Surface Investigations of Asteroids: Science Justification and the Need for Instrument Development.

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Introduction: One of NASA's current objectives is to send humans to an asteroid. In order to make this goal feasible, it is critical to perform in-situ measurements to characterize these surfaces in order to understand the environment that astronauts, vehicles, and equipment will be exposed to while exploring. Currently, there is very little knowledge about the geophysical and geotechnical properties of asteroids. There is a lack of scientific data on the properties of regolith, as well as a lack of understanding of how regolith responds in its unique microgravity environment [1]. To truly understand the data from remote sensing, surface interaction is key. Characterizing the surface, the regolith, and its properties all feeds into obtaining ground truth.

Need For Surface Interaction and In-Situ Investigations: Near-Earth asteroids come within 121 million miles of the Sun [2]. Asteroids are of scientific interest largely because of the information they will provide about the origins of the Solar System. Additionally, asteroids provide an exploration interest because of their presumed high volatile content that could provide possibilities for in-situ resource utilization [3]. Asteroid detection capabilities are being improved and missions like NEOWISE are identifying more reasonable targets for future robotic and human missions. However, technology development is needed to enable these future missions to perform meaningful science objectives. As discussed at the Small Body Assessment Group (SBAG) proceedings from SBAG 8 (Jan. 2013), the success of asteroid missions such as Japan's Hayabusa and China's Chang'e 2 show there is "significant interest from our international partners in both robotic and human exploration missions to these targets" [4]. In order to increase the science return of these missions, we must address the current, existing gap in asteroid surface characterization. We must start now on developing the instruments that will interact with the surface of asteroids.

Understanding the Effects of Regolith: The surfaces of airless planetary bodies are covered with a layer of dust particles, rock fragments, and glass particles called regolith. Although surfaces of asteroids differ from the lunar surface, we can take lessons learned from Apollo about the detrimental effects of lunar regolith. When NASA sends missions to an asteroid, and eventually to Mars, many of the subsystems could be affected; instruments, spacesuits, airlocks, vehicles, hardware, robotics, and the crew could be impacted [5,6]. It is critical that regolith studies be done for asteroid surface material in order to understand the environment that astronauts and equipment will face.

Consensus in the Planetary Science Community: In a Planetary Science Decadal Survey (PSDS) White Paper addressing Laboratory Studies for Planetary Sciences, the planetary science community agrees that "future missions should focus more on in-situ investigations" [7]. The paper states that "at present, we do not have enough new instruments" and that "basic laboratory research with potential in-situ instrument development even at laboratory scale (TRL0) should be strongly supported". During SBAG 1 (Jan 2009), it was stated that technology development is necessary in order to support small body missions including instrumentation for in-situ study [4]. A 2011-2020 PSDS white paper on Asteroids also confirms the need for in-situ studies of asteroids. The paper states that "for in-situ science, probes and small landers need to be developed that can accommodate a range of instrumentation" [8]. At the 43rd Lunar and Planetary Science Conference (2012), a presentation on asteroid precursor exploration indicates that although recent and successful missions to asteroids such as Hayabusa, NEAR, and Dawn have certainly increased our knowledge, still many questions exist [3]. It also identifies the need for "characterizing the properties of asteroid regolith" as a necessity to understanding telescopic observations and to prepare for future human exploration of asteroids.

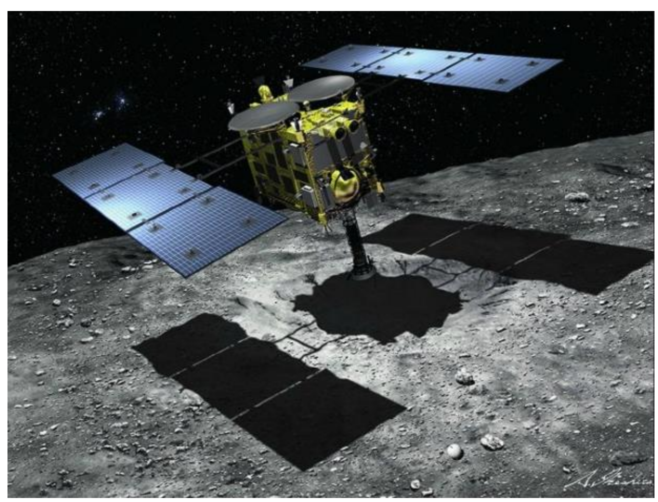

Figure 1: Artist's concept of Hayabusa 2 landing on the surface of asteroid 1999 JU3 (Image: JAXA)

Past and Current Asteroid Missions: This section provides a brief description of relevant missions and instruments. Several of these missions were limited to remote sensing.

NEAR: NASA and Johns Hopkins' Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft was sent to rendezvous with the asteroid Eros. In 2001, NEAR became the first spacecraft to land on the surface of an asteroid. It used innovative sensors and detection equipment to take images of the surface and collect information on Eros' structure and composition [2]. NEAR made several discoveries about the characteristics of Eros, including the presence of a layer of debris resulting from a long history of impacts.

Hayabusa: JAXA's Hayabusa mission to near-Earth asteroid Itokawa was the first to land on, take off from, and return samples from an asteroid. Hayabusa's mini-lander called MINERVA (Micro/Nano Experimental Robot Vehicle for Asteroid) was unsuccessful, but would have used its three small color cameras to relay images of the surface of the asteroid [9]. The Hayabusa spacecraft itself had some complications, but landed on the surface in 2005 and managed to obtain a small collection of particles that were returned to Earth in 2010.

Dawn: Missions such as NASA's Dawn Spacecraft are studying asteroids; however, its capabilities are limited to remote sensing [10]. In 2011, Dawn arrived at Vesta and became the first spacecraft to visit a main-belt asteroid. In 2015, Dawn will arrive at Ceres.

Rosetta: ESA's Rosetta spacecraft rendezvoused with Comet 67P/Churyumov-Gerasimenko on August 6, 2014. In November 2014, it will be the first ever attempt to land on a comet. The 100 kg lander, Philae, will make in-situ measurements at the comet's surface. A group is currently working to select the landing site for Philae, and even with Rosetta just 100 km above the comet, much remains unknown about the surface [11]. Comets, like asteroids, will reveal information about the formation of the Solar System.

Hayabusa 2: JAXA will visit another near-Earth Apollo asteroid in approximately 2018. JAXA realizes the importance of sending a lander to the surface to study it, hence the plan for the Mobile Asteroid Surface Scout (MASCOT) being developed for the Hayabusa-2 mission. MASCOT will in-situ map the asteroid's geomorphology, the intimate structure, texture and composition of the regolith [9,12,13]. Hayabusa 2 will also have three MINERVA mini-landers.

OSIRIS-REx: NASA's OSIRIS-REx will launch in 2016 to near-Earth asteroid Bennu, arriving in 2018. It will use imagers and spectrometers to gather information about the topography, mineralogy, and chemistry of the carbonaceous asteroid [14]. Several of these capabilities are limited to remote sensing. The in-situ capabilities such as the space-qualified SamCam will help to document the samples obtained from the sample acquisition mechanism.

Fly-by missions: In the last 25 years, several missions have observed asteroids remotely [10]. The Galileo spacecraft took images of asteroids Gaspra and Ida. Rosetta, on its way to Comet 67P, took images of asteroids Steins and Lutetia. NEAR, on its way to Eros, flew by asteroid Mathilde. Similarly, Stardust, Chang'e 2, Deep Space 1, Vega 2, and Deep Impact have all encountered asteroids or comets. None of these missions visited the surface. A review of these heritage missions involving asteroids further supports that surface interaction is considerably lacking.

The Need to Visit the Surface: As useful as these missions have been, they fail to produce the type of data that can only be acquired on the surface. Ground observations, rendezvouses, and fly-bys can provide information on rotation rates, asteroid taxonomic class, general composition, shape, and size. However, we must investigate the surface in order to determine internal structure, detailed composition, surface topography, collisional history, particle size distribution, particle behavior, and mechanical properties of the particles.

Interacting with the Surface: The missions discussed above did/will not all involve surface interaction. In fact, the only tools used for asteroid surface interaction to date are for Hayabusa, where a slug fired into the regolith was meant to disturb the surface and collect samples. In contrast, on the Moon, the astronauts used a number of manual tools (tongs, hammer, shovel, coring tubes, rake, electric drills) [15]. Additionally, the Apollo lunar rover wheels moved the regolith, as did the Soviet Lunokhod rovers. Surveyor utilized a remote controlled arm with a scoop and the Soviet Luna probe picked up samples using a drilling mechanism. Martian tools include the MSL, Viking, and Phoenix rover arms. Lessons learned from Apollo and Mars experiences can be applied to the next generation of tool development.

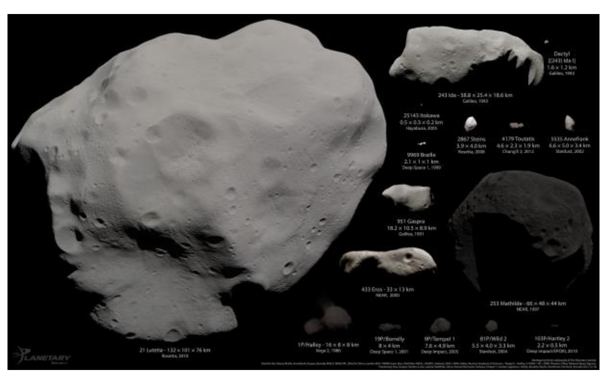

Figure 2: Asteroids and comets visited by spacecraft as of Dec 2012, excluding Vesta; only 2 have visited surface (Image: Planetary Society)

Asteroid Science and Associated Instruments: The planetary science community has detailed what science should be investigated on the surface. For each of these scientific objectives, associated instruments have been considered. For instance, to obtain a rough mineralogical composition, a near-IR spectrometer could be used. To characterize particle size distribution of regolith in-situ and characterize other regolith properties such as structure and texture, the instrumentation could utilize visible imagery using CCD cameras. The table below provides an idea of the type of asteroid science we are interested in, along with the associated instrumentation. The table begins with global characterization and works its way down to surface and subsurface characterization.

Table 1: Asteroid Science and Associated Instrumentation

Asteroid Science	**Associated Instrumentation**
Global properties: *mass, shape, density, rotation, porosity*	Radioscience measurements, LIDAR, imagers, spectrometers
Presence of volatiles	Spectrometers, hyperspectral imagers, micro-GPR (ground penetrating radar)
Local magnetic field detection	Micro-magnetometer
Interior and surface structure	Passive/active seismic measurements, radar
Topography	Imagers, optical cameras, LIDAR, radar
Mineralogical composition	Visible, near-IR, x-ray, gamma-ray spectrometer; hyperspectral imagers
Radiation characterization	Dosimeter
Temperature, thermal inertia	Hyperspectral imager, RFID surface acoustic wave (SAW) sensors, IR detector
Surface roughness	Hyperspectral imager, LIDAR
Dust environment characterization	Imagers, optical camera, Langmuir Probe
Surface mobility: *granular flow, regolith movement, particle levitation*	Imagers, optical camera, RFID SAW sensors
Particle size distribution	Micro-imagers
Particle properties: *structure, texture, shape, thickness*	Visible imager
Cohesion, friability, surface strength, compaction	Penetrometer, imagers, load cell, physical interaction tool
Mechanical properties of surface: *compressive strength, tensile strength, shear strength, toughness, hardness*	Penetrometers, gages, specialized tests
Albedo of particles	Imagers, optical camera, IR detector
Subsurface environment characterization: *voids, clumps, mass concentrations, temperature, thermal inertia*	Penetrometers, micro-GPR, thermocouples

Asteroid Surface Characterization: Understanding the properties listed in the table are critical for future exploration of asteroid surfaces. The microgravity environment affects the geology. Concerns like surface mobility were made aware by visiting Itokawa. The movement of regolith particles on the surface is a consideration when interacting with the surface. For instance, to use the surface of the asteroid as a relative navigation aid, it is essential to know if the surface particles are moving and by how much. Anchoring to the surface is already challenging due to the low gravity and the unknown distribution of particle sizes [16]. This will be even more challenging on a surface where the particles are moving. Characterizing and quantifying these asteroid attributes is necessary for understanding these bodies. Additionally, to understand the geological context of the observations and samples, it is imperative to visit multiple sites on the surface.

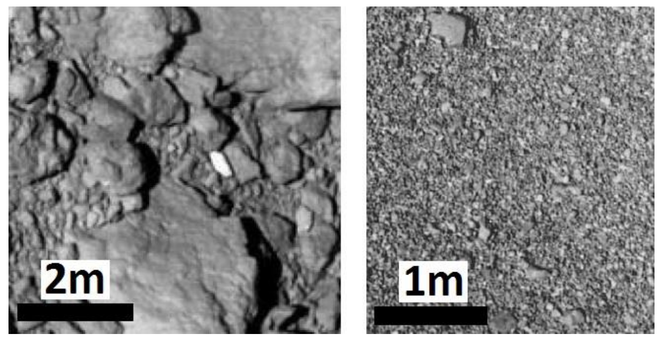

Figure 3: Surfaces of Itokawa showing rough terrain on the left and smooth terrain on the right (Image: JAXA)

Instrument Packaging and Development: To enable these instruments to visit the surface of an asteroid, there will be a need to miniaturize components and package instruments into small volumes. These packages could be modeled after CubeSat technology. Instrument development can be advanced through modeling and computational analyses, observational and experimental design, and systems engineering.

Analog Experiments using Meteorites: In the laboratory, analog experiments could be conducted using meteorites identified from known asteroid locations. For instance, a particular group of meteorites (howardites, eucrites, and diogenites) likely originated from asteroid Vesta [17]. Other meteorites can be linked to an asteroid type (i.e. LL chondrites are representative of Itokawa's surface). This can serve as a platform for testing equipment and methodologies for future samples. A method and tool set could be developed now such that when there is a new asteroid sample, the technology is already in place to analyze it. These analog experiments can answer questions about how instruments will react to different types/sizes of materials and what characteristics they can identify. In addition, there exists the potential for testing flight-like instruments in a microgravity environment by performing experiments onboard the microgravity plane.

Conclusion: A review of past and current missions to asteroids illustrates that more research needs to be done to visit and interact with the surface of asteroids. The planetary science community has expressed the need for robotic precursor missions to interact with and characterize the surface. Technology development is needed for instrumentation to perform the desired science. Once the surface environment of asteroids is better understood, scientists and engineers can apply this data to make future missions successful. In-situ investigations and surface interactions, potentially performed using the type of instrumentation discussed here, are essential. Missions to small bodies will help answer fundamental questions about the origin and evolution of the Earth and the Solar System. Within NASA, this research would benefit the Science Mission Directorate (SMD) and the Human Exploration and Operations Mission Directorate (HEOMD). SMD will benefit from the science aspects of the instrumentation and HEOMD will benefit from the exploration aspects of this research.

The data gained from characterizing surface regolith and its properties can be used to better design and engineer any instruments and equipment that will investigate asteroids. Equipment can be developed on Earth to test the harsh effects of the regolith, and may prevent damage to subsystems that would otherwise be susceptible. Knowledge gained will help determine how future robotic missions, and eventually crew, will interact with the surface–from landing, to attaching, to deploying equipment. Prior knowledge and experience with the surface environment will improve the operational efficiency of the crew, reduce the equipment mass brought along on the mission, and reduce the safety risk to the crew and mission.

The success of any future missions to an asteroid will depend on such technology. If we are to send astronauts to an asteroid in the coming decades, it is necessary now to begin development of in-situ instruments that can characterize the surface during robotic precursor missions and pave the way for human exploration.

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