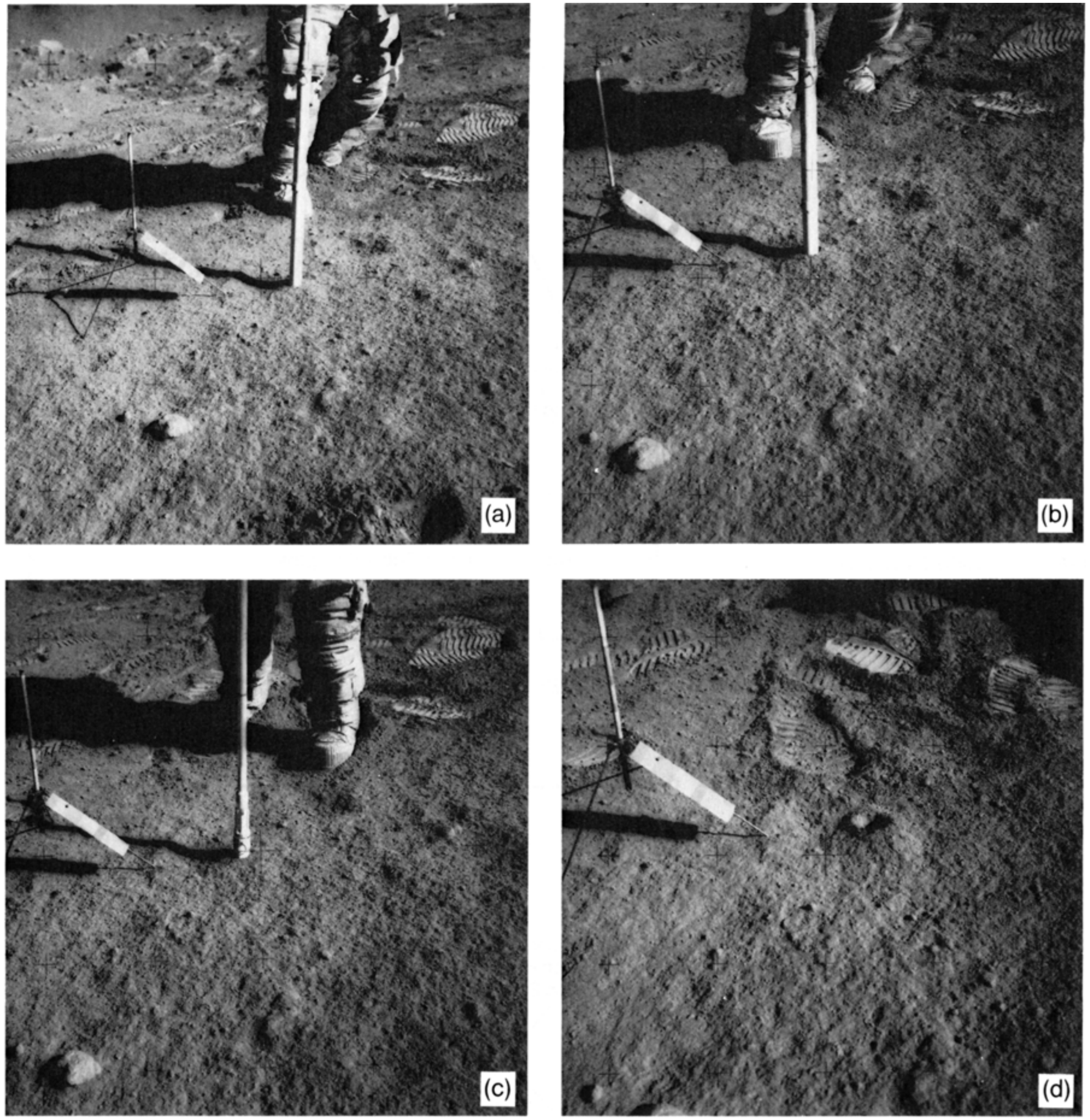
- We have observations of regolith distribution on the Moon, asteroidal, and small moon surfaces
- Optical, radar, spectral, thermal measurements are used to determine particle sizes on remote surfaces
- Size distribution typically has a power-law slope
  - For Eros, Itokawa, and others slope seems to be close to ~3
  - Eros, for instance, has particles sizes ranging from fines (< cm-sized dust) to larger boulders (>10 m) (Thomas et al., 2002)



  - A shallower slope may indicate that boulders have experienced less processing, including breaking, sorting, and transporting (*Thomas et al.* 2002).

Figure: Murdoch, et al. 2015, Asteroids IV

Lunar Surface Drilling Challenges

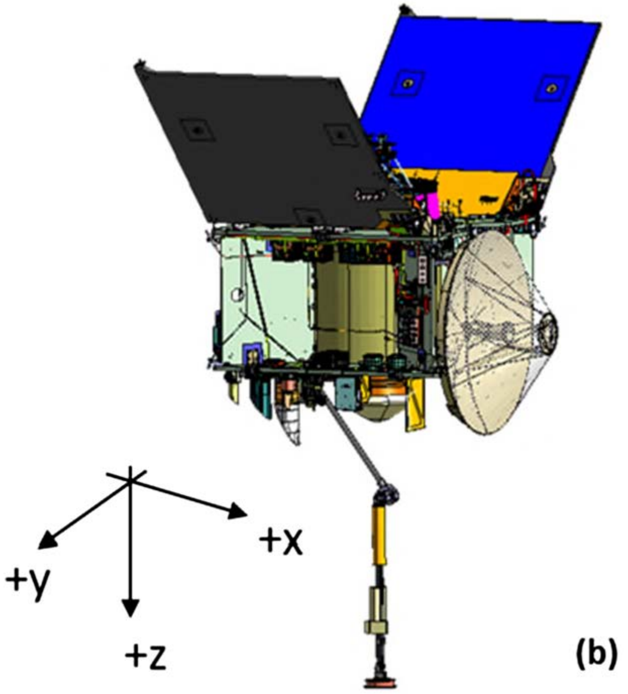


- Apollo 15 used a drive core tube sampler that had been extensively tested on the ground. However, it got stuck much sooner than expected.
- Soil was more compacted than expected! Had to really compact it down in Earth-based tests to reproduce the results
- Subsequently refined drill/sampling mechanism design for Apollo 16/17, and did different/better astronaut training

Asteroid Surface Sampling

- NEAR Shoemaker
- Hayabusa-1 and -2 missions
  - Landers, sampling mechanisms
- OSIRIS-REx TAGSAM
  - Sampling mechanisms

- Cometary: Rosetta mission w/ Philae lander



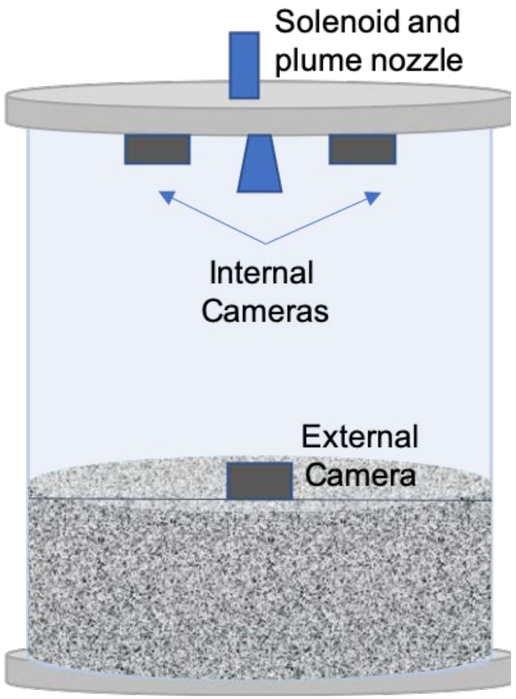
Ground-based experiments - 1*g*

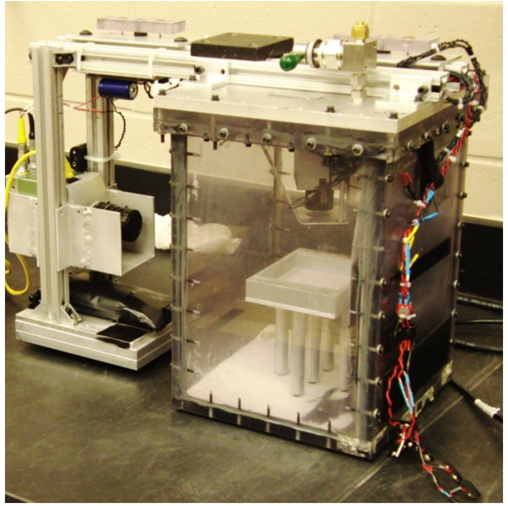
- Challenges to most experiments – they occur on Earth
  - $g = 9.8$ m/s^2
  - Gravitational forces dominate over most forces of interest in particle and surface interactions, but this is NOT true on all other planetary bodies
  - Vacuum, even high vacuum, does not approach that in space
- Surface electrostatic effects are thought to play a significant role in particle-particle interactions
  - on small-body surfaces
  - in small-body interiors
  - in early planet formation processes

Ground-based experiments – vacuum and μg

- Few seconds of freefall time
- In the CMR:
  - ~0.8 sec freefall time
  - Drag shield can be equipped for cleaner μg
  - Experiment volume typically ~10″x10″x12″
  - Experiment volume evacuated to ~.1-1 Torr
  - Automated trigger at drop
    - Battery powered, Arduino, high-speed camera w/ buffer

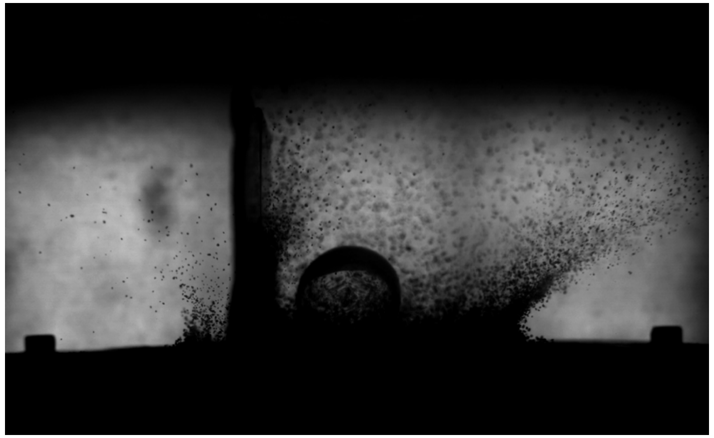
- Experiments include low-velocity impacts, and more recently plume interactions

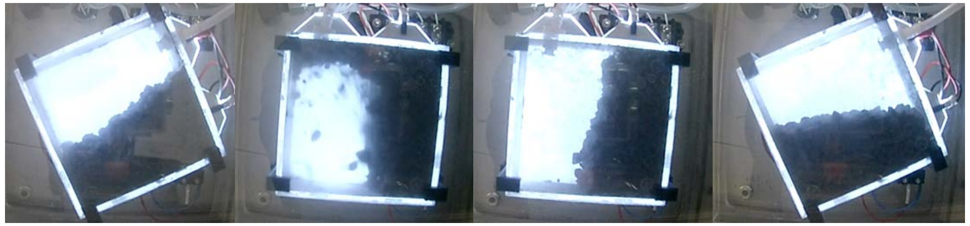




Parabolic flights – vacuum and (~30 sec) μg

- Science/tech that can be achieved in <30 sec
  - Typical experiments include human factors, combustion, liquid behavior, gas behavior
- Testbed for rapidly testing prototype experiments
- Low-gravity environment
  - simulate lunar, martian gravity with modified parabolas
  - simulate large asteroid environments with mg gravity
  - simulate small asteroid environments by free-floating





Suborbital Flights - vacuum and (~few min) μg

- Suborbital offers the chance for more data
  - Several experiments per flight, and
  - repeatability/modification opportunities.
- Longer μg environment
  - can use lower velocity regime
  - can observe evolution of ejecta post-impact
- Can test technologies for planetary surface exploration (sampling, landing, etc.)
- Explore effects of launch/landing conditions

Orbital – International Space Station

- National Lab
- **Long-term, stable** μg environment
  - use even lower velocity regime
  - explore long-term evolution of regolith and particle size distributions
  - relative importance of surface forces on particles over time
  - operations in low-gravity environments -
  - internal and external payloads

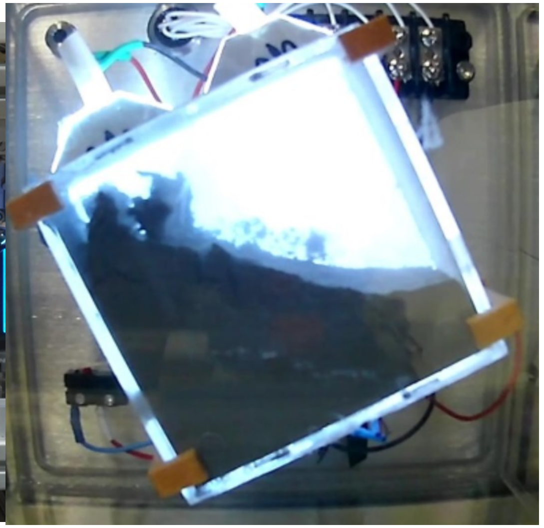
- A new planetary analog environment?
- Additional challenges and opportunities with crew interactions

Operating in Microgravity

- What do we need to test/measure/refine to reduce risk for off-Earth operations?
  - What remote measurements can we take that will improve our understanding of surfaces?
  - How can we improve models to more accurate reflect the complex dynamics?
- What testing can be done in 1-*g*? Short duration low-*g*?
  - How appropriate is it to scale up/down? *(size, gravity level, etc.)*

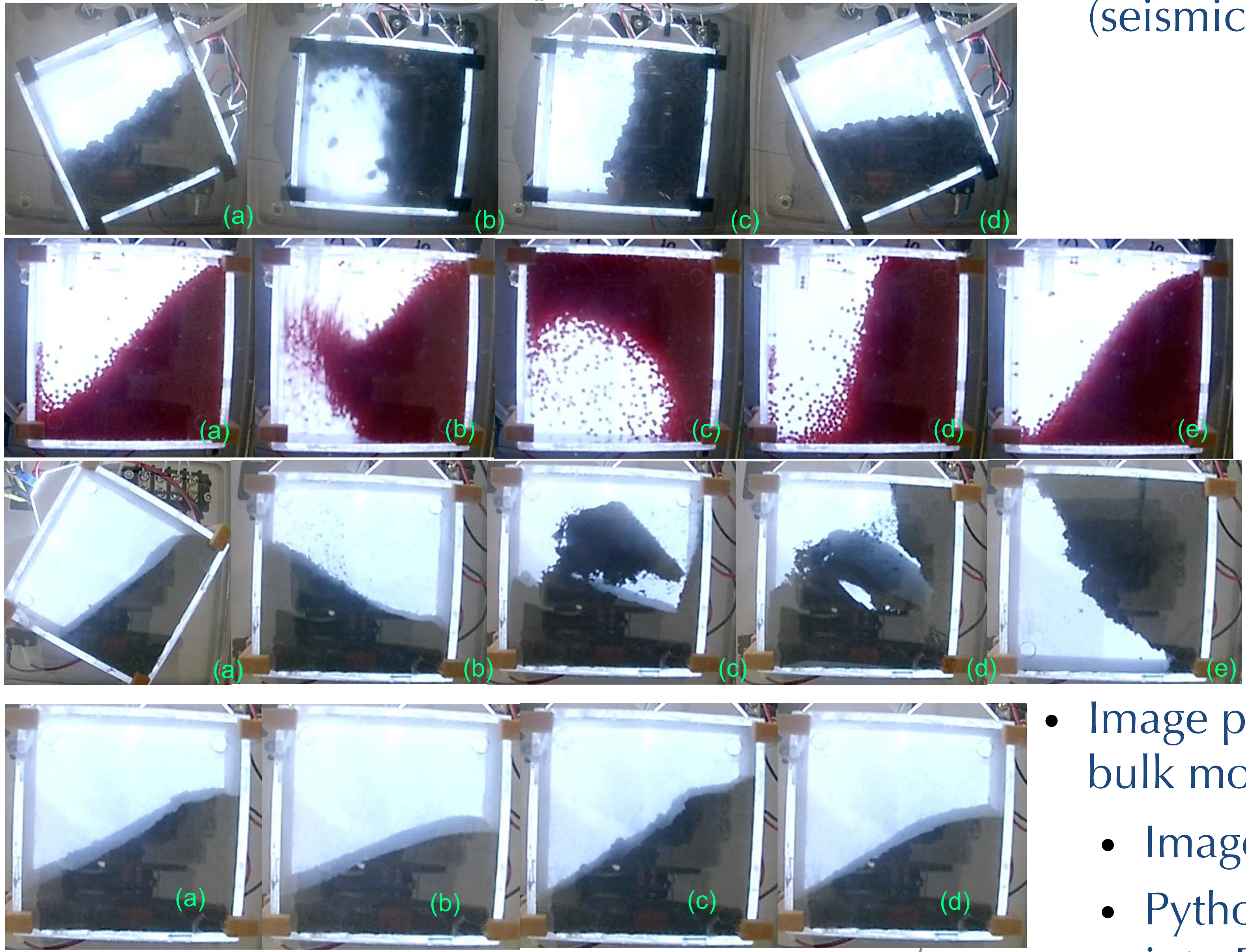
SLOPE Experiment

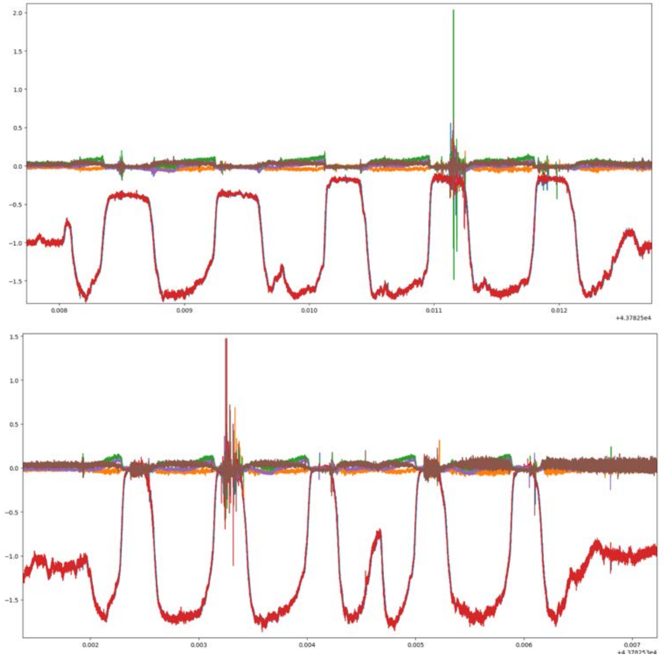
- SLOPE = Simulating LOw-gravity Planetary Environments
- Study the effects of angle of repose and gravity level on mass movement of granular material
- Provide students an opportunity to participate in the full life cycle of a planetary science space experiment.



SLOPE Experiment

- Use variable g-levels to look at regolith motion due to change in slope, vibration (seismic) effects, and jetting effects.



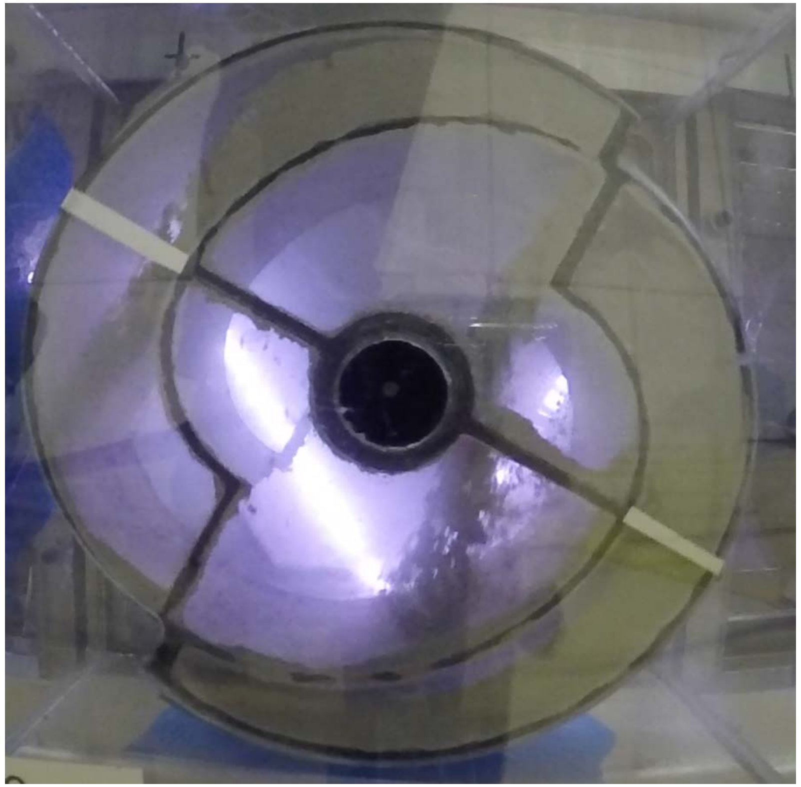


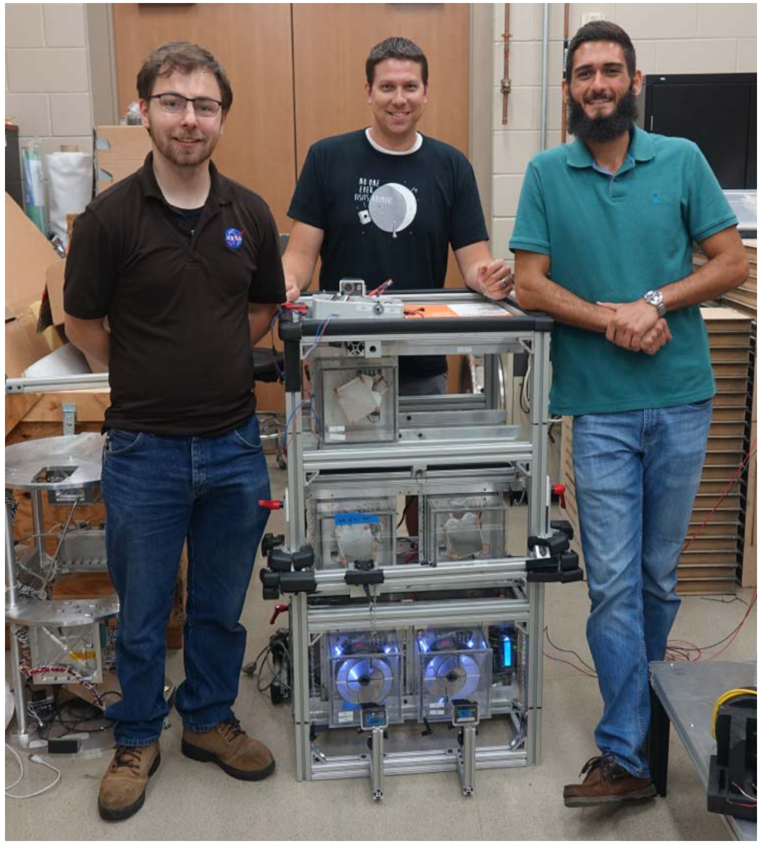
- Describe phenomenology

- Image processing to determine slope angles, bulk motion
  - ImageJ (current) – manual edge detection
  - Python: edge detection after thresholding into B&W images

Tech Demo – RAZZOR wheel testing

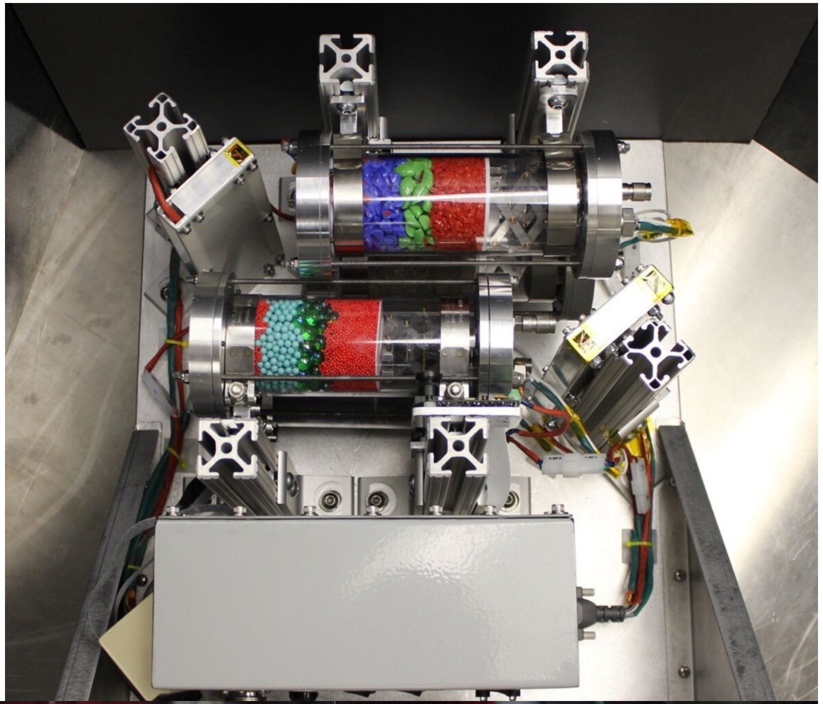
- Testing a the "bucket drum" mechanism in variable gravity with realistic simulant





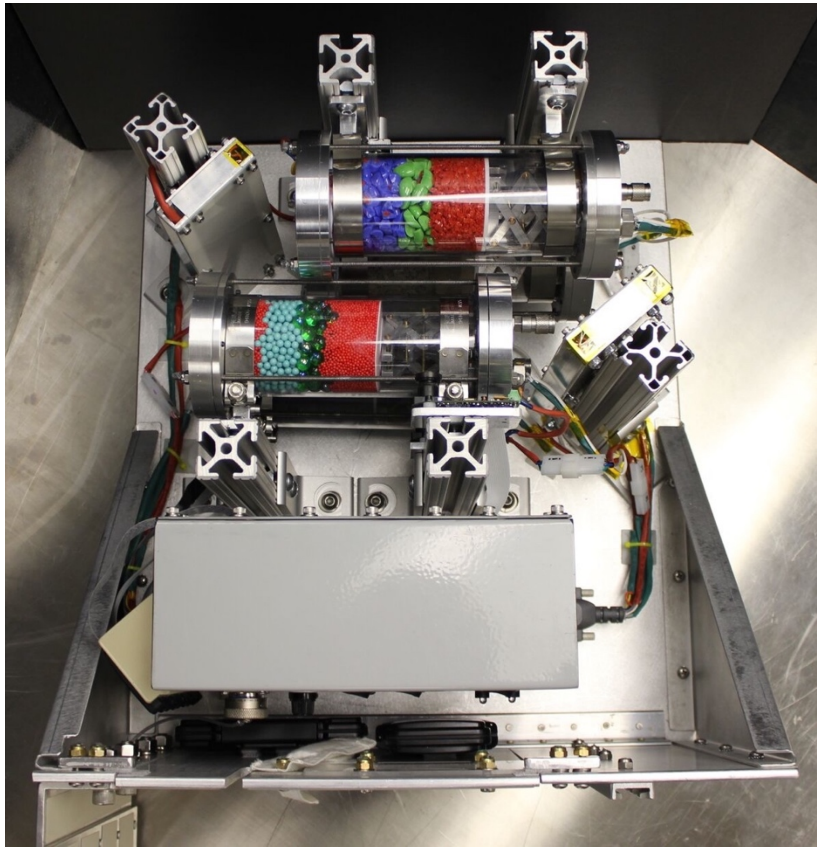
Strata Family of Experiments

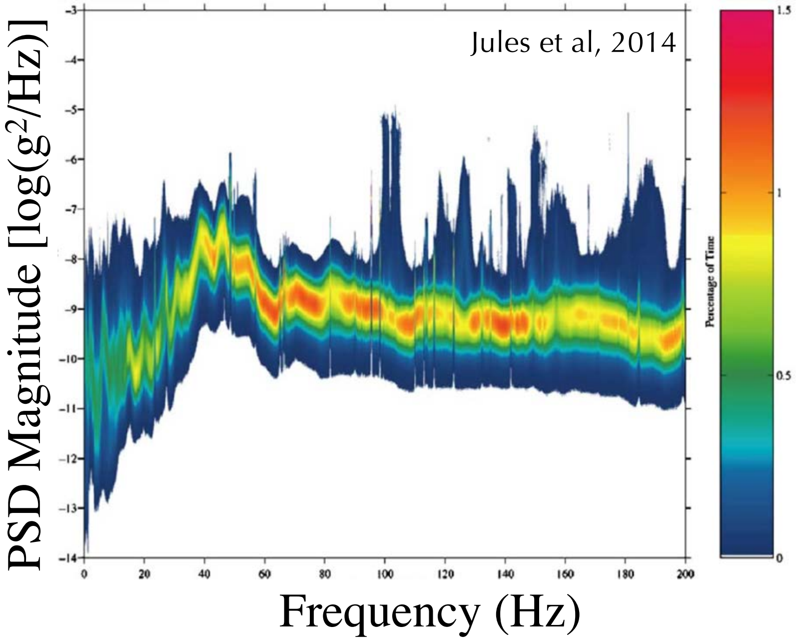
- Studies the mixing and segregation dynamics of surface regolith
  - Granular motion, potential Brazil Nut effect
- Goal: provide a better understanding of regolith dynamics and properties of asteroid surface layers
- Characterized by camera observations of granular motion
  over time, additional acceleration measurements
- 4 tubes loaded with 4 simulants:
  - spherical glass beads
  - glass shards
  - meteorite simulant
  - carbonaceous chondrite

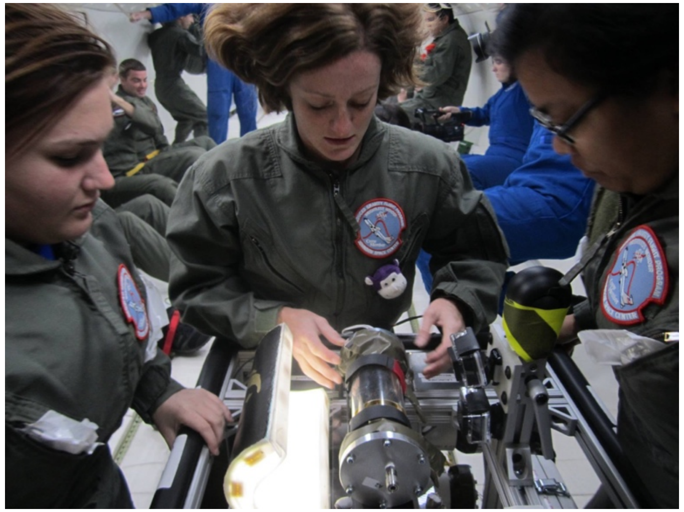


Strata-1

- Passive experiment - used the ISS gravity and vibration environment to simulate asteroid conditions
- ISS provided accelerometer data from the SAMS instrument
- Gravity vector can be derived from the MAMS instrument



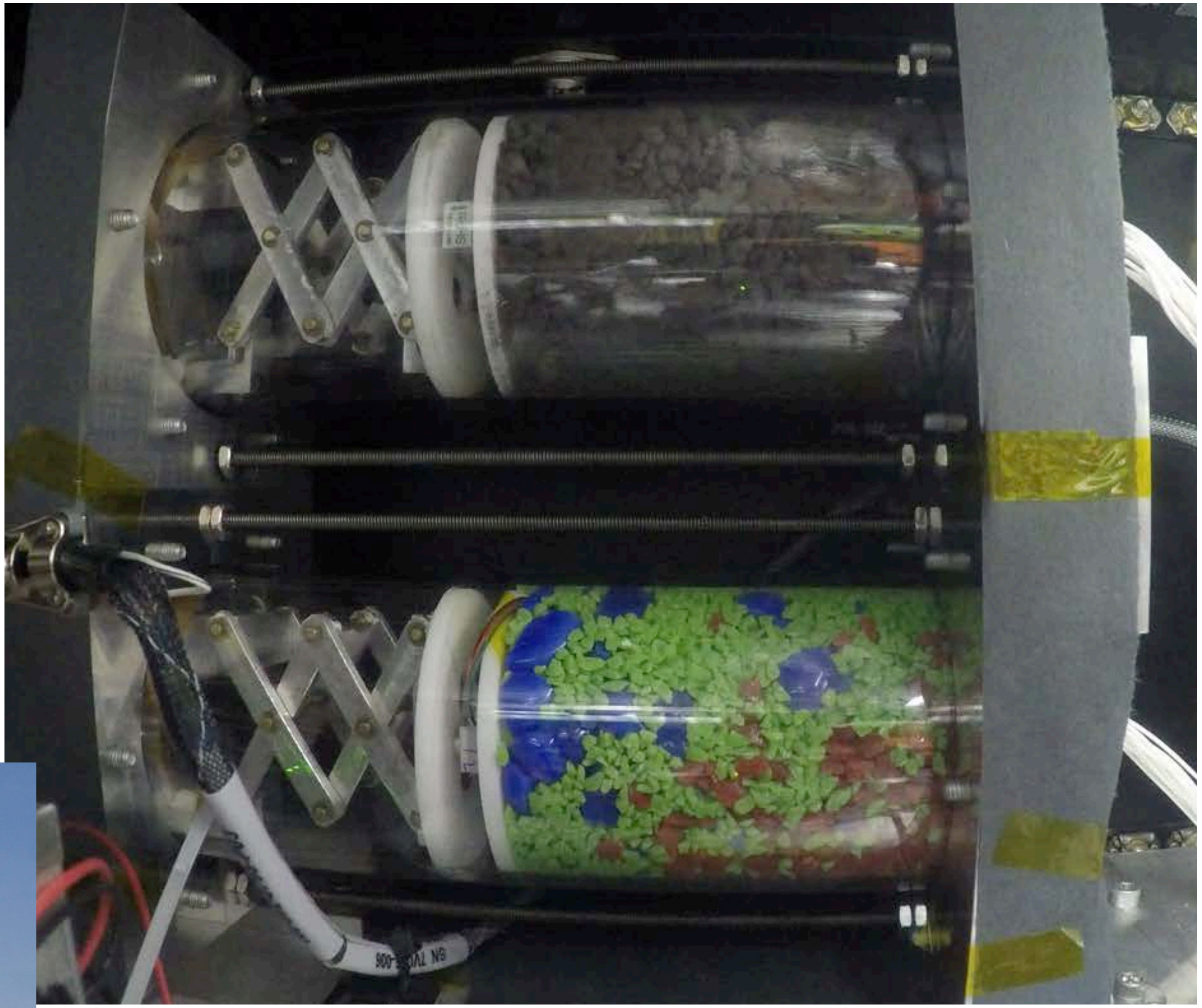




Vibrations and seismic sorting

Strata – S1

- Similar hardware, added sensors for force/compression measurements
- Monitor behavior during launch and landing
- Blue Origin Flight 2 May 2019
  West Texas Launch Site
- ~3 minutes of microgravity conditions



- Supported through the NASA REDDI program

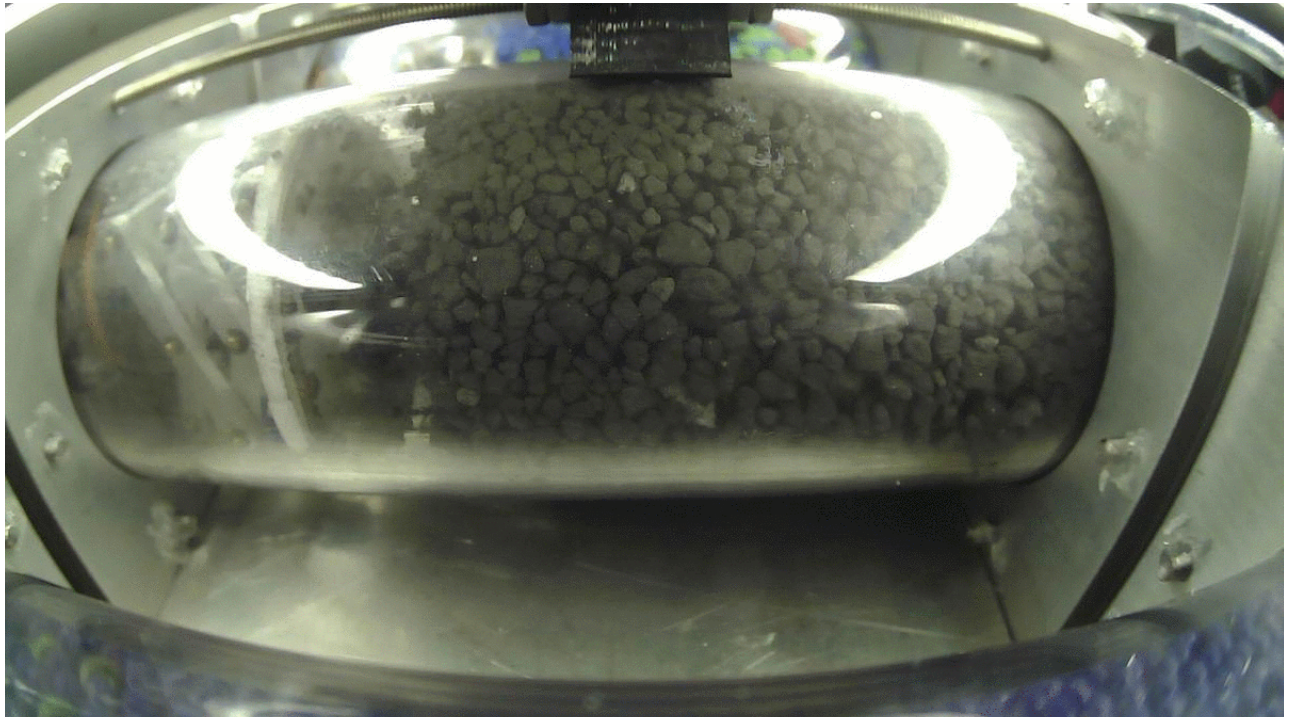
Hermes – Cassette 1

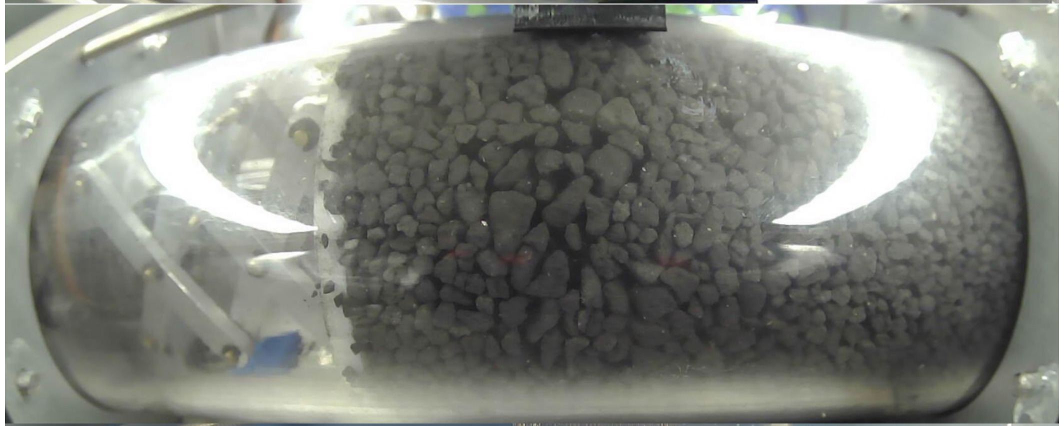
- Hermes is now an ISS facility instrument
  - Main "locker" hardware, electronics remain with facility
  - "Cassettes" of experiments can be exchanged
  - Capabilities include power, data down, and vacuum

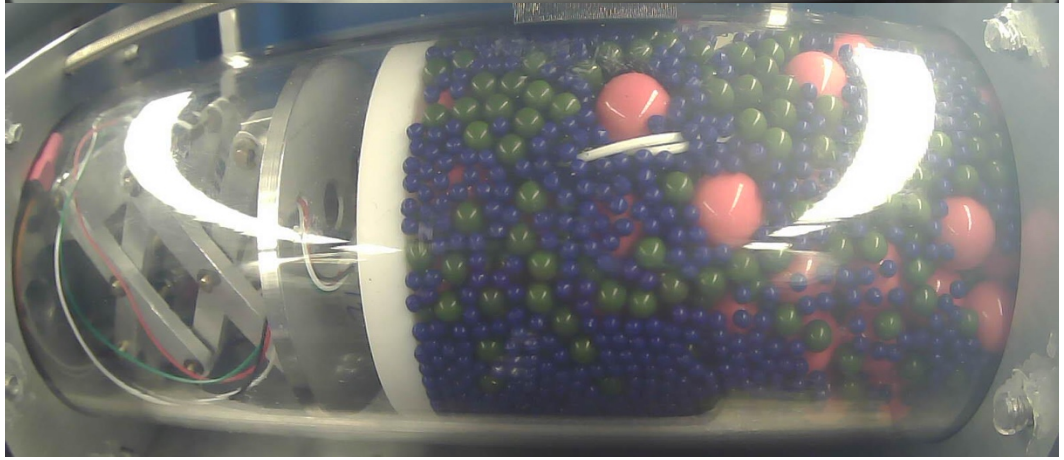
- Facility w/ Cassette 1 launched on Space-X CRS-17 on 4 May 2019
- Installed on ISS 17 July 2019

- Nominal 6-8 month mission
  - Vacuum activation within the first week
  - Experiments are sequentially being activated, tested
- Additional sensors:
  - Force, compression measurements
  - Vibration motor for some active control

Hermes – Cassette 1





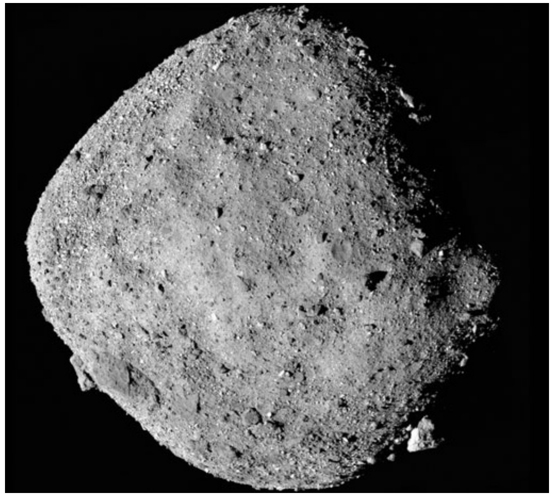


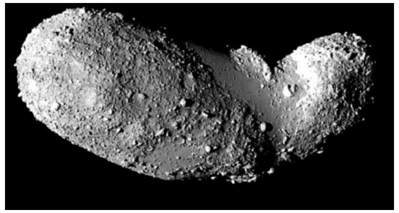
Strata-1…Hermes

- The μg environment on ISS is very dynamic!
  - Relatively low background accelerations (~10^{-6} *g*), but a large number of disturbances, higher amplitude signals across frequencies, and periodic signals
  - Sometimes disturbed by activity with other experiments

- Looking into effects of accelerations at different frequencies to determine relationship to observed motion

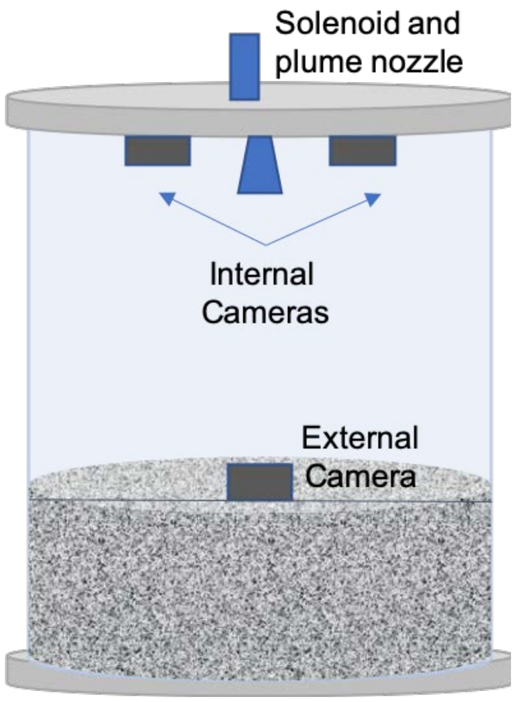
- Hermes platform will allow for future experiments that can be *science* and/or *exploration* driven:
  - regolith composition, size differences, etc.
  - active vibration control
  - testing penetrometers, anchoring, jets, other disturbances



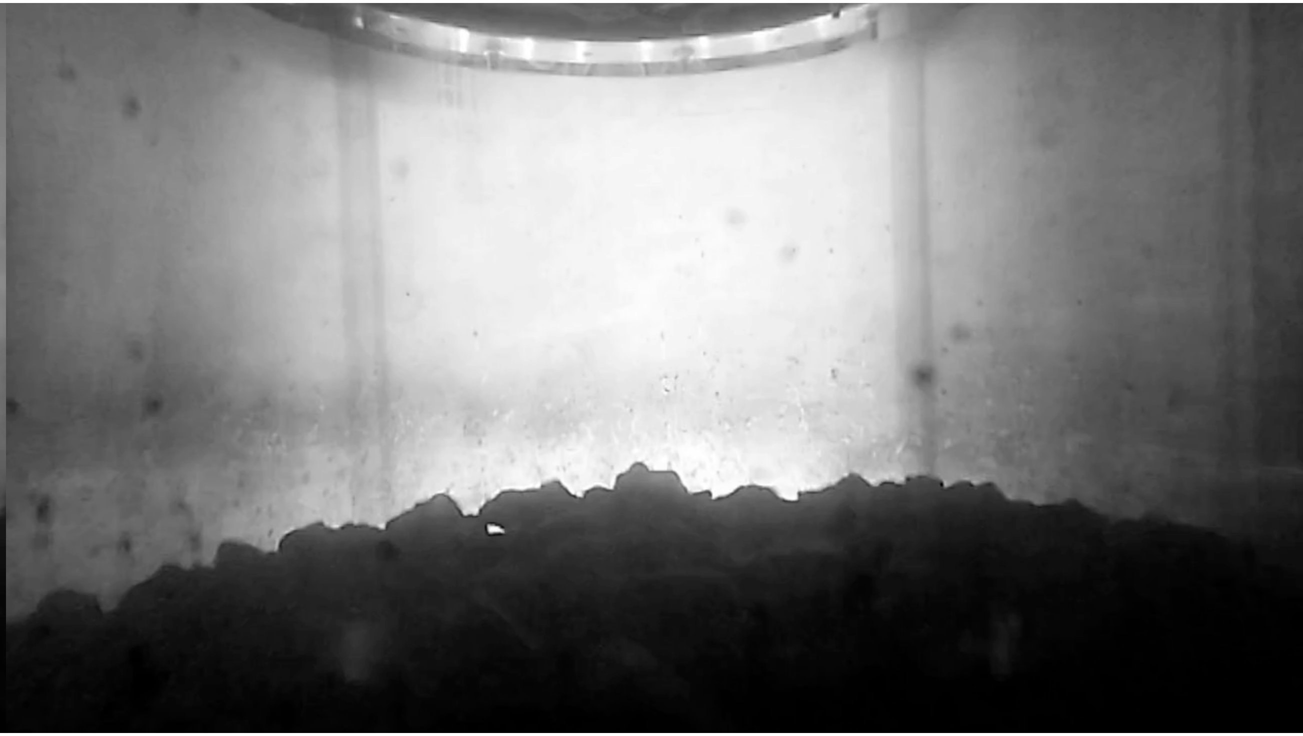


Granular-gas interactions

- Plume-surface interactions of increased interest to NASA and commercial partners
  - Landing on planetary surfaces typically requires engines, and engine exhaust/plumes will interact with the surface
  - Regolith surfaces have complex interactions with these plumes – blowing, entrainment, etc.
  - Charged particles in the plumes adds complexity



Gas-granular interactions



1g

mg

Exolith Lab CI Simulant
cm-size particles with fines

Gas-granular interactions

1g mg

Exolith Lab CI Simulant
cm-size particles with fines

Discussion

adove@ucf.edu