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Conference on Spacecraft Reconnaissance of Asteroid and Comet Interiors

January 8–10, 2015
Tempe, Arizona

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LPI Contribution No. 1829

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Preface

This volume contains abstracts that have been accepted for presentation at the Conference on Spacecraft Reconnaissance of Asteroid and Comet Interiors, January 8–10, 2015, Tempe, Arizona.

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Program

Thursday, January 8, 2015

	Location: ISTB4 Building, Lobby
8:30–9:45 a.m.	**Breakfast** (hosted by sponsor)
	Onsite Registration
	Poster and Exhibit Set-Up
	Location: Armstrong Hall
10:00 a.m.	**Opening Remarks**
	SESE Director, Lindy Elkins-Tanton Introduces Arizona State University President Michael Crow
	Michael Crow – Opening Remarks (10 min)
10:15 a.m.	**Morning Keynotes** (Chair: Erik Asphaug)
10:15 a.m.	Nancy Chabot – Science and Exploration of Small Planetary Bodies (20 min)
10:35 a.m.	Lindley Johnson – News from NASA (20 min)
10:55 a.m.	**Break** (15 min – Refreshments provided)
11:10 a.m.	Chris Lewicki – Business Models for NEOs (20 min)
11:30 p.m.	Jens Biele – Landing on Small Bodies: Rosetta and Beyond (30 min)
12:00 p.m.	Paul Abell – Robotic Reconnaissance and Human Exploration (15 min)
12:15 p.m.	Megan Bruck Syal – Current Issues in Planetary Defense (15 min)
	Location: ISTB4 Building, Lobby
12:30 p.m.	**Lunch** (hosted by sponsor)
1:30 p.m.	**Upcoming Missions** (Chair: Julie Castillo-Rogez)
1:30 p.m.	Takashi Kubota – Hayabusa 2 Mission and Current Status (30 min)
2:00 p.m.	Tetsuo Yoshimitsu – MINERVA Lander in Hayabusa 2 Mission (15 min)
2:15 p.m.	Andy Frick – Low Cost NEO Reconnaissance with NEAScout (15 min)
2:30 p.m.	Andy Klesh – Deep-Space Small Sats and INSPIRE (15 min)
2:45 p.m.	**Break** (15 min – Refreshments provided)
3:00 p.m.	**Technologies for Low Cost Exploration** (Chair: Andy Klesh)
3:00 p.m.	Patrick Michel – AIDA Mission Concept (15 min)
3:15 p.m.	Jekan Thangavelautham – Technologies for *In-Situ* Reconnaissance (15 min)
3:30 p.m.	Julie Castillo-Rogez – Next Generation Low-Cost Small Platforms (15 min)
3:45 p.m.	John Dankanich – Small Satellite Propulsion and Enabling Technologies (15 min)
4:00 p.m.	**Posters** (2 hrs)
	Location: ISTB4 Building, 1st Floor, Marston Theater
6:00 p.m.	**Planetarium Show and AstroRecon Visualization***
	* Depending on responses, we will set aside some time for viewing short HD mission concept videos and modeling simulations.

Friday, January 9, 2015

	Location: ISTB4 Building, Lobby
8:30–9:30 a.m.	**Breakfast** (hosted by sponsor)
	Location: Armstrong Hall
9:30 a.m.	**Meteorites and Missions** (Chair: Melissa Morris)
9:30 a.m.	Jamie Kimberley – Strength of Stony Meteorites (15 min)
9:45 a.m.	George Flynn – Physical Properties of Meteorites (15 min)
10:00 a.m.	Danny Glavin – Amino Acids in Meteorites (15 min)
10:15 a.m.	Desiree Cotto-Figueroa – Scale-Dependent Studies of Meteorites (15 min)
10:30 a.m.	**Break** (15 min – Refreshments provided)
10:45 a.m.	**Sky's the Limit I** (Chair: Michael Busch)
10:45 a.m.	Hirotoma Noda – Hayabusa 2 Laser Altimeter (15 min)
11:00 a.m.	Steve Chesley – Kinetic Impactor Technology (15 min)
11:15 a.m.	Kris Zacny – Approaches to Exploration, Sample Return, and ISRU (20 min)
11:35 p.m.	Dan Scheeres – Dynamical Approaches to Small Body Exploration (25 min)
	Location: ISTB4 Building, Lobby
12:00 p.m.	**Lunch** (hosted by sponsor)
	Location: Armstrong Hall
1:30 p.m.	**Sky's the Limit II** (Chair: Christine Hartzell)
1:30 p.m.	Michael Busch – Bistatic Radar Imaging of NEOs (15 min)
1:45 p.m.	William Butler – Oil and Gas Seismology Applied to Small Body Reconnaissance (15 min)
2:00 p.m.	Nick Moskovitz – The Mission-Accessible NEO Survey (15 min)
2:15 p.m.	Ron Ballouz – Numerical Simulations of Rubble Piles (15 min)
2:30 p.m.	Kieran Carroll – Gravimetric Studies of Asteroid Interiors (15 min)
2:45 p.m.	Alain Herique – Radar Determination of Interior Structure (15 min)
3:00 p.m.	**Break** (15 min – Refreshments provided)
3:15 p.m.	**Student Presentation Lightning Round** (Chair: Julie Castillo-Rogez)
4:15 p.m.	**Posters**
	Location: Desert Botanical Gardens, Dorrance Center
6:00 p.m.	**Banquet**
6:55 p.m.	Jim Bell Introduces ASU NewSpace and Banquet Speaker
7:00 p.m.	Lindy Elkins-Tanton (Banquet Speaker)

Saturday, January 10, 2015

	Location: ISTB4 Building, Lobby
8:00–9:00 a.m.	**Breakfast** (hosted by sponsor)
	Location: Armstrong Hall
9:00 a.m.	**Panel I: Intersecting Themes** (Chair: Erik Asphaug) Paul Abell, William Butler, Lindley Johnson, Patrick Michel, David Morrison, Carol Raymond
10:15 a.m.	**Break** (15 min – Refreshments provided)
10:30 a.m.	**Panel II: Future of Small Body Exploration** (Chair: Christine Hartzell) Michael Busch, Andy Klesh, Marco Pavone, Vishnu Reddy, Kevin Walsh
12:00 p.m.	**Adjourn** Lunch (available for purchase)

ROBOTIC RECONNAISSANCE MISSIONS TO SMALL BODIES AND THEIR POTENTIAL CONTRIBUTIONS TO HUMAN EXPLORATION.

P. A. Abell[1] and A. S. Rivkin[2], [1]Exploration Integration and Science Directorate, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, paul.a.abell@nasa.gov, [2]The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, andy.rivkin@jhuapl.edu.

Introduction: Robotic reconnaissance missions to small bodies will directly address aspects of NASA's Asteroid Initiative and will contribute to future human exploration. The NASA Asteroid Initiative is comprised of two major components: the Grand Challenge and the Asteroid Mission. The first component, the Grand Challenge, focuses on protecting Earth's population from asteroid impacts by detecting potentially hazardous objects with enough warning time to either prevent them from impacting the planet, or to implement civil defense procedures. The Asteroid Mission involves sending astronauts to study and sample a near-Earth asteroid (NEA) prior to conducting exploration missions of the Martian system, which includes Phobos and Deimos.

The science and technical data obtained from robotic precursor missions that investigate the surface and interior physical characteristics of an object will help identify the pertinent physical properties that will maximize operational efficiency and reduce mission risk for both robotic assets and crew operating in close proximity to, or at the surface of, a small body. These data will help fill crucial strategic knowledge gaps (SKGs) concerning asteroid physical characteristics that are relevant for human exploration considerations at similar small body destinations.

Small Body Strategic Knowledge Gaps: For the past several years NASA has been interested in identifying the key SKGs related to future human destinations. These SKGs highlight the various unknowns and/or data gaps of targets that the science and engineering communities would like to have filled in prior to committing crews to explore the Solar System. An action team from the Small Bodies Assessment Group (SBAG) was formed specifically to identify the small body SKGs under the direction of the Human Exploration and Operations Missions Directorate (HEOMD), given NASA's recent interest in NEAs and the Martian moons as potential human destinations [1]. The action team organized the SKGs into four broad themes:

1) Identify human mission targets;
2) Understand how to work on and interact with the small body surface;
3) Understand the small body environment and its potential risk/benefit to crew, systems, and operational assets; and
4) Understand the small body resource potential.

Each of these themes were then further subdivided into categories to address specific SKG issues.

Robotic Precursor Contributions to SKGs: Robotic reconnaissance missions should be able to address specific aspects related to SKG themes 1 through 4. Theme 1 deals with the identification of human mission targets within the NEA population. The current guideline indicates that human missions to fast-spinning, tumbling, or binary asteroids may be too risky to conduct successfully from an operational perspective. However, no spacecraft mission has been to any of these types of NEAs before.

Theme 2 addresses the concerns about interacting on the small body surface under microgravity conditions, and how the surface and/or sub-surface properties affect or restrict the interaction for human exploration. The combination of remote sensing instruments and *in situ* payloads will provide good insight into the asteroid's surface and subsurface properties.

SKG theme 3 deals with the environment in and around the small body that may present a nuisance or hazard to any assets operating in close proximity. Impact and surface experiments will help address issues related to particle size, particle longevity, internal structure, and the near-surface mechanical stability of the asteroid. Understanding or constraining these physical characteristics are important for mission planning.

Theme 4 addresses the resource potential of the small body. This is a particularly important aspect of human exploration since the identification and utilization of resources is a key aspect for deep space mission architectures to the Martian system (i.e., Phobos and Deimos).

Conclusions: Robotic reconnaissance of small bodies can provide a wealth of information relevant to the science and planetary defense of NEAs. However, such missions to investigate NEAs can also provide key insights into small body strategic knowledge gaps and contribute to the overall success for human exploration missions to asteroids.

References: [1] A. S. Rivkin et al. (2013) Small Bodies Assessment Group Special Action Team report on small body strategic knowledge gaps. http://www.lpi.usra.edu/sbag/meetings/jan2013/presentations/sbag8_presentations/MON_1330_Sykes_SBAG_SKG_SAT_report.pdf

COMET RADAR EXPLORER.

E. Asphaug[1] and the CORE Science Team, [1]Arizona State University, Tempe

Introduction: Missions to cometary nuclei have revealed major geological surprises: (1) Global scale layers – do these persist through to the interior? Are they a record of their formation? (2) Smooth regions – are they landslides originating on the surface? Are they cryovolcanic? (3) Pits – are they impact craters or sublimation pits, or rooted in the interior?

The spectacular successes of the Rosetta mission are ongoing and add to the overall state of wonder about comets. The deeper questions persist: How do primitive bodies accrete? What is the interior compositional distribution? What drives cometary activity and evolution? CORE can also tell us the answer to a more practical question: Where do we go to collect the best samples, and what is their context related to the global interior? Briefly stated, our goals are to find out *what's inside*, *what makes it work*, and *how it formed*.

Comet nucleus: The Comet Radar Explorer (CORE) mission uses a Mars-heritage radar to image the detailed internal structure of the nucleus of 10P/Tempel 2. This ~16×8 km prolate Jupiter Family Comet (JFC), or its parent body, originated in the outer planets region possibly millions of years before planet formation. Several times the diameter of Rosetta target 67P/Churyumov-Gerasimenko, the target of our investigation is perhaps more closely akin to the ~20-40 km diameter targets of the 2019 post-Pluto New Horizons flyby. It is a weakly producing comet, but is slowing by 20 seconds per perihelion, indicating regular repeated activity or shifting of moment of inertia.

Radar imager: CORE arrives post-perihelion and observes the comet's waning activity from safe distance. Once the nucleus is effectively dormant, the spacecraft enters a ~20-km dedicated Radar Mapping Orbit (RMO) and begins using the powerful Radar Refection Imager (RRI), a JPL/ASI collaboration.

The exacting design of the RRI experiment and the precise navigation of RMO will achieve a highly focused 3D radar reflection image of internal structure, to 30 m range resolution, and tomographic images of velocity and attenuation to a few hundred meters resolution, tied to the gravity model and shape.

Science and navigation camera: The color camera to be built by DLR will produce maps of the surface morphology, albedo, color, texture, and photometric response, and images for navigation and shape determination. It will also monitor the structure and dynamics of the coma, and its dusty jets, allowing their correlation in 3D with deep interior structures and surface features.

Thermal imager: A broadband thermal imager to be built at ASU will obtain repeated high-resolution temperature maps to probe the near-surface layers heated by the Sun. Maps of thermal inertia will be correlated with the radar boundary response, and photometry and texture, probing surface materials attainable by future robotic excavation missions. Thermal images will reveal areas of sublimation cooling around vents and pits, and the secular response of the outer meters as the nucleus moves farther from the Sun.

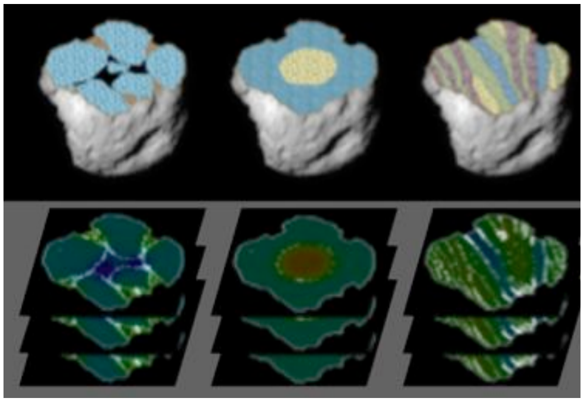

Figure 1. Schematic representation of hypothesis discrimination using radar imaging and tomography.

Figure 2. CORE acquires a dense network of radar echoes from polar orbit to obtain a 3D 'CAT scan' of the comet nucleus. It utilizes mature techniques of planetary radar, in a 3D geometry that leads to high definition migration imaging and tomography.

Title talk: Development of communication technologies and architectural concepts for interplanetary small satellite communications

Abstract

Space communication systems face unique challenges with respect to wired or wireless terrestrial communication systems. They are subjected to very stringent constraints in metrics like mass, power, and cost, and they need to satisfy an increasing throughput demand while transmitting from long distance in the harsh space environment. These challenges are especially critical for small satellite missions and they motivate the need for developing new design strategies as well as new communication technologies. The first part of the talk will focus on a new communication technology developed to support high gain/ high data rate and radio science for small satellite missions: inflatable antenna. Design features, electromagnetic simulations, and environmental tests will be described. The second part of the talk focuses on cooperative communication approaches in which multiple CubeSats communicate cooperatively together to improve the link performance with respect to the case of a single satellite transmitting. Different approaches will be discussed

NUMERICAL SIMULATIONS OF SPACECRAFT-REGOLITH INTERACTIONS ON ASTEROIDS.

R.-L. Ballouz[1], D.C. Richardson[1], P. Michel[2], and S.R. Schwartz[2], [1]Department of Astronomy, University of Maryland, College Park, USA, [2]Lagrange Laboratory, University of Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, Nice, France.

Introduction: NASA's OSIRIS-REx mission will rendezvous in 2018 with the near-Earth asteroid (101955) Bennu and attempt to touch down and obtain a sample from its surface. The regolith surface's behavior in response to the spacecraft's intrusion is difficult to predict due to the asteroid's extremely low-gravity environment (on the order of 10 micro-g's.) We have been carrying out high-resolution (N > 100,000) numerical simulations of the intrusion of a realistic physical model of the sampling device into a bed of cm-size spherical particles to explore the relationship between the spacecraft's response and the dynamical behavior of the regolith. If the granular bed is too compliant, then the spacecraft may sink into the asteroid. If the granular bed is not compliant enough, then the spacecraft may not be able to obtain an appropriate sample. This is further complicated by the fact that the degree of compliance is also dependent on the material properties of the regolith surface (size distribution, local slope, friction coefficients, shape effects). The ultimate goal of this study is to construct a library of touchdown outcomes as a function of the potential observables (local slope, estimated maximum angle of repose, and to a limited exited particle size distribution). We study the effect of varying the regolith's material properties (cohesive, frictional, and dissipative parameters) in order to place limits on the range of possible outcomes. The library will be useful for sample-site selection based on available observables, and, upon sampling, may aid in interpreting the physical properties of the regolith (e.g., depth and density) by comparing measurements from on-board instruments with simulation data. Preliminary results show that grains with low coefficients of friction (smooth particles) provide little resistance and the spacecraft sinks into the asteroid. For high coefficients of friction (effectively mimicking grain angularity), the regolith is much less compliant, and the spacecraft is only able to penetrate the first few centimeters of the surface layer. This result suggests that for high grain angularity, the regolith directly underneath the sampler is able to shear thicken due to particle interlocking.

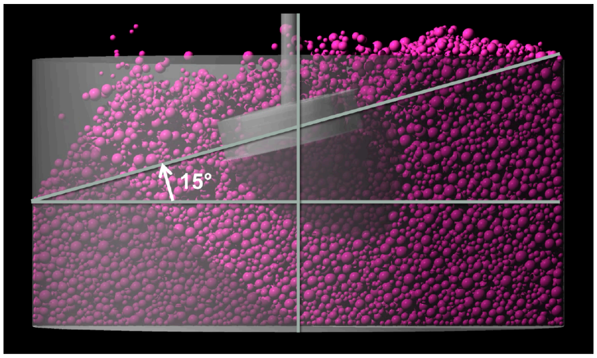

Figure 1 A device penetrates a `gravel'-like regolith with a power law size distribution of particles. The device causes a fluid like splash response of the ejecta, but the material directly underneath the device shear-jams into a solid-like state.

KUIPER: A DISCOVERY-CLASS OBSERVATORY FOR OUTER SOLAR SYSTEM GIANT PLANETS, SATELLITES, AND SMALL BODIES.

J.F. Bell III[1], N.M. Scheider[2], M.E. Brown[3], J.T. Clarke[4], B.T. Greenhagen[5], A.R. Hendrix[6], M.H. Wong[7] and the Kuiper Team, [1]School of Earth & Space Exploration, Arizona State Univ., Tempe AZ (Jim.Bell@asu.edu); [2]Univ. Colorado/LASP; [3]Caltech; [4]Boston Univ.; [5]JPL/Caltech; [6]PSI; [7]UC Berkeley.

Introduction: Kuiper is a Discovery mission concept dedicated to groundbreaking outer solar system science and exploration, with a significant component dedicated to the spectroscopic characterization of Kuiper Belt Objects (KBOs), Centaurs, Trojans, and irregular satellites. Through comprehensive time-domain and statistical population studies of the giant planets, their active satellites, and these important outer solar system small body populations, we will answer key Decadal Survey questions and provide the data sets and results needed to plan the next round of outer solar system New Frontiers and Flagship missions.

Mission Overview: The recent Planetary Decadal process has identified the most important science goals for the study of the outer solar system. However, after the end of the Cassini and Juno missions in 2017, outer solar system science could face over a decade (at least) without new U.S. missions. The Survey thus noted the critical role that space-based telescopic observations, especially those enabling significant time-domain and target coverage, can play in advancing key planetary science questions. We are thus proposing a dedicated planetary space telescope, implementable in the Discovery program, to conduct three diverse Decadal-scale science investigations.

Named after pioneering planetary astronomer Gerard P. Kuiper, the mission will address 9 of the Decadal's 10 Key Questions by studying 1) the giant planets, 2) their major satellites, and 3) key dynamical classes of small bodies that populate the outer solar system. Kuiper's three diverse investigations will enable significant advances in outer solar system science, through time-domain observations and substantial time on the targets. Advances in understanding the connections between weather and climate in giant planet atmospheres, as well as the interactions between giant planet atmospheres, satellites, and their external environments (*e.g.*, auroral, solar wind, plumes, impacts), require consistent, well-calibrated, nearly-continuous observations spanning timescales from hours to years.

Small Bodies Focus: Progress in understanding the ways that small outer solar system bodies can be used to understand the details of early giant planet migration requires compositional knowledge of statistically significant members of key dynamical populations. Observations with the required temporal coverage and fidelity needed to address these and many other important outer solar system Decadal science goals simply cannot be obtained from ground-based telescopes, or existing or planned space telescopes.

Specifically for outer solar system small bodies, Kuiper will conduct a rigorous spectral survey from 400 to 1600 nm of thousands of known outer solar system small bodies from key dynamical populations, including cold classical KBOs; red, hot classical KBOs; very red, hot classical KBOs; less red Jupiter Trojans; red Trojans; Centaurs; and the irregular satellites of the giant planets. Included among this population will be a significant sampling of very small objects (< 50 km diameter), including many down to magnitude V ~ 25.

Science Goals: Kuiper's outer solar system small bodies goal has three primary science objectives:

Smooth Migration vs. Catastrophic Scattering: Did the giant planets migrate smoothly to their present positions or were they catastrophically moved by dynamical instability? Kuiper will trace differences between smooth migration and dynamical instability by mapping (through VIS-NIR spectroscopic parameters) the scattering of the cold classical Kuiper Belt into the resonant & non-resonant populations of the Kuiper belt.

The Kuiper belt-Jupiter Trojan connection: Are the KBOs & Jupiter Trojans derived from the same source populations, as required by a dynamical instability or are they distinct as predicted in slow migration? The Jupiter Trojans and KBOs are currently spectrally distinct. Do the intermediate populations trace a surface evolution allowing us to connect these populations?

Pair-wise accretion vs. gravitational collapse: Did the planetesimal making the small bodies of the outer solar system for from slow pairwise accretion or through fast gravitational collapse? Slow planetesimal accretion builds populations that are then collisionally ground down. Freshly-exposed water ice, a signature of such collisions, should be visible in the fresh surfaces of the smallest bodies

Kuiper's combination of spatial resolution, spectral resolution, far-UV to near-IR coverage, and substantial time-domain sampling will offer an efficient, affordable, and highly relevant facility guaranteed to yield diverse, new insights and to inform planning of *in situ* missions for future decades.

LANDING ON SMALL BODIES: FROM THE ROSETTA LANDER TO MASCOT AND BEYOND.

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Introduction: Recent planning for science and exploration missions has emphasized the high interest in the close investigation of small bodies in the Solar System. In particular in-situ observations of asteroids and comets play an important role in this field and will contribute substantially to our understanding of the formation and history of the Solar System.

Philae

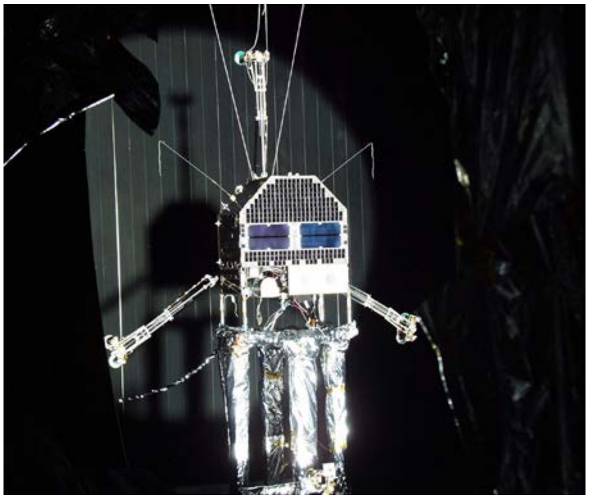

Figure 1: Lander FM (in Thermal-Vacuum Test at IABG,October 2001)

The first dedicated comet Lander is Philae, an element of ESA´s Rosetta mission to comet 67/P Churyumov-Gerasimenko. Rosetta was launched in 2004. After about 6 years of cruise (including three Earth and one Mars swing-by as well as two asteroid flybys) the spacecraft went into a deep space hibernation in June 2011. After approaching the target comet in early 2014, Rosetta was re-activated. The cometary nucleus was characterized remotely to prepare Lander delivery on 12 Nov 2014. The actual landing and first results will be discussed, with an emphasis on technology and sampling.

The Rosetta Lander was developed and manufactured, similar to a scientific instrument, by a consortium, consisting of international partners. Project management is located at DLR in Cologne/Germany, with co-project managers at CNES (France) and ASI (Italy). Mainly scientific institutes provided the subsystems, instruments and the complete, qualified lander system. Operations is performed in two dedicated centers, the Lander Control Center (LCC) at DLR-MUSC and the Science Operations and Navigation Center (SONC) at CNES. This concept was adopted to reduce overall cost of the project and is foreseen also to be applied for development and operations of future small bodies landers.

MASCOT

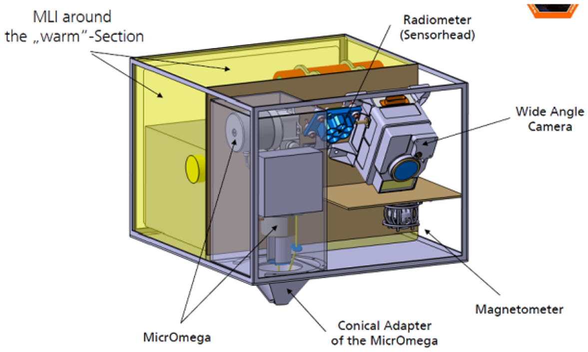

Figure 2: MASCOT design; overall dimensions are 295x275x195 mm^3

A mission profiting from experience gained during Philae development and operations is MASCOT, a proposed surface package for the Japanese Hayabusa 2 mission. MASCOT is a small (~10 kg) mobile device, delivered to the surface of asteroid 1999JU3 that will operate there for about 16 hours. During this time a camera, a magnetometer and an analytical instrument will be operated to provide ground truth and even support the selection of possible sampling sites for the main spacecraft. MASCOT is a flexible design that can be adapted to a wide range of missions and possible target bodies. Also the payload is flexible to some extent (with an overall mass in the 3 kg range). The first MASCOT was launched aboard JAXA's Hayabusa-2, on 30 November 2014 and is currently on its way to asteroid 1999 JU3. Landing is in the 2018/2019 timeframe.

Sampling:

Currently we study advanced sampling landers for small bodies in the ~100 kg mass based on the Philae and MASCOT heritage and experience. A few concepts will be presented.

High-Resolution Bistatic Radar Imaging in Support of Asteroid & Comet Spacecraft Missions. M. W. Busch[1], L. A. M. Benner[2], M.A. Slade[2], L. Teitelbaum[2], M. Brozovic[2], M.C. Nolan[3], P.A. Taylor[3], F. Ghigo[4], J. Ford[4], [1]SETI Institute, 189 Bernardo Ave Suite 100, Mountain View CA 94043 USA; mbusch@seti.org , [2]Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena CA 91109 USA, [3]Arecibo Observatory, PR-625, Arecibo PR 00612 USA, [4]National Radio Astronomy Observatory, P.O. Box 2, Rt. 28/92, Green Bank WV 24994 USA.

High-resolution imaging of potential targets in advance of any spacecraft mission is important for reducing mission cost and risk and improving science returns. In particular, ground-based radar imaging provides highly-accurate ephemerides and shape and spin state information for objects that pass near the Earth. At higher resolution, radar images show surface features such as boulders and potential fissures and constrain internal structure. Examples of radar observations of objects prior to spacecraft arrival include Itokawa [1], Bennu [2], Toutatis [3,4,5], and 103P/Hartley 2 [6].

Recent upgrades to the Deep Space Network (DSN) Goldstone Solar System Radar allow the transmitted waveform to be modulated at up to 40 MHz [7], providing resolution as fine as 3.75 m in line-of-sight distance for nearby targets, primarily near-Earth asteroids (NEAs). Bistatic observations, transmitting with an antenna at Goldstone and receiving with either another Goldstone antenna or a larger antenna such as the Arecibo Observatory or the Green Bank Telescope, give the highest possible sensitivity combined with high resolution. High-resolution bistatic radar imaging has revealed spin state changes for Toutatis and the presence of boulders on many NEAs. Examples include 2005 YU55 [8], Toutatis [9], Duende (2012 DA14) [10], and 2014 HQ124 [11].

In the near future, a new high-resolution transmitter on Goldstone's DSS-13 antenna will be able to transmit a signal modulated at 80 MHz, improving line-of-sight resolution by a factor of two to 1.875 m. This will allow many new projects: seeing previously-invisible surface details; measuring the size distributions of boulders and craters on NEAs; obtaining better estimates of the masses and densities of asteroids from radiation pressure perturbations to their trajectories; and further improved trajectory predictions for small spacecraft targets.

As with the current 3.75-m-resolution system, the new high-resolution transmitter will provide the best scientific results when operated in bistatic mode with a large antenna as the receive station. Equipment recently installed at Arecibo and scheduled for installation at Green Bank by early 2015 is able to record 80-MHz-coded radar echoes.

Somewhat further into the future, a 1.875-m-resolution transmitter may be installed on a 34-m antenna at the DSN's Canberra complex [12]. Although less sensitive than bistatic observations between Goldstone and Arecibo or Green Bank, this would allow radar detection of objects in the far southern sky, which current radars cannot see. It would facilitate rapid follow-up of newly discovered radar targets and of small NEAs making very close flybys, which move very quickly across the sky at closest approach, preventing those objects from being lost.

These new capabilities for high-resolution radar imaging will further improve characterization of potential mission targets.

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ASTEROID AND COMET SURFACE GRAVIMETRIC SURVEYING CAN REVEAL INTERIOR STRUCTURAL DETAILS.

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Introduction: Surface gravimetry is a standard terrestrial geophysics exploration technique. As nothing blocks gravity, this approach can detect subsurface structures with contrasting densities, both shallow and deep. This is used to infer local geological structural details. In the exploration of other planetary bodies, the only surface gravimetric measurements taken to date have been on the Lunar surface, during several Apollo missions, including a traverse comprising 22 gravity measurements during Apollo 17 [1], [2], [3]. Here we discuss the application of this technique to asteroids and comets. Due to the small sizes of some of these bodies, global surface gravimetric surveys are practical with a suitable lander/roving spacecraft, and such surveys could provide otherwise-unobtainable information about the complete internal structure of such a body. A suitable gravimeter is in development, and its capabilities are discussed here, along with those of a lander/rover designed to carry that instrument.

Gravimetric Surveying Applications on Asteroids and Comets: Several applications of asteroid and comet surface gravimetry have been identified. One is to determine the mass of such a body. By landing a suitable gravimeter on the surface, a single measurement determines local gravity plus effects due to the body's rotation. Assuming the location of the lander on the body and the body's rotational state is measured by other means, the body's mass is easily determined. This is discussed in [4] and [5].

Also discussed in [4] is a method of estimating the mass of a boulder on the surface of an asteroid or comet, by making a series of vector gravity measurements at various distances from the boulder, and comparing the deviation of the local vertical relative to the estimated vertical direction absent the boulder. This follows much the same method used by Maskelyne in "weighing" the mountain Schiehallion in 1774 [6]. On an asteroid or comet the compensation for surface topography will be very different than on Earth; a whole-body shape model will likely be necessary to estimate the topographical gravity signal adequately.

Finally, [4] and [5] both discuss carrying out whole-body surveys on asteroids, by landing a vector gravimeter on such a body in a spacecraft capable of roving about that body's surface, and making measurements at a large number of well-distributed measurement stations. Both scientific and resource-prospecting information can be gained thereby.

Extrapolating From Terrestrial Gravimetric Surveying: The basic elements of terrestrial gravimetric surveying carry over to the asteroid/comet case --- making measurements at multiple survey station locations on the surface using a suitable gravimeter instrument, then developing a model of a subsurface density distribution which is consistent with the measurements. (There is no analogue for terrestrial airborne gravimeter surveying around such bodies, as they lack an atmosphere to support an airborne vehicle in a non-ballistic trajectory, and on a ballistic trajectory a gravimeter gives a zero reading.) However, environmental differences (e.g., very low gravity) drive differences in gravimeter requirements, and these drive changes in instrument design. Also, an asteroid/comet surface gravimeter would need to be carried within a spacecraft capable of roving the surface of such a body, which would be very different from the means used for transporting and supporting terrestrial gravimeters. Further, the extremely rugged topography of such bodies, compared to that of the Earth, leads to alternate approaches for compensating for the topographical gravity signal.

Equipment Needed: Gedex's VEGA (*VEctor Gravimeter for Asteroids*) instrument, in development, will make vector gravity measurements with an absolute accuracy of 1-10 nano-G on bodies whose gravity is in the sub-milli-G range; it has a mass of 1.5 kg, and dimensions of 10x10x15 cm. Gedex and the Space Flight Laboratory at the University of Toronto have developed an initial design for a 15 kg, 25 cm cube lander/tumbling-rover (GRASP, for *GRavitational Asteroid Surface Probe*) capable of carrying a VEGA instrument to a small asteroid, supported by a mothership, and conducting gravimetry surveying operations.

Survey Data Processing and Interpretation: Using auxiliary data from other instruments, gravity due to subsurface density variations will be distinguished from topography-signal and rotation effects. Inversion will be used to infer interior density distribution from the gravity measurements.

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DECADAL SURVEY AND EXPLORATION SCIENCE WITH NEXT GENERATION LOW COST SMALL PLATFORMS.

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Most of the key science priorities of the Planetary Science Decadal Survey rely on observations that involve sampling or close proximity observations of a variety of bodies. These observations address chemistry responsive to origin science and habitability as well as observational strategies for deep interior probing via internal or field geophysics. Increased interest in the reconnaissance of small bodies for Human exploration, planetary defense, and in situ resources calls for in situ chemistry and geophysics measurements as well as approaches to probe small body soil properties for geotechnical assessment.

Major progress in the miniaturization of instruments and subsystems is opening the door to novel architectures for in situ observations and multi-site field measurements. High science return per dollar architectures may be approached via scalable and modular platforms to enable a range of science objectives. Following the footsteps of Earth-observing Cubesats, a number of recent concepts have been exploring the potential for Cubesats to return science grade observations at a variety of bodies, either as independent or as secondary platforms. Concepts so far cover multi-site magnetic and gravity field sampling, atmospheric probing, high-resolution imaging, and strategic knowledge gap specific packages (imaging, dosimeter, dust analyzer, etc.)

Low cost landers are also gaining momentum, starting with the MASCOT lander developed by the German space agency, the Hedgehog lander developed by Stanford and JPL under NASA's Center Innovation Fund and NASA Institute for Advanced Concepts, minimalistic lander concepts developed at JPL, as well as penetrators and biology inspired concepts.

Key to the exploration with small platforms is the miniaturization of science grade instruments that retain high performance despite highly constrained resources and short lifetimes. Small instruments for a variety of applications are gaining maturity, especially instrumentation for geophysical probing. The development of techniques for sampling material in low gravity environment, such as laser-excited spectrometry decreases the need for mechanically heavy and power intensive sampling techniques.

Algorithms for onboard data processing and triage allow increasing the science value per bit and can help select observation and sampling sites when conditions limit the pace of ground involvement.

This presentation will review the state of the art in small instruments and science operations in the context of reconnaissance mission concepts for the Human exploration of near earth asteroids and Mars' moons and environment.

Acknowledgements: Part of this work is being developed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. The Hedgehog project is supported by NASA's Institute for Advanced Concepts.

A FIBER-COUPLED PLASMONIC SPECTROMETER FOR IN SITU CHARACTERIZATION OF ASTEROIDS.

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Introduction: We discuss the development of a novel plasmonic spectrometer for the *in situ* characterization of asteroid surface and subsurface environments. This instrument will be used to distinguish between various asteroid types (ordinary chondrites, carbonaceous chondrites, metallic, and basaltic) using optical and near-infrared (NIR) reflectance spectra, as well as to examine surficial deposits of potential interest for *in situ* resource utilization (ISRU). The spectrometer will be coupled to a probe via optical fibers, and thus can be used for surface measurements as well as the study of compositional variations with depth.

Technology Description: We are considering a multifaceted approach where we explore illumination and light gathering strategies for on- or near-surface studies of asteroids using optical fibers. The gathered light will then be sent to a plasmonic spectrometer designed using the principles of extraordinary optical transmission. This design enables the transmission of light through subwavelength apertures that have been patterned in a metallic film with a regularly repeating periodic structure. The interaction of light with the metal surface results in excitation of electrons and the formation of a surface plasmon. The regularly spaced structure on the surface enables much higher transmission efficiency as a result of constructive interference due to the presence of surface plasmon resonances. An array of these apertures will be used for wavelength discrimination and the acquisition of a spectrum (Fig. 1). We will explore both the optical and near-infrared spectral regions in order to fully characterize an asteroid surface spectrum with a resolving power ($\lambda/\Delta\lambda$) of greater than 2000.

Using a nanoscale optical/NIR spectrometer on a probe will enable the identification of volatiles, organics, and metals of interest for ISRU. Furthermore, depending on the porosity of the asteroid's surface, such a probe could be used to make measurements on and below the surface to explore the variation of volatile composition with depth. A NIR version of our proposed plasmonic spectrometer could cover 1.5 to 3.5 µm to provide access to organic absorption features. Water and OH also have absorption bands in this spectral region (OH stretch at 1.4 µm, H_2O bend at 1.9 µm, and a fundamental vibrational overtone of H_2O at 3 µm, which is the strongest of the three). Until fairly recently water ice was not thought to exist in large quantities in the Asteroid Belt. However, 2.2 – 4.0 µm spectra of 24 Themis are well fitted by a mixture of ice-coated pyroxene grains and amorphous carbon [1], suggesting that water ice is more prevalent in the Asteroid Belt than previously thought. Obtaining signatures of OH and/or H_2O ice or admixtures is critical for ISRU applications, and will be enabled with this proposed technique.

Results: We will present numerical modeling results showing the anticipated sensitivity levels of a plasmonic spectrometer as related to asteroid reflectance spectra. We will also present a mission scenario with a notional concept of operations to demonstrate the utility and functionality of such an instrument for ISRU interests.

References: [1] Rivkin, A. S. and Emery, J. P. (2010) *Nature 464*, 1322.

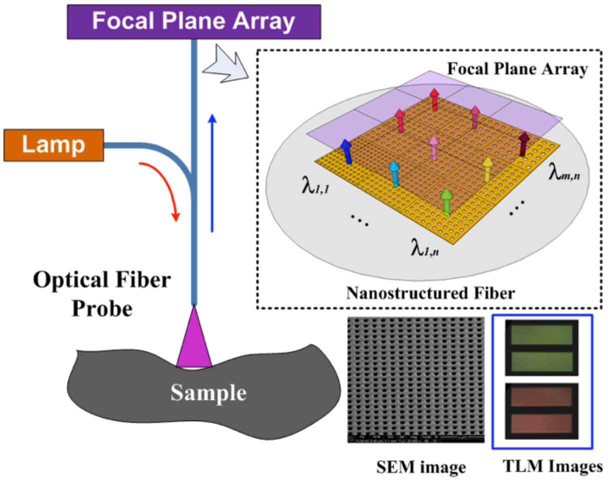

Figure 1. Schematic drawing of the plasmonic spectrometer. At lower right is an SEM image of a 2D grating fabricated by co-author Cho's group for photon-SPP conversion. Additionally, two transmitted-light-microscope (TLM) images of the fabricated nanostructures show wavelength-selective optical transmission.

A Kinetic Impactor Technology Demonstration Option for the BASiX Mission. S. R. Chesley[1], D. J. Scheeres[2], P. A. Abell[3], E. Asphaug[4], and D. S. Lauretta[5], [1]Jet Propulsion Laboratory, Calif. Inst. of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, [2]Univ. Colorado, Boulder, CO, [3]NASA Johnson Space Center, Houston, TX, [4]Arizona State Univ., Tempe, AZ, [5]Univ. Arizona, Tucson, AZ.

Introduction: We propose to fly a kinetic impactor demonstration in concert with the proposed BASiX Discovery mission. BASiX is a mission proposal to visit binary asteroid (175706) 1996 FG3 and perform repeatable geophysics experiments in order to reveal the geotechnical properties of a rubble pile asteroid and understand the dynamical evolution of a binary asteroid system. A key mission objective for BASiX is the delivery of small high-explosive BlastPods to the asteroid's surface that would be used to probe the mechanical properties of the surface and subsurface materials.

The proposed kinetic impactor spacecraft would launch with the BASiX mission as a secondary payload. The BASiX Impactor would separate immediately after launch and continue on its own trajectory to an impact with the secondary body of 1996 FG3, arriving after BASiX has completed its baseline mission at the asteroid. The concept is similar to the ISIS mission concept that proposed to use the OSIRIS-REx spacecraft to observe an impact at that mission's asteroid target (101955) Bennu [1].

An ambitious TDO: The BASiX Impactor is to be proposed as a Technology Demonstration Option (TDO) as a part of the BASiX Discovery proposal. The 2014 Discovery Announcement of Opportunity (AO) states that TDOs must be clearly separable from the primary mission in the event that the TDO is not selected or the development does not conclude successfully. The BASiX Impactor concept certainly fulfills this requirement because the two spacecraft are built and delivered to the launch pad separately. And even late in development the impactor can be eliminated or replaced with a mass simulator. After the post-launch separation, BASiX carries out its entire primary mission without reference to the impending arrival of the kinetic impactor.

The Discovery AO also indicates that TDOs should demonstrate relevant technologies that may enhance the host mission's science or that of future missions. The BASiX Impactor TDO would demonstrate two key technological abilities, namely precision terminal guidance and asteroid deflection techniques. While the technology for a hypervelocity impact with targeting accuracy ~50 m is available, it has yet to be demonstrated in an interplanetary environment. And measuring an asteroid's change in velocity in response to such an impact would dramatically improve confidence in our technical ability to perform a real-world asteroid deflection.

Schedule: The BASiX Impactor TDO would launch with BASiX in Dec. 2020. BASiX arrives at 1996 FG3 in May 2024 and conducts its prime mission, including Science Enhancement Activities for nine months, concluding in Feb. 2025. The impactor arrives in June 2025 with an arrival mass of 600 kg and an impact velocity of 16 km/s. This translates to 78 GJ of kinetic energy (19 t TNT equivalent).

Objectives: The BASiX Impactor would significantly extend the science returns of the BASiX mission by anchoring two points on the energy curve. A BlastPod explosion would release an energy of 20 MJ, enough to create a crater up to several meters in diameter, while the BASiX Impactor would release 4000× more energy and would create a 10× larger crater. The experiment would be a direct and immediate test of the knowledge gained from the primary mission. The prime mission is focused on the primary body, and the Impactor would extend the knowledge to the secondary with a much deeper look into the interior.

The impact would also induce seismic waves that travel through the body and reflect off boundaries. This would induce lower energy disturbances far from the impact site, providing a seismic experiment that may loft material, cause landslides and topple boulders across the body. The comparison of pre- and post-impact imagery would provide strong constraints on the local and global stability of rubble pile asteroid surfaces.

The impact would also induce a change in velocity of the target asteroid of roughly 0.12 mm/s. This effect would be readily detectable as a change in the binary system mutual orbit, and thus would reveal the amount of momentum enhancement derived from escaping ejecta, a key question for planetary defense applications.

Conclusion: The BASiX Impactor TDO would lead to significant science enhancement and provide the first-ever asteroid deflection demonstration. By utilizing an already-present observer spacecraft it would leverage significant NASA investments for a dramatic gain in our understanding of how asteroids respond to kinetic impactor deflections.

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MECHANICAL PROPERTIES OF ASTEROID MATERIALS: CLUES FROM ANALYSIS OF SPACECRAFT IMAGES AND RESULTS FROM LABORATORY EXPERIMENTS.

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Introduction: To the extent that the morphology and bulk mechanical behavior of surface rocks and regoliths of small asteroids might be representative of the materials and mechanical properties of the interiors of these small objects, study of regoliths and regolith analogs can provide important information relevant to planning for future spacecraft operations there.

Coefficient of Restitution of Eros' Regolith: Ejecta blocks represent the coarsest fraction of Eros' regolith and are important, readily-visible, 'tracer particles' for crater ejecta-blanket units that may be linked back to specific source craters, thus yielding valuable information on physical properties of Eros (e.g., regolith structure and target strength) and constraining various aspects of impact cratering in low-gravity environments (e.g., ejecta mass/speed distributions and amount of retained ejecta). Dynamical models [1,2] show that the combination of irregular shape and rapid rotation of an asteroid can result in markedly asymmetric ejecta blankets (and, it follows, ejecta block spatial distribution), with locally very sharp/distinct boundaries. Counts of boulder number densities in NEAR-Shoemaker MSI images across a portion of a predicted sharp ejecta-blanket boundary associated with the crater Valentine confirm a distinct and real ejecta-blanket boundary, significant at least at the 3-sigma level [3]. The same numerical dynamical model can be used to 'back track' the landing trajectories of ejecta blocks with associated landing tracks in an effort to constrain potential source regions where those blocks were ejected from Eros' surface in impact events. The observed skip distances of the blocks upon landing on Eros' surface and the landing speeds and elevation angles derived from our model allow us to estimate the coefficient of restitution, ε, of Eros' surface for impacts of 10-m-scale blocks at ~5 m/s impact speeds. We find mean values of ε of ~0.09–0.18.

Fracture Mechanics of Meteorite Samples: The 'strength' or 'threshold collisional specific energy', which is the energy required to disrupt the target such that the largest fragment has 50% of the mass of the target (a parameter called Q^*_D), is frequently used in modeling the effects of impacts on asteroids. Q^*_D is derived from the best fit to the power-law plot of the relative mass of the largest fragment ($M_{largest}/M_{total}$) versus impactor specific energy for a suite of impact experiemtns resultd for a particular target material. Impacts into nine anhydrous meteorite targets produced a value of ~1400 J/kg for Q^*_D [5] while Q^*_D falls in the range from ~700 to 800 J/kg for collisions into non-porous glass, basalt, and granodiorite targets. This result, that anhydrous meteorites are twice as strong as terrestrial basalt, was confirmed by [6] who performed a series of impacts on a single 464 gm sample of an ordinary chondrite meteorite and found that this anhydrous meteorite was significantly stronger than the two gabbro targets they disrupted under similar conditions. It is important to determine the mechanical/physical properties of the asteroids by measurements on actual samples of the asteroids, the meteorites, rather than using values obtained on terrestrial rocks in modelling asteroid cratering and disruption.

Laboratory Experiments with Cohesive Powders: We are conducting laboratory experiments to investigate the role of cohesion in governing regolith processes and geomorphological expression on small solar system bodies [7]. Our goals are to develop an improved understanding of the geomorphological expression of granular media in the microgravity environments of regoliths on small asteroids and to quantify the range of expected mechanical properties of such regoliths. In addition to examining and quantifying the morphology of faults and fractures in columns and piles of various cohesive powders used as regolith simulants, and the angles at which slope failures occur, we have to date noted with interest that the talus slopes resulting from the collapse of the columns and piles often contain a number of distinct 'boulders' formed from self-cohesed 'clods' of the powder material. The superficial resemblance of these 'boulders' to the coarse fraction of the regolith in regions of the surfaces of Eros and Itokawa suggests that some care be applied in interpreting all such large fragments on these objects as necessarily composed of competent hard rock.

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PSYCHE: JOURNEY TO A METAL WORLD.

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Visiting an iron core. We propose to visit the exposed iron core of a protoplanet by sending a mission [1] to (16) Psyche, by far the largest exposed iron metal body in the asteroid belt. At Psyche we will explore, for the first time ever, a world made not of rock or ice, but of iron (Fig. 1).

This mission would be a journey back in time to one of the earliest periods of planetary accretion, when the first bodies were not only differentiating, but were being pulverized, shredded, and accreted by collisions.

Of all the bodies we can reach, this one offers a unique window into this violent history. Orbiting in the outer main belt at 3 AU, 16 Psyche is large (240 x 185 x 145 km), dense (as high as 6 g/cm^3), and made almost entirely of metal (Fe-Ni, based on radar and spectra) [2-7].

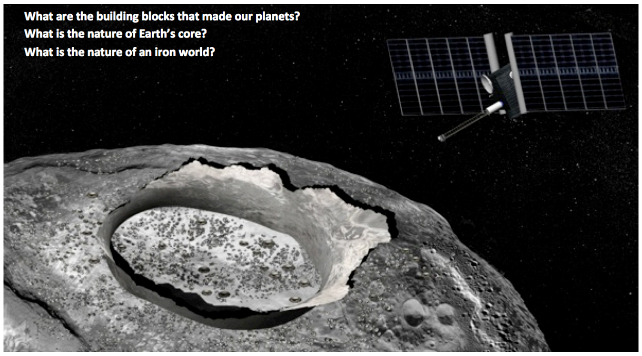

Figure 1: *Artist's conception of an orbiter around (16) Psyche. Impacts into metal will likely differ from those into silicates or ice; here frozen ejecta flaps are envisioned, though we cannot know what will be found at Psyche. Abundant compressional scarps are expected because of the high contraction of iron when it freezes. (JPL/Corby Waste)*

Planetesimals that formed earlier than about 1.5 to 2 Ma after the first solids in the solar system had sufficient heat from short-lived radionuclides to differentiate into a metallic core and a silicate mantle.

Models show that among the abundance of collisions, some destructive "hit and run" impacts could strip differentiated bodies of their silicate mantle, leaving an exposed metal core [8, 9]. The leading hypothesis for (16) Psyche's identity results from this scenario: a bare planetary core dating from the formation of the solar system.

Studying Psyche in situ offers the planetary science community a unique chance to learn how cores form and solidify by measuring their composition and magnetic state as frozen at an intermediate stage of the planet formation cycle.

The surviving metal core may have been molten before stripping, and may also have been melted by the impacts that stripped it or by later impacts. A melted core may produce a core dynamo and attendant magnetic field as it cools. Iron meteorite compositions indicate that protoplanet cores in some cases crystallized from the inside out (like the Earth's core), and in others from the outside in [10-12]. A body stripped of its mantle is most likely to cool from the outside in.

We expect to be able to determine how this body solidified. Only crystallization from the outside in would produce material below its Curie point during the period of dynamo action and thus capable of becoming magnetized. Fractional solidification should produce a measurable signal in nickel in the metal.

Fundamental advances in understanding planetary formation and interiors. The science questions this mission will address are:

1. Understand a previously unexplored component of the building blocks of planets and life: the iron cores of differentiated bodies. What are the earliest cores made of? How do they solidify? Do they produce magnetic fields?
2. Look inside the terrestrial planets, including Earth, by directly examining the building blocks of a differentiated body, which otherwise could not be seen. What light elements are included in the metal? What is its oxidation state?
3. Explore a new type of world. For the first time, examine a world not made of rock or ice, but of iron. What are the tectonics of a metal world?

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PASSIVE ASTEROID RADIO TOMOGRAPHY WITH THE JUPITER-IO CMI T. Marshall Eubanks, Asteroid Initiatives LLC, Clifton, VA, USA (tme@asteroidinitiatives.com)

Introduction: An important goal in the *in situ* exploration of asteroids by spacecraft is the determination of not just the surface characteristics of a target asteroid, but also its interior structure, such as density, porosity and compositional changes at depth. Information about the complex dielectric constant along a ray-path, which is related to these quantities, can be determined by monitoring the transmission and reflection of High Frequency (HF) radio waves in the band 1 - 40 MegaHertz (MHz), as has been demonstrated by numerous terrestrial Ground Penetrating Radars (GPRs) and in space by the MARSIS (1.3 - 5 MHz) and SHARAD (15 - 25 MHz) radar systems currently in orbit around Mars. While these radars have a demonstrated ability to image 100s of meters beneath the Martian surface, they are optimized for Martian orbit conditions, which are largely not applicable to missions to small Near Earth Asteroids (NEA). MARSIS and SHARAD operate $\sim$300 km from the Martian surface, andx are fairly large and power-intensive (SHARAD uses a 10 W transmitter and MARSIS requires 60 watts total DC power).

For a solar sail powered mission to a 50-meter diameter NEA the spacecraft will not be able to stop with respect to the target, so that any reconnaissance will be done as a series of close flybys. A smaller "cubesat" type spacecraft with solar sail propulsion, such as the the Near Earth Asteroid (NEA) Solar Scout [1], will not be able to afford the power budget of a typical GPR, or the mass and complexity required for a two spacecraft bistatic radar system such as the CONSERT system operating between Rosetta and Philae. This paper will explore another possible solution for internal imaging of small bodies, Passive Asteroid Radio Tomography (PART) using a coherent natural radio source, the Jovian Io-DAM, which has also been proposed as the source for passive reflectometry of subsurface oceans on Europa and the other Galilean satellites[2].

Radio Emissions from the Jovian Cyclotron Maser Instability: The Jupiter Io-Decametric radiation (Io-DAM) are the strongest radio emissions from Jupiter, with an $\sim$30 MHz emission bandwidth [3], a typical power of $\sim 2 \times 10^{11}$ W and short duration "S-burst" power up to $\sim 10^{13}$ W at peak [4]. The Jupiter S-bursts are thus an interesting possible radio source for PART. These bursts are predictable, circularly polarized, strong ($\sim 10^5$ Janskies (Jy) as seen from a NEA orbit), naturally chirped in frequency, and very coherent, with brightness temperatures $> 10^{10}$ K. The Jovian S-bursts are strong enough to provide good reception with a simple dipole antenna here on Earth, and thus in the vicinity of a NEA.

CMI sources emit radiation in a fairly narrow cone, and can thus only be seen when this emission cone illuminates the observer. This leads to a periodic emission with a fairly small duty cycle (the fraction of time, typically expressed as a percentage, in which a source is active). The UCD sources have duty cycles from 5% to 30%, similar to that of Jupiter's 14%; the rapidly rotating UCDs are thus radio loud for some minutes or tens of minutes every 2-3 hr and the Io-flux tube is radio-loud for $\sim$6 hr every 42.5 hr [5]. The existence of a CMI duty cycle, plus the variability of emission strength between cycles, implies that a single radio observation of a particular region of the sky would not necessarily detect a nearby nomadic planet in that region; observations will have to be repeated to detect all of the nomadic planet CMI down to the radio flux density limit.

Jupiter Io-DAM PART: As would be expected with such high brightness temperatures, VLBI observations of the S-bursts shows that they are quite coherent, emitted by areas $\sim$400 km across in the Jovian auroral regions [6]. Such coherent emissions would support interferometric phase referencing between multiple antenna, but with a coherence length of order a few Earth radii, the phase references would need to be located close together. Clearly, the minimal PART solution would involve multiple antennas located in close proximity, e.g., dipoles deployed on opposite ends of a solar sail. As the DAM is circularly polarized, the use of either crossed dipole antennas or circularly polarized helical antennas may offer advantages. Work is on-going to determine the tradeoffs between the number and deployment of antennas and the computational requirements for tomography.

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THE PHYSICAL PROPERTIES OF METEORITES AND INTERPLANETAERY DUST PARTICLES: IMPLICATIONS FOR THE PROPERTIES OF STONE ASTEROIDS.

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Introduction: Most asteroids for which porosities have been inferred have porosities ranging from 20% to >50%, with a mean of ~30% porosity [1]. Porosity significantly affects the physical properties of rocks, including the strength, thermal conductivity, seismic velocity, and dielectric permeability. Some asteroids have high enough porosities to affect their internal structure, gravitational field, response to impacts, and collisional lifetimes. This suggests modeling the behavior of asteroids using the physical properties of low- to moderate-porosity terrestrial rocks is not appropriate. Most/all stone meteorites and a significant fraction of interplanetary dust particles (IDPs) are believed to be fragments of asteroids, with some IDPs sampling comets. Thus, the physical properties of meteorites and IDPs provide indications of the properties of their parent asteroids [2]. Thermal evolution modeling indicates that, within each group (H, L, or LL) of ordinary chondrite meteorites, increasing thermal metamorphism correlates with increasing formation depth in ~100^+ km diameter parent asteroids [3], so these meteorites permit determination of properties of asteroids at depths ranging from the near surface to the deep interior.

Effects of Porosity: Meteorites generally exhibit significant porosity, with three distinctly different types of porosity, cracks, gaps, and vugs, identified by computed microtomography and examination of thin sections. Specific classes of meteorites are associated with different types of asteroids based on similarity of visible and near-infrared reflection spectra, However, the mean porosity of ordinary chondrite meteorites is lower than that of the associated S-type asteroids and the mean porosity of carbonaceous chondrite meteorites is lower than that of the C-type asteroids. This indicates meteorites do not sample the entire range of porosity observed in asteroids – in particular, the highest porosity material is missing in the meteorite population.

Strength. Porosity reduces the compressive, tensile and sheer strengths of rocks. While the compressive strengths of the strongest ordinary chondrite meteorites are comparable to low-porosity terrestrial basalt (100 - 300 MPa), meteorite measurements span a much wider range. Some highly metamorphosed ordinary chondrites, potentially sampling deep interiors of asteroids, have very low compressive strengths -- 20 MPa for the L5 Elenovka [4] and 6 MPa for the L6 Holbrook [5].

An alternative measure of strength is the response to hypervelocity impact, characterized by the parameter Q^*_D, the impactor energy per unit target mass producing a disruption with the largest fragment being one-half the target mass. Energy that goes to compressing voids is not available for disruption, so porous targets require more energy per unit mass for disruption than non-porous ones. Q^*_D for 9 ordinary chondrites is ~1400 J/kg [6], about twice that of non-porous basalt.

Speed of Sound and Shock Attenuation. As expected, the speed-of-sound decreases with increasing meteorite porosity [7]. However the speed-of-sound is also affected by the type and distribution of porosity, particularly cracks. Two samples of the Saratov L4 ordinary chondrite gave significantly different sound speeds – 2357 m/s for a normal sample and 1320 m/s for a sample exhibiting a well-developed crack [2].

Shock is attenuated over a much shorter distance in porous rocks [8, 9] and x-ray tomography after hypervelocity cratering of pumice showed no detectable alteration of texture outside the crater [9]. Rapid attenuation of shock waves and variation of sound speed with local crack density will hamper efforts to characterize interiors of highly porous asteroids by seismic studies.

Thermal Properties: Modeling thermal evolution requires the thermal conductivity and heat capacity. Thermal conductivity and porosity of stone meteorites are strongly correlated [10], while the heat capacity of ordinary chondrites is similar to quartz [11].

Conclusions: Meteorites and IDPs constrain the physical properties of asteroids. However, meteorites likely sample only part of the range, with IDPs sampling higher porosity. Atmospheric deceleration fragments the weakest meteors, since strengths of stone meteors, inferred from breakup dynamics, are only 1/10th to 1/100th the strengths measured on stone meteorites of the same class [12]. This may explain why the mean porosity is lower for meteorites of a given class than for asteroids having a similar reflection spectra.

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Design of Lander Pods for Near Earth Asteroids.

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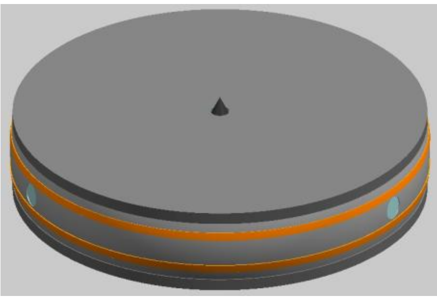
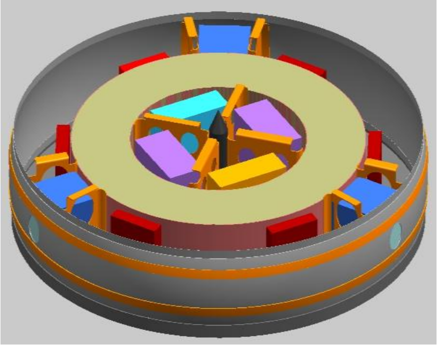
The Small Bodies Assessment Group conducted a study in 2012 to identify critical SKGs for Exploration of Small Bodies, primarily near-Earth objects (NEO) and Phobos and Deimos. This SBAG study was motivated by the 2011 Global Exploration Roadmap, by the International Space Exploration Coordination Group, which focuses on the “Asteroid Next” scenario in the context of enabling Human Mars Exploration. Many of these SBAG SKGs may be addressed by small landing Pods that may be placed on the NEAs or moons of Mars for *in situ* investigation.

We have been developing the concept and preliminary design for a set of Pods that could be deployed from a spacecraft bus orbiting a Near Earth Asteroid (NEA). These Pods would not have an active propulsion system, but rather would be deployed by springs to cancel the orbital velocity of the spacecraft. Several Pods, each of ~20 kg mass, would then slowly descend to the surface over a period of a couple of hours. The impact velocity is small, about equivalent to a laptop computer sliding off its owner’s lap; the Pods would be ruggedized to withstand such an impact. Pods would be flat, pancake shaped, and symmetrical, so that it does not matter which side is facing up.

One of the main science goals from the seismic experiment is to determine the interior structure of the asteroid, whether as a solid body or a “rubble pile”. The other goal is to expose fresh unweathered regolith from the cratering for spectrographic mineralological mapping. The third goal is to characterize surface dust and plasma. The orbiting spacecraft would provide radio relay for 40 kbps signal from the Pods.

The Pods would have instrumentation to investigate both the interior structure and the regolith of these asteroids. Cameras with micro-lens would obtain microscopic images of the regolith particles; a Langmuir Probe would investigate the electric field and plasma environment at the surface, and the mechanism of electrostatic charging and levitation of dust particles. Each Pod could carry ~10 kg of PETN explosive material. The detonation would send seismic signals through the interior of the asteroid, to be recorded by sensitive accelerometers on the other Pods. The orbiting spacecraft would then observe the resulting crater, for spectroscopic images of the freshly exposed regolith.





NEA SCOUT: A CUBESAT ARCHITECTURE TO CHARACTERIZE NEAR-EARTH ASTEROIDS.

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Abstract: Emerging nano-spacecraft concepts and capabilities, including advanced telecommunications, radiation tolerant avionics, and propulsion systems, are enabling unique opportunities to affordably characterize near-Earth asteroids (NEAs). Known or newly discovered NEAs periodically return to Earth's vicinity, resulting in a diverse pool of potential exploration targets that constantly changes over the course of a just a few years. While this population of NEAs is relevant to human exploration, planetary science, planetary defense, as well as in-situ resource mining, these potential exploration targets are often too small and faint to be effectively characterized with Earth-based assets. Furthermore, no asteroids significantly smaller than 500 m in (average) diameter have been closely observed, leaving uncertainties about their morphology, composition, environment, and dynamics. This makes the case for proximity observations of NEAs with a small, affordable, and repeatable platform extremely compelling. Sponsored by NASA's Advanced Exploration Systems program, NASA's Marshall Space Flight Center (MSFC) and Jet Propulsion Laboratory (JPL) are jointly developing the NEA Scout mission to become a pathfinder for such observations using a "6U" CubeSat bus (<12 kg launched mass) propelled by a solar sail and equipped with a science-grade visible imager. Exploration science objectives include the determination of an NEO physical properties (size, rotation), local environment, geomorphology, and color class typing. JPL is developing the NEA Scout flight system, building on JPL's INSPIRE spacecraft which is slated to become the first CubeSat operating in deep space. MSFC is providing the ~85 m^2 solar sail, based on the NanoSail-D2 mission which demonstrated a CubeSat-deployed solar sail in 2011, as well as the Planetary Society's upcoming LightSail mission. NEA Scout is expected to launch as a secondary payload aboard Exploration Mission 1 (EM-1) of the Space Launch System (SLS) sometime between December 2017 and November 2018. The reference mission for NEA Scout is a slow (<20 m/s), close (<1 km) flyby of asteroid 1991 VG, although other viable targets exist depending on ultimate launch conditions, as well as potential new discoveries.

Acknowledgements: This work is being developed at Marshall Space Flight Center and the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

INVESTIGATING THE EFFECTS OF COSMIC RAY EXPOSURE ON AMINO ACIDS IN METEORITES: IMPLICATIONS FOR FUTURE SMALL BODY SAMPLE RETURN MISSIONS.

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Introduction: Carbonaceous chondrites represent a very primitive class of meteorites that contain 2-5 wt% organic carbon, most of which is from organic matter thought to represent some of the oldest and least altered organic material in the Solar System [1]. The solvent-extractable organic carbon in these meteorites contains a variety of different classes of organic compounds with a range of abundances up to several hundred parts-per-million. Many recent studies of the soluble organic component of carbonaceous meteorites have focused on amino acids since these prebiotic molecules are the monomers of proteins and enzymes found in all life on Earth. Over 80 different amino acids have been identified in the CM Murchison meteorite and hundreds of amino acids with up to nine carbons have been detected in this meteorite [2].

The NASA OSIRIS-REx asteroid sample return mission scheduled to launch in 2016 will return to Earth at least 60 g of material from the near-surface (top few cms) of the near-Earth B class asteroid Bennu in 2023. The spectra of Bennu are consistent with a CI or CM meteorite [3]. Exposure of the surface of airless bodies, like Bennu, to solar and galactic cosmic radiation could lead to significant modification and destruction of organic material. Energetic particles and their secondaries can penetrate and deposit energy up to 4 meters in depth regardless of the asteroid's chemical composition, porosity and water content [4]. Therefore, to maximize the chances of returning organic-rich material from the surfaces of asteroids and comets, it is imperative that future missions identify regions on the surfaces of these bodies that have experienced the least amount of space weathering and exposure to cosmic radiation. Here we present amino acid results from recent experiments on ɣ-ray exposed samples of the Murchison meteorite and discuss *in situ* data that will be collected by OSIRIS-REx to characterize variations in space weathering across the surface of Bennu.

Murchison Irradiation Experiments: A 15 g fragment of the Murchison meteorite was crushed to a powder and homogenized by mixing. Three separate aliquots (~ 1 g each) of the meteorite powder were transferred to individual glass test tubes and sealed at ~ 50 mtorr air. Two of the samples were then exposed to ɣ-radiation doses of 1 MGy and 2 MGy (a 2 MGy dose is equivalent to ~ 1 million years of cosmic ray exposure at 2 cm depth) at room temperature using a ^{60}Co source, while the third sealed sample was not exposed to ɣ-radiation. After exposure, the total abundances of amino acids in acid-hydrolyzed hot-water extracts of the Murchison samples were chromatographically determined [2] and compared to the amino acid abundances in the non-exposed Murchison sample. We found that on average ~30% of the amino acids in the 2 MGy exposed Murchison sample were destroyed. The amino acid destruction rate in Murchison was similar to pure dry amino acid standards exposed under the same conditions, and in agreement with previous ɣ-radiation studies of pure amino acids [5]. Our data are consistent with theoretical predictions that minerals or insoluble organic matter in meteorites cannot shield amino acids from cosmic radiation.

Space-Weathering Effects: Previous studies of S-asteroids have suggested that reddening of surface spectra obtained from these asteroids compared to laboratory spectra of ordinary chondrites could be explained by space weathering, with bluer regions associated with fresh young craters and recently exposed surfaces [6]. However, current published literature on space weathering of low albedo objects such as Bennu is inconclusive about the spectral effects of space weathering. For the OSIRIS-REx mission, a variety of indicators from the *in situ* remote sensing measurements will be used to assess the probability of space weathering on the surface of Bennu including visible and infrared spectral continuum slope and band depth, x-ray fluorescence, normal reflectance albedo and color ratio maps, crater and boulder proximity, regolith particle size, and surface slopes [7]. In addition, the surface morphology including evidence for recent impacts will be important in identifying locations on the surface of the asteroid that represent the least altered material. These measurements will feed directly into the Bennu Sample Site Selection process for Science Value, which will be expressed as an Integrated Science Value Map.

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A DIRECT OBSERVATION THE ASTEROID'S STRUCTURE FROM DEEP INTERIOR TO REGOLITH: WHY AND HOW DO IT? A. Herique[1] and FANTINA team, [1] Institut de Planétologie et d'Astrophysique de Grenoble - IPAG UJF/CNRS, Bat D de Physique - BP. 53, 38041 Grenoble cedex 9 – France, alain.herique@obs.ujf-grenoble.fr.

The internal structure of asteroids is still poorly known and has never been measured directly. Our knowledge is relying entirely on inferences from remote sensing observations of the surface and theoretical modeling. Is the body a monolithic piece of rock or a rubble-pile, an aggregate of boulders held together by gravity and how much porosity it contains, both in the form of micro-scale or macro-scale porosity? What is the typical size of the constituent blocs? Are these blocs homogeneous or heterogeneous? The body is covered by a regolith whose properties remain largely unknown in term of depth, size distribution and spatial variation. Is it resulting from fine particles re-accretion or from thermal fracturing? What are its coherent forces? How to model its thermal conductivity, while this parameter is so important to estimate Yarkowsky and Yorp effects?

After several asteroid orbiting missions, theses crucial and yet basic questions remain open. Direct measurements of asteroid deep interior and regolith structure are needed to better understand the asteroid accretion and dynamical evolution and to provide answers that will directly improve our ability to understand and model the mechanisms driving Near Earth Asteroids (NEA) deflection and other risk mitigation techniques. There is no way to determine this from ground-based observation. Radar operating from a spacecraft is the only technique capable of achieving this science objective of characterizing the internal structure and heterogeneity from submetric to global scale for the benefit of science as well as for planetary defence or exploration.

The deep interior structure tomography requires low-frequency radar to penetrate throughout the complete body. The radar wave propagation delay and the received power are related to the complex dielectric permittivity (i.e to the composition and microporosity) and the small scale heterogeneities (scattering losses) while the spatial variation of the signal and the multiple paths provide information on the presence of heterogeneities (variations in composition or porosity), layers, ice lens. A partial coverage will provide "cuts" of the body when a dense coverage will allow a complete tomography. Two instruments concepts can be considered: a monostatic radar like Marsis/Mars Express (ESA) that will analyze radar waves transmitted by the orbiter and received after reflection by the asteroid, its surface and its internal structures; a bistatic radar like Consert/Rosetta (ESA) that will analyze radar waves transmitted by a lander, propagated through the body and received by the orbiter.

Imaging the first ~50 meters of the subsurface with a decimetric resolution to identify layering and to reconnect surface measurements to internal structure requires a higher frequency radar on Orbiter only, like Wisdom developed for ExoMars Rover (ESA) with a frequency ranging from 300 MHz up to 2.7 GHz. At larger observation distance, this radar working in SAR mode maps surface and sub-surface backscattering coefficient. In the frame of AIDA mission, this is a unique opportunity to estimate regolith rearrangement in the impact area.

Bistatic tomography radar and high frequency radar are proposed to instrument the AIDA/AIM mission (ESA). In the frame of the M4 Cosmic Vision ESA call, low frequency and high frequency radar is also proposed for the Castalia mission to a Main Belt Comet, for Marco Polo 2D to a D-type asteroid and for PhobEx to Phobos.

This paper reviews the benefits of direct measurement of the asteroid interior. Then the radar concepts for both deep interior and near surface sounding are shown.

STRESS AND FAILURE ANALYSIS OF RAPIDLY ROTATING ASTEROID (29075) 1950 DA.

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Introduction: Near-Earth asteroid (29075) 1950 DA is currently considered to be among the most hazardous asteroids due to its close encounter to the Earth in 2880 [1]. Busch et al. [2] conducted comprehensive radar observations of this asteroid and derived two possible shape models, a prograde model and a retrograde model. Farnocchia & Chesley [3] reported that the orbital semi-major axis of 1950 DA has been changing due to the Yarkovsky effect and confirmed that the retrograde model was consistent with their analysis. Because of its spin period, 2.1216 hr, this object may be close to its structural failure point if this body is a rubble pile. If 1950 DA has no cohesion, the bulk density should be higher than 3.5 g/cm^3 to prevent the body from failing structurally [2].

Rozitis et al. [4] reported that 1950 DA is a rubble pile and requires a cohesive strength of at least 44 Pa to 74 Pa to keep from failing due to its fast spin period. They analyzed its internal structure using Holsapple's averaging technique. Since this technique considered the averaged stress over the whole volume, it discarded information about the asteroid's failure mode and internal stress condition. This paper develops a finite element model and revisits the analysis of the failure condition of 1950 DA by Rozitis et al. [4].

Techniques: Holsapple [6] developed a finite element model, including plastic deformation characterized by the von Mises yield criterion to consider the failure condition of a rotating, non-gravitating ellipsoid. We extend his model to a model that can take into account self-gravity and plastic deformation characterized by the Drucker-Prager yield criterion. For our computations we use a commercial finite element element software, ANSYS, version 15.03. For the modeling, we do not consider material-hardening and softening. Under the assumption of an associated flow rule and uniform material distribution, we identify the deformation process of 1950 DA when its constant cohesion reaches the lowest value that keeps its current shape. We investigate the internal condition of the 1950 DA retrograde model at the current spin period.

Results: The results show that for the bulk density estimated by Rozitis et al. [4], 1.0 g/cm^3 - 2.4 g/cm^3, to avoid structural failure the internal core requires a cohesive strength of at least 75 Pa - 85 Pa. It suggests that for the failure mode of this body, the internal core first fails structurally, followed by the surface region (see Figure 1). This implies that if cohesion is constant over the whole volume, the equatorial ridge of 1950 DA results from a material flow going outward along the equatorial plane in the internal core, but not from a landslide as has been hypothesized (see Figure 2). Thus, the body's failure state is not close to either surface material being shed or landsliding. Also, given that plastic flow will in general increase volume in an associated flow rule [7], this failure mode predicts that the central core of the asteroid may have a reduced density, which is a previously unpredicted state for such oblate, rapid rotators.

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Figures:

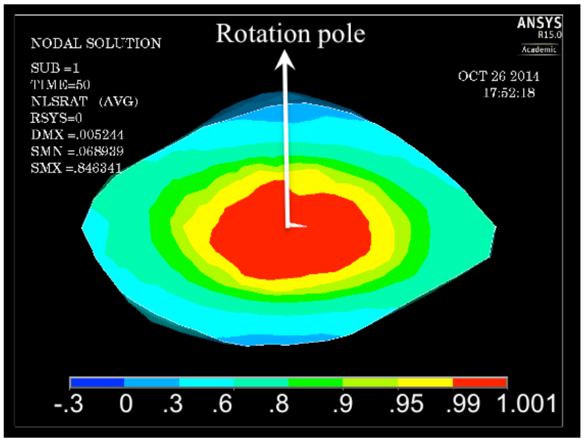

Figure 1 Stress solution. The value from 0.99 to 1.001 shows plastit deformation (the internal core).

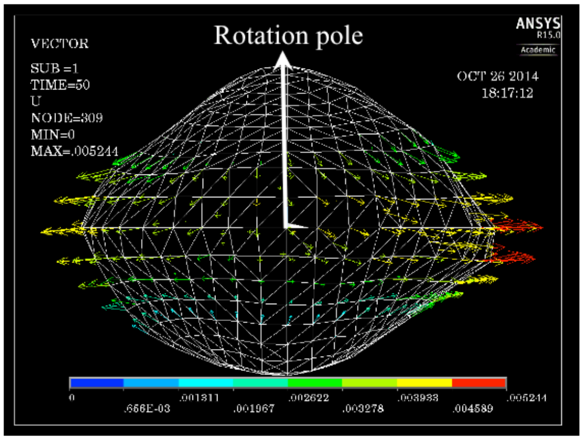

Figure 2 Total deformation vector in meters.

RECOVERING AND MINING ASTEROIDS WITH A GAS-SEALED ENCLOSURE.

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Introduction: Weakly consolidated rubble piles and primitive asteroids are the most scientifically interesting for planetary defense, in-situ resource utilization and origin-of-life studies, and are prime targets for an asteroid recovery mission. It has been proposed to bring a small asteroid to the near-Earth environment, in part to enable the most detailed studies of their internal structure and material properties in a manned mission [1]. Sadly, it is a challenge to manipulate weakly cohesive asteroids without disturbing their surface and internal structure for later study. Also, the low gravity of small asteroids creates challenges because loose regolith can quickly pollute the spacecraft operational environment.

Sealed enclosures: A common solution to these problems is to first create a sealed enclosure around the asteroid. If this can be accomplished without touching the asteroid, then the sealed enclosure will prevent any subsequently loosened debris from poluting the spacecraft environment [1].

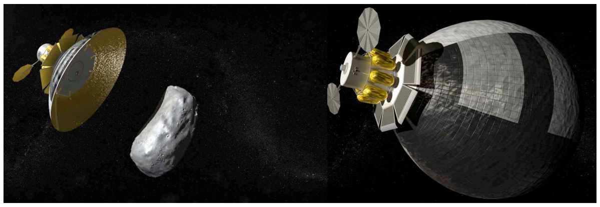

Fig. 1: Concept of creating a sealed enclosure around the asteroid for asteroid recovery or mining [2].

In a paper submitted to NewSpace, we show that such a sealed enclosure can also be used to manipulate the asteroid for recovery [2]. Filled by xenon gas, turbulent dissipation can slow down the asteroid tumble and spin relative to the spacecraft, without putting excessive pressures on the asteroid. After de-spinning, the gas can then be used to transfer the force supplied by an ion engine to the asteroid without touching the asteroid by gently blowing at its surface. The gas will affect the cohesion forces of the asteroid, but the differential pressures exerted on the asteroid and surface regolith are expected to be much less than the combined cohesion forces of weakly consolidated rubble piles and fragile primitive asteroids.

In addition, the future of asteroid mining and sustainable space travel architectures depends on yet-to-be-demonstrated abilities to create a sealed enclosure around an asteroid without disturbing the asteroid [2]. Not only is debris prevented from polluting the spacecraft environment, the enclosure also enables the collection of volatiles from a heated regolith and makes it possible to use gasses such as CO to extract metals from the asteroid. Sufficient vapor pressure inside the enclosure enables the use of liquid water and other solvents.

The volatiles and concentrated solvents could in turn be used to refuel and resupply spacecraft from captured asteroids repositioned on orbits so that they can support a sustainable spaceflight infrastructure.

Future asteroid reconnaisance missions can support the development of asteroid enclosure technologies and methods of creating a seal, thus paving the road to sustainable human space travel to Mars.

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CASTALIA – A MISSION TO A MAIN BELT COMET. G. H. Jones[1], K. Altwegg[2] , I. Bertini[3], A. Bieler[4], H. Boehnhardt[5], N. Bowles[6], A. Braukhane[7], M. T. Capria[8], A. J. Coates[1], V. Ciarletti[9], B. Davidsson[10], C. Engrand[11], A. Fitzsimmons[12], A. Gibbings[13], O. Hainaut[14], M. Hallmann[15], A. Herique[16], M. Hilchenbach[5], M. Homeister[13], H. Hsieh[17], E. Jehin[18] W. Kofman[16], L. M. Lara[19], J. Licandro[20], S. C. Lowry[21], F. Moreno[19], K. Muinonen[22] , M. Paetzold[23], A. Penttilä[22], Dirk Plettemeier[24], D. Prialnik[25], U. Marboeuf [2], F. Marzari[26], K. Meech[27], A. Rotundi[28,29], A. Smith[1], C. Snodgrass[30], I. Thomas[6], M. Trieloff[31], [1]UCL Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK (g.h.jones@ucl.ac.uk), [2]U. Bern, CH, [3]U. Padova, IT, [4]U. Michigan, USA, [5]MPS, Göttingen, DE, [6]U. Oxford, UK, [7]DLR, Bremen, DE, [8]INAF/IAPS, Rome, IT, [9]LATMOS/UVSQ, Guyancourt, FR, [10]U. Uppsala, SE, [11]CNRS, Paris, FR, [12]QUB, Belfast, UK, [13]OHB System AG, Bremen, DE, [14]ESO, [15]DLR, Bremen, DE, [16]IPA/UJF, Grenoble, FR, [17]Academia Sinica, Institute of Astronomy & Astrophysics, Taiwan, [18]U. Liège, BE, [19]IAA, Granada, ES, [20]IAC, Tenerife, ES, [21]U. Kent, Canterbury, UK, [22]U. Helsinki, FI, [23]U. Köln, DE, [24]TU Dresden, DE, [25]U. Tel Aviv, IL, [26] INFN, Padova, IT, [27]IfA, Honolulu, USA, [28]Università di Napoli "Parthenope", IT, [29] INAF-IAPS, Roma, IT, [30]Open U., UK, [31]U. Heidelberg, DE

Main Belt Comets (MBCs), a type of Active Asteroid, constitute a newly identified class of solar system objects. They have stable, asteroid-like orbits and some exhibit a recurrent comet-like appearance. It is believed that they survived the age of the solar system in a dormant state and that their current ice sublimation driven activity only began recently. Buried water ice is the only volatile expected to survive under an insulating surface. Excavation by an impact can expose the ice and trigger the start of MBC activity. We present the case for a mission to one of these objects, to be submitted to the European Space Agency's current call for an M-class mission.

The specific science goals of the Castalia mission are:

1. Characterize a new Solar System family, the MBCs, by in-situ investigation
2. Understand the physics of activity on MBCs
3. Directly sample water in the asteroid belt and test if MBCs are a viable source for Earth's water
4. Use the observed structure of an MBC as a tracer of planetary system formation and evolution.

These goals can be achieved by a spacecraft designed to rendezvous with and orbit an MBC for a time interval of some months, arriving before the active period for mapping and then sampling the gas and dust released during the active phase. Given the low level of activity of MBCs, and the expectation that their activity comes from only a localized patch on the surface, the orbiting spacecraft will have to be able to maintain a very close orbit over extended periods - the Castalia plan envisages an orbiter capable of 'hovering' autonomously at distances of only a few km from the surface of the MBC.

The strawman payload comprises a Visible and near-infrared spectral imager, Thermal infrared imager, Radio science, Subsurface radar, Dust impact detector, Dust composition analyser, Neutral/ion mass spectrometer, Magnetometer, and Plasma package. In addition to this, a surface science package is being considered.

At the moment, MBC 133P/Elst-Pizarro is the best-known target for such a mission. A design study for the Castalia mission has been carried out in partnership between the science team, DLR and OHB System AG. This study looked at possible missions to 133P with launch dates around 2025, and found that this, and backup MBC targets, are reachable by an ESA M-class mission.

A proposal in response to the ESA M4 call for missions is currently being prepared. More details, and an opportunity to register your support for the proposal, are available at http://bit.ly/mbcmission

Strength of Stony Meteorites Samples Subjected to Various Loading States.

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Introduction: Recent and forthcoming asteroid reconnaissance missions (e.g. Hayabusa, OSIRIS-REx) will provide new insight to fundamental questions such as the origins/evolution of these small bodies, as well as more applied topics such as mitigating potential threats to our planet. Many of the topics of interest are dependent upon the physical properties of the body under observation. One physical property of interest is the strength of the constituent materials. The strength properties are relevant to understanding the collisional evolution of the asteroids (e.g. [1]), and also provide information useful for planning future reconnaissance missions focused on in-situ or sample return studies. Lacking strength data from actual asteroid material, meteoritic material is a "semi-terrestrial" analog that represents the composition, microstructure, and associated properties of actual asteroid material.

Here we present recent measurements of the strength of meteoritic material (GRO 85209) under a wide range of loading conditions, such as compression and tension, over a range of loading rates relevant to impact and other processes active in the Solar System. These data serve to augment existing studies related to the strength of stony meteorites [2, 3, 4, 5, 6, 7] which have focused primarily on the low rate uniaxial compressive strength.

Materials and Methods: Meteorite GRO 85209 is an L6 chondrite consisting primarily of a matrix of low-Ca pyroxene (21% Fs) with blocky iron nickel grains and some olivine grains (25% Fa) [8]. Optical microscopy of thin sections is used to determine microstructural properties such as grain size and flaw size distributions. The uniaxial compressive and tensile (Brazilian disk) strengths were measured under quasistatic loading using a MTS load frame, while dynamic measurements were performed using a Kolsky Bar [9].

Results & Discussion: The stress–time history and corresponding high speed images of a GRO sample subjected to dynamic compressive loading is shown in Fig. 1. The stress–time history shows that stress increasing at a constant rate of 26 MPa/μs up until the peak stress (compressive strength) of 255 MPa is reached approximately 10 μs after loading began. The image corresponding to this peak stress (t1) shows that there are few cracks visible on the sample surface, but initiation sites of future cracks are indicated by the red arrows. As time progresses (t2-t6), more initiation sites appear (red arrows) and existing cracks extend and open. These cracks serve to reduce the stress in the sample and lead to eventual failure and fragmentation of the sample.

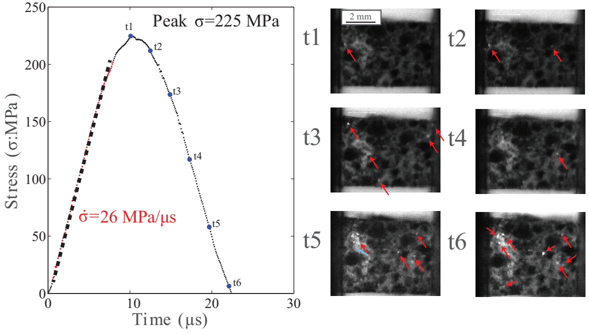

Fig. 1. Stress history of a GRO sample subjected to dynamic compression at a stress rate of 26 MPa/μs.

Further analysis of high-speed images from this and other experiments indicates that the iron-nickel grains are the most common sites for crack initiation under tensile and compressive loading. The identification of the micro structural flaws that serve as crack initiation points allows for comparison with strength models that incorporate flaw distributions (e.g. [10]), which will hopefully allow for better understanding of the effects of microstructure on the strength of meteorites and their parent bodies.

Conclusions: The results presented here will provide baseline data that may be used in planning of future reconnaissance missions. Furthermore these results may allow more rapid understanding of the properties of asteroids identified as threats, thus speeding up the response time of mitigation efforts.

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USING LOW-COST OFF-THE-SHELF COMPONENTS FOR THE DEVELOPMENT OF AN ON-ORBIT CUBESAT CENTRIFUGE LABORATORY.

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Summary: Missions to asteroid pose many challenges in terms of cost, schedule and technology readiness. Nearly 50 % of surface missions to asteroid have resulted in loss of spacecraft. An orbital centrifuge laboratory designed for studying accretion experiments and rubble pile dynamics of asteroids can be a low-cost technology development tool that minimizes technology risk associated with landing, surface mobility and manipulation.

The concept of an orbit centrifuge is not new. However previous designs were ambitious and consisted of a stationary spacecraft connected to a rotating one. The inherent complexity and requirement for large customized components had resulted in spiraling costs and schedule that led to the eventual cancellation of these programs. Our approach is to start small. To demonstrate the utility of this orbital centrifuge laboratory, we plan on launching a 3U CubeSat, called Asteroid Origins Satellite (AOSat I) that will spin about one of its axes at a rate of 1 rev/min to produce 0.0001G.

The spacecraft will be built for the most part using commercial off-the shelf components that have significant space heritage such as communication equipment, onboard computer, attitude control components, power system and cameras. This minimizes costs, schedule and risk. The science instruments and various deployment mechanisms are being developed in-house and offer a unique opportunity to train the next generation of scientists and engineers while developing asteroid exploration technology. Plans are underway in leveraging what is being learned from AOSat I to the development of even larger on-orbit centrifuge platforms with application ranging from planetary science, life-science and on-orbit manufacturing..

AIDA: ASTEROID IMPACT AND DEFLECTION ASSESSMENT MISSION UNDER STUDY AT ESA AND NASA.

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Introduction: The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to demonstrate asteroid impact hazard mitigation by using a kinetic impactor to deflect an asteroid. AIDA is a joint ESA-NASA mission, which includes the ESA Asteroid Impact Mission (AIM) rendezvous spacecraft and the NASA Double Asteroid Redirection Test (DART) mission. The primary goals of AIDA are (i) to test our ability to impact a small near-Earth asteroid by an hypervelocity projectile and (ii) to measure and characterize the deflection caused by the impact. The AIDA target will be the binary asteroid (65803) Didymos, with the deflection experiment to occur in October, 2022. The DART impact on the secondary member of the binary at ~6 km/s will alter the binary orbit period, which can be measured by Earth-based observatories. The AIM spacecraft will monitor results of the impact in situ at Didymos.

Current status: Both AIM and DART have been approved for a Phase A/B1 study, starting in February 2015 for 15 months. Baseline payloads for AIM include a navigation camera, a lander (based on DLR MASCOT heritage), a thermal infrared imager, a monostatic high frequency radar, a bistatic low frequency radar (on the orbiter and on the lander), and some opportunity payloads based on cubesat standards. AIM is conceived as a small and simple platform with no mechanisms providing a flight opportunity to demonstrate technologies to advance future small and medium mission. As such, AIM will also demonstrate for the first time the use of deep-space optical communication. It will allow for the first time accessing direct information on the internal and subsurface structures of a small asteroid, and with DART, determining the influence of those internal properties on the impact outcome. The DART mission will use a single spacecraft to impact the smaller member of the binary near-Earth asteroid Didymos in October 2022. DART uses a simple, high-technology-readiness, and low-cost spacecraft to intercept Didymos. DART hosts no scientific payload other than an imager for targeting and data acquisition The impact of the >300 kg DART spacecraft at 6.1 km/s will change the mutual orbit of these two objects. By targeting the smaller, 150 m diameter member of a binary system, the DART mission produces an orbital deflection which is both larger and easier to measure than would be the case if DART targeted a typical, single near-Earth asteroid so as to change its heliocentric orbit. It is important to note that the target Didymos is not an Earth-crossing asteroid, and there is no possibility that the DART deflection experiment would create an impact hazard. The DART asteroid deflection demonstration targets the binary asteroid Didymos in Oct 2022, during a close approach to Earth. The DART impact will be observable by ground-based radar and optical telescopes around the world, providing exciting opportunities for international participation in the mission, and generating tremendous international public interest, in the first asteroid deflection experiment.

Conclusion: AIDA will return fundamental new information on the mechanical response and impact cratering process at real asteroid scales, and consequently on the collisional evolution of asteroids with implications for planetary defense, human spaceflight, and near-Earth object science and resource utilization. AIDA will return unique information on an asteroid's strength, surface physical properties and internal structure. Supporting numerical simulation studies and laboratory experiments will be needed to realize the potential benefits of AIDA and will be an integral part of the mission. Various communities will thus be involved and working groups are defined to support the mission studies.

Additional Information: Support from ESA and NASA is acknowledge.

THE MISSION ACCESSIBLE NEAR-EARTH OBJECT SURVEY (MANOS).

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Introduction: The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded survey status by NOAO. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, ultimately providing a comprehensive catalog of physical properties (astrometry, light curves, spectra). Particular focus is paid to sub-km NEOs, for which little data currently exists. These small bodies are essential to understanding the link between meteorites and asteroids, pose the most immediate impact hazard to the Earth, and are highly relevant to a variety of planetary mission scenarios. Telescopically accessing these targets is enabled through a combination of classical, queue, and target-of-opportunity observations carried out at 1- to 8-meter class facilities in both the northern and southern hemispheres. The MANOS observing strategy is specifically designed to rapidly characterize newly discovered NEOs before they fade beyond observational limits.

Target Selection: Targets for MANOS are selected based on three primary criteria: mission accessibility (i.e. $\Delta v < 7$ km/s), size ($H > 20$), and observability. Our telescope assets allow us to obtain rotational light curves for objects down to V~22, visible spectra down to V~ 21, and near-IR spectra down to V~ 19. MANOS primarily focuses on targets that are recently discovered. We employ a regular cadence of remote and queue observations to enable follow-up characterization within days or weeks after a target of interest is discovered. We currently have the capability to characterize roughly 10% of all new NEO discoveries. To date we have observed nearly 150 NEOs and are significantly contributing to the accumulated knowledge of physical properties for sub-km NEOs (Figure 1).

Survey Status: An overview of early science results from MANOS include: (1) an estimate of the taxonomic distribution of spectral types for NEOs smaller than ~100 meters, (2) the distribution of rotational properties for approximately 100 previously unstudied objects, and (3) models for the dynamical evolution of the overall NEO population over the past 0.5 Myr. In addition we are actively developing a new set of online tools at asteroid.lowell.edu that will enable near realtime public dissemination of our data products while providing a portal to facilitate coordination efforts within the small body observer community. We will present highlights from MANOS with an emphasis on the importance of rapid-response ground-based characterization of mission accessible NEOs.

Acknowledgments: We acknowledge support for MANOS from NOAO through a significant allocation of observing resources. We also acknowledge observing support from Lowell Observatory and NASA's IRTF. MANOS is supported through the NASA NEOO Program under Grant No. NNX14AN82G.

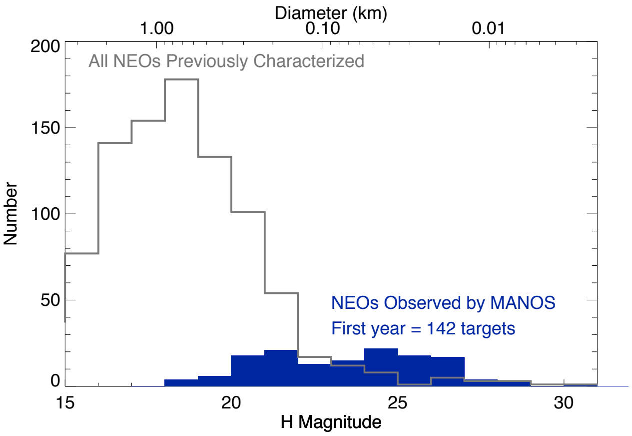

Figure 1: Absolute magnitude distributions of all previously characterized NEOs (i.e. visible spectra, near-IR spectra, albedos, and/or rotational light curves) and the set of 142 NEOs observed during the first year of MANOS operations. In this time MANOS has become the predominant source of physical data collected for NEOs smaller than approximately 100 meters.

CERES: A HABITABLE SMALL BODY? M.Neveu[1], S. J. Desch[1], J. C. Castillo-Rogez[2]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85281, USA. [2]Jet Propulsion Laboratory, Pasadena, CA 91109, USA. Email: mneveu@asu.edu.

Introduction: The main-belt object Ceres (radius≈475 km, density≈2100 kg m^{-3}, semi-major axis 2.7 AU), is an exciting place to explore planetary habitability. Abundant volatiles could have shaped Ceres in a way analogous to that suspected on icy moons.

Hydrothermalism: Ceres' surface seems blanketed by products of the interaction between silicate rock and liquid water, including carbonates [1]. Could liquid water persist inside so small a world, without tidal heating, until the present day? Simulations using our detailed thermal models suggest that it could [2,3], provided volatile or salt antifreezes are present, and that long-lived radionuclide decay warms up the liquid. That is, for liquid to persist, it must be at depth in contact with a rocky core. To what extent could water-rock interaction occur? Our detailed core cracking simulations suggest that micro- and macro-fractures may pervade the entire core, providing a large interface for interaction [3].

Cryovolcanism: Ceres is releasing water vapor to space [4]. Whether this activity is cometary or cryovolcanic is unknown. We have shown that explosive cryovolcanism on icy dwarf planets is facilitated by gas products of hydrothermal activity [5]. Species such as CH_4 or H_2, produced by water-rock reactions, can exsolve during fluid ascent, thereby making cryovolcanic fluids buoyant in ice.

Both putative hydrothermal and cryovolcanic activity are reminiscent of processes occurring on icy moons. Europa's ridges seem filled with salt rising from its interior [6,7], and pluming activity may have been observed [8]. Enceladus displays intense cryovolcanic activity, and sodium and silica likely coming from its core are ejected in its plume [9]. Such observations have made these icy worlds prime foci for exploration, as mixing reduced rocky material with oxidized fluids and ices creates energy gradients and leaches nutrients which could support life [7,9]. Could Ceres' interior also be habitable? The implications are tantalizing: since dwarf planets make up 75% of all round worlds in the solar system, abodes for life may be much more common than initially anticipated.

Clearing the Window Into Habitability Processes: Our understanding of icy world habitability hinges on surface observations, the window into interior hydration and transport processes that provide ingredients for life. On icy moons, this window has so far been obscured: scarce impurities at their surface hamper state-of-the-art investigations. Signals at the limit of detection make the identification of even major species ambiguous [6,9]. Minor species, overwhelmed by the signature of water ice, remain undetected. In contrast, Ceres' warmer surface is ice-free and blanketed by minerals. This profusion of rocky material may be contributed mainly by exogenic infall. However, the possible identification of products of water-rock interaction [1] could provide clearer insight into hydration and interior-surface exchanges on icy worlds.

Ongoing Exploration: In 2015, the Dawn spacecraft will carry out a reconnaissance and extensive geological and chemical mapping of Ceres. Dawn's instruments will help investigate its habitability. A near-infrared spectrometer will identify locally abundant species unidentified in current global averages. A gamma ray and neutron detector will probe elemental compositions at meter depths. A visible camera will provide context and morphologies characteristic of transport processes. Tracking of Dawn's orbit will probe Ceres' internal structure to reveal the depth of the water-rock interface. Thus, Dawn will assess and possibly characterize the nature of aqueous processes on Ceres.

Future Exploration: As habitable icy worlds are a prime target of planetary exploration, there is a crucial need to understand their workings [9]. The exploration of Ceres by Dawn will likely not yield the final word on its possible habitability. Ceres' relative proximity, presence of possible mineral tracers of redox reactions, and status as possible archetypal round world in planetary systems might make it a compelling target for affordable follow-up exploration. To inform future investigations, we will present our latest results on the internal thermal evolution and geochemistry of Ceres.

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SCIENTIFIC MEASUREMENTS OF HAYABUSA-2 LASER ALTIMETER (LIDAR)

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Introduction: As a successor of Japanese Hayabusa Asteroid mission, Hayabusa-2 is scheduled to be launched in winter 2014. The target asteroid of Hayabusa-2 is now called 1999 JU3, which has C-type spectral type. C-type asteroids are considered to be more primitive than S-type asteroids because of its further heliocentric distance, and to be good targets to know the origin and the history of the solar system. After the Earth gravity assist operation in winter 2015, the spacecraft will be inserted into the transfer orbit, and it will arrive at 1999 JU3 in the middle of 2018. After one-year remote observation and three touchdown operations for sampling, it will leave the asteroid in winter 2019 and then return to the Earth with samples of the asteroid in winter 2020.

Laser Altimeter (LIDAR) : As a part of the Attitude and Orbit Control Subsystem (AOCS), the laser altimeter called LIDAR is developed. LIDAR measures altitudes of the spacecraft from a surface of the asteroid by taking a time of flight of bounced laser pulse on the asteroid surface. Basically the LIDAR data are used for navigation of the spacecraft, and they are particularly important during touchdown operation. Besides, the LIDAR data will be served for scientific analysis of the shape, mass, and surface properties of the asteroid in order to elucidate physical evolution of minor bodies such as impact fragmentation and coagulation. Namely, LIDAR range data will be used for determination of the asteroid shape combined with camera data. Also, through free-fall operation toward the asteroid, LIDAR range data combined with range and Doppler measurement data from the ground station will be used for the determination of asteroid GM value.

Design of Hayabusa-2 LIDAR is based on that of the first Hayabusa (Table 1, [1]). The size and weight are 240 x 228 x 290 mm and 3.5 kg, respectively. The specification of the laser pulse energy and beam divergence are 10 mJ and 1 mrad circular respectively, which meets the requirement for the return pulse detection in the link calculation from the so-called “home position”, nominal 20 km away from the asteroid, where the spacecraft stays for global mapping observation.

Compared to the LIDAR aboard first Hayabusa, several functions and telemetries are added for scientific observation. Firstly, the energy monitor of transmitting laser is added. Combined with the energy monitor of receiving pulse, the surface reflectance of the asteroid at the laser wavelength of 1064 nm can be estimated. Secondly, the dust counting mode is added. In the normal ranging mode, when the return laser pulse is detected, the range counter reports the count and stops the measurement for every laser shot. In this mode, the range is divided into 50 pieces, and in each of the pieces the detection flag is reported. If dusts levitate above the surface of the asteroid, some of these pieces will report the photon signals and it must be the evidence for the circum-asteroid dust. Lastly, the LIDAR is equipped with the laser transponder mode. It is used for the demonstration of the optical data transmission from the spacecraft to the ground laser station and vice-versa, when the spacecraft is near the Earth for the Earth gravity assist operation in one year after the launch. Although it is an engineering experiment, this experiment offers the first opportunity of confirmation of the performance of the LIDAR, especially the link budget and optical alignment after the launch.

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Table 1. Nominal Specification of Hayabusa-2 LIDAR.

Parameter	Value
Altitude range	30 m ~ 25 km or longer
Range resolution	0.5 m
Range accuracy	± 0.6 m (by 30-m altitude measurement)
Pulse repetition rate	1 Hz (max.)
Receiver telescope	Cassegrain type
Telescope diameter	127 mm
Pulse energy	~10 mJ
Pulse width	< ~10 nsec
Pulse divergence	1 mrad
Field of view	1.5 mrad
Receiver detector	Si-APD
Power consumption	17.9 W (with heater)

THE RECONNAISSANCE OF APOPHIS (RA) PICOSATELLITE MISSION CONCEPT.

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Introduction: Obtaining a better understanding of primitive bodies such as asteroids is a primary goal in advancing the field of planetary science. Previous and upcoming missions [1, 2] focus on sample return objectives, but significant questions about asteroidal compositions, surface environments, and interior structure still remain. Some asteroids could pose a potential threat to Earth and are classified as potentially hazardous asteroids (PHAs). One such asteroid, 99942 Apophis, presents a unique opportunity to study a PHA up close due to its spectral characteristics, size, and proximity [3, 4]. Here we propose our preliminary mission concept of a picosatellite designed and built to explore the surface of Apophis and answer key questions for future asteroid lander missions: 1) What is the rate of dust accumulation on a foreign object on Apophis, a representative of the small bodies population? and 2) Is our system a feasible solution for mobility operations in a micro-gravity environment for a picosatellite without a propulsion system?

Science Objective: Dust collection on spacecraft poses a major hazard for future asteroid exploration missions. We want to study the dust (particles 2μm to 2 cm in diameter) accumulation rate in order to inform particulate damage mitigation strategies. This is also an opportunity to study the natural cohesion rates of particulates in a microgravity environment and potentially identify the mechanisms affecting their mobility [5]. To do this we plan to use a Raspberry Pi Cam [6] from SparkFun to directly photograph the dust accumulating on a non-refractive surface (NRS). We plan to photograph the NRS once every 20 minutes for 2.5 hours and then clean the surface using current carried through a transparent coating called the Electrodynamic Dust Shield (EDS). An algorithm will then count the number of dark to light pixels and send that data down, with some images also being sent to correlate the pixel data. This will yield longitudinal data about the effect of solar angle on dust accumulation rates.

Technology objective: This picosatellite is also designed to move 0.25m away from the landing site and is required to take scientific data from at least three locations. At this time the lack of imaging data of Apophis prevents us from identifying a landing location. Mobility increases the probability of mission success by enabling the picosatellite to move in case the original landing location and orientation are less than ideal. Our current mobility strategy is to use three reaction wheels and a flywheel. We have plotted the maximum velocities and angles at which we can move, taking into account the escape velocity of Apophis.

Structure and Subsystems: Our total mass limit is 500g and our total volume must not exceed 10cm x 10cm x 5cm; therefore, all structures and subsystems must be as light and as durable as possible. We are currently at a 15.6% mass margin, a 31.38% volume margin, and a 16.67% power budget margin. The material we will use for our frame is Aluminum 6063-T1 alloy. We will use two 10Wh batteries to power our picosatellite on the surface, sufficient even if 25% of the full battery power is lost during transit. We are planning to use the Tyvak Intrepid system board which combines the onboard computer, the EPS, the inertial measurement unit, and the radio transceiver, all in one package [7].We are also working on thermal control strategies to keep the systems alive in the extreme cold, a larger concern than mitigating the sun's heat.

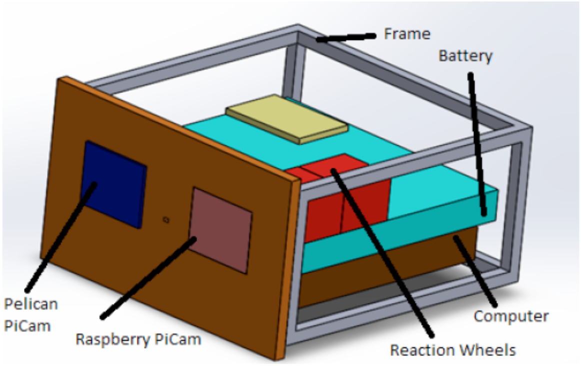

Figure 1: A preliminary CAD model of our picosatellite, with approximate dimensions of reaction wheels, Raspberry Pi cams, and computers .

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ASTEROID ORIGINS SATELLITE (AOSAT): SCIENCE IN A CUBESAT CENTRIFUGE. V. Perera[1], D. Cotto-Figueroa[1], J. Noviello[1], E. Asphaug[1], and M. Morris[2]. [1]Arizona State University (School of Earth and Space Exploration, PO Box 876004, Tempe, AZ 85287-6004. viranga@asu.edu), [2]State University of New York at Cortland (Physics Department, PO Box 2000, Cortland, NY 13045-0900).

Introduction: It is vital to study asteroids for two reasons. First, since asteroids are remnant bodies from the early solar system, by understanding their origin we can characterize the early planet formation epoch. This important first step called primary accretion [1], where dust in the protoplanetary disk coagulated into planetesimals (~1 km sized objects), is not well understood due to the difficulty of having a representative long-duration (~days to months) zero-gravity laboratory. Earth-based laboratories are only able to conduct zero-gravity experiments lasting for about ten seconds [2]. Second, regolith on the surface of asteroids have a unique behavior due to the low-gravity environment [3] and thus understanding this behavior is a necessary first step for future sample return or mining missions. Therefore, we propose a CubeSat mission called the Asteroid Origins Satellite (AOSAT) as a low-cost laboratory to study primary accretion and asteroid surface properties. In addition, AOSAT will serve as a precursor to future missions and help test techniques for the exploration of asteroids.

CubeSat Layout: AOSAT will be a 3U CubeSat with the dimensions of 10 cm x 10 cm x 34 cm and with a mass of less than 4 kg (see Figure 1).

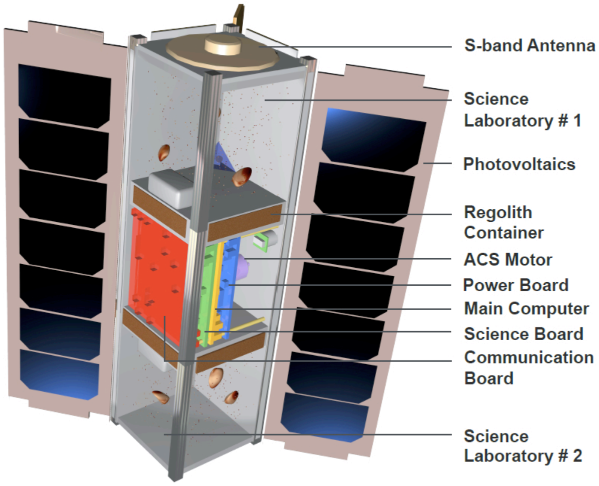

Figure 1: CAD model cutout of AOSAT with notable components identified.

The central chamber will house the spacecraft electronics (e.g. main computer, attitude control system, communications system, etc.) while the two outer chambers will contain ground up meteorite regolith and a number of cameras to capture high-resolution images and video of the regolith. Having two chambers will allow us to have regolith of different grain sizes in each chamber such that one of the chambers could be specialized to study the primary accretion process and the other one to study the asteroid-like regolith behavior. The attitude control system will be able to keep the CubeSat stable with minimal oscillations as well as be able to stably spin the CubeSat along its maximum moment of inertia axis.

Flight Experiments: In a stable zero-spin spacecraft state, regolith inside the CubeSat will be free to interact in a manner similar to that of the early solar system. AOSAT will pioneer realistic primary accretion experiments due to the long-duration zero-gravity environment and the use of material similar to that of the early solar system and present day asteroids (i.e. ordinary chondrite meteorite material). Since AOSAT will be able to stably spin about its axis of maximum moment of inertia, it will be able to create a patch of regolith that will be representative of regolith on an asteroid surface. In the spinning state, artificial gravity will push the regolith inside the end chambers outwards and once it is against the end wall, it will behave similar to regolith on an asteroid (e.g. a spin rate of one revolution per minute will create artificial gravity of 10^{-4} g which is the average surface acceleration due to gravity of a 1 km size asteroid). Since it is important to understand the angle of repose in low gravity environments [3], we will be able to measure the angle for varying g-levels. Also, we will use a mechanism to induce a "seismic shock" to stimulate regolith motion to test the concept of photoseismology [4]. We will then quantify the differences in the surface morphology before and after the shock using methods that have been refined in previous asteroid studies [5, 6]. The high-resolution images and video will significantly contribute to the understanding of both primary accretion and the regolith behavior on asteroids.

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IMPACT HAZARD MITIGATION RESEARCH AT LOS ALAMOS NATIONAL LABORATORY: CURRENT STATUS AND WHAT WE COULD LEARN FROM SPACECRAFT RECONNAISSANCE.

C. S. Plesko[1], Jim M. Ferguson[2], Galen R. Gisler[2], Robert P. Weaver[2], [1]Los Alamos National Laboratory, XTD-NTA (plesko@lanl.gov), [2]Los Alamos National Laboratory, XTD-PRI

Introduction: Los Alamos National Laboratory (LANL) has been tasked by the National Nuclear Security Agency (NNSA) to study the mitigation of the impact hazard of asteroids and comets on the Earth. We are modeling two possible methods of hazard mitigation; deflection or disruption of a hazardous object by kinetic impactor or nuclear burst. Kinetic impactors transfer momentum directly through impact and through a target-dependent momentum enhancement by ejected target material. Nuclear devices impart momentum to the target object by vaporizing target material and lofting it, and in some cases entrained solid material, away from the body. The implementation of these mitigation methods would be a multivariate function of the geometry of the situation, the yield or mass of the device, and the composition of the object

Methods: We use several numerical methods to model energy deposition and predict target response.

Hydrocode Models of Impacts. We use the RAGE hydrocode [1] with several strength and porosity models to simulate the impact of different impactors into target asteroids of varying shape and composition, including both sub-mesh scale and macro-scale voids.

Hydrocode Models of X-ray Energy Deposition. Approximately 97% of the energy emitted by a nuclear device is in the form of kinetic energy (debris) and thermal radiation (x-rays). We model this portion of the energy using the RAGE hydocode's gray diffusion radiation transport model that simulates the flow of wavelike light in a problem in combination with the SESAME equation of state and opacity tables [2]. Gray diffusion is similar to a black body model except the bodies absorb and radiate with an inefficiency, $\sigma < 1$.

Particle Transport Code Models of Neutron Energy Deposition. The remaining energy is released as nuclear radiation (neutrons and gamma rays), which deposit their energy much deeper in the target than x-rays do, so they may have a significant effect on the amount of debris and momentum ejected from the surface. We model the nuclear radiation energy deposition using the MCNP particle transport code [3].

Model Results to Date: We have conducted a series of verification and validation models previously [4][5]. Currently, we are modeling a simplified analog of asteroid Bennu, the Osiris-REX mission target, in collaboration with Lawrence Livermore National Laboratory [6], who are modeling the same target. Impact models conducted by Gisler use a 64-cm-diameter impactor striking the target at 20 km/s. He is exploring the effects of target properties on momentum enhancement (Fig. 1). X-ray deposition models by Weaver, Plesko, and Ferguson, explore the dynamic response of both solid objects and those with macro-scale porosity, and the energy required to disrupt km-scale bodies (Fig. 2). MCNP models by Ferguson and Plesko explore the dependence of neutron energy deposition on object composition (Fig. 3)

Model Constraints from Spacecraft Reconnaissance: We cannot assume that spacecraft reconnaissance data will be available for a specific PHO prior to a mitigation attempt. The deflection mission would likely be the first spacecraft rendezvous. Spacecraft reconnaissance data is most valuable to us as aggregate information about the diversity of objects we might encounter, particularly information about possible internal structure and composition, macro- and microporosity, and the heterogeneity of structure and composition observed for a given object and across dynamical families and spectral types.

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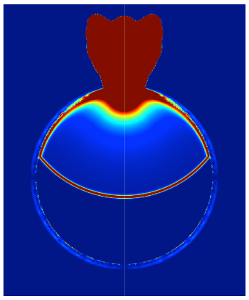
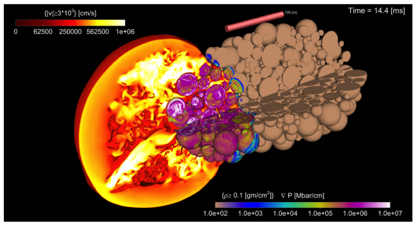


Fig. 1 (left): Ejecta v< 1m/s at t=0.1s, 64 cm impactor at 20 km/s into a 500 m solid quartz sphere.

Fig. 2 (below, middle): 1 Mt X-ray energy burst deposited into a 1 km x 0.5 km aggregate of spherical basalt boulders.



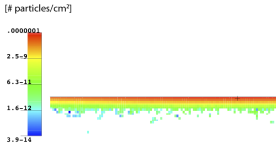


Fig. 3 (bottom): MCNP model of neutron deposition into CI Chondrite, mean free path 2.9 cm.

APOPHIS EXPLORER, TAKING THE OPPORTUNITY OF ITS 2029 FLYBY FOR A CHARACTERIZATION MISSION

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The asteroid APOPHIS, discovered in 2004, is a 250 to 300 meter wide Potential Hazardous Asteroid that will come back very close to the Earth on April 13, 2029.

The same way as a gravity assist maneuver is currently used for a deep space probe, the gravitational pull of the Earth during its pass will dramatically modify the APOPHIS orbit around the Sun. It will nevertheless remain a potential danger for the future, and, as such, will deserve special attention possibly for several generations.

During its 2029 pass, APOPHIS will be easily visible from the Earth and most of its geometry and thermal properties will be well determined from ground based observations. However, the characterization of its interior will not be achievable from purely terrestrial observations. Such a characterization, which can only be achieved through a space mission, is essential for planning mitigation operations, should these be necessary in the future.

The passage of APOPHIS close to the Earth in 2029 offers a great opportunity to better characterize this object and to observe the possible changes in its inner layout and its surface characteristics that could be triggered by the differential pull from the Earth at its closest approach.

The payload would consist of a suite of instruments designed for the following investigations:

- General features (shape, mass, spin, gravity) : radio science investigation, wide and narrow angle cameras in the visible domain
- Surface : cameras (VIS) and spectro imager (IR)
- Sub surface : monostatic radar (high frequency, reflecting mode), seismology (3 micro stations), artificial craterization
- Core : monostatic radar (low frequency, reflecting mode), seisomology (same as above)

The deposit of a radar reflector for long term tracking purposes is also investigated.

A possible mission scenario would be a launch in 2027 with an arrival in December 2028 after a 1.7 year cruise with a plasma thruster propulsion system, for a fuel consumption of less than 45 kg. This would allow around 4 months in the vicinity of APOPHIS to run a smooth characterization programme ending with the deposit of the surface instruments several weeks before the close approach.

As a member of the Space Mission Planning Advisory Group (SMPAG) that is being setup by the UN/COPUOS, CNES has studied a mission scenario that would dramaticaly improve our knowledge of APOPHIS characteristics, mandatory to define any mitigation mission.

This paper presents the objectives of the mission and its preliminary design.

MUON IMAGING OF ASTEROID AND COMET INTERIORS.

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Introduction: What if we could look inside an asteroid or comet? Information on their internal density structure and macroporosity would provide powerful constraints on their formation and evolution as well as information needed for planetary defense, mining, and in situ resource utilization. At present, the internal structure of small bodies must be inferred from surface morphology (e.g. by optical imaging or radar) and indirectly from other observations. We are investigating new methods to directly map the deep interior structure of small solar system bodies using secondary particles, such as muons, produced by galactic cosmic ray (GCR) showers within the body itself. Relativistic muons produced in abundance by GCR showers in Earth's atmosphere can penetrate large distances through rock (~ 1 km at 1 TeV) and have been used to image large structures, natural and synthetic, on Earth's surface. [1-3]

Challenges: Extension of "muography" [2] to asteroids and comets presents several technical challenges. Muons are made in the top meter of the regoliths of asteroids and comets (Fig. 1). Their rate of production is significantly lower than in Earth's atmosphere and depends on regolith density, which varies over the surfaces of asteroids and comets. The effect of surface density and geometry on muon production must be removed from radiographic data sets in order to resolve deep, interior density variations. Finally, the muon telescope must be capable of measuring transmitted muons separately from various background sources.

Approach. Using models, validated by experiments, we show that interior contrast can be detected using a compact muon telescope with about 1 m^2 aperture with integration times ranging from hours to weeks for 100-m to 1-km asteroids [5,6]. The intrinsic spatial resolution is on the order of meters. Practical limits for resolution and contrast sensitivity depend on integration time and telescope design. Concepts for a telescope that could be deployed in situ or on an orbiting spacecraft are described. Regolith density within the top meter of an asteroid can be determined from radar observations. A pilot mission that combines remote radar measurements with muography of a near-Earth asteroid is presented. Alternatively, the flux of prompt muons produced by the decay of charmed mesons is insensitive to regolith density and may also provide information on interior structure.

This work is funded by the NASA Innovative Advanced Concepts program (NIAC).

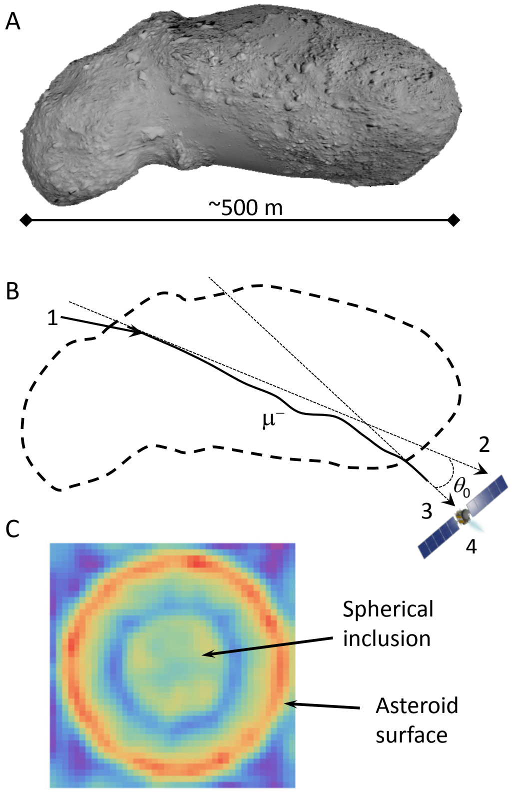

Figure 1. **A**) Small rubble pile asteroid 25143 Itokawa.[4] **B**) Path of a high energy muon (μ^-) through the asteroid: 1) incident GCR; 2) initial direction of the muon; 3) final direction of the muon as it exits the asteroid; 4) detection of the muon by a telescope deployed on an orbiting spacecraft. The deflection of the muon is exaggerated (θ_0 is less than a few 10s of milliradians for muons that can readily penetrate the asteroid). The flux of transmitted muons arriving at the spacecraft is sensitive to the density of intervening materials. [5] **C**) A simulated tomograph of a small, spherical asteroid reconstructed from orbital muon radiographic data reveals asteroid interior structure. [6]

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3D SUBSURFACE IMAGING TECHNIQUES WITH SIGNAL SPARSITY FOR ASTEROID INTERIORS.

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Introduction: We aim at technological advances and innovations in 3D subsurface imaging with the presence of signal sparsity [1,2,3]. Our goal is to enable detection and classification of valuable mineral and metal resources contained by a small planetary object which is vital for future asteroid mining prospects [4]. Due to strict limitations of space missions it is necessary to innovate new energy and payload efficient technologies to fill the role of seismic blasts, deep boreholes and high-energy radars utilized in terrestrial land surveys. It is also essential to develop computational methods and algorithms that enable robust recovery of subsurface structures from a minimal set of sparse data. The key feature for successful results is a careful mission design phase [4] in which the applied signaling scenario and inversion procedure will have to be thoroughly studied and tested. Our research with our partners deals with these essential aspects including numerical simulations [1,3], sparse transmitter and receiver placement [1,2,3], advanced forward and inverse methodology [1,3], tests with laboratory targets [2], and scientific benchmark model development.

Signaling scenarios: We study both seismic [2] and radio frequency signaling [1,3] methods. In both cases, the number of signal sources will have to be relatively low leading to a sparse signal structure. A radio signal can be transmitted and received using a (i) orbiter-to-orbiter (ii) lander-to-orbiter (iii) lander-to-lander or approach. A seismic transmitter (transducer) requires a direct surface contact, but the signal can be recorded, e.g., via laser, meaning that scenarios (ii) and (iii) suit for seismic imaging.

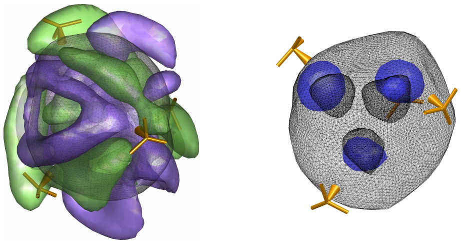

Figure 1: *Left: A simulated sparse 10 MHz radio signal exiting a small 57--73 m asteroid. Green and purple color visualize a positive and negative isosurface, respectively, and a tetrahedral source (lander) configuration is shown by the antenna symbols. Right: A reconstruction (blue) of the interior structure (grey) computed based on the signal travel time.*

Regolith models and data sets: Asteroid regolith can have a very complex structure featuring internal voids, porosity, cracks, and boulders. It can also contain extraordinary amounts of metals and minerals with high permittivity. Because of this diversity, we use both numerical [1,3] and laboratory experiments [2] to ensure the best possible result reliability. We record complete data sets of the target objects utilizing advanced measurement technologies including 3D laser point cloud and vibration surveys as well as computerized tomography (CT scan). Consequently, both surface and subsurface structures together with important signal characteristics can be reproduced with high accuracy.

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PANDORA – DISCOVERING THE ORIGIN OF THE MOONS OF MARS.

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Why Phobos and Deimos?

After decades of intensive exploration of Mars, fundamental questions about the origin and evolution of the martian moons, Phobos and Deimos, remain unanswered. Their spectral characteristics are similar to C- or D-class asteroids, suggesting that they may have originated in the asteroid belt or outer solar system. Perhaps these ancient objects were captured separately, with orbits circularized by the action of gas drag in the solar nebula or early martian atmosphere, or maybe they are the fragments of a captured asteroid disrupted by impact. Various lines of evidence hint at other possibilities: one alternative is co-formation with Mars, in which case the moons contain primitive martian materials. Another is that they are re-accreted ejecta from a giant impact and contain material from the early martian crust. Thorough characterization of their global composition is required to determine their origins. The Phobos ANd Deimos ORigin Assessment (PANDORA) mission, proposed in response to the 2014 NASA Discovery Announcement of Opportunity, will acquire new information needed to determine the provenance of the moons of Mars.

Finding an answer to the origins question.

The mission design provides a powerful and robust framework for this investigation. PANDORA will travel to and successively orbit Phobos and Deimos to map their chemical and mineral composition and further refine their shape and gravity. Geochemical data, acquired by nuclear- and infrared-spectroscopy, can distinguish between key origin hypotheses. High resolution imaging data will enable detailed geologic mapping and crater counting to determine the timing of major events and stratigraphy. Data acquired by the instrument suite will be used to characterize regolith properties, determine the nature of and relationship between "red" and "blue" units on Phobos, and determine how Phobos and Deimos are related. After identifying appropriate material representative of their bulk composition, careful analysis of the mineralogical and elemental composition of this material will allow discrimination between the formation hypotheses for each Moon.

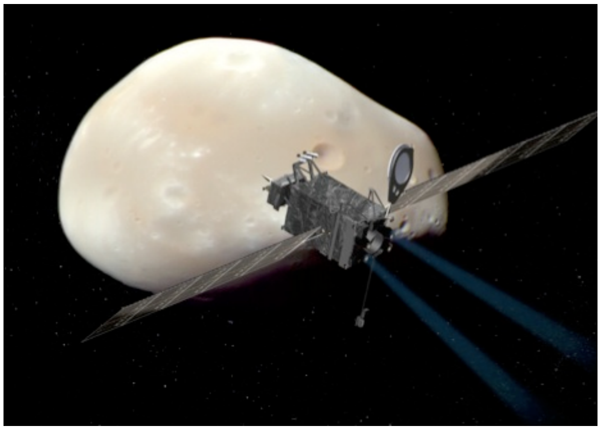

Figure 1. The PANDORA Spacecraft (shown here at Deimos) will map the moons of Mars to answer the question of their origin.

Implications for the early solar system.

The information acquired by PANDORA can be compared with similar data sets for other solar system bodies, including Mars, Mercury, the Moon, Vesta and Ceres, as well as data from meteorite studies. Understanding the formation of the martian moons within this larger context will yield a better understanding of processes acting in the early solar system, including the distribution of planetesimals. PANDORA's data will provide new constraints on the conditions that existed near the end of Mars' accretion and/or on the mode of Mars' final growth itself.

In-Situ Measurement and Determination of an Asteroid's Material and Inertia Properties. Rodney Rocha, Aerospace Engineer, Structural Engineering Division/Loads & Dynamics Branch, Mail Code ES6, NASA Johnson Space Center, Houston TX 77058, Telephone 281-483-8889, rodney.rocha@nasa.gov

Introduction:

It is proposed that an un-crewed robotic spacecraft will attach itself to an asteroid and perform autonomous and/or human tele-operated in-situ experiments. Low-cost and innovative methodologies will be developed to measure an asteroid's material and strength properties such as average mass density, bulk moduli such as Young's Modulus and shear modulus, tensile and compressive strengths, coefficients of friction, some thermal properties (e.g., heat conduction), etc. Then, utilizing on-board vehicle propulsion and specially applied flight control maneuvers, the coupled spacecraft/asteroid system will perform in-flight dynamics experiments on either a visited asteroid or else on one captured while being towed by the robotic vehicle to a Lunar Distant Retrograde Orbit (DRO) for long-term stable parking. On the long transit to DRO, the robot vehicle will perform rigid-body and flexible-body type dynamic flight maneuvers to reveal the asteroids total mass, rigid-body inertia properties such as moments and products of inertia, center-of-mass location and determination of its possible temporal shifting and changing during the transfer to DRO, etc. These measurements will be vital to knowing how to best insert (via smart flight control) the asteroid into a stable DRO parking and to provide invaluable and science- and safety-related information before human crews come later to sample and retrieve asteroid material.

References: None provided. This is a unique proposed endeavor.

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REGOLITH PHYSICAL PROPERTIES FROM REMOTE TEMPERATURE: LABORATORY MEASUREMENTS OF HEAT FLOW THROUGH PARTICULATES IN A VACUUM.

Andrew. J. Ryan[1*] and Philip. R. Christensen[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ. [*]Corresponding author: andy.ryan@asu.edu.

Introduction: The temperature of a planetary surface is strongly controlled by the rate of heat conduction through the uppermost centimeters and meters of regolith. Diurnal heating from solar radiation produces characteristic temperature cycles that are related to the physical properties of the regolith, such as grain size, roundness, sorting, layering, composition, and induration. Knowledge of these properties can aid in the selection of landing/sampling sites and in the elucidation of past and present surface processes. We have designed an experimental system to determine the affects of the aforementioned regolith properties on thermal conductivity, the results of which will greatly increase the ability to interpret remote temperature measurements.

Background: Cyclic heat flow on a planetary surface is directly related to thermal inertia, which is a function of bulk thermal conductivity, specific heat, and density: $I=(k\rho c)^{1/2}$ Thermal conductivity in particular depends on the size of the regolith particles [1].

Various thermal models were formulated to investigate the transfer of heat at the lunar surface during the Apollo era in an effort to better constrain the physical properties of the lunar regolith. The inherent difficulties associated with modeling heat flow through a network of irregularly-shaped dust particles necessitated laboratory measurements to determine the thermal conductivity of powders in a vacuum [2–5].

Models and laboratory measurements for heat transfer through fine-grained particulates (e.g., dust and sand) continue to improve [6–8]. However, recent missions to airless bodies (e.g., Hayabusa, Rosetta) and remote thermal inertia estimates of asteroid Bennu have revealed that boulders and coarse-grained (~mm–cm) materials are apparently commonplace [9]. Very few measurements of heat conduction through coarse, angular geologic materials have been conducted, typically due to experimental technique limitations. Similarly, there is a dearth of theoretical models for evaluating heat flow through these types of materials due to their complexity.

Experimental method: Heat conduction through particulates in a vacuum is temperature dependent; it is important that experimental samples be cycled through the full range of temperatures expected in nature. Furthermore, pressure must be sufficiently low that the mean free path of the gas molecule is larger than the average size of the sample pore space, such that the gas does not contribute to the bulk thermal conductivity of the sample.

Our method is as follows: An infrared camera monitors the change in a sample's surface temperature in response to a thermal pulse. The sample is located in an environment chamber where the temperature and pressure are precisely controlled. The thermal conductivity of the sample is retrieved by fitting a time-dependent finite element model for heat conduction (COMSOL Multiphysics®) to the laboratory sample surface temperature. Data calibration and boundary conditions are monitored continuously during a run using a series of temperature sensors and radiometric targets (blackbody and lambertian). Modeling efforts validated by initial results from measurements in a Mars environment chamber have demonstrated thermal conductivity's temperature dependence [10–11], as well as the marked effects of induration [12].

The strengths of this method are that it allows coarse, complex (angular, mixed, layered) samples and it assumes that conductivity is temperature dependent. Many previous studies utilized techniques (e.g., line-heat source method) that preclude the use of coarse-grained or coarsely heterogeneous samples.

Impact: Our radiometric experimental measurements will be used to develop an empirical model that relates grain size, roundness, grain size distribution, and heterogeneity (e.g., layering) to temperature-dependent bulk conductivity in a vacuum. This will be an invaluable tool for remotely determining the physical properties of regolith on airless bodies by means of thermal-infrared spectral or bolometric measurements. Such information will be useful for sample collection, landing, resource utilization, and remote geologic interpretations.

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Probing the Interior Structure of Comets and Asteroids using Observational Techniques

Nalin H. Samarasinha (Planetary Science Institute)

Our knowledge of the interior structure of comets and asteroids is critical in understanding the formation era of the Solar System and their subsequent collisional and thermal evolution. In addition, a detailed understanding of the interior structure of comets and asteroids, especially Near Earth Objects, is an integral part for (a) designing effective mitigation strategies of a potential Earth impactor and (b) developing effective resource utilization techniques for future extended space missions or as economic resources.

Currently, the interior structure of small bodies is not well understood, and only a glimpse of the details is known. Most of our understanding is gathered from remote observations that derived rotational rates and orbital characteristics of binary systems etc.

However, a number of direct or interventional techniques that require a space mission have been proposed (e.g., radar tomographic, impactor based, high-energy muons).

Considering the likely diversity among the interior structure of comets and asteroids, it is prudent to follow a dual approach, namely continued remote observations as well as targeted space missions.

In this conference, I will discuss some select observational tools of the interior structure including both remote and in situ observations.

ATTITUDE CONTROL SYSTEM FOR LOW-SPEED CUBESAT CENTRIFUGE TO SIMULATE ASTEROID SURFACE CONDITIONS.

S. Shah[1], A. Cannady[1], I. Alizadeh[1], J. Thangavelautham[2], E. Asphaug[2], [1]School for Engineering of Matter, Transport and Energy, [2]School of Earth and Space Exploration, Arizona State University.

Summary: AOSat is a 3U CubeSat based centrifuge that will be launched into low Earth orbit in the 2015-2016 timeframe. The satellite will be used to answer fundamental questions of how dust accretes into larger objects under microgravity conditions and to simulate asteroid surface conditions by spinning at upto 1 rev/min to produce 0.0001g. An Attitude Determination and Control System (ADCS) capable of producing and keeping this low spin rate is challenging. Typically a conventional satellite spins at high angular velocities and is spin stabilized using the gyroscopic effects.

In contrast, AOSat will be spinning at much lower rates that prevents us from exploiting this phenomenon. AOSat poses additional challenges, due to its limited volume that prevents use of 3-axis reaction wheels. AOSat with its small the moment of inertia compared to large satellites is subject to faster dynamic response and consequently higher sensitivity to perturbation torques which make attitude control stability more difficult. The only viable option for AOSat is to use magneto-torquers in combination with a reaction wheel. Magneto-torquers alone cannot provide AOSat with total control authority, hence a novel method of utilizing 3 magneto-torquers and 1 reaction wheel to achieve full control of AOSat is proposed. This allows AOSat to periodically dump all excess momentum.

The proposed method has been successfully implemented using a state feedback control method to achieve stabilization of AOSat and required 1 rev/min. Simulation results show that settling time for AOSat-from a stationary state to one rev per minute takes 500 seconds. These results account for all significant disturbance torques the satellite will be experiencing in low earth orbit. The state feedback control algorithm shows that it is a robust system that can overcome these disturbances. Work is proceeding on testing the approach using an attitude control test-bed in preparation for flight hardware integration and testing.

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Dynamical Approaches to Small Body Exploration

D.J. Scheeres
University of Colorado

Small bodies present interesting and significant challenges for their robotic and human exploration, driven largely by their extreme dynamical environment. While most planetary and Earth orbiting space missions have dynamics that are well-described by classical orbital mechanics, the small body environment introduces a wide range of difficulties that must be understood and addressed for the safe and effective navigation of vehicles. While this environment presents challenges in terms of understanding what will happen to a vehicle trajectory, it also presents many opportunities that are not feasible for more traditional missions. Specifically, the low gravity fields and strong exogenous perturbations enable the use of innovative and customizable trajectories for observations. The unique surface environments make it feasible to ballistically deploy smaller satellites or robots down to the surface where they can perform innovative measurements and experiments. In fact, it is even feasible to turn an entire small body system into a geophysical laboratory where unprecedented scientific experiments can be performed. This talk will present an overview of these situations and present a range of example mission designs that either have been or are being proposed.

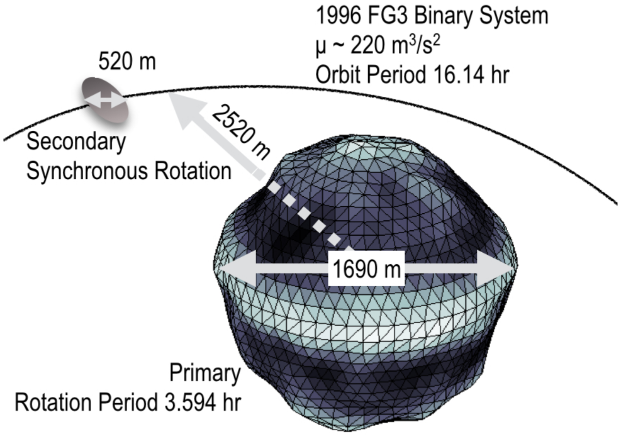
A Geophysical Laboratory for Rubble Pile Asteroids: The BASiX Mission

Small rubble pile asteroids exhibit a diverse range of evolutionary behaviors and morphologies, driven by an array of poorly understood geophysical effects. The complex ways that these bodies evolve belies their simple structure: gravitational aggregates of shattered primitive bodies. Their evolution can be dramatic, such as seen in the active asteroids P/2013 P5 and P/2013 R3, or may be subtly masked, such as in the tide-BYORP equilibria of singly-synchronous binary asteroids. Their evolutionary outcomes can defy the imagination, such as asteroid 1950 DA which is spinning faster than its gravitational attraction yet is held together by weak van der Waals forces (Rozitis et al. 2014), or present us with profound mysteries, such as how the Almahata Sitta meteorite could be comprised of such diverse components.

Beyond these motivations, the study of rubble pile asteroid geophysics can shed insight into any solar system environment where gravitational aggregates interact in a micro-gravity setting, ranging from the protoplanetary disc to planetary ring systems. The broad study of the geophysics of aggregates in such micro-gravity environments is becoming both a unifying theme and emerging field of study.

Out of the many diverse and complex forms that rubble pile asteroids take on, the study of NEA binary asteroids can in particular be used to expose the geophysics of micro-gravity aggregates. Binaries are an expression of micro-gravity geophysics due to the manner in which they form and their continuing evolution. Due to our ability to visit, probe and interact with NEA, we can also turn them into geophysical laboratories.

This talk will introduce the science of the Binary Asteroid in-situ Explorer (BASiX) Discovery mission, which proposes to turn the primitive C-Type binary asteroid (175706) 1996 FG3 into such a geophysical laboratory. Exploring this body enables us to probe a broad range of rubble pile asteroid properties: internal tidal dissipation (through FG3's documented tide-BYORP equilibrium), the nature of surface heterogeneities on primitive bodies (well documented for FG3), the intrinsic seismic and strength properties of micro-gravity aggregates, and the processes that form and evolve such binaries.



Binary asteroid 1996 FG3 is one of the best characterized binaries known, enabling a detailed mission plan and design to be developed prior to launch.

HUMMINGBIRDsCHARM (HsC) / NEO-NEA Characterization Missions

Dan Scheld[1], Terry Gamber[1], C. B. Dreyer[1] , Logan Knowles[2], David Hall[1], and Jeffrey Hayden[1]

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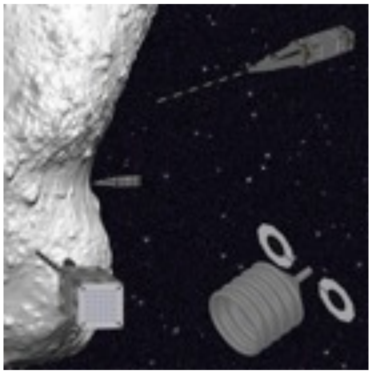
ABSTRACT

Introduction: The HUMMINGBIRDsCHARM (HsC) concept has been described as a set of multiple missions that will intercept and "interview" target NEOs/NEAs. The "charming" aspect of this concept is the requirement that we send multiple vehicles to each target. A Charm is a gathering of Hummingbirds. The HsC missions are intended to meet the clear guidance driven by the NEO/NEA communities; OBSERVE-TOUCH-EARLY-OFTEN, ie, that we "Observe & Touch" and we provide this capability "Early & Often". There are several excellent mission concepts coming forth to meet the remote NEO/NEA "observational" need, for example SENTINEL, NeoCAM and NESS. The HsC missions are intended to meet the "tactile", "touch" component of the guidance "quartet"; OBSERVE-TOUCH-EARLY-OFTEN. "Early" and "often" drives the need for Overwhelmingly Cost Effective (OCE) systems requiring simplification and reduced complexity and necessitates that there need be a "many-off", production mode approach implemented in spacecraft design, build, and availability. HsC is highly motivated by the concept of providing a "service" to the NEO/NEA communities. HsC enables unique opportunities at each target in providing complete characterizations of target properties. Each "CHARM" includes a Touch & Go vehicles (TAGs) that "flit" in close to the target and provides up-close visual and tactile data along with an Observer/ Communications (ObsComm) vehicles that relays both TAG and ObsComm video along with instrument data streams from all vehicles. Modern technologies in avionics for spacecraft control, communications, and navigation permit the Hummingbirds to be small enough that multi-spacecraft missions can be launched on the more moderate-sized rockets. Since the Hummingbird vehicle designs are identical, no redundancy is implemented in their design, thus reducing the cost of implementing that complexity. Hummingbird Habitat, ie, mothership concepts are also being evaluated as HsC delivery systems for deep space targets. The complete application and advantages in using HUMMINGBIRDsCHARM concept in small body missions are covered in the presentation.



The HsC Concept as applied in an Asteroid Capture Scenario

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Asteroid Geophysics and Quantifying the Impact Hazard

D. Sears (BAERI), D. H. Wooden (NASA Ames), D. G. Korycanksy (UCSC)

Probably the major challenge in understanding, quantifying, and mitigating the effects of an impact on Earth is understanding the nature of the impactor. Of the roughly 25 meteorite craters on the Earth that have associated meteorites, all but one was produced by an iron meteorite and only one was produced by a stony meteorite. Equally important, even meteorites of a given chemical class produce a wide variety of behavior in the atmosphere. This is because they show considerable diversity in their mechanical properties which have a profound influence on the behavior of meteorites during atmospheric passage. Some stony meteorites are weak and do not reach the surface or reach the surface as thousands of relatively harmless pieces. Some stony meteorites roll into a maximum drag configuration and are strong enough to remain intact so a large single object reaches the surface. Others have high concentrations of water that may facilitate disruption. However, while meteorite falls and meteorites provide invaluable information on the physical nature of the objects entering the atmosphere, there are many unknowns concerning size and scale that can only be determined by from the pre-atmospheric properties of the asteroids. Their internal structure, their thermal properties, their internal strength and composition, will all play a role in determining the behavior of the object as it passes through the atmosphere, whether it produces an airblast and at what height, and the nature of the impact and amount and distribution of ejecta.

J-ASTEROID, A VISUALIZATION AND MISSION PLANNING TOOL FOR SMALL BODIES.

M. E. Smith[1], P. R. Christensen[1], S. Anwar[1] and S. Dickenshied[1], [1]Arizona State University, School of Earth and Space Exploration, Mars Space Flight Facility.

Introduction: The history of our solar system is an topic that we have pondered for centuries. The answers to our questions on the formation of our solar system, Earth and even Earth's oceans may reside in asteroids. Asteroids could be the precursor to the origins of life and, with the continuous improvement of technology and the exploration of our solar system, they are the next step for robotic exploration.

JMARS (Java Mission-planning for Analysis and Remote Sensing) is a Geographic Information System (GIS) that was developed by Arizona State University's Mars Space Flight Facility. JMARS was developed as a mission planning and data-analysis tool for NASA's orbiters, instrument teams, students and even the general public. The mission planning tool was originally written for the THEMIS (THermal EMision Instrument System) instrument on board the Mars Odyssey spacecraft. JMARS has a variety of planetary bodies within the GIS such as many of our solar system's planets, satellites and asteroids. In recent years, JMARS has been enhanced to support the exploration of asteroids and small celestial bodies. These enhancements led to the creation of J-Asteroid. J-Asteroid is currently being used on two NASA funded missions that are exploring small bodies.

The Dawn spacecraft was launched on September 27, 2007 and its current objective is to visit the two largest objects in the asteroid belt, Vesta and Ceres. Dawn has already visited Vesta and is currently on course to reach Ceres by April, 2015. If Dawn successfully reaches Ceres, it will be the first spacecraft to travel to two extraterrestrial bodies. J-Asteroid is serving as the data visualization tool for the Dawn science team.

J-Asteroid has also been chosen by the OSIRIS-REx mission to be the planning and visualization tool.

OSIRIS-REx Mission: The OSIRIS-REx mission is being operated by the University of Arizona's Lunar and Planetary Laboratory in collaboration with NASA Goddard Space Flight Center and Lockheed Martin Space Systems. The scheduled launch date is in September, 2016. The goal of the mission is to travel to Bennu and return samples from the asteroid. Bennu is a carbon-rich asteroid that may contain the answers to our solar systems origination and history. It will be the first NASA mission to return samples to Earth from an asteroid.

J-Asteroid was customized to support the OSIRIS-REx science team. The team will be using J-Asteroid for planning, commanding and visualization.

Payload: OSIRIS-REx has several instruments on board that will help meet the science objectives, navigation and communication of the mission. J-Asteroid was altered to accommodate the planning and visualization of all the instruments on board the spacecraft. These instruments include: OLA (OSIRIS-REx Laser Altimeter), OCAMS (OSIRIS-REx CAMera Suite), OTES(OSIRIS-REx Thermal Emission Spectrometer), OVIRS(OSIRIS-REx Visible and InfraRed Spectrometer), REXIS(REgolith X-ray Imaging Spectrometer), TAGSAM(Touch-and-go Sample Acquisition), SRC(Sample Return Capsule), GN&C LIDAR(Guidance, Navigation, and Control LIDAR), TAGCAMS(Touch-and-Go Camera System).

Conclusion: J-Asteroid is a visualization and mission planning GIS that was enhanced from the original software suite, JMARS. J-Asteroid allows mission planners the ability to communicate with the payload instruments to create an opportunity for science team members to visualize and process the data.

Preliminary Results From The Neowise Mission. S. Sonnett[1], A. Mainzer[1], J. Bauer[1], T. Grav[2], J. Masiero[1], C. Nugent[1], E. Kramer[1], [1]Jet Propulsion Laboratory / California Institute of Technology (Sarah.Sonnett@jpl.nasa.gov), [2]The Planetary Science Institute.

Introduction: Understanding the numbers, orbits, and physical properties of near-Earth objects (NEOs; asteroids or comets with perihelia less than 1.3 AU) is essential both for characterizing the population of objects that pose a potential impact hazard, as well as for planning an appropriate mitigation strategy should one be discovered on a threatening trajectory. Of the ~11,000 known NEOs currently discovered, only the most basic properties (orbital parameters and absolute magnitude H) are known for all but ~2,000. Roughly 1,000 new NEOs are discovered over all size ranges per year; however, well-determined physical measurements such as taxonomic classification or radar-derived sizes and shapes are determined for only ~100 of these. Furthermore, these ~11,000 known NEOs are only a small fraction of the total population.

Given the need for improvement in our knowledge of NEOs, the NEOWISE mission's primary objectives are to detect, track, and characterize NEOs as well as other minor planets. NEOWISE has begun regular delivery of asteroid and comet candidates to the Minor Planet Center. As with data from the prime mission, the infrared images from the reactivated NEOWISE mission will be useful for characterizing physical properties such as size and albedo for minor planets.

Observations: NEOWISE began as the Wide-field Infrared Survey Explorer (WISE; principal investigator E. Wright of UCLA), a NASA Medium-class Explorer mission that surveyed the entire sky in four infrared wavelengths simultaneously (3.4, 4.6, 12 and 22 microns) [1]. The spacecraft is in a sun-synchronous polar orbit, allowing continuous observations near 90-degrees solar elongation. WISE's primary scientific objectives were to find cool stars and ultraluminous infrared galaxies. However, NASA's Planetary Science Division provided the resources needed to archive and publicly serve all of the single exposures, to create tools to support solar objects out of the data in near-real time. These tools are collectively known as NEOWISE [2]. During the fully cryogenic portion of the prime mission, the NEOWISE project extracted detections of >158,000 minor planets, including >34,000 new discoveries. Among the detections were ~700 NEOs (of which 135 were new discoveries) and 160 comets, including 21 new cometary bodies. During the 3-band and post-cryogenic mission phases, >13,500 minor planets were observed, including 116 NEOs [3,4].

WISE was reactivated in December 2013 and renamed NEOWISE, acquiring ~12 images (at a spacing of ~3 hours) of each moving object identified [5]. Since the original solid hydrogen refrigerant has been exhausted, an operating temperature of ~75K (ensuring background-limited performance in the two bluest bandpasses - 3.4 and 4.6 microns) is achieved passively by pointing at zenith. The 32 months spent in hibernation have had a negligible effect on the image quality, sensitivity, photometric and astrometric accuracy, completeness, and rate of minor planet detections.

All data products from the NEOWISE prime mission, including the single-frame images and extracted source lists, have been delivered on scheduled. These images and detections are available through NASA's Infrared Science Archive (IRSA) hosted at the Infrared Processing and Analysis Center at Caltech. The restart of NEOWISE will result in the delivery of an additional three years of survey data. Data releases of images and sources will be made annually through IRSA. Candidate minor planet position-time associations ("tracklets") are being delivered to the Minor Planet Center on an ongoing basis. After three years, precession of the orbital plane will make it difficult to keep scattered light out of the telescope's boresight, bringing a natural end to the mission.

Science Highlights: The reactivated mission has discovered 34 NEOs as of November 2014, most of which are large and dark. At its completion, the NEOWISE project will provide diameters and albedos for ~20% of the known NEO population. Since reactivating in December 2013, NEOWISE has observed 11 comets, including the previously unknown Halley family comet C/2014 C3 (NEOWISE). NEOWISE has also observed comet C/2013 A1 (Siding Spring), which had a close encounter with Mars in October 2014. Various morphologies are apparent throughout the dataset, including dust comae, tails, and trails. In addition, we are able to study the thermal and physical properties of cometary nuclei. CO and CO_2 production rates can be constrained since the 4.6 micron band contains emission lines from these species, enabling us to examine trends of cometary activity with varying heliocentric distance and dynamical family [6].

NEOWISE data have enabled us to advance our understanding of asteroid families by using albedos in conjunction with orbital elements to refine known families and identify new ones that previously could not be disentangled from the background population. These new lists allow us to better constrain the size distribution of family members at the sizes probed by NEOWISE. NEOWISE data have also allowed for measurements of average surface thermal inertia of near-Earth asteroids. We are also using thermal lightcurves to determine rotation properties of Jovian Trojans and Hildas, which help diagnose planetary migration history.

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Asteroid seismology: using natural frequencies distribution to infer internal structure

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Seismology, or mechanical wave propagation through the body, is a primary mechanism we currently have for looking at the interior of asteroids and comet nuclei. Seismology has been very successful in exploring the interior structure of the Earth, but for small bodies at remote locations in the solar system we are heavily constrained by the number of seismic sources and measuring devices, probably only 2 to 3 for each for a space mission. One approach to best utilizing the limited instrumentation is to study the full body vibrations or the natural frequency distribution (spectrum). Can we infer things about the interior structure based on measured distribution of natural frequencies? Asteroids and comet nuclei have varied outer shapes, as well as the possibility of interior structure ranging from rubble piles to large monolithic pieces. Natural frequency distributions are affected by both exterior shape and interior structure. Using large-scale numerical simulations, we have computed the natural frequency distributions for a sphere, an ellipsoid, and from computations assuming the outer surface shape of asteroid Itokawa, where a detailed surface map exists due to the Japanese Hayabusa mission. The distributions show qualitative behavior relating to both outer shape and interior structure: irregular outer shapes smooth the natural frequency distribution while internal structure leads to clumping of the natural frequencies. These qualitative differences are discussed and may be sufficient to allow the qualitative determination of interior structure, thus providing input to origin questions and deflection techniques.

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Introduction: The National Radio Astronomy Observatory's Green Bank facility has several antennas available for spacecraft communications, Doppler tracking and radar, and provides unparalleled support infrastructure for data processing and recording equipment.

The 100 meter Robert C. Byrd Green Bank Telescope (GBT) is currently capable of receiving signals at frequencies from 300 MHz to 86 GHz and has an aperture efficiency of over 30% at 100 GHz [1]. It is also the largest, steerable dish antenna in the world with sky coverage as far as -45 degrees declination. State of the art receivers on the GBT contribute to excellent system noise figures in the 0.3 to 0.5 dB range at frequencies below 40 GHz. This, in addition to the tremendous collecting area of the GBT, results in unprecedented sensitivity across the entire frequency range.

The GBT has been used for spacecraft tracking in notable ESA and NASA missions. During its decent, the Doppler shift of the Huygens probe uplink to the Cassini spacecraft was tracked by the GBT after the probe's launch from the Cassini spacecraft until its landing on the surface of the Saturnian moon Titan. Difficulties with the onboard Doppler wind experiment made the data collected by the GBT the primary source of information regarding wind velocities encountered during the decent of the Huygens probe [2].

The Doppler shift of the UHF links from the Phoenix Mars lander was tracked in a similar manner to aid in investigating Martian winds and to help determine the point of landing. After landing, the UHF links continued to be tracked, and showed the Doppler shift due to the relative motion of Mars with respect to the Earth.

Numerous projects have used the GBT in bistatic radar experiments and include imaging of nearby asteroids [3] and hidden geological features below the Lunar surface [4]. A particularly exciting GBT radar result was the discovery of Mercury's molten core [5].

In addition to the GBT is the NRAO 140-ft Telescope, a fully operational, 43 meter antenna useable through 27 GHz. This antenna is currently an Earth station for the RadioAstron project [6], performing wideband data and X-band Doppler tracking downlink tasks, and is capable of uplinking reference tones should the spacecraft's onboard references become unreliable.

Other fully operational antennas at Green Bank include the 20 meter antenna, which is capable of high slew rates and good efficiency to K-band and a 13.7 meter antenna with good efficiency to Ku-band. Three 26 meter antennas, which are currently not in operation, have good efficiency through Ku-band.

Green Bank has extensive infrastructure to support signal processing and recording of received signals. Fiber optic links from all antennas to the Jansky Lab building are in place. A shielded control room suite provides climate controlled and secure locations for signal processing and recording equipment, a utility power feed of 12,000 kVA with high reliability, and protection of the site antennas from RFI through its location in and coordination of the National Radio Quiet Zone, provide users of Green Bank facilities with an unparalleled advantage in performing their missions and experiments.

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STRATEGIES FOR THE GEOLOGIC MAPPING OF SMALL AIRLESS BODIES: DAWN AT VESTA AND CERES.

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Introduction: NASA's Dawn spacecraft orbited the main belt asteroid (4)Vesta from July 2011-September 2012, and conducted a lengthy orbital study of this unique protoplanet [1,2]. A geologic mapping campaign was developed as part of the Nominal Mission to provide a systematic, cartography-based initial characterization of the global and regional geology of Vesta. In this abstract we present the final global geologic map of Vesta (**Figure 1**), and look ahead to plans to conduct a similar geologic mapping campaign at dwarf planet (1)Ceres beginning in Winter 2015.

Purpose & Goals of Mapping: Geologic maps are tools to understand the evolution of the terrestrial planets. The goal of geologic mapping is to place observations of surface features into their stratigraphic context to determine the geologic evolution of planetary surfaces [3,4]. The advantage of geologic mapping over photogeologic analyses alone is that it reduces the complexity of heterogeneous planetary surfaces into comprehensible portions, in which discrete material units are defined and characterized based upon specific physical attributes related to the geologic processes that produced them. The final goal of global geologic mapping is to identify a geologic timescale for a planetary object, so that its geologic evolution can be easily compared with other objects [5]. The goal of the Vesta global mapping was 1) to support the Geophysics group by providing geologic-stratigraphic context of surface features, and 2) to better support the analysis of data from the Visible and Infrared Spectrometer (VIR) and the Gamma Ray and Neutron Detector (GRaND).

Plans for Ceres: NASA's Dawn spacecraft will arrive at Ceres in mid-March, and begin its orbital mission in April 2015. The Dawn Science Team plans to implement a similar geologic mapping campaign at Ceres as was done at Vesta, but using fewer mappers and combining or subdividing quadrangles as necessary to map Ceres surface efficiently based on its surficial geology.

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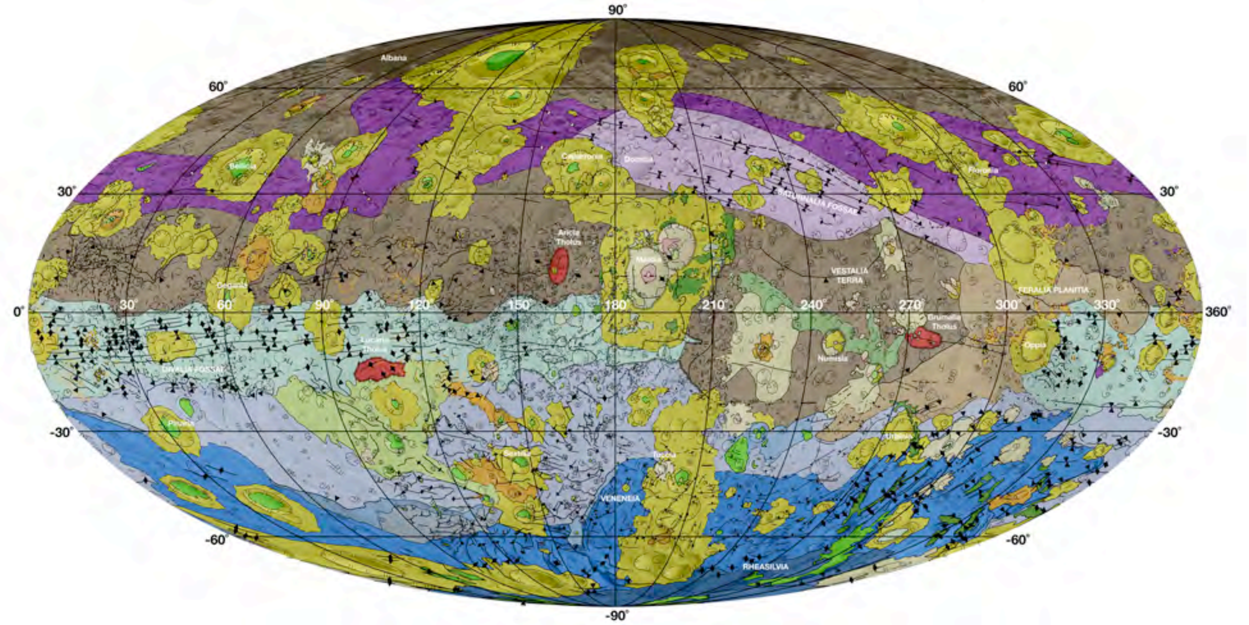

Figure 1. The high-resolution global geological map of Vesta derived from Dawn spacecraft data. Brown colors represent the oldest, most heavily cratered surface. Purple colors in the north and light blue represent terrains modified by the Veneneia and Rheasilvia impacts, respectively. Light purples and dark blue colors below the equator represent the interior of the Rheasilvia and Veneneia basins. Greens and yellows represent relatively young landslides or other downhill movement and crater impact materials, respectively. This map unifies 15 individual quadrangle maps published in the December 2014 Special Issue of *Icarus*. Map is a Mollweide projection, centered on 180° longitude using the Dawn Claudia coordinate system.

R^{2}S: A TECHNOLOGY DEMONSTRATOR FOR NEO RECONNAISSANCE MISSION. P. F. Wren[1], R. A. Fevig[1], N. Kaabouch[2], M. E. Nelson[3], F. Bourbour[1], J. W. Snarr[2], D. Ghosh[2], C. Church[1], [1]Department of Space Studies, University of North Dakota, Clifford Hall Room 512, 4149 University Ave Stop 9008, Grand Forks, ND, 58202, [2]Department of Electrical Engineering, University of North Dakota, Upson Hall II Room 160, 243 Centennial Drive Stop 7165, Grand Forks, ND, 58202 [3]Department of Aerospace Engineering, Iowa State University, 0625 Howe Hall, Ames, IA, 50011.

Introduction: Of the 9000 known Near Earth Objects (NEO), many have the potential to collide with the Earth. Depending on its size, results could range from local effects to damage and casualties on a global scale. Some NEOs may be detected decades before their possible impact, as with 99942 Apophis [1], while others may be identified with little warning. The development and demonstration of technologies that can be quickly deployed to characterize NEOs is critical to ensure readiness to deal with these threats.

To assess and respond to a potential impactor, the object's composition, internal structure, and mass must be determined. Constraints on the internal structure of a small asteroid may be derived from modeling the gravitational field during close proximity operations. Initial investigations into the feasibility of backing out the internal structure of such an NEO have been conducted [2]. A small spacecraft deployed in the vicinity of an NEO could use tracking data, and possibly images [3] to create a gravity model that would help to constrain the mass distribution of the object.

The University of North Dakota, in cooperation with Iowa State University, has been granted a NASA ELaNa program opportunity to launch a 1U CubeSat into low Earth orbit and demonstrate technologies capable of collecting data useful to gravitational modeling, as well as to general characterization of NEOs.

Mission: The mission objectives for the Rapid Response Spacecraft (R^{2}S) are to demonstrate on-orbit image mosaicking and super-resolution processing to extend the capabilities of small imagers, and to demonstrate small spacecraft constellation operations.

R^{2}S will capture images of the Earth along with certain metadata (time, location and orientation information), and then attempt to assemble them into a mosaic image. Super-resolution techniques will be used to enhance the images [4], and the final images will be downlinked to a ground station.

R^{2}S will also communicate with multiple satellites in the Global Positioning System (GPS) to determine its location relative to these satellites, and report this information to the ground station.

Spacecraft: The 1U CubeSat spacecraft bus for R^{2}S consists of commercial off-the-shelf (COTS) hardware: the structure, onboard computer (OBC), electrical power system (EPS), and transceiver. Only the command and data handling software will be developed internally. The use of space-proven components allows for greater focus on the development of the custom payload.

Payload: To meet the mission objectives, R^{2}S incorporates two visible-light imagers, a GPS receiver, an inertial measurement unit, and a dedicated microprocessor to manage these instruments and process collected data. Each payload element is discussed here.

Visible Light Imagers. Two cameras will be mounted on adjacent faces of R^{2}S (a separation angle of 90°) to increase the likelihood of capturing useful images of the Earth.

GPS Receiver. A GPS receiver and antenna will be used to determine the current position of R^{2}S as part of constellation operations. The position information is also stored with captured images.

Inertial Measurement Unit (IMU). R^{2}S will carry an IMU containing multi-axis gyroscope and accelerometer to measure the relative orientation of the spacecraft over time. This information will also be stored with captured images.

Payload Microprocessor. Distinct from the OBC, this high-performance microcomputer will be responsible for controlling cameras, selecting useful images, building image mosaics, performing super-resolution processing, and managing the GPS and IMU.

Conclusion: R^{2}S is on the candidate list for an ISS launch in 2016. Operating R^{2}S in low-Earth orbit will be the culmination of a multi-year effort involving UND and ISU students from across the country, fulfilling another primary mission objective to provide a unique educational experience.

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APPROACHES TO EXPLORATION, SAMPLE RETURN, AND IN SITU RESOURCE UTILIZATION ON COMETS, ASTEROIDS AND SMALL MOONS.

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Introduction: Over the past decades, Honeybee Robotics and its partners has been developing technologies for exploration and utilization of small bodies. Here we present example of several technologies: PlanetVac [1], Kinetic Impactors [2], and Mobile In Situ Water Extractor [3].

PlanetVac: PlanetVac shown in Figure 1, is a regolith sample acquisition mission concept that uses compressed gas to blow material from the surface up a pneumatic tube and directly into a sample return container. To demonstrate this approach, the PlanetVac lander with four legs and two sampling tubes has been designed, integrated, and tested in vacuum chamber. The tests included a drop from a height of approximately 50 cm onto the bed of regolith, deployment of sampling tubes into the regolith, pneumatic acquisition of sample into an instrument (sample container) and the rocket, and the launch of the rocket. This successful demonstration was funded by the Planetary Society: https://www.youtube.com/watch?v=DjJXvtQk6no

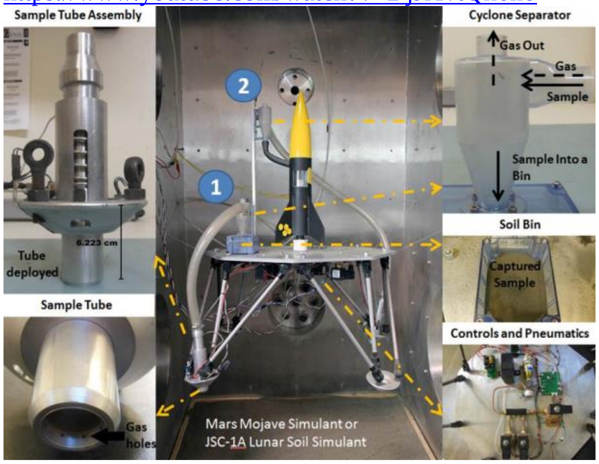

Figure 1. PlanetVac suspended within a vacuum chamber. Number 1 indicates cyclone separator connected to an instrument, while the number 2 cyclone is connected to a rocket.

Kinetic Impactors: Thumpers are ~20 kg, ~50 cm diameter, spherical kinetic probe that can be deployed to the surface with predetermined and controlled speed (Figure 2). The probe has an integrated accelerometer, cameras, avionics, and transmitter. The deceleration profile can be used to estimate the strength of the regolith surface. The Shotgun system uses a large number of small projectiles fired at low velocity at the surface of a body or at the boulder. If a ball impacts regolith, it will create a crater whose size is a function of regolith strength and density. If a ball impacts a boulder it will bounce back at a speed proportional to rock strength. If the rebound speed cannot be measured, hollow balls packed with retroreflectors could be used ("paintballs"). The shell can be designed to break and release retroreflectors when impacting rock of certain strength.

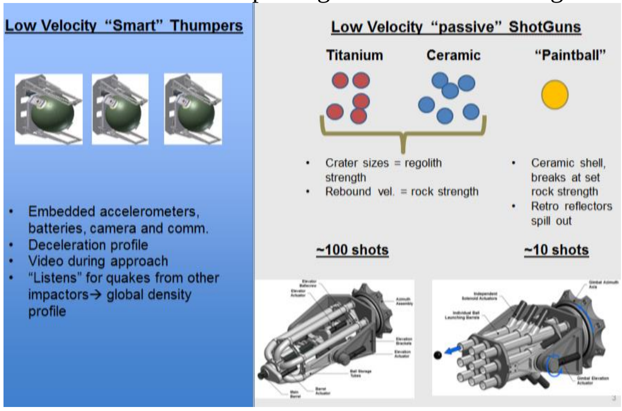

Figure 3. Thunpers and Shotguns.

Mobile In Situ Water Extractor or MISWE: The MISWE integrates mining and water extraction systems into a single unit. The water extraction process follows three steps: 1) mining the soil using deep fluted auger, 2) extracting the water from soil within the flutes, and 3) discarding the soil. The MISWE breadboard demonstrated water extraction effectivness of 90% (10% water was lost). The energy efficiency was 80%, based on max. theoretical.

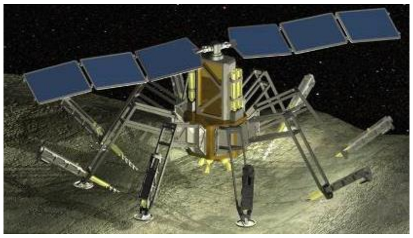

Figure 4. Mobile *In situ* Water Extractor (MISWE) with 8 water reactors attached to each leg of the lander. The reactors are placed at oblique angle to provide anchoring.

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