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COMPOSITIONS OF BINARY NEAR-EARTH OBJECTS: IMPLICATIONS FOR THEIR INTERNAL STRUCTURE.

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Introduction: Several lines of evidence suggest that approximately 16% of all near-Earth objects (NEOs) are binaries [1-3]. Since NEO dynamical lifetimes are relatively short (~ 10^6 - 10^7 years) [4], an active mechanism must be generating new NEO binary pairs [5]. The favored formation mechanisms for binary NEOs invoke close flybys of the Earth (or Venus) by their parent bodies and involve either tidal disruption [6], or rotational spin-up and disruption [7], after one or several planetary encounters. These types of disruption events are thought to only occur if the parent NEO bodies are either composed of physically weak materials (e.g., strengths similar to carbonaceous meteorites) or were gravitationally bound rubble piles with little or no internal strength.

Assuming that binary NEOs are generated primarily by disaggregation of km-scale NEO parent bodies during close planetary flybys, then the two models of parent body weakness predict different compositional patterns for the formation of NEO binaries. If NEO binaries form primarily from physically weak materials, they should be dominantly similar in composition to carbonaceous CM- or CI-type meteorite materials. However, if these binaries form primarily from disruption of strengthless rubble piles, then there shouldn't be any particular compositional preference.

Spectral Observations: An observational campaign to obtain near-infrared spectra of NEOs has been implemented using the NASA IRTF and SpeX instrument [8] since October, 2001. One of the first objects to be observed of this campaign was 1998 ST_{27}, which was simultaneously imaged by radar and determined to be a binary object [9]. The spectral response of this NEO demonstrated a significant upturn beyond ~ 2.2 µm and a broad absorption feature centered near 1.0 µm [10] (Figure 1). The upturn was interpreted to be due to thermal emission from a low albedo object at a small heliocentric distance and was used to estimate the albedo of 1998 ST_{27} at 0.05 ± 0.01 [10].

The broad absorption feature of 1998 ST_{27} located near 1.0 µm is one that is sufficiently intense to compete with the already strongly absorbing (*i.e.*, ~ 5% albedo) surface material. Given the low albedo of this binary NEO, the mineral species producing this feature must have a high absorbance at these wavelengths in order to produce a detectable effect on such a dark surface. Among plausible meteoritic minerals, the most probable candidates are the iron-rich phyllosilicates present in the CM2- and CI1-carbonaceous chondrites [11].

Other binary NEOs have been observed by our research group, such as 1999 HF_1 and 2005 AB, which have similar features to those of 1998 ST_{27}. Hence they have also been identified as having affinities to carbonaceous chondrite assemblages [12]. This suggests that carbonaceous-type materials are not uncommon among members of the binary NEO population.

However, observational data of two other objects indicate that carbonaceous compositions are not the only type of materials detected in the spectra of these objects. Binary NEOs (66063) 1998 RO_1 and 2003 YT_1 have been identified as having mineral assemblages similar to other meteorite groups found among the terrestrial collections.

NEO (66063) 1998 RO_1 was detected to be a binary both by lightcurve and radar observations [13]. Spectral observations obtained from the IRTF demonstrate that this object has two absorption features, one asymmetric band centered near 1 µm, and one symmetric band centered near 2 µm (Figure 1). A more precise analysis indicates that this binary NEO has spectral parameters similar to the L-chondrite meteorites [14]. These meteorites represent one of the more commonly found groups on Earth and are considered to be physically strong relative to the carbonaceous chondrite class.

One of the more unique binary NEOs to be observed in terms of composition so far to date during this NEO observational campaign is 2003 YT_1. This object was also discovered to be a binary based on lightcurve observations and radar observations [15]. The near-infrared spectral data obtained from the IRTF also demonstrates well defined 1 and 2 µm features. However, unlike the spectral features of the previous binary NEO, analyses of these features suggest that this particular object has a surface assemblage dominated by orthopyroxene, with no detectable olivine present [16].

The estimated pyroxene chemistry from detailed spectral analysis and the lack of any obvious olivine content suggest that this NEO's parent body experienced significant heating with a large amount of melt production. Given that the inferred pyroxene mineralogy lies near that of the diogenite-eucrite boundary, this suggests that 2003 YT_1 may have a compositional affinity to the basaltic achondrite meteorites (*e.g.*, howardite-eucrite-diogenite (HED) clan of meteorites) [16]. Such mineralogies are similar to basalts found on Earth (*e.g.*, the basaltic lava fields on Hawai'i's Big Island) and represent relatively physically strong geologic materials.

Interpretation of Internal Structure: As mentioned above, lightcurve and radar observations suggest that a particular NEO has a significant chance (~ 16%) of being a binary object and therefore likely to be a gravitationally bound rubble pile [2,3]. However, it should be noted that the estimated fraction of binary objects among the NEO population is only a lower limit. Lightcurve techniques can only detect binary NEOs in a certain range of orientations, and radar observations are limited by the distance to the NEO and size of the secondary [5]. For example, data from 1998 ST_{27} demonstrated that most of the echoes of its 120 m secondary were weak for a majority of the observations, which implies that other NEOs imaged by radar could have small, undiscovered satellites below the radar detection threshold [9]. Therefore there could be many more binary NEOs that have yet to be detected.

The observed carbonaceous meteorite compositions of some of these objects support the suggestion that binary NEOs can be generated from physically weak materials. However, L-chondrite and HED assemblages observed for the other binaries do not represent physically weak materials. Thus if the favored mechanism for formation of binary NEOs is disaggregation during close planetary flybys, then the current compositional variety of binary NEOs (Figure 1) suggests that a significant fraction of the NEO parent bodies are gravitationally bound rubble piles, and not simply just composed of weak carbonaceous materials. In addition, recent data obtained by the Hayabusa spacecraft of the potentially hazardous asteroid (PHA) Itokawa seem to suggest that this asteroid is a prime example of a rubble-pile with ~ 40% porosity [17].

Therefore, ground-based observations and spacecraft data suggest that the NEO population may contain a significant number of objects that experienced a relatively vigorous impact history during their lifetime. Hence there is a good probability that a NEO selected for future investigation, could be a strengthless rubble-pile as opposed to a solid rock or metal fragment.

Conclusions: Hence, ground-based studies are important in constraining the relative number of objects within the NEO population that have internal structures similar to gravitationally bound rubble piles. PHAs, like Itokawa, are particularly susceptible to disruption because of their close encounters with the Earth. Therefore, a large percentage of this subset of the NEO population may be rubble-piles. Although these objects can pose the greatest risk of an impact with Earth, they are also some of the easiest objects to visit with spacecraft. Thus any sensors designed to investigate the composition and internal structure of an NEO should be developed with the possibility of encountering a rubble-pile asteroid with a significant amount of porosity.

The information gained on the internal structure of NEOs is not only valuable from a scientific perspective, but is critical for planning possible hazard mitigation scenarios and developing future spacecraft missions to potentially hazardous NEOs for further investigation and possible resource utilization.

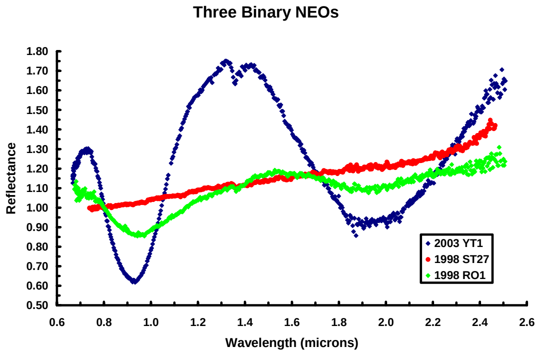

Figure 1 – A comparison of spectra from three different binary NEOs obtained using the NASA IRTF/SpeX system. The spectra are normalized to 0.8 µm. These data demonstrate the variety of materials that exist among the binary NEO population.

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ASTEROID SURFACES AS EXPRESSIONS OF SEISMIC INTERIORS.

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Summary: Asteroid surface morphologies are expressions of the acoustic properties of their interiors. At least, that is an hypothesis, which if proven true might allow us to one day know what an asteroid is all about just by looking at it. This paper explores the hypothesis and suggests how it might be tested by a modest cratering experiment.

Background: Asteroid and comet interiors remain the subject of theoretical inference [1]. Bulk densities have been measured for a number of asteroids [2], and ~33×13×13 km asteroid 433 Eros appears to have a homogeneous mass distribution at km-scales [3]. That is about all we know beneath the optical (~micrometer) and thermal (~centimeter) skin depths. Densities of small asteroids are invariably lower – sometimes much lower – than what is expected on the basis of the likely analog rocks. Ordinary chondrite meteorites are thought to come from the S asteroids, and carbonaceous chondrites from the C asteroids, but densities only agree if you allow for substantial porosity [2].

Mechanical Properties. How do porous asteroids behave, mechanically? Do they have landslides? How do their craters form? These are not trivial questions, for three reasons. One, we do not know the scale or structure of this porosity. It could be macroscopic fissures and voids, or it could be microscopic pores in a dust ball. Two, we do not very well understand the mechanical properties of granular media even under well-controlled laboratory conditions on Earth; there are as many new advances in this field as there are in asteroid science (e.g. [4]). Three, we especially do not understand the mechanical behaviors of granular materials when gravity is as low as a millionth that of Earth.

In a study of asteroid 243 Ida, it was argued [5] that an abundance of parallel surface fractures observed in one location resulted from a major cratering event in another, with acoustic stresses channeling and focusing through a somewhat competent interior. That work owed much to the original work in this area by [6], who correlated the striking fracture patterns on the Martian satellite Phobos to its major impact crater Stickney, from which he could deduce an elastic Poisson ratio.

Crater erasure is probably a better seismic tool for small asteroids, since the stresses involved in an impact may be too weak to fracture rock, but might jumble the surface if it is loosely bound. (Or perhaps, paradoxically, it is the larger asteroids that are more intact, and the smaller asteroids that are preferentially rubble piles.) It is similarly argued [7] that seismic energy from the ~7 km diameter impact crater Shoemaker Regio preferentially erased craters in the terrains closest to it spatially, including on the back side. This requires mechanical coupling of some sort.

What emerges from these studies is a recognition that asteroid surfaces can give clues to their interiors. Perhaps structural properties of asteroids can be understood through simple flyby imaging.

Itokawa. Wherefore the paucity of craters on tiny Itokawa? Seismic shaking seems contradictory, considering that it appears to be a rubble pile [8]. Granular solids attenuate stress energy rapidly, so that an impact that would reset Itokawa's cratered surface would have to be relatively recent, and relatively large. No large, young impact structures exist. It is also problematic that this most recent resetting event must erase its own crater, as no large fresh craters are observed. If there has been a resetting event, it must have been either a small impact which left a small crater, or an impact large enough to trigger global reverberations that lasted longer than the crater formation timescale.

The latter possibility does not seem reasonable, given that a gravity regime crater on an asteroid can take an hour to form. Assume, for example, that Itokawa is a rubble pile, with an acoustic velocity of ~100 m/s, and a wave crossing timescale of several seconds. For a crater to be erased by its own seismic energy, reverberations must persist for about a thousand wave crossing times, since that is how long it takes for the crater to form.

It is then logical to ask just how small of an impact can cause global vibrations to an asteroid, sufficient to reset the rest an asteroid's surface. If the answer is "very small", compared to the size of the asteroid, then asteroids that size are not expected to have large craters, since more frequent small impacts keep erasing them. It appears that large asteroids do not have their surfaces easily reset by seismic shaking – something as major as Shoemaker Regio is required to do this, and only partially, on Eros. If the bombardment rate is known (*not* the crater production function, since that is the question being asked), and if the population of "smallest fresh craters" is known from a survey of asteroids, then one could derive the attenuation rate of shock and acoustic energy with distance from an impact, if the seismic resurfacing is indeed the mechanism of landscape erasure on asteroids.

Asteroid as Geophone. Seismic experiments on asteroids have been proposed for some time, and most of these involve the development of surface packages containing accelerometers or geophones, plus an acoustic trigger (an impact or explosion, or a penetrator containing a thumper). But given the cost and complexity of surface packages, it is worth considering whether precarious surface features on an asteroid can serve as gratis geophones, responding to the reverberations by landscape evolution: toppling of boulders, shifting of rock fields, triggering of landslides and dust clouds. If an artificially induced seismic event on a small asteroid triggers global changes, then the asteroid is well-coupled mechanically; if only local (the crater and its ejecta) then it is poorly coupled. It is a basic and relatively easy measurement that casts light upon how a given asteroid responds to collisions – how it absorbs momentum, what size impact it can withstand before it shatters, how big a crater forms. The measurement also influences the science of asteroid hazard mitigation, since it allows for seismic modeling of an asteroid interior, and for the first directly scaleable cratering event observed in microgravity.

Attenuation of Stress in a Porous Asteroid. Consider a 500 m diameter small asteroid of density 2 g cm^{-3}, with surface escape velocity v_{esc}=50 cm/s. On such an asteroid, shaking the surface a mere 10 cm/s resets the landscape at a scale of at least 10 m. But powerful stress waves in geologic media attenuate rapidly, with peak particle velocity dropping as $1/r^{1.87+/-0.05}$ [9]; another report [10] finds a similar exponent for rocks and a steeper exponent (~2.2) for alluvium, corresponding to greater irreversible effects such as crushing and alteration.

One is tempted to infer that rubble piles are strongly attenuative, but this is not necessarily the case. Intense short wavelength energy dissipates as mechanical heating and is also strongly scattered, until sharp pulses disperse to the scale of the medium's heterogeneity. There is at present no theory for the broadening and decay of a coherent wave in a granular material [12], but it seems possible that distal waves in a well-packed rubble pile could propagate almost elastically once they are broader than the rubble and weaker than the threshold of granular cohesion or friction.

The peak stress in an elastic stress wave is approximately $\sigma = \rho\ c\ u_p$, where u_p is the peak particle velocity (the wiggling, not the wave propagation). Now, a typical powdery soil has a cohesion of about 10^5 dyn/cm^2, and a sound speed of ~100 m/s. Since we only need to wiggle a small asteroid a few cm/s to modify its landscape, stresses of only ~10-100 dyn/cm^2 need to be supported during compression (P-wave), or surface or shear-wave, loading. A powder-rich asteroid might behave elastically to these low stresses, allowing the asteroid to ring like a bell at very subtle velocities which may nevertheless trigger global geomorphic activity under ultra low gravity. When the compressive pulse reflects at the free surface it would act to shake loose (unload) and thereby mobilize material.

Shake Your Backside. Very low amplitude stress waves have not been measured for granular solids. The author is typing this sentence at about one cm/s, and net displacements needing measurement are also quite small. Assuming the attenuation exponent is 1.87, then the detonation of 10 kg of high explosive on the surface of an asteroid will cause 0.1 cm/s of antipodal motion on the same 500 m asteroid. This is only enough to cause ground motions of a few cm. In the elastic limit, $<v>_{RMS}$ falls only as ~r^{-1}. If v~$r^{-1.5}$, say, then the antipodal velocity is ~2 cm/s for the same scenario, enough to toss rocks a distance ~10 m. These are measurable differences, so it is a valid experiment.

There are finally some implications regarding artificial means of changing the momentum of an asteroid, because it is possible to shake more material off the back than off the front, causing it to move in the opposite direction as intended. If the exponent is 1.2, then the antipodal velocity is ~20 cm/s, almost equaling escape velocity. The same blast would cause the escape (and net momentum loss) of considerable material off the back side of a not-much-smaller asteroid. This attests to the fact that the main thing to get right about a hazardous asteroid, is its diameter.

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LOW-GRAVITY PENETROMETRY OF ASTEROIDS AND COMETS.

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Introduction: There are a number of contexts in which space hardware may interact mechanically with the solid material present in a low-gravity environment at the surface of an asteroid or comet, possibly penetrating to some depth and yielding useful information. These contexts range from low-speed scenarios, such as passive free-fall to the surface, to hypervelocity impact. Such penetrating devices may be classed as penetrators, anchors, impactors, 'moles', etc.

Measurements performed for engineering or scientific reasons using the penetrating hardware are generally termed penetrometry, though strictly speaking the term referred originally in the terrestrial context to the measurement of geotechnical parameters, with application in fields such as foundation engineering in the construction industry.

An increasing range of sensors can now be incorporated into penetrometry devices, addressing both physical properties (mechanical, electromagnetic, acoustic, etc.) and composition (elemental, molecular, etc.). Another application that can fall under the umbrella of penetrometry is sampling, where the device is not just inserted into the sub-surface but extracts a sample of the target material for analysis elsewhere.

Penetrometry encompasses both payload hardware on a spacecraft as well as cases where the penetrometer *is* the spacecraft, i.e. a penetrator delivering its own payload to a surface.

Application to Asteroids and Comets: Having been applied in the first instance to the Moon, Venus and Mars[1], penetrometry is now reaching a broader range of extraterrestrial targets including, most recently, Titan. Penetrometry sensors are currently en route to a comet nucleus on board the *Rosetta* mission's comet lander *Philae*.

We can expect variants of the technique to feature in a number of forthcoming mission scenarios for asteroids and comets [2]. These include the following:

- Asteroid or comet sample return
- Anchoring of landers
- Impact penetration of penetrators
- Demonstrating of asteroid mitigation techniques and supporting measurements or technologies
- Emplacement of sensors for *in situ* analysis

While many aspects of penetrometry are generic, some particular constraints and issues arise for use of the technique in the low-gravity, airless environment of asteroids and comets. This talk will examine some of these issues and the challenges and opportunities that arise.

For example, a high degree of integration between the penetrometry subsystem and the instrumentation is usually required, given the tight resource envelope and operational constraints. Issues of robustness to shock, adequate pre-flight testing and simulation are also important.

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ASTEROID & COMET SURFACE SAMPLING METHODS FROM NON-LANDED SPACECRAFT.

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Introduction: The motivations for performing reconnaissance on asteroid and comet interiors are many and the current profound lack of knowledge is a central one. Studying small bodies in more depth will expose information about the primitive stages of the solar system, investigate small bodies as a potential source for water and organics on Earth and elsewhere in the solar system, characterize Near Earth Objects to assess and mitigate threats of Earth impacts, and explore whether small bodies may be utilized for resources for space travel and on Earth.

Much can be learned via remote sensing however many of the above motivations will require direct observations of material from the asteroids and comet nuclei. There are multiple analytical models of the composition and structure of these bodies and due to their diversity, many may be correct. More data must be supplied to increase the fidelity of these models, especially in terms of the surface, near-subsurface, and deep interior. Due to available funding projected for spacecraft missions, the difficulty of landed missions on small bodies, and the diversity of the small bodies, it is likely that a number of low complexity missions will take place in the coming decades. Such missions would employ remote sensing methods such as ground penetrating radar and gravity mapping to probe the interior. Direct measurement of *in situ* material will help to characterize the composition and physical properties with much higher fidelity, as well as anchor the coarser data sets. If the methods of acquiring surface samples are simple enough, better observations will be facilitated through sample return to Earth.

A range of sampling methods have been investigated, from those that require spacecraft fly-by's, to surface hovering, to surface landing. Due to the single high relative velocity interaction with the small body, fly-by missions are limited in terms of the number of sampling sites on the body and on the type of material samples acquired. Due to the difficulty of landing and performing mechanical operations in a low gravity environment, often micro-gravity similar to Low Earth Orbit, full surface landing may be possible only as flagship missions. Non-landed surface hovering missions seem necessary to fit Discovery class mission architectures aiming to survey a large number of bodies with limited funds.

Mission Architectures: Non-landed surface sampling missions will have fairly common architectures. Re-flight of a simple spacecraft design such as NEAR is likely, with modifications for a sampling and sensing payload. Missions to asteroid surfaces are much simpler than those to comet nuclei due to the clearly hazardous conditions presented by material ejection. Spacecraft shielding, such as Stardust's Whipple Shield, would be required as well as more capable solar array and antenna gimballing and overall Attitude Control System. The sample sensing payloads would likely include imaging, compositional analysis, and physical properties testers, accommodated by a sample handling system. Sample return missions would employ a return capsule and separation method similar to Stardust or Genesis.

Sampling methods. Even among non-landed sampler there is a wide range of proposed designs. Most of the designs would acquire material from the shallow surface, penetrating millimeters, centimeters or decimeters depending on the surface properties. Regolith and icy fines or plugs are collected, from milligrams to grams. To allow the spacecraft to hold a safe distance from the surface, accounting for autonomous station keeping accuracy, proposed samplers employ either tethers, booms, or a release & recapture method. Figure 1 below shows a schematic view of a surface sampling operation using a tethered impact sampler.

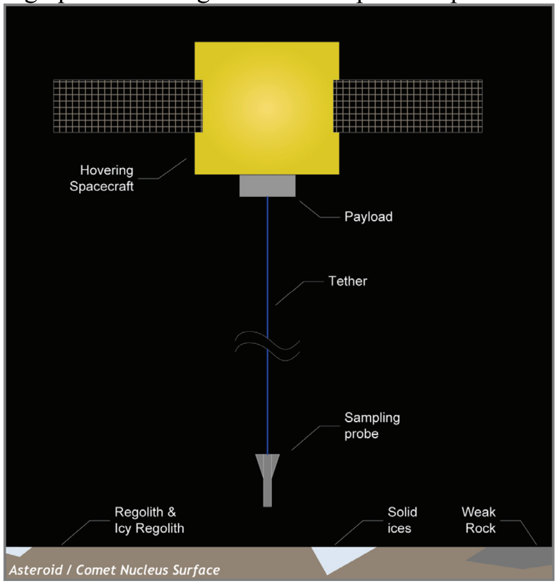

Figure 1: Schematic of a Non-Landed Surface Sampling Mission

The following sections describe a rough state of the art summary of non-landed sampler designs, with more detail on work performed by Honeybee Robotics. The samplers are grouped by those that perform in sub-second and in multiple second time duration interactions with the surface.

Sub-Second Interaction: The samplers of the lowest complexity and perform with the lowest operational risk are those that engage and disengage from the surface in a nearly-instantaneous manner. The low complexity is a result of what is possible to design into a high speed surface impactor. The low operational risk is a result of the minimal physical engagement with the surface and with the short time duration where the spacecraft is engaged with the surface. The short duration allows for the inevitable spacecraft motion and uncertainties in station keeping with respect to the surface.

Impactors & collectors. – The Deep Impact mission used a means of disturbing the surface of a small body to observe the effects. Missions have been proposed to send in an impactor and follow behind with the primary spacecraft that collects the ejected material to then perform analysis. Such a mission is essentially a combination of Deep Impact's and Stardust's methods. This approach represents the simplest and coarsest method for surface sampling.

Impact core ejection & recovery. Lorenz, et al. at University of Arizona developed an impact sampler with collaboration from Honeybee Robotics.[1] The functionality of the sampler is unique in that upon impact with the surface a sample is acquired, the sample capsule fires out of the impactor, and the spacecraft then reacquires the sample capsule. This method completely isolates the sampling dynamics from the spacecraft however it adds the complexity of capturing the sample capsule. A well proven capture method makes this approach a promising one.

Tethered harpoon. – The notion of firing a simple harpoon sampler into the surface and reeling it back in with a tether has been investigated as well. Honeybee Robotics recently finished an SBIR Phase I contract developing such an approach, designing a robust, universal sampling tip and proving the feasibility of it through laboratory testing. Figure 2 shows computer models of the final breadboard hardware used to test the design. The sampler system fires a tethered harpoon at the surface and the harpoon uses exchangeable sampling tips to acquire samples. The tips are robust to acquiring samples from consolidated ices, icy soils, and brecciated soils, as well as loose granular material. Since the contract also address Titan as a design case, the tip design also collects liquids. Once material is collected inside the tip, the tip is transferred and the sample is ejected into a sample handling device to support observations. Testing has shown high reliability, even in cryogenic ices and on tilted surfaces. The robustness of the tip to different materials makes mission operations much lower risk. The simplicity of the device allows the entire system to be low in mass, volume and cost.

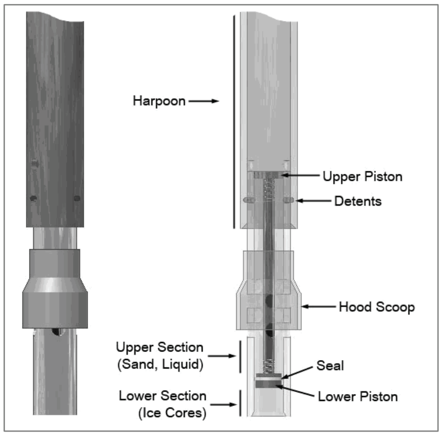

Figure 2: CAD Drawings of Honeybee Robotics Impact Sampler

Adhesives. Another approach for very brief encounter sampling is the use of adhesive substances to collect loose fines and small rocks. Investigations have been done on flight ready adhesives, including testing them in regolith simulant materials. SpaceWorks, Inc. of Arizona[2] identified Solimide foam as a potential adhesive substrate and investigated various adhesives.

Multiple Second Interaction: If a mission requires acquisition of more material and possibly sampling of materials of higher strength such as rock, it may be advantageous to design for a longer duration interaction. Honeybee Robotics has developed the Touch & Go Surface Sampler which uses high speed counter-rotating cutters to break into material if necessary and draw it into a sample cavity. Figure 3 shows one generation of the sampler in a microgravity testbed on the KC-135.

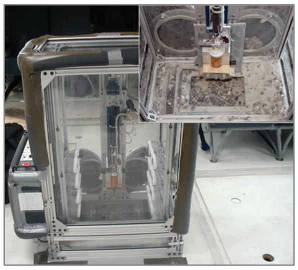

Figure 3: TGSS KC-135 Testbed, sampling tray inset

A similar design has been developed at JPL. The Brush-wheel sampler concept developed for the Gulliver Deimos sample return discovery proposal[3] uses counter-rotating brushes to draw material in. Both designs require a boom to extend to the surface and to draw the sampler back to the spacecraft for sample transfer.

Conclusion: Extending much of the methods referenced here through further hardware development and testing will help as enabling elements in future mission planning.

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SURFACE ANCHORING AND DEFLECTION CONCEPTS FOR EARTH-CROSSING COMETS AND ASTEROIDS.

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Introduction: The threat posed by earth-crossing comets and asteroids necessitates systems with the ability to both characterize their composition and alter their earth-bound trajectories. Current strategies for threat mitigation included ballistic destruction as a means of fragmentation or diversion. However, this method carries the risk of either being ineffective due to the lack of knowledge of comet and asteroid composition, or the greater risk of generating several smaller hazardous objects. Additionally, in situ characterization is desirable for both our understanding and for effective comet/asteroid destruction or diversion. As such, a landing system is required to serve as both a platform for in situ measurements and a stage for destruction/deflection systems.

Controlled landing on a low mass-object will require a robust platform that can rapidly secure itself upon touchdown. Two concepts for surface anchoring are proposed here. In the first, the lander will make contact with the surface with a primary penetration device that provides the initial anchoring force and gathers impact data. The main anchoring force will be provided by several pyrotechnic harpoons that will penetrate through loosely compacted surface material. Depending on the integrity of this surface material, multi-stage harpoons may be utilized to penetrate deeper into the comet or asteroid. After establishing an anchor point, the lander will proceed with in situ measurements, including remote sensing and characterization of the object's interior.

The Rosetta mission launched in 2004 employs a similar landed system to study the comet 67P. However, the Rosetta lander and past proposed landers include complex descent and landing systems with multiple actuators and propulsion systems. The approach proposed here includes several low-cost anchors that would be deployed from a single orbiter. Safe landing would be achieved by a combination of robust mechanical design and a simplified descent and landing system to soften the impact. With minimal actuators and other delicate subsystems, the lander would serve mainly as an anchor point and stage for measurement devices and a deflection system.

The second proposed surface anchoring concept draws upon Honeybee Robotics' heritage from the Champollion Mission, for which several of the listed authors developed the Sample Acquisition and Transfer Mechanism (SATM). The SATM drill (TRL 6) was designed to penetrate and acquire samples up to one meter below the comet Temple 1's surface. This same technology could be utilized to anchor a lander in the ultra-low gravity environments that exist on comets and asteroids. In the proposed concept, a lander would touchdown upon the object's surface and deploy a small harpoon or spike to provide the small initial anchoring force required for drilling. Three SATM drills would then sequentially penetrate into the surface at different angles with respect to the surface, providing a stable platform for a propulsion system. The anchoring drills could also serve as *in situ* measurement devices. The data produced from drilling can provide valuable information on soil strength and stratigraphy, which would be useful for understanding near-surface composition. With a secure link established between the lander and the comet or asteroid, and with the compositional information provided by drill feedback, secondary deflection systems can then be deployed.

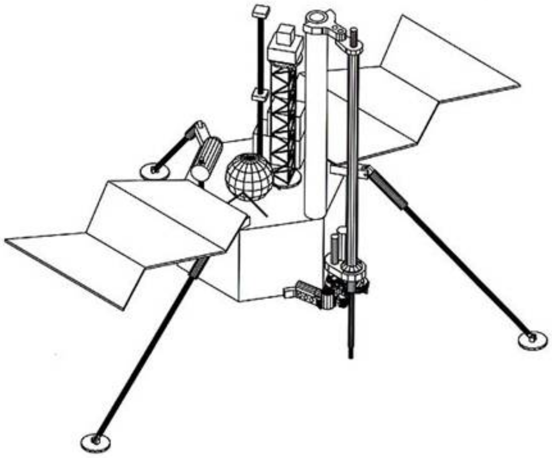

Figure 1: Champollion lander with SATM drill

Establishing a reliable anchor point on the surface of an earth-crossing comet or asteroid would provide a stage for secondary deflection systems. Traditional devices would include rocket engines or other similar high-force propulsion systems. A secondary approach would utilize a tether attached to both the orbiter and the deployed lander. The orbiter could then act as a tow vehicle, deflecting the comet or asteroid. This system would operate on the principle that a small amount of force applied over several years would be enough to divert a threatening comet or asteroid. With warning times on the order of decades before Earth impact, diversion by means of low-complexity harpoon or drill anchoring and sensing devices coupled with a propulsion source provides a reliable system for both studying and mitigating the threat of earth-crossing comets and asteroids.

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THE POSSIBLE INTERNAL STRUCTURE OF JUPITER FAMILY COMETARY NUCLEI. M. J. S. Belton, Belton Space Exploration Initiatives, LLC, Tucson AZ 85716 (e-mail: michaelbelton@beltonspace.com).

I present considerations on the internal structure of Jupiter family comets that have emerged from the discussion of the results of Deep Impact and other remote sensing space missions to comets. The rest of this abstract is identical to that of a paper that has been submitted for publication to *Icarus* under the authorship of Belton and 14 other authors.

"We consider the implications of the hypothesis that the layering observed on the surface of Comet 9P/Tempel 1 from the Deep Impact spacecraft and on other comet nuclei imaged by spacecraft (*i.e.,* 19P/Borrelly and 81P/ Wild 2) *is ubiquitous on Jupiter Family cometary nuclei and is an essential element of their internal structure.* The observational characteristics of the layers on 9P/Tempel 1 are detailed and considered in the context of current theories of the accumulation and dynamical evolution of cometary nuclei. The works of Donn (1990), Sirono and Greenberg (2000) and the experiments of Wurm *et al*. (2005) on the collision physics of porous aggregate bodies are used as basis for a conceptual model of the formation of layers. Our hypothesis is found to have implications for the place of origin of the JFCs and their subsequent dynamical history. Models of fragmentation and rubble pile building in the Kuiper Belt in a period of collisional activity (*e.g*., Kenyon and Luu, 1998, 1999*a*, 1999*b*; Farinella *et al*, 2000; Durda and Stern, 2000) following the formation of Neptune appears to be in conflict with the observed properties of the layers and irreconcilable with the hypothesis. A change in the fragmentation outcome model and/or long term residence in the scattered disk (Duncan and Levison 1997; Duncan *et al.* 2004) may provide a more benign environment before transfer to the inner solar system and explain the long term persistence of primordial layers. In any event, the existence of layers places constraints on the environment seen by the population of objects from which the Jupiter family comets originated. If correct, our hypothesis implies that the nuclei of Jupiter family comets are primordial remnants of the early agglomeration phase and the physical structure of their interiors, except for the possible effects of compositional phase changes, is largely as it was when they were formed. As they become active near the sun their top layers undergo severe modification and many layers may be completely removed by sublimational erosion to exhume primordial layers that lie immediately below. Differences seen in the topography of observed surface layers may be a reflection of their 'exposure time' to the local environment during the accumulation phase before being covered by new layers. We propose a new model for the interiors of Jupiter Family cometary nuclei, called the *Talps* or "layered pile" model, in which the interior consists of a core overlain by a pile of randomly stacked layers. The core is the original aggregate on which the growth was initiated. The overlying layers are predicted to increase in their average lateral extent and average thickness as the surface is approached. An estimate of the central pressure yields a value that is not expected to be high enough to overcome the anticipated compressive strength ensuring structural integrity. As a result the internal mass distribution should be essentially homogeneous. We discuss how several of the salient characteristics observed on comets – layers, surface texture, indications of flow, compositional inhomgeneity, low bulk density low strength, propensity to split, *etc*, might be explained in terms of this model. Finally, we make some observational predictions and suggest goals for future space observations of these objects."

CHARACTERIZATION OF THE INTERNAL STRUCTURE OF COMET 67P/CHURYUMOV-GERASIMENKO USING THE CONSERT EXPERIMENT DATA.

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Abstract: In this paper we present the latest results of the modeling of the CONSERT experiment (Comet Nucleus Sounding by Radio-wave Transmission). This novel experiment is part of the scientific package equipping the Rosetta spacecraft and will study the nucleus of comet 67P/Churyumov-Gerasimenko in 2014.

The CONSERT experiment aims to characterize the internal structure of the cometary core in term of heterogeneity distribution by analyzing time-delays and phase perturbations affecting radiowaves propagating through the nucleus. The principle of this experiment is detailed in [1] and [2]. To prepare the CONSERT scientific operations, dedicated instrument simulations and data processing techniques are under investigation. We showed in previous works [3,4] that the Ray-Tracing Method (RT) is an efficient way to simulate waves propagation in a two-dimensional nucleus model and that a Tikonov-like inversion scheme is capable of reconstructing the nucleus interior and to characterize its structure and composition.

In this presentation, we generalize the use of the RT technique to three-dimensional models with plausible nucleus shapes and realistic internal structures. We show that CONSERT is capable of detecting characteristic signatures leading to the identification of the gross distribution of the comet material (homogeneity, stratifications, chunks, etc.). Using these signatures as a priori information, we present examples of image reconstruction of the nucleus interior for several orbital configurations (example Figure 1). We finally show the impact of the spacecraft orbital configuration and the volume of the recorded CONSERT data on the quality of the inversion result.

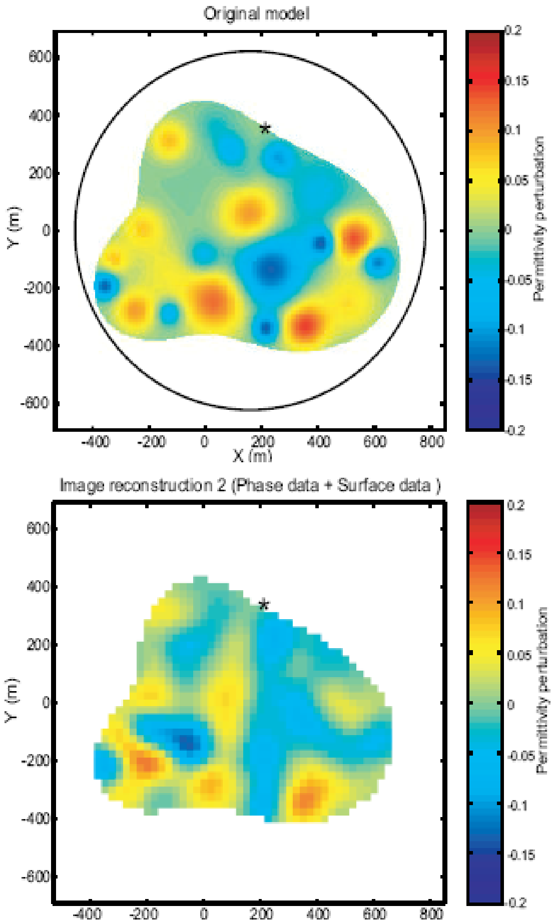

Figure 1: Example of a nucleus reconstruction result: (Upper fig.) Cross section of the original nucleus model (with a background permittivity= 2). (Lower fig.) Reconstruction using the phase perturbation and a priori values for the surface permittivity perturbations.

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TOMOGRAPHY OF AN ASTEROID USING A NETWORK OF SMALL SEISMOMETERS AND AN ARTICICIAL IMPACTOR.

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Introduction: In the frame of a R&T study of the French Space National Agency (CNES) the study of the seismic response of spherical models of asteroids has made possible the computation of accelerations as a function of epicentral distance [1].

In this work, we compute an optimal frequency band required for seismological investigation of spherical kilometer-sized models of asteroids.

These two studies allow us to suggest a set of specifications for a short period seismometer to image the internal structure of a spherical kilometer-sized asteroid.

Maximum accelerations: Previous simulations, based on the free-oscillations summation technique, have been applied to spherically-symmetric layered asteroid models with a diameter of 1 km. The assumed seismic source is a typical impact of a "Don Quijote" type projectile: a mass of 400 kg hitting the surface at 10 km/s [2] at the North pole. We assume one seismometer located each 5° of epicentral distance on half of the asteroid (Fig. 1).

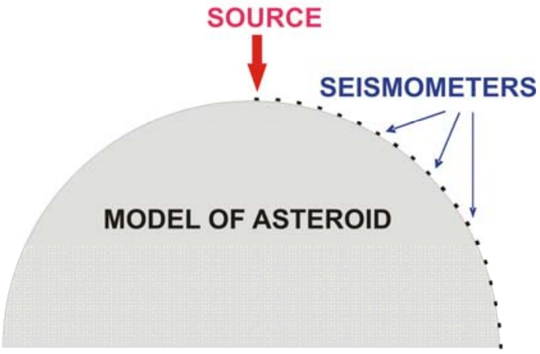

Figure 1. Starting conditions of the modeling of the seismic response on a spherical model of asteroid.

Firstly, the results have shown a decrease and a refocusing of surface waves that varies as 1/sqrt(sinθ), with θ the epicentral distance.

Secondly, this study has permitted to identify the two most influent parameters on the maximum accelerations that are: 1) the size of the asteroid and 2) the impact direction of the projectile.

The curve of maximum accelerations as a function of the epicentral distance computed for a "Don Quijote" type source behaves linearly as a function of the kinetic momentum (m.v) of the source. Then, such curve could be used for passive impacts considered as a seismic source. The maximum acceleration occurring at a given epicentral distance of a given simulated passive impact could then be inferred. This will be useful, in future work, to quantify the rate of infilling craters on an asteroid impacted by a succession of projectiles.

Optimal frequency band: We estimated the optimal frequency band required to image the interior of a kilometer-sized asteroid. Seismograms have then been computed in different frequency ranges. The frequency band showing the highest portion of the signal would be the more appropriated for studying the interior of spherical kilometer-sized asteroids.

These preliminary simulations as well as considerations on the size of embedded rocks in regolith, suggest an optimal frequency band of 1 to 50 Hz for seismological studies of spherical kilometer-sized asteroids. This allows us to issue a preliminary set of seismometers requirements. We then present an overview of a potential low mass sensor that could be deployed on the asteroid surface in order to image its interior.

A preliminary system description will be done, and several candidates for short period seismometers payload will be described.

Conclusion: Further studies will aim to model wave propagation based on fully three-dimensional numerical techniques such as the spectral-element method [3]. This method applied to different models of asteroids (spherical models, as well as a model of the asteroid Eros) will provide a new approach of the seismometers specifications. The diffraction from both the surface and the interior will then be analyzed, and the effect of the asphericity on the seismic response of an asteroid will be highlighted.

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ANALYSIS OF 433EROS LINEAMENTS AND IMPLICATIONS FOR INTERIOR STRUCTURE.

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Abstract: We map several lineament sets on the surface of Eros, several of which are clearly related to visible impact craters. However, other lineament sets suggest that different parts of the asteroid may have undergone different stress histories. Some of these sets infer internal structure, at least on a local level. These may derive from Eros' parent body, and suggest that while coarsely fractured, Eros' interior may have portions that have not undergone a common history. We will present different evolutionary scenarios based on these surface lineaments.

Introduction: As part of the Near-Earth Asteroid Rendezvous mission, the NEAR-Shoemaker spacecraft orbited the asteroid 433Eros for a year from 2000-2001. The NEAR Multi-Spectral Imager (MSI) collected tens of thousands of high resolution images and as a result Eros is the most comprehensively imaged asteroid in the solar system. Previous mapping of lineaments on Eros has supported the suggestion of planes throughout the asteroid [1,2]. We are creating a global database of all Eros lineaments to better understand the global distribution of these features and thus understand more about the interior structure of the asteroid.

We identify types of lineaments across the surface using a combination of NEAR Laser Rangefinder (NLR) topographic data and MSI images, and classify them according to region, including areas suggestive of thicker regolith. We compare lineament orientation to impact craters to determine if there is a causal relationship between cratering events and lineament formation. We perform a numerical analysis on similarly oriented lineations to determine whether they could represent pre-existing planar structures through the body of the asteroid. We also compare lineament orientation to models of thermal contraction and downslope scouring as methods of lineament formation.

Mapping Process: It is particularly challenging to map lineament orientations on a non-spherical body (Eros is the shape of a yam, measuring 34 km on the long axis). To address this issue we are mapping the lineaments directly on the Eros shapefile using POINTS, developed by Jonathan Joseph at Cornell University. POINTS accesses a database of over 140,000 MSI images. Lines can be drawn on each of these images and, since the lines are saved to the shapemodel, the lines will appear in the same locations on all other images opened in POINTS. We mapped lineaments on images with resolutions ranging from approximately 5 to 11 meters per pixel. Mapping on these high resolution images allows the best possible identification of linear features, but the image footprints are not large enough to observe regional lineation patterns. When images with lower resolutions (~35 m/p) are opened in POINTS, previously mapped lineations are present and regional patterns emerge.

We then identify types of lineaments across the surface using a combination of NEAR Laser Rangefinder (NLR) topographic data and MSI images. Lineament types were evaluated to help determine that sets that were grouped by orientation are of similar morphology.

Observations: We have mapped 2141 lineations on 180 high resolution (5-11 m/p) images of Eros, creating a global lineation map of the asteroid. These lineations have been grouped into sets according to location and orientation. Many different sets of lineaments can be identified. Some are clearly related to specific impact craters. We have identified lineaments radial to two unnamed craters and ten of Eros's 37 named craters: Psyche, Leylie, Majnoon, Narcissus, Eurydice, Tutanekai, Cupid, Pygmalion, Galatea and Valentine. Given their proximity and orientation relative to the craters it seems most likely that these lineaments were formed as a direct result of an impact event.

Other lineament sets have no obvious relationship to impact craters. Some of these are global in extent and may describe planes through the asteroid: these lineament sets may be related to interior structures. We compare their patterns to various models of lineament formation, including 1) interior configuration and structure, 2) cratering mechanics, 3) thermal stresses that occurred during orbit migration and 4) downslope scouring.

Planar Lineaments: It is not obvious on a non-spherical body whether lineaments are associated with each other in a systematic way. Lineations that appear to be similarly oriented could in fact have no correlation at all. However, because they were mapped directly onto the shape model, the lineations are described in three dimensions and can be modeled to define planes that cut through the asteroid. The unit normal of these planes gives a pole whose latitude and longitude is binned in 10 degree bins and then weighted by the length of each lineament. If the lineaments were randomly placed on the surface we would expect that no single pole would dominate after binning. If the lineaments are similarly oriented than a single dominant pole should emerge.

Planar Set 1: The globally distributed lineation set mapped in Figure 1 was originally grouped according to their apparent orientation. Several of the lineations are extremely long, up to 10's of kilometers, and were mapped on multiple MSI images. When planes are modeled through the lineations in this set the poles cluster at 90 degrees, which suggests that there is a preferred orientation for these lineaments.

It is possible that this set is hinting at a pre-existing planar structure in the asteroid. However, the lineation orientations are also consistent with fragmentation due to impact on the long side of an ellipsoid target [3]. The impact that caused these lineations could be Psyche, Himeros or Shoemaker or some combination of the three.

Planar Set 2: A second set of lineations also describe a plane well (Fig. 2), but this plane does not obviously follow any predictions of models of impact, downslope scouring or thermal contraction. We therefore suspect that these lineations may represent a pre-existing internal structure. These lineations do not describe the same plane as the pre-existing planar structure inferred by [2].

Planar Set 3: Near the southern lip of Shoemaker are a series of pit chains and beaded grooves first observed by [1]. Aligned with these features, in both the northern and southern hemispheres, are 137 lineations (Fig. 3) that describe a plane well. As with planar set 2, these lineations may represent internal structure, although not in the same plane as features previously identified [2].

This set consists of an unusually high number of pit chains (21); interestingly, the pit chains in the set are located in areas predicted to have thicker regolith [4,5]. This is consistent with models of pit chain formation [6,7], where overlying regolith drains into pre-existing fractures. These groves are therefore likely to have existed before the formation of Shoemaker, the main provider of this regolith.

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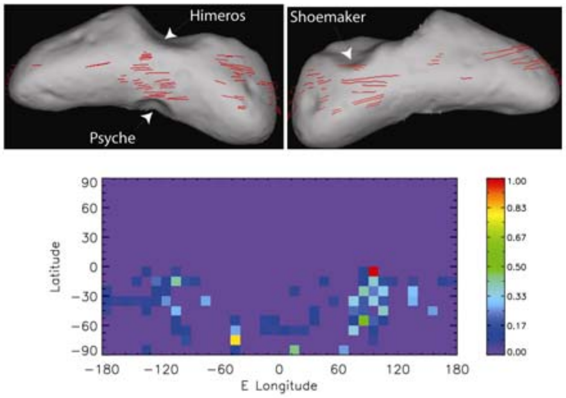

Figure 1. Planar set 1 lineations, shown mapped on the shape model. The poles of the planes described by the lineations cluster at 90° and -90°.

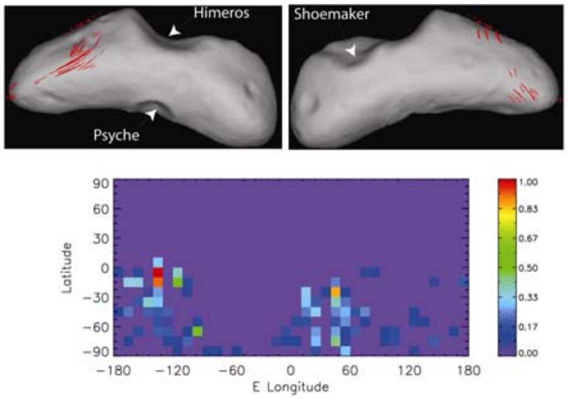

Figure 2. Planar set 2 lineations, shown mapped on the shape model. The poles of the planes described by the lineations cluster at 50° and -130°.

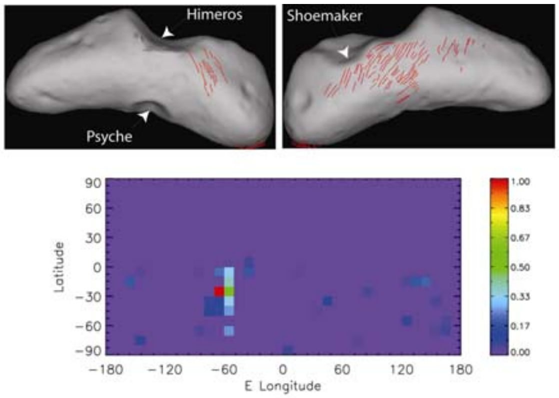

Figure 3. Planar set 3 lineations, shown mapped on the shape model. The poles of the planes described by the lineations cluster at -60°.

ASTEROID UNIQUE DEFLECTION AND COLLISION EXPERIMENT (AUDACE).

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Introduction: Take two main belt asteroids, passing by as close at least as we wish an NEA would miss the Earth. Put a transponder on the smaller one, push it slowly towards the larger one to impact on it, and register the event.

AUDACE: (*Acronymous of* “*Asteroid Unique Deflection and Collision Experiment*”. *Iin Italian: "daring*”.) Due to the large amount of catalogued asteroids available nowadays, we are in a situation in which it is statistically possible to well determine a bunch of pairs of asteroids in the Main Belt that may approach each other in the next future, say in an interval of 10 to 30 years, to distances similar to the distance we would need to divert an NEA away from its way on a head-on collision with the Earth.

Once identified the best pair (possibily one with a mass ratio such that fragmentation would be likely in a collision) a mission can be designed for placing a transponder on the smaller one, in such a way that it is diverted to collide with the other one. The same mission should include the possibility to register the outcome of the event.

In this way, two goals might be reached within the same single mission: checking if the option of deflecting an hazardous asteroid is technically and practically at our reach, and – if the first part is successful - performing the first ever experiment of a collision between true asteroids, that would give crucial information on collisional properties and internal structure of asteroids.

ITOKAWA, A VERY SMALL RUBBLE PILE.

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Introduction: Five asteroids have now been studied with spacecraft: Gaspra and Ida/Dactyl which are S-type asteroids visited by Galileo; Mathilde which is the C-type asteroid visited by the NEAR mission, the S-type asteroid Eros which was studied by NEAR both from orbit and after landing on the surface; and now the small S-type asteroid Itokawa visited by Hayabusa. Understanding collisional evolution and internal structure of the asteroid was a key objective in all cases. Is the outcome of collisional evolution most often to create mechanically coherent collisional shards, or aggregates of small fragments held together by gravity ("rubble piles"), and how do these outcomes depend on asteroid size?

Discussion: Geologic evidence from spacecraft studies of three similar-sized S-type asteroids (mean diameters 31 km for Ida, 16 km for Eros, 14 km for Gaspra) indicates that all of these are mechanically coherent shards rather than rubble piles. Densities for two of these (Eros and Ida) indicate about 25% porosity for both. The most detailed information is available from Eros after NEAR [e.g., 1,2,3]: it is a shattered, fractured body, with at least one through-going fracture system and an average of about 20 m regolith overlying a consolidated substrate, as evidenced by a global fabric of linear structural features (ridges and grooves) and square craters [4]. Eros is not a strengthless rubble pile that was collisionally disrupted and re-accumulated, with jumbled spatial relations between components. The presence of global scale linear structural features that are not geometrically related to any of the large impacts on Eros further suggests that it is a collisional fragment of a larger parent body.

The 53 km, C-type Mathilde has even higher porosity than Eros, at least ~50%, which has led to suggestions that Mathilde may be a rubble pile. However, there is also evidence for a 20-km long scarp, comparable in length to the radius of Mathilde [5], and there are structurally controlled, polygonal craters. Mathilde has at least one global scale structural component with sufficient strength (cohesion or shear strength) to influence late-stage crater growth. The high porosity of Mathilde may also be to some extent microscopic, from preservation of a primordial accretion texture.

Despite ambiguous observational evidence for a rubble pile Mathilde, and evidence that three S-type asteroids larger than 10 km are not rubble piles, the theoretical consensus is that most asteroids larger than ~km size should be rubble piles [6], whereas small asteroids of size <<1 km are predicted to be monoliths.

In this context, the Hayabusa visit to the 0.32 km, S-type asteroid Itokawa was the first to an object significantly below 1 km size. Initial reports [7,8,9] indicate that Itokawa has a very low density 1.9 g/cc, significantly less than that of the compositionally similar asteroids Eros and Ida, and consistent with a rubble pile structure. Moreover, Itokawa lacks the global fabric (mainly ridges and grooves) that indicates a coherent but heavily fractured structure for Eros. However, there are apparent boulder alignments on Itokawa, suggesting that at least some of its rubble components are larger than 100m size.

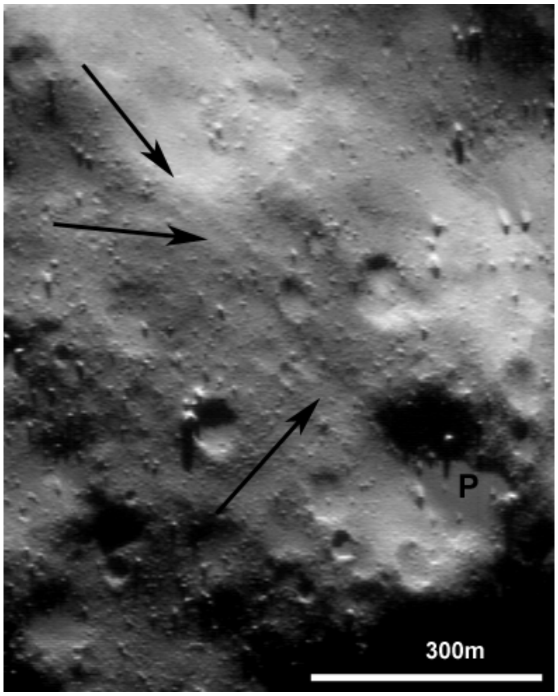

Figure 1. Eros from 19 km, with 300 m scale bar (~mean diameter of Itokawa). Arrows mark linear structural features comprising global fabric. P marks a pond on Eros.

Further geologic evidence for a rubble pile Itokawa is summarized as follows. Blocks as large as those found on Itokawa could not have formed on a body the size of Itokawa, and the volume of mobile regolith on Itokawa is too great to be consistent with its craters. Itokawa's mobile regolith volume is consistent with extrapolation of its boulder size distribution assuming gravel-sized particles (see below), suggesting a fragmentation size distribution. Blocks and regolith may have formed on a larger parent body, which was subsequently disrupted catastrophically such that some of the fragments reaccreted to form Itokawa. The possibility of gravitational accumulation of an object as small as Itokawa after a disruption event, creating a rubble pile with a surface average escape velocity of only 17 cm s^{-1}, is remarkable. Gravitational sedimentation of coarse regolith to produce the globally segregated smooth areas in areas of low geopotential occurred subsequently.

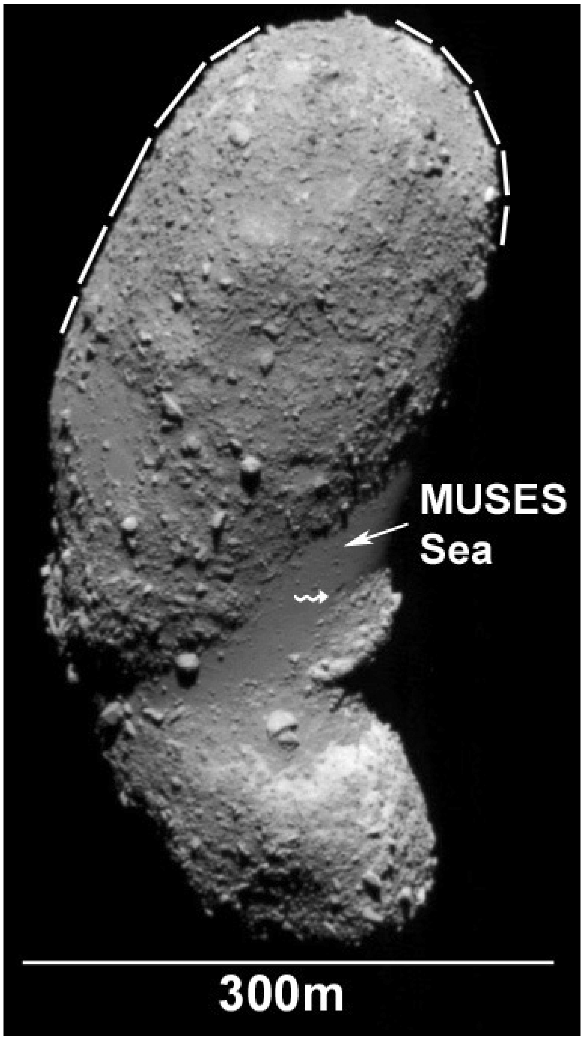

Figure 2. Itokawa from 8.5 km range (0.86 m/px), with 300m scale bar. Global segregation into blocky and smooth areas (e.g., the “MUSES Sea”). Wiggly arrow marks a 10m bowl-shaped crater. White bars around limb have thickness corresponding to 2.6 m, so that added depth of regolith fill would bury all but the tallest blocks in the region.

If Eros and Itokawa had similar collisional histories, at least one giant crater would be expected on Itokawa, and the crater density would be close to equilibrium saturation down to crater sizes of about 4 m diameter. An image at the resolution of Figure 2 (~400 px across the mean diameter) would be expected to show on the order of a thousand craters. Moreover, in an Eros image at this resolution, in terms of pixels across the object, only a handful of the largest blocks would be barely resolved. In contrast, far fewer craters are found on the surface of Itokawa, and the rough areas on Itokawa are covered with blocks at several m size.

The smooth areas of Itokawa consist of coarse, gravel-sized regolith as shown by data obtained from the Itokawa landings. The individual cobbles are resolved in close-up images, and moreover a high coefficient of restitution is inferred from the (unplanned) spacecraft bounces off the surface of the asteroid. True fines are apparently absent. The coarse regolith on Itokawa is mobile, as evidenced by the global segregation into rough and smooth areas. Direct evidence of such mass motion is found in close-up images showing imbricated boulders. The effective cohesion of Itokawa material must be extremely small to permit such mass motion.

The rough areas of Itokawa are close to saturated with meter-size blocks, and regolith there may also consist of coarse, angular material. This is suggested by the high gravitational slope of the southern “neck” region of Itokawa, which has an unusually large value of about 40°. No significant area of Eros has such a large slope. The friction angle of coarse, angular cobbles can approach such high values. Talus and flow fronts are not evident in this region.

In summary, Itokawa provides the first observations of the geology of a gravitational aggregate, which is distinctly different from the surface geology of Eros, and which therefore also strengthens the interpretation that Eros is not a rubble pile but a collisional shard. Are most asteroids <<1 km formed as rubble piles like Itokawa? Confirmation of a rubble pile structure for an object as small as Itokawa has profound implications for collisional evolution and planet formation processes.

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SURFACE PROBES FOR THE IN-SITU CHARACTERIZATION OF SMALL BODIES.

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Introduction: A comprehensive strategy for the characterization of asteroids and comets should include missions that measure the structure and composition with in-situ instrumentation deployed on the surface of the object. In this presentation, we describe a concept for a set of self-righting surface probes that are deployed from a nearby rendezvous spacecraft. These probes are used to assess the composition and geophysical state of cometary or asteroid surface and interior environments.

Probe Description: Each surface probe payload notionally includes a set of cameras for imaging the body surface at mm-scale resolution, an accelerometer package to measure surface mechanical properties upon probe impact, an APX spectrometer for measuring surface elemental composition, and an explosive charge (nominally 1kg) that can be remotely detonated at the end of the surface mission to serve as a seismic source for the accelerometers that are resident in the remaining probes. In addition, this explosive charge excavates an artificial crater that can be remotely observed from the nearby rendezvous spacecraft. The external shape of the probe is ideally spherical, with the accelerometer package located at the center-of-mass, to minimize any measurement biases that are generated by the geometry of the impact.

Structural Characterization. A network of small probes has the capability to characterize the structure of the target body in at least three distinct ways, each on a different spatial scale. First, measurement of the probe deceleration upon impact will constrain the porosity of the top tens of cm in the near-surface at the impact site. Impact into a highly porous surface will be largely inelastic, as experienced by the target marker deployment on Hayabusa [1]. Probes deployed from a hovering rendezvous spacecraft roughly a km away from the target body have impact velocities of only a few m/s if allowed to simply free-fall to the surface. Thus, the impact can be tolerated by conventional accelerometer packages without the need for shock hardening. Second, observation of the crater formation resulting from the detonation of the high explosive will yield information on the strength and porosity of the body on scales of tens of meters, roughly the crater diameter expected [2]. Third, the deployment of multiple probes on the surface has the potential to act as a seismic tomographic network for measuring the interior structure if the probes are detonated sequentially. Proper inversion of the seismic data requires accurate knowledge of the body shape and probe location, both of which can be provided by the nearby rendezvous spacecraft. However, probes that are simply resting on the surface of the asteroid present a major implementation issue in a microgravity environment: any accelerations due to the arrival of surface or body waves that are imparted to the probe may dislodge it (even to the point of launching it off the surface!) if the probe is not properly anchored. Surface coupling schemes are therefore critical in this approach, and will be discussed in greater detail.

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MATHEMATICAL MODELS USING ISOMORPHISMS AND QUANTUM FORMALISM, FOR THE OBTENTION OF RISK WAVE FUNCTIONS ON SPACECRAFTS: APPLICATION TO VOYAGER-2 MISSION OF NASA, FOR JUPITER-SATURN TRAJECTORY.

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Introduction: The aim this work is to show the results obtained in relation to mathematical models, applied to the risks analysis in spatial activities. The models were designed and applied specifically for the risks control associated to the Voyager program of NASA, being of principal interest the Voyager-2 mission for the encounter with Jupiter and Saturn (July 9, 1979 and August 25, 1981 respectively). Will be specified here the basic concepts used in the development of the models, describing the mathematical and physical formalisms involved, as well as the obtention of orbital-gravitational factors, that will determine the degrees of influence in the manifestation of structural damage, caused by spatial perturbation across of the Jupiter-Sun-Saturn chain, and showing numerical results.

Analytical Method and Results : The model in its fundamental component is based in the Wigner's Distribution for negative probabilities [2], which is expressed as:

$$W(x,p) = (1/2\pi) \int_{-\infty}^{\infty} \psi^* xR\ (xR - s/2)\ \psi xR\ (xR + s/2) \times \exp(-ispR)\ ds,$$

$$= (1/2\pi) \int_{-\infty}^{\infty} \psi^* pR\ (pR + s/2)\ \psi pR\ (pR - s/2) \times \exp(-isxR)\ ds,$$

where xR and pR represent position and momentum respectively, for a vector-risk R in a work activity in static or dynamic regime. The mathematical structure associated to the existence and materialization of risks in accidents, coincides with the abstract form of the isomorphism, where the vector space in the domain is represented by a mathematical subspace $\mathcal{B}$, whose elements are vectors-risk with aleatory behavior; and being the vector space in the codomain, one physical environment, whose elements are quantum probability densities, images of the vector space before mentioned (codomain). These images that can coexist in static and dynamical conditions, are connected by a bijective function $\mathcal{F}$, being the dimension for both vector spaces equivalent to n = 4, then graphically the functions of link are showed as:

$$\mathcal{F} : \mathcal{B} \subset \xi^4 v \longrightarrow \xi^4 f \equiv \mathcal{F} : (\ r1,\ r2,\ r3,\ r\ t\ ) \longrightarrow (\ D\psi 1,\ D\psi 2,\ D\psi 3,\ D\psi t\ ),$$

Being the ri and $D\psi i$, the mathematical components of a vector R in the vector subspace $\mathcal{B}$, and the components of probability density associated to a wave function ψR in the incidents space $\xi^4 f$ respectively, being besides r t and $D\psi t$ temporary components in both spaces, where the term $D\psi t$ adopts spatial positions of escape, i.e., with a extrapolation out of $\xi^4 f$. The components of the vector space in the codomain generate complete wave functions Ψi, associated to the Ri, which possess probabilistic structure or natural, and that satisfy besides the Heisenberg's Uncertainty Principle [3], therefore: "The probability of to find the risk Ri defined by the wave function $\psi Ri(\ ti\ )$ in the interval dt around t is $|\psi Ri(\ ti\ )|^2 dt$" [1,3]. The complete wave functions Ψi in the vector space $\xi^4 f$ acquire gaussian form, which are pure or perturbed for closed or open systems respectively. Is possible to identify besides the existence of "entropy spaces" s, between $\xi^4 f$ and $\xi^4 v$ that define an unstable regime and aleatory behavior, which are generated in static mode of action, and that are "relative" to the elements of an activity in dynamical mode. Inside of this structure an "incidents space" is defined by, $\mathcal{E}inc \equiv (\xi^4 v) \cup (\xi^4 f)$, being the "accident" defined by $(\xi^4 f) \cap s$, in dynamical mode and that define a manifestation of energy from $\xi^4 v$ to $\xi^4 f$. Then, the entropy space si, is defined by any Ri that is not included in the procedures of some activity. The formalism before described is applied to activities in the space, working with planetary wave functions, modified as:

$$\Psi spatial \equiv (\ Ags / Agp\ )\ (\ Vvo / Vvop\ )\ \Psi planet,$$

being (Ags / Agp) < 1 a gravitational factor, and 1 < (Vvo / Vvop) < 1 an orbital factor, and where:

Ags = acceleration of gravity at the space (m/s^2).
Agp = acceleration of gravity at a planet (p) (m/s^2).
Vvo = orbital velocity at the space (m/s).
Vvop = orbital velocity of a planet (p) around the Sun (m/s).

The orbital factor is approximately obtained through the calculation of escape velocities from both Jupiter and Saturn:

$$VE = VEo + (2\pi Rp / Tp) + (GMs / Dp,s)^{(1/2)} + (1/8) \int_{0}^{(2\pi Rp/8Vo)} (GMp/D^2v,p)dt ,$$

being these the components of: escape velocity from a planet (p), spin velocity for a planet (p), orbital velocity for a planet (p), and gravitational influence associated to a planet (p). These components will influence on both velocity and trajectory of a spacecraft in the space, being besides:

Rp = radius of a planet (p).
Tp = period of a planet (p).
Ms = mass of the Sun.
Dp,s = distance between a planet (p) and the Sun.
Mp = mass of a planet (p).
Dv,p = distance of approximation from Voyager-2 to planet (p).
VEo = previous escape velocity.

Results and Conclusions: The results obtained are:

a. (Ags / Ag Jupiter)(Vvo Voyager-2 / Vvo Jupiter) $= 3.18024 = (1.0123)\pi \succ 1$.
b. (Ags / Ag Sun)(Vvo Voyager-2 / Vvo Sun) $= 6.24962E(^{-} 8) \prec 1$.
c. (Ags / Ag Saturn)(Vvo Voyager-2 / Vvo Saturn) $= 6.13963 = (1.9543)\pi \succ 1$.

The numerical results show an interesting aspect, the involved risks in the Voyager-2 mission, specifically in (a) and (c), reveal an apparent duplication of intensity from Jupiter to Saturn, and this intensity tends to be annulled in the intermediate trajectory, i.e., between Jupiter and Saturn, by a reduced influence from the Sun. The numerical results show major probability of fall in Saturn that in Jupiter. According to this, is possible to deduce initially:

1. The intensity of the risks varies inversely with the mass of the planets.
2. A great proximity is observed with both values of π and factors of π, which indicates a numerical and mathematical structure.
3. The numerical variations are determinable in the time.

These numerical models are feasible of application to a great variety of spatial activities, including both new Exploration Programs and new Mars Exploration Rovers.

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TROJAN ASTEROID INTERIORS AS A TARGET FOR SPACECRAFT EXPLORATION.

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Context and Properties: To date 2050 Trojans are known, with an estimated $5.9x10^5$ larger than 1km [1,2] (compared to $\sim 6.7x10^5$ for the Main Belt). An explosion of interest in physical studies of asteroids in the 1970s benefited the Trojans as well. They were found to have very low albedos [e.g. 3], which has been confirmed by more recent work [4,5], and the extremely high lightcurve amplitude (and therefore extreme shape) of 624 Hektor was quickly uncovered [6]. Despite this exciting result, lightcurves have been measured for relatively few Trojans, although one study concluded that Trojans with diameters < 90 km are fragments, while larger objects are primordial [7]. This is in agreement with interpretation of a change in slope of the size frequency distribution[1,2].

Reflectance spectroscopy at visible wavelengths failed to discover any absorption features, but revealed red spectral slopes, comparable to outer belt D-type asteroids [8]. The low albedo and red slope were modeled by mixtures of (hydrated) silicates, carbon black, and complex organics [8]. This result was incorporated into a solar nebula condensation sequence in which increasing organic content is responsible for red slopes in the outer belt and Trojan swarms [9]. Visible spectroscopy through the present has continued to show featureless spectra with slopes that range from neutral (gray) to moderately red [e.g., 10–13]. No ultra-red slopes comparable to many Centaurs and KBOs have been detected among the Trojans. Near-infrared spectroscopy has also failed to detect any clear absorption features, including no evidence for H_2O, no 1 and 2 μm silicate bands, and no absorptions from organics or hydrated minerals [e.g., 14–17]. Note that Vis-NIR spectra can be modeled without the use of organics (just silicates and amorphous carbon) [18,19], and the absence of absorptions in the 3-4 μm range may strongly limit the type and abundance of organics possible on these surfaces [19]. Discrete mineralogical features attributed to fine-grained (~few μm), anhydrous silicates were recently detected in mid-IR thermal emission spectra of three Trojans using the Spitzer Space Telescope. The mineralogy may resemble that of cometary silicates, and the spectral shape indicates that the surfaces are probably either very porous or that the grains are imbedded in a matrix that is relatively transparent in the mid-IR [20].

Although some significant uncertainties remain, we have learned a lot about the surfaces of Trojans from ground-based observations over the past three decades. Unfortunately, all of the studies summarized above only sense the upper few mm (at most) of the surface. With judicious choice of space weathering mechanisms, these results can be made to fit nearly any model for the interior composition and structure of Trojans. The observation with the most direct implication for internal composition of Trojans is the discovery and follow-up astrometry of a Trojan binary (617 Patroclus), which yielded a density of 0.8 ± 0.2 g/cm^3 [21]. The most straightforward interpretation includes both significant bulk porosity and a relatively significant ice fraction in the interior.

Motivation for a mission: Dynamical models of the origin and evolution of the Jupiter Trojans are equally intriguing. [22] showed using numerical techniques that the Trojan swarms are stable over >4.5 Gyr against gravitational perturbations from the other giant planets, though the region of stability is decreasing, and the overall diffusion of objects is out of rather than into stable librating orbits. Gas drag in the early nebula could reverse that trend, capturing objects. [23] found that a growing Jupiter would naturally capture objects into the Lagrange points without the need for substantial gas remaining after giant planet formation. In both of these scenarios, capture of objects already orbiting near Jupiter is most likely, though small fractions could come from scattering from the Main Belt or Kuiper Belt. Such scattering would be less likely before the giant planets fully formed, so the [23] mechanism would probably result in a more homogeneous population of mid-solar nebula objects than the gas drag model. More recently, [24] suggested a migrating giant planet model which predicts that, as Jupiter and Saturn pass through a mutual 2:1 resonance, the Jupiter Trojan swarms are first emptied of their initial residents, then repopulated with material primarily originating in the Kuiper Belt. In this scenario, the final Trojans pass through a high-eccentricity phase which brings them close to the sun, devolatilizing their surfaces. According to this model, the Trojans' bulk interior composition should then reflect the diversity of the Kuiper Belt, with only a small fraction of objects from the inner or middle solar nebula.

While these models are cast here in terms of the origin of Trojan asteroids, they have far broader implications concerning the formative stages and evolution of the Solar System (and, by extension, other planetary systems), including the structure of the Kuiper Belt, the properties of outer planet systems, and the impact history of the inner Solar System (i.e., late-heavy bombardment), among others. The interior compositions of Trojan asteroids are a key to distinguishing between these different hypotheses, providing a deeper understanding of the origin and dynamical evolution of the Solar System. Furthermore, linked analysis of surface and internal composition will illuminate important surface altering physical processes that can be leveraged in the continuing remote study of small bodies in both the inner and outer Solar System.

Ground-based observations remain critical to our understanding of Trojan asteroids, and continuing studies form the ground will certainly be beneficial. For example, very few phase curves exist for Trojans, and additional phase measurements would help constrain the structure of their surfaces. Similarly, lightcurve periods and amplitudes have been measured accurately for only a handful of Trojans, and only one (624 Hektor) has a reasonable pole solution. Deep searches for comet-like behavior (comae and/or tails) could help constrain the abundance of near-surface volatiles. Vis-NIR spectroscopy continues to uncover somewhat diverse spectral shapes. Spectra of small Trojans may offer the best ground-based hope of getting a glimpse of internal, primordial compositions. Additional mid-IR spectra would allow determination of silicate mineralogy, as recently detected by Spitzer on three Trojans, and whether it tracks with the diversity of Vis-NIR spectral shapes. While beneficial, particularly for determining surface properties, these ground-based studies will not reliably constrain internal composition, and, therefore, will not be able to unleash the full potential of the Trojans for testing hypotheses of Solar System formation and evolution. A spacecraft mission to the Trojans is necessary.

Discussion: The recognition of Trojan asteroids as important spacecraft targets is not new. The Decadal Survey ranks a Trojan mission as a high priority for NASA, with “deep ties to understanding the origin of primitive bodies” and offering “new insights into space weathering and other processes affecting” small bodies. The Outer Planets Assessment Group (OPAG) supports the Decadal Survey’s priorities with respect to small bodies, and also specifically calls out the Trojans (along with Centaurs) as high priority targets for spacecraft missions. As introduced above, it is necessary that such a mission have the capability to investigate the internal composition of Trojans along with surface characterization.

As a target for a spacecraft mission, we note that the Jovian Trojans are not located “on the way to somewhere else.” They are not accessible as flyby targets for typical outer Solar System missions (e.g., 2002 JF56 imaged by New Horizons), as the typical spacecraft will use Jupiter for gravity assisted acceleration. To study the Trojans requires a dedicated mission.

Key spacecraft investigations of Trojans necessarily must focus on both surface and interior properties. Visible wavelength imaging would focus on geology and geomorphology, including cratering and collisional history, clues to internal structure, and comparision of landforms with those on comets as well as other small bodies. Visible and infrared (near and middle IR) spectral mapping would focus on heterogeneities in surface composition, particularly impact-induced exposures that reveal subsurface composition. Radio science techniques will permit determination of asteroid mass; combined with shape information from images, this will yield bulk density. However, an active means of getting below the surface will be necessary for adequate determination of internal composition and structure. Experiments to be considered include (but are not limited to) a Deep Impact style collision; direct measurements by a lander with a penetrator, drill, or scoop; gamma ray spectroscopy, and subsurface radar.

Like the famous horse devised by Odysseus, a spacecraft mission to the Trojan asteroids would allow us to penetrate formidable barriers to knowledge and enter into a better understanding of our Solar System.

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