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Large Adaptive Optics Survey of Asteroids (LAOSA): Size, Shape, and Occasionally Density via Multiplicity.

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Database: We retrieved all asteroid observations from Gemini and European Southern Observatory (ESO) archive database, which were recorded within the last three years using the adaptive optics (AO) systems available on the Very Large Telescope (VLT-8m UT4) and the Gemini North 8m telescope. We also included our own observations taken with the Keck-II AO system. Because of their large apertures, the angular resolutions on these near infrared images (1-2.5 μm) are close to the diffraction limits of the telescopes (~0.06 arcsec for VLT and Gemini, and ~0.05 arcsec for Keck at 2.1 μm). At the time of writing, this large database (named LAOSA) includes 1013 observations corresponding to 347 observed asteroids, which consists of 29 Near-Earth Asteroids, 300 main-belt asteroids with m_V<14, 18 Jupiter Trojan and 1 Centaur. We summarized below the main results obtained after a global analysis of this database, and subsequently considered the case of multiple asteroids

Analysis: All frames were processed and analyzed following the method as described in [1]. For each frame, we have estimated the minimum size of a satellite that can be positively detected with the Hill sphere of the system by estimating and modeling a 2-σ detection profile: on average, a moonlet located at 2/100 x R_{Hill} (1/4 x R_{Hill}) with a diameter larger than 10 km (4 km) would have been unambiguously detected. The calculation of an upper limit of detection for each asteroid is crucial considering that new, high performance AO facility, such as Laser Guide Star or larger aperture telescope (TMT-30m) will soon be available. The publication of previous surveys will help to optimize the target lists for possible new search programs.

The apparent size and shape of asteroid was estimated by fitting an ellipsoid function on the deconvolved frame. 199 main-belt asteroids with an angular diameter larger than ~60 mas (corresponding to D >80 km at the average distance of 1.9 AU) are resolved.

Result: The analysis of this large database is still in progress. Based on a relative small sample of 41 Keck AO observations of 33 asteroids [1], we can conclude that the average size of the asteroids is in agreement with IRAS radiometric measurements [2], although asteroids with D<200 km were typically underestimated by 6-8%. Nevertheless, the size a/b ratio for most of the asteroids were in close agreement with those derived from lightcurve measurements in the literature [3].

Comparison with 3D-lightcurve inversions. 9 Metis, 52 Europa, 87 Sylvia, 130 Elektra, 192 Nausikaa, 423 Diotima, and 511 Davida were compared with lightcurve inversion model [4]. The deconvolved images are similar to the lightcurve models validating both techniques (see Fig. 1). The AO images also allowed us to remove the ambiguity of photometric mirror pole solution inevitable for asteroids moving close to the plane of the ecliptic (52 Europa and 192 Nausikaa).

Multiplicity in the main-belt. We confirmed the existence of moonlets around 22 Kalliope, 45 Eugenia, 87 Sylvia, 107 Camilla, 121 Elektra, 130 Elektra, 283 Emma, 379 Huenna, 702 Pulcova, 3749 Balam, 4674 Pauling, and the binary nature of 90 Antiope. These binary systems were discovered in 1999-2005 using various AO systems by two teams led by W. Merline (SWRI) and J.-L. Margot (Cornell U.). Several AO images suggest the existence of other binary systems. Additional observations will be recorded using mostly the Keck AO system to confirm these discoveries. The percentage of binary main-belt asteroids, considering our limit of detection, is estimated to 6%. The ratio of contact binaries based only on the Keck survey, which provides the best angular resolution, is surprisingly high (6%), suggesting that non-single configuration is common in the main-belt.

Diversity of the orbits in the main-belt: The orbits of several main-belt binary systems were derived based on a campaign of observations using the AO systems available on the VLT in 2004 [5] and in progress at the Gemini telescope. The orbits of 45 Eugenia and 121 Hermione moonlet companions (~5% the size of the primary) [6] are quasi-circular with a low inclination. They are located well inside the Hill sphere of the primary (~2/100 x R_{Hill}). The circular and equatorial orbits of (87) Sylvia I Romulus (P =3.65 days, a =1360 km) and (87) Sylvia II Remus (P =1.38 days, a = 706 km, so ρ = 1.2 g/cm^3), the first multiple asteroidal system discovered [7], are also similar to the orbit of 107

Camilla moonlet (P =3.71 day, a = 1240 km, ρ = 1.9 g/cm^3). This finding suggests that these four binary systems share a similar origin, most likely the result of a disruptive collision of a parent asteroid. In contrast, other binary asteroidal systems show some significant differences in several properties such as eccentricities and/or semi-major axes. 283 Emma's companion has an eccentric orbit (e ~0.11), with P =3.38 days and a =600 km, leading to an extremely low density (ρ= 1.1 g/cm^3) considering D_{IRAS}= 148 km. 379 Huenna's moonlet revolves in ~82 days, much farther from its primary (a =3,380 km, corresponding to 1/7 x R_{Hill}) describing an eccentric orbit (e ~0.25). Its density of 1.2 g/cm^3 is derived for this C-type asteroid ($D_{Spitzer}$ =102.4 km). Its moon size is estimated to be ~5 km. 3749 Balam, the smallest asteroid of our binary survey (D ~7 km) is a difficult binary system. Preliminary analysis suggest that its ~3-km size moonlet orbits at 1/5 x R_{Hill} (a ~ 290 km) in 80±20 days (with e ~0.3-0.9). Because the eccentricity and the size of the primary are poorly constrained, a large uncertainty remains on the density. We are also finalizing the analysis on the orbits of 130 Elektra and 702 Pulcova, including recent observations taken at Gemini.

The case of 90 Antiope doublet asteroid. The long-term adaptive optics (AO) campaign of observing the double asteroid 90 Antiope carried out from 2003 to 2005 permitted the prediction of the circumstances of mutual events occurring during the July 2005 opposition [6]. This was the first opportunity to use complementary lightcurve and AO observations to extensively study the 90 Antiope system, an interesting visualized binary doublet system located in the main-belt. The combined use of these complimentary observations has enabled us to derive a reliable physical and orbital solution for the system (shapes, surface scattering, bulk density, and internal properties).

Our model is consistent with a system of slightly non-spherical components, having a size ratio of 0.954 (with R_{avg} = 43 km, separation of 170 km), and exhibiting equilibrium figures for homogeneous rotating bodies. A comparison with grazing occultation event lightcurve suggests that the real shapes of the components do not vary by more than 4 km with respect to the Roche equilibrium figures. The J2000 ecliptic coordinates of the pole of the system are λ_n = 200±0.5° and α_n = 38±2°. The orbital period was refined to P = 16.5051±0.0001 hours, and the density is found to be slightly lower than previous determinations, with a value of 1.19±0.03 g/cm^3 [8].

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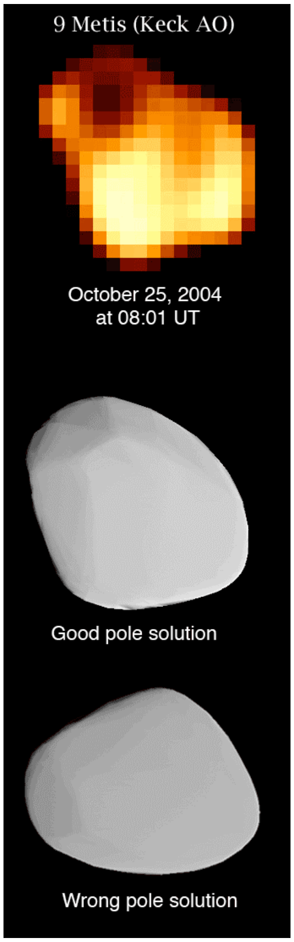

Figure 1: (9) Metis observed with Keck AO system at 2.1 μm with a pixel scale of 9.94 mas. The deconvolved image is at the top. The asteroid is nearly seen from the pole (viewing angle of 20°). Surface marking with contrasts up to 50% are clearly detected on this image. A comparison with the apparent shape and orientation with [9] shape model, pole solution and known lightcurve rotational phase confirms the accuracy of their model. The bottom 3D-model displayed Metis asteroid with the clearly wrong solution.

THE POTENTIAL PUSH AND PULL OF THE DEVELOPMENT AND CONSTRUCTION OF SOLAR POWER SATELLITES TO EARTH ORBIT COLONIZATION AND INNER SOLAR SYSTEM COLONIZATION: ASTEROIDS AS A SOURCE OF CONSTRUCTION MATERIAL.

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Introduction: Currently the worlds manned space exploration is several decades behind where it was predicted to be when the Apollo missions started in the 1960's.

Why?

Simply because aside from some interest in remote sensing and telecommunications in Earth Orbit there is no ecomomic necessity to go into space even though as with all colonization initiatives they usually benefit the parent nation that embarks on those endeavors.

To only do science in space is not enough of a economic or social push and pull to get a real permanent foothold in space. The development and construction of Solar Power Satellites might be that societal push pull to get a real manned foothold into space.

Currently the majority of our worlds civilization is based on both solid carbon and hydrocarbon sources of energy. It is obvious to even an elementary student that this situation of what our world's energy supply is based on will not last forever it might not even last for more than at the most another generation. The United States and the West is fighting its second 'oil' war in half a generation. If the ecomoic resources that were devoted to prop up our carbon based energy civilization was instead used to develop alternative energy supplies especially Solar Power Satellites then it might be possible to avert a global energy catastophe by the end of this generation.

Solar Power Satellites are a viable technically possible technology that with cooperation and integration of the world's various space capable nations could start to produce energy being beamed back to Earth within ten years.

Technological Elements of Solar Power Satellites:

The gravity well of the Earth would mean that it would make sense for the raw material for some of the construction material to come to GEO from either Asteroids or from the Moon. Material shipped from the surface of the Moon would also have a gravity well to contend with although it would be a smaller one than the gravity well for material sent up from Earth.

This is why the geochemical understanding of asteroids must occur so that they might be developed as a resource that has less requirements for delta V's than the equivalent mass lifted off from the Earth's surface.

Conclusion: If Solar Power Satellites were constructed it would mean a permanent presence of man in space at the same time as averting the potential catastrophe of our world's energy supply and consumption being reduced.

The quarries of Earths future structural development in Earth Orbit and in Inner Solar System development will definitely be the Asteroids in the Inner Solar System.

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THE IMPORTANCE OF METEORITE RECOVERY AND UNDERSTANDING ASTEROID GEOLOGY FOR INNER SOLAR SYSTEM RESOURCE DEVELOPMENT.

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Discussion: It has been proposed that an eventual non-terrestrial source of strategic mineral resources could come from the asteroid belt.[1] The only significant material geological samples from the asteroid belt are from meteorites. They can compare the spectral signature of the meteorite samples and then compare it to the spectral signature of the large asteroids in the asteroid belt. The asteroid belt is closer to Low Earth Orbit (LEO) then the surface of the Earth in terms of the energy required to move mass. Ts being based on the Delta Velocity force that is required to get to low Earth Orbit from the Earth's surface compared to the Delta Velocity force needed to get to Low Earth Orbit from the Asteroid belt. Long term resource and distribution and development of inner solar system geological resources depend on an understanding of the chemical and geochemical nature of objects that would be mined in the inner solar system especially the asteroid belt. Terrestrial sources of strategic minerals is decreasing and ultimately the only new source of new mineral deposits for Earth and Earth orbit is the asteroid belt. The gravitational well from the Moon's surface to Low Earth Orbit is also more costly then from the Asteroid Belt.

Trojans as Resource: The Trojan asteroids are also a potential source of materials. Also we would like to not have all of eggs in one basket in case of a cosmic disaster on the Earth. Within the next several centuries space could be utilized for the development of resources that could be used to develop build energy producing systems such as Solar Power Satellites that could beam energy back down to the Earth from Low Earth Orbit. The infrastructure in Low Earth Orbit to develop Solar Power Satellites would need substantial construction materials that might be acquired from the Asteroid belt. It might seem very speculative but meteorites are a '*Poor Man's Space Probe*' and with the over 30,000 distinct separate meteorite samples that have been recovered it would seem that we have just to today enough separate samples to do geochemical analysis for several generations. With the advent of Antarctic meteorites the mass of material is the problem the samples are being recovered quicker then they can be looked at by scientists in detail.

The next step is a greater emphasis on learning and understanding the geology of the various asteroid bodies that would likely be quarried for use in the near future for potential LEO construction and maybe for rare strategic mineral resources transported back the Earth's surface.

Conclusion: Space to any extent will only be colonized when there is a need for the resources of the inner solar system for mans push out to find new planetary homes. Sadly, the push and pull of the history of exploration shows that true colonization not just exploration occurs when economic incentives and/ or geo-political considerations occur: not because of any potential scientific benefits.

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EUROPEAN PROJECTS TO FURTHER OUR UNDERSTANDING OF THE IMPACT RESPONSE, THE SURFACE AND INTERIOR PROPERTIES OF SMALL BODIES FROM SPACE.

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Introduction: In recent years, two projects of space missions devoted to small bodies have been discussed within the European Space Agency and among the European community of planetary scientists. One of this project, the Don Quijotte concept, is currently in Phase A and is aimed at testing our ability to deflect a small asteroid. The other project, a sample return mission to a pristine Near-Earth Object, has been indicated among the priorities in ESA Cosmic Visions 2015-2025, and will be the subject of a proposal by the European community. A summary of these projects in their current state is presented.

The Don Quijotte Mission : In January 2004, ESA established an international panel, called NEOMAP (Near-Earth Object Mission Advisory Panel), consisting of six European scientists active in studies of Near-Earth asteroids, with the task of advising ESA on cost-effective options for participation in a space mission to contribute to our understanding of the terrestrial impact hazard and the physical nature of asteroids. Of three rendezvous missions reviewed, the Panel considered the Don Quijote concept, a test of deflection of an asteroid, to be most compatible with the criteria and priorities established in this framework. Don Quijote consists of two satellites launched in separate interplanetary trajectories. One is planed to be insterted into orbit around a 500 meter-size asteroid, the other 500 kg one will arrive a few months later and will collide with the asteroid at 10 km/s in order to make a small deflection measured by the orbiter. This project has the potential to teach us a great deal, not only about the internal structure of a NEO, but also about how to mechanically interact with it. It is thus the only mission that could provide a vital missing link in the chain from threat identification to threat mitigation. Considering possible participation from countries outside Europe, the Panel felt that the Don Quijote concept is compatible with current interest and developments elsewhere and may readily attract the attention of potential partners. Following an invitation to tender and the subsequent evaluation process, three industrial teams have been awarded a contract to carry out the mission phase-A studies until the end of 2006.

A Sample Return Mission to a Pristine NEO : ESA Cosmic Vision 2015-2025 aims at furthering Europe's achievements in space science, for the benefit of all mankind. The plan has been created by the scientists. Then, ESA' multinational Space Science Advisory Committee prepared the final plan, which contains a selection of themes and priorities. In the theme concerning how the Solar System works, a Near-Earth Object sample return mission is indicated among the priorities. A proposal had been initiated by Dr. A. Barucci (Meudon Observatory, France) and serves as a basis to make a new study of Sample Return mission within a large European community and possible collaboration with the Japanese Space Agency JAXA to reply to the ESA Cosmic Vision AO. The principal objectives are to investigate on 1) the properties of the building blocks of the terrestrial planets; 2) the major events (e.g. agglomeration, heating, ...) which ruled the history of planetesimals; 3) the primitive asteroids which could contain presolar material unknown in meteoritic samples; 4) the organics in primitive materials; 5) the initial conditions and evolution history of the solar nebula; and 6) how they can shed light on the origin of molecules necessary for life.

These projects appear clearly to have the potential to revolutionize our understanding of primitive materials.

CARBON-BEARING SPHERULES AND THEIR SOURCES IN ASTEROIDS.

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Introduction: Carbon-bearing spherules can be found as product of shock wave explosions from carbon-bearing materials found on the Earth, which are mixed with Fe and Ni from meteoroids [1-3]. Content of carbon in micro-spherules is considered to be strong indicator of materials and their sources during shock wave explosions. The purpose to this paper is to elucidate carbon contents and sources of carbon-bearing spherules on asteroids, which are applied from data on spherules on the Earth measured with using non-destructive and in-situ analyses of analytical scanning electron microscopy [1-3].

Three-types of carbon-bearing spherules on the Earth: There are major three sources of carbon at carbon-bearing spherules found on the Earth as follows:

1) Carbon from air molecules.
2) Carbon from carbonate rocks.
3) Carbon from meteorites or comets.

If there is no carbon in target materials of shock wave explosions as in the above first case, all sources of carbon-bearing spherules of Fe-rich composition are supplied from carbon oxides in air which is low carbon-content of spherules due to low contents of carbon in N_2 and O_2-rich atmosphere of the Earth. If carbon-rich meteorites and comets collide to carbon-free target rocks of granite or sandstone on the Earth as in the above third case, all sources of carbon-bearing spherules of Fe-rich composition are supplied from carbon in meteorites and comets which is intermediate carbon-content of spherules, because carbon content of carbonaceous chondrites (ca. 4 % in total content [4]) mixed with Fe show limited source during impact explosion, and because carbon in comets without any Fe can easily vaporized to air molecules during explosions. If any kinds of projectiles of meteorites hit carbon-bearing rocks of limestone as in the above second case, carbon-rich spherules can be formed from wide target rock with carbon during expanded impact explosions. Carbon content of carbon- bearing spherules formed during shock wave explosions on the Earth can be classified as the following three types [1-3]:

1) Low carbon content of air explosions.
2) Intermediate carbon content of impacts from meteorites to carbon-free rocks.
3) High carbon content of impacts to carbon-bearing carbonate rocks.

Carbon-bearing Spherules on asteroids: As asteroids have no air carbon, there are no carbon-bearing spherules of above first case with low carbon content on asteroids. As the parent body of carbonaceous chondrites is considered to be localized or irregularly distributed carbon-bearing target rock due to its density and material circulation. Although carbonaceous chondrites have a few carbon content [4] which is lower than carbonate rocks of limestone, carbon-bearing spherules formed by impact with carbonaceous chondrites will reveal intermediate type of carbon content on target rocks of carbon-free asteroid parent body. Carbon oxides in comets without major Fe can easily vaporized to air molecules during impact explosions:

1) No low carbon content of air explosions type in asteroids.
2) Probable intermediate carbon content of impacts with carbonaceous meteorites and carbon-free rocks on asteroids.
3) No high carbon content of impacts to carbon-bearing carbonate rocks on asteroids.

Carbon for life on cyclic planet of the Earth: The Earth reveals two types of carbon circulation systems as follows [5] :

1) *Large circulation of materials system:* This type can be found among air (gas state), sea water (liquid state) and rocks (solid state) due to change of carbon for three states. Among them carbonate rocks of limestone and calcite mineral group (as bio-minerals) can be formed during sea water (liquid) state. This indicates that formation of bio-minerals of limestone is required for sea water on the planet.
2) *Small circulation of material system:* This type can be found between air (gas state) and water (liquid state) in living-species and plants of photosynthesis.

Application of carbon cycle system to asteroids: Two complicated carbon cycle systems on the Earth are inevitable for living species as background environments (in large circulation system of parent body) and real active environments (in small circulation system of living species). These two circulation systems cannot be found on any types of asteroids or comets even if there is any carbon or organic molecules (as in carbonaceous meteorites). Carbon cycle systems on asteroids are summarized as follows:

1) No large carbon cycle system among three states on asteroids as large environments.
2) No small carbon cycle system between two states on asteroids as small environments.

In short, any life organics will not be expected from the asteroids and comets due to no material circulation system (Table 1).

Table 1. Summary of carbon-bearing spherules on asteroids.

1)	Carbon-bearing spherules:	Intermediate content of carbon.
2)	Source of carbon:	Mainly from projectiles of carbonaceous meteorites and/or comets.
3)	Life organic carbon materials:	No formation due to no materials circulation system on asteroids.

Summary: The present results are summarized as follows (cf. Table 1):

1) There are major three sources of carbon and carbon content at carbon-bearing spherules found on the Earth.
2) There is no low carbon content of air explosions type in asteroids. Probable intermediate carbon content of impacts with carbonaceous meteorites and carbon-free rocks will be found on asteroids.
3) There is no high carbon content of impacts to carbon-bearing carbonate rocks on asteroids.
4) From large circulation of materials system of the Earth found among air (gas state), sea water (liquid state) and rocks (solid state), formations of bio-minerals of calcite-group minerals and limestone is required for sea water on the planet. From small circulation of material system of the Earth, active change between air (gas state) and water (liquid state) in living-species and plants of photosynthesis is inevitable for life organic materials.
5) As there are no large and small carbon cycle systems among three states on asteroids, any life organic materials will not be expected from asteroids and comets

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ENHANCING SCIENTIFIC RECONNAISSANCE OF SMALL BODIES USING RADIOISOTOPE ELECTRIC PROPULSION.

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Introduction: In the last two decades, a number of small bodies have been explored to differing degrees by spacecraft (Table 1). The majority of these missions have involved flybys, and only one, the NEAR mission, has involved extended observations at a small body. While the data acquired during flybys has greatly enhanced our knowledge of small bodies, the knowledge gained from the year-long study of the asteroid 433 Eros has clearly demonstrated the value of spending extended periods of time carrying out reconnaissance of an object [1]. For example, the data obtained at Eros enabled the determination of an appropriate site for landing, and could equally well have enabled the optimal choice of sampling sites or locations for landed packages such as geophones.

In order to undertake comprehensive reconnaissance of a small body to determine its interior structure, we would argue that flybys are insufficient, and that only extended orbital missions can enable the appropriate science return.

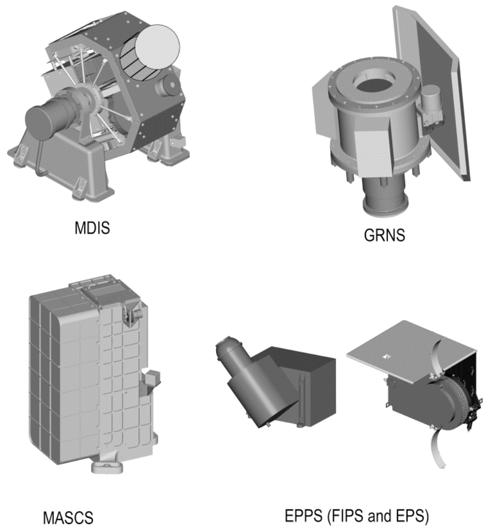
In many cases, radioisotope power supplies are enablers for small-body missions, especially those further out in the solar system, and propulsion is the significant technical driver. Radioisotope-Electric Propulsion (REP) can enable many of these missions by combining a small (~500 kg dry mass) spacecraft with a focused payload (~50 kg) and advanced radioisotope power sources for a mission cost on the order of that for a New Frontiers mission [2]. REP systems may, in addition, allow extension of the science goals in the recent report published by the National Research Council "New Frontiers in the Solar System: An Integrated Exploration Strategy" (the “Decadal Survey”) [3] by enabling orbital missions of bodies for which only flyby missions are possible with chemical propulsion. REP systems can also enable an interstellar precursor mission, the subject of a more recent NRC report “Exploration of the Outer Heliosphere and the Local Interstellar Medium” [4].

The key reason why REP spacecraft would be ideal for characterization of small bodies such is their capability of orbiting more than one body in a single mission. Rather than sending numerous spacecraft, with the associated development, assembly, test, launch and operations costs for each, ***a REP spacecraft could visit at least 2, and possibly more, bodies for the cost of only one mission***. Furthermore, most technology for this class of missions already exists; the only technology development required is that of the next generation Stirling Radioisotope Generator (SRG), which is currently in NASA’s technology plan, and so is already underway. With continued development, REP missions could be available for small body characterization within the next decade.

Target	Type	Spacecraft	Agency	Year	Type of Encounter
Giacobini-Zinner	Comet	ICE	NASA	1985	Tail fly-through
Halley	Comet	Suisei	Japan	1986	Hydrogen corona imaging
		Sakigake	Japan	1986	Sunward flyby
		Vega 1	USSR	1986	Flyby
		Vega 2	USSR	1986	Flyby
		ICE	NASA	1986	Distant observations
		Giotto	ESA	1986	Nucleus flyby
Gaspra	S-Asteroid	Galileo	NASA	1991	Flyby
Grigg Skjellerup	Comet	Giotto	ESA	1992	Flyby
Ida	S-Asteroid	Galileo	NASA	1993	Flyby
Mathilde	C-Asteroid	NEAR-Shoemaker	NASA	1997	Flyby
Eros	S-Asteroid	NEAR-Shoemaker	NASA	1999	Orbit for 1 year
Borelly	Comet	Deep Space 1	NASA	2001	Flyby
Tempel 1	Comet	Deep Impact	NASA	2005	Comet impact

Table 1: Previous small body missions.

Exploration of small bodies using REP: We have been investigating mission concepts that use small electric propulsion engines, ~1 kWe radioisotope power, and low-mass spacecraft construction techniques [Gold et al., this meeting]. Our objective is to find practical missions to high-priority targets, with reasonable travel times and a reasonable science payload. The high power-to-mass ratio of planned radioisotope power systems enables New-Frontiers class missions that carry a significant science payload to new destinations. The PARIS (Planetary Access with Radioisotope Ion-drive System) spacecraft take advantage of high-efficiency SRGs or new thermoelectric converters to provide the power for an electric propulsion system. These low-thrust missions launched to a high C3 are especially effective for exploring objects in shallow gravity wells in the outer solar system.


MDIS

GRNS

MASCS

EPPS (FIPS and EPS)

Fig. 1. Candidate payload instruments from the MESSENGER mission to orbit Mercury

In order to investigate how the surfaces of small bodies relate to their interiors, we consider a focused PARIS mission with a payload that can map the elemental and mineralogical composition of the surface of a small body (Fig. 1, Table 1), however, some or all of the proposed instruments could be exchanged for lidar or radar experiments, or seismic sensors that could be deployed from orbit.

Since REP missions are mass constrained, the payload must consist of highly miniaturized instruments to enable a comprehensive set of measurements. We have selected a suite of candidate instruments from those currently in flight on NASA's MESSENGER Mercury orbiter mission [5], since these instruments are already miniaturized to accommodate the MESSENGER mass constraints. Table 2 lists the candidate payload and its mass, power, and bit rate. During cruise, the science data rate to a Near Earth Object or Trojan asteroid is approximately 100 bits per second. Fig. 1 shows model drawings of the candidate payload components. About 900 W of power are required for this mission.

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Table 2. Candidate Payload

PAYLOAD	**MASS (kg)**	**POWER (W)**	**DATA**
Mercury dual imaging system (MDIS)	6.8	6.7	12000
Mercury atm & surface composition spectrometer (MASCS)	3.1	5.9	1000
Gamma-ray & neutron spectrometer (GRNS)	13.4	23.6	1000
Energetic particle and plasma spectrometer (EPPS)	2.6	6.4	1000
Dual data processing units	3.3	4.2	30
Total	**32.9**	**52.1**	**15030**

IMPACT GENERATED SEISMIC ACTIVITY ON FRACTURED-MONOLITH ASTEROIDS: A SEISMIC PROPAGATION THEORY.

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Fractured Asteroids: The Galileo images of 951 Gaspra and 243 Ida, as well as the NEAR-Shoemaker observations of 433 Eros, revealed highly battered objects, with extensive systems of ridges and grooves on their surfaces, several large concavities (presumed to be from impacts [1,2]), and highly irregular shapes; indicative of some structural strength [3-10]. Rather than being single stone monoliths or highly pulverized `rubble-piles,' these features suggest that these asteroids are something in between. Further work characterized an entire spectrum of asteroid structural types, called `gravitational aggregates', which span the extremes from monolith to rubble-pile [11]. Britt, et al. [12] identified a transition group in the central region of this spectrum, called `fractured monoliths' and placed 951 Gaspra and 243 Ida into this transitional category, where 433 Eros likewise falls.

The Lunar Crust Analogy: While describing the geology of 243 Ida, Sullivan, et al. [6] suggested a likely similarity between the internal structure of a fractured S-type (stony) asteroid and the uppermost crustal layers of the Earth's moon [13]. Both are composed of silicate rock, presumably began as monolithic structures, and have since been exposed to impactor fluxes of similar power-law distribution for millions to billions of years [14]. This similarity should produce similar fracture structures within each, consisting of (1) a thin, comminuted regolith layer on the surface, (2) a highly fractured mixture of rock and regolith beneath (a `megaregolith' layer), and (3) a decreasing gradient of fractured bedrock below. In the case of the upper lunar crust, this fracture structure extends to depths of about 20-25 km [14], but in the case of asteroids the size of Gaspra, Eros, and Ida, this fracture structure should extend throughout the body.

Seismic Theory Development: This type of structure provides us with an advantage in modeling the seismicity of fractured asteroids, in that the seismic behavior of the upper lunar crust in response to impacts was well characterized during the Apollo era. These lunar seismic studies showed that the dispersion of seismic energy in a fractured, highly scattering medium becomes a *diffusion process*: which can be modeled mathematically using either analytical or numerical techniques [13,15].

Application to 433 Eros: In our previous work [15], we successfully used this form of seismic energy diffusion theory to investigate the 'global' morphological effects of impact-induced seismic acttivity on fractured asteroids, and on 433 Eros in particular. The primary question under study was whether (or not) impact-induced seismic shaking could destabilize slopes and cause gradual downslope regolith migration, degrading and eventually erasing small impact craters -- and producing the observed paucity of small craters on this body. This modeling work produced excellent agreement with the empirical observations, particularly with regard to the time evolution of crater morphology and the statistics of the impact cratering record. Nevertheless, we noted that there is considerable uncertainty with regard to the asteroid's actual seismic and regolith properties: we based our results on values appropriate to the upper lunar crust. The next logical phase would be to obtain direct, *in situ* measurements of the asteroid's regolith properties and it's seismic response to either natural or artificial impacts.

Future Missions: This modeling work also demonstrated the potential of seismic studies of asteroids to investigate their interiors. Such studies could not only give us information about the internal structure of these bodies; such as major fracture boundaries, internal stratigraphy, voids, and small-scale fracture spacing; but could also provide information about composition, elastic response, and seismic dissipation properties. Both reflection and standard seismological techniques could be employed, building upon our experience with the Apollo seismic experiments and taking advantage of the advances that have occurred in the field since that time.

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Radio Reflection Tomography: A Technique to Reveal the Interior of Asteroids and Comets.

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Introduction: Radio Reflection Tomography (RRT) is a uniquely capable technique for imaging the interior structure of any small, isolated geological body with size smaller than 2 km. An HF RRT mission consists of a HF radar sounder that transmits pulses between 1-30 MHz and receives echoes all around an asteroid or a comet. Today's space-qualified radar sounder instrument technology is mature thanks to recent HF radar instruments like Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) aboard Mars Express spacecraft [1] and the SHARAD (Shallow Subsurface Radar) instrument aboard NASA's Mars Reconnaissance Orbiter. The recent results from MARSIS, which is developed jointly by NASA/JPL and ASI, has demonstrated the power of orbital radar sounders to reveal the hidden geologic structures below the surface of Mars.

RRT Technique: The requirements for a successful RRT mission are:1) Precise *a posteriori* knowledge of spacecraft ephemeris in the asteroid coordinate system, 2) A dense coverage on a closed surface around the object, 3) radio wave penetration within the object (no necessarily through the eniter object), 4) A proper choise of radar frequency band(s) to allow optimum penetration and imaging resolution and 5) imaging algorithms that will transform time-domain radar echoes to the volumetric images of the asteroid’s interior.

At JPL, our spacecraft navigation team has demonstrated that it is able to orbit a small object and collect data as demonstrated by the NEAR mission with precise a posteriori ephemeris knowledge which is key in coherent radar imaging and required by the RRT imaging technique [2] Optical navigation achieves this requirement with large margin, along a polar orbit with the asteroid spinning underneath. Our team has also designed schemes to achieve dense coverage around the object under a number of case studies for objects with sizes between 500 m and 1000 m.

The radar frequency selection is a function of asteroid composition class and size. We are currently developing wideband HF radar technology that is able to address the RRT instrumentation needs. The dielectric properties of asteroid samples are also being investigated in order to evaluate radar penetration depth and imaging sensitivity. The RRT investigation is not only a structural probe of an asteroid's interior, but also a compositional probe that gives an inside view.

The final component of an RRT imaging system is the ground processing software that operates on the individual echoes and produces a volumetric image of dielectric contrast within the object. The mathematical and physical foundations of the RRT imaging technique are well understood and have been applied to a range of applications such as industrial non-destructive testing [3], ground penetrating radar [4], and medical ultrasonic imaging and more relevant is the radargrams generated recently by MARSIS instrument which demonstrate the functionality of the key ingredient of the RRT processor.

Impact: The RRT technique will provide the first data that directly senses the interior structure and composition of asteroids. This is significant for science as well as for strategies required to deal with the hazards of Near-Earth Objects (NEOs) and will provide information required for mining comets and asteroids for resources such as ice in support of human exploration. Asteroids and comets also provide information about the early solar system and how larger bodies accrete from smaller components.

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ROTATIONAL DAMPING AND EXCITATION AS PROBES OF THE INTERIOR STRUCTURE OF ASTEROIDS AND COMETS.

N. H. Samarasinha

The rate of damping of energy for an asteroid or a comet in a non-principal axis spin state depends on the size, spin rate, degree of excitation as well as the internal structure. On the other hand, rate of rotational excitation for a rigid body depends on the external torques, spin rate, and the moments of inertia of the body.

I will discuss spacecraft reconnaissance and ground-based observational opportunities where rotational damping and excitation could be used as probes to infer structural parameters of asteroids and comets.

BRIGHTNESS/COLOR VARIATION ON ITOKAWA: SPACE WEATHERING AND SEISMIC SHAKING.

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Introduction: Hayabusa is a Japanese engineering spacecraft by ISAS/JAXA aiming at sample return from S-type asteroid (25413) Itokawa [1]. Itokawa is a small near Earth asteroid (550m x 300m x 240m). Between September and November 2005, Hayabusa observed Itokawa's surface by Asteroid Multiband Imaging CAmera (AMICA) and Near Infrared Spectrometer (NIRS). AMICA has a wide bandpass filter and seven ECAS-compatible narrowband filters: 380 (ul), 430 (b), 550 (v), 700 (w), 860 (x), 960 (p), and 1010 nm (zs) [2]. Spectral range of NIRS is between 760nm and 2100nm. From 7km, AMICA observed the whole surface of Itokawa with resolution 70 cm at solar phase angle around 10 degree. The highest resolution during close approaches was less than 1cm [3].

Brightness/color variations on Itokawa: Itokawa is heterogeneous in both color and brightness (Fig. 1) [3]. The brightness difference is approximately 10-20% on distant images and as high as 30% on close-up images. Brighter areas usually correspond to at locally elevated zones and at gravitationally steep zones, although some steep zones are not bright. Brighter areas are bluer and darker areas are redder in color [4, 5]. No previously observed asteroids show such large variations in both of these characteristics. These variations may be due to the space weathering process [6].

Muses Sea area on Itokawa is displayed in Fig. 2. Muses Sea (the landing site) is composed of cm-sized pebbles which should have transported from other areas. Shirakami is one of the distinctly brightest regions on Itokawa. In this region, the brightest area (a) has very steep slope, which is steeper than a typical angle of repose of granular materials. The elevated zone with moderate slope angle (b) consists of boulder-covered dark areas (10m-scale patched areas) and boulder-poor bright areas. Typical boulder size on the dark patched area is about 1m. The neighbouring darker area (c) is covered continuously with numerous boulders. The morphology here suggests that the bright surface of Shirakami was formed by removal of the superposed dark boulder rich layer. The area (a) is a totally excavated whereas the area (b) is partially excavated due to boulder movements. In Fig. 2, brightness of of Yatsutagake (d) might be also explained by excavation of a darker superposed layer. At the foot of Shirakami and Yatsugatake extends a darker and boulder-rich zone (denoted by e). Figure 3 is a close-up image of the elevated area to the north of the Muses Sea. Here are observed bright patched surfaces of a few meter scale. Some boulders on brighter surface are dark, which would suggest darker materials should superpose on brighter materials.

Space weathering and seismic shaking: In comparison with color observation [4, 5] and experimental data [7, 8], we consider that the darker materials experienced more space weathering than the brighter materials. High resolution images suggest that boulders' surface was optically weathered. After the emplacement of boulders, Itokawa's surface was weathered by micrometeorite impacts (and irradiation by high-energy particles). Then, dark weathered boulder-rich surfaces were removed, leading to the exposure of underlying relatively fresh bright area (Fig. 4). Probably Itokawa shows brightness/color heterogeneity because it is too small to be covered with regolith.

Although there are a couple of apparent bright craters which would be explained by direct excavation, most of bright areas might not be related to local impact events. Seismic shaking or tidal distortion during planetary encounter would be possible cause of surface movements of dark bouldered layer. Since clear brightness difference prevail on all over Itokawa, the seismic shaking may have been a single event. The observed morphology that locally elevated regions are bright could be explained by the seismic shaking (E. Asphaug, personal comm.), since surface motion at elevated region would be stronger though concentration of internally propagating waves. The fact that the brighter areas are striking at both ends of Itokawa could be explained by the shaking process, since the both ends have relatively low escape velocity and concentration of propagating waves could be expected.

Figure 1 Composite color images of Itokawa constructed from b-, v-, and w-band data. Top: Eastern hemisphere including the Muses Sea. Bottom: Western hemisphere. The contrast adjustment was done in each image to enhance the color variation [3].

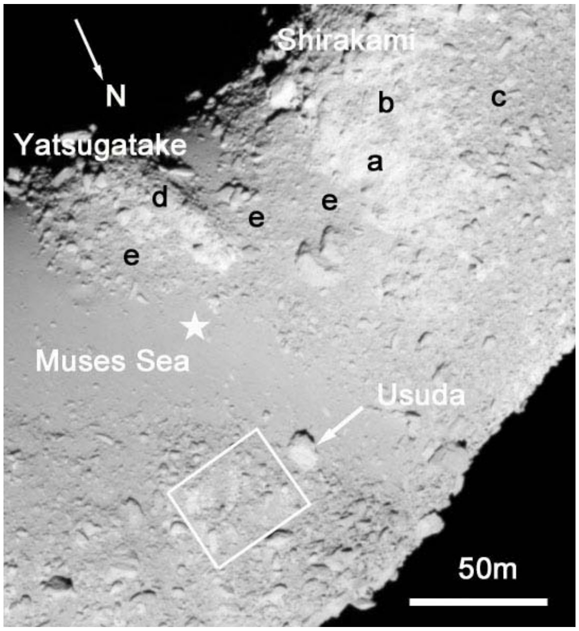

Figure 2 The Muses Sea area on Itokawa where detailed feature of Yatsugatake-Shirakami region is involved. The smooth area is the Muses Sea which includes possible landing spot of Hayabusa (denoted by a white stellar mark). Yatsugatake is a bright rough ridge to the west of the Muses Sea. A white rectangle is the area of Fig. 3. (ST_2474731509)

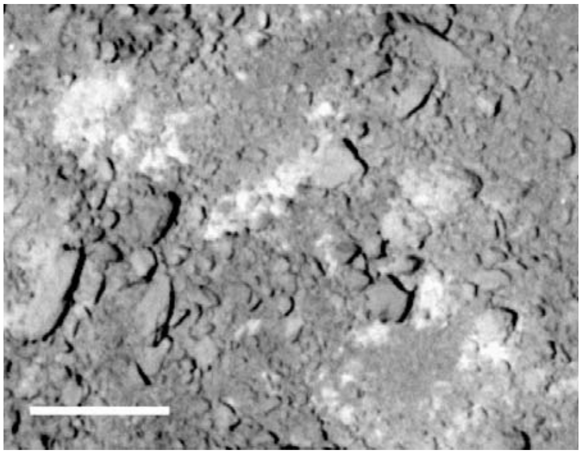

Figure 3 Close-up v-band image of a region to the north of the Muses Sea (just to the east of Usuda boulder). Scale in the figure is 10 m. The brightness contrast is enhanced in this image for clarity. (ST_2530292409).

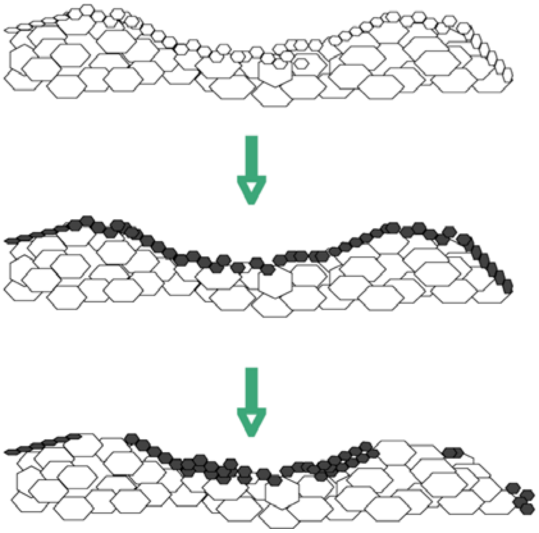

Figure 4 A model of brightness heterogeneity on Itokawa's surface. After the boulder emplacement, the surface layer with boulders are weathered. Then, seismic shaking or planetary encounder would move the surface dark layer, leading to excavate underlying fresh bright materials.

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GLOBAL GARDENING ON ASTEROIDS.

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Abstract The environment NEA live in subject them to a variety of perturbations that can change their rotational angular momentum. These range from subtle changes over time due to YORP torques to abrupt changes due to planetary flybys. As the angular momentum of an NEA changes, the configuration of the components of the NEA may also change once certain energetic thresholds are crossed. These reconfigurations can be global, meaning that major changes in the orientation of the body's components may occur, potentially exposing material previously contained in the body interior and burying previously exposed material. This abstract discusses the basic mechanics that govern such global reconfigurations by exploring the minimum energy configurations of contact binary NEA. The implications for the study of asteroid interiors is clear.

Background Recent images of Itokawa and Eros as well as many results obtained from radar astrometry of asteroids show that these bodies can have distinct components that rest on each other, so called contact binaries. The poster child of such contact binaries is now Itokawa and its "head" and "body" [1]. Given the wealth of data we have on this body's size, shape, mass and apparent rubble pile structure means it will also be the focus of future research on this topic.

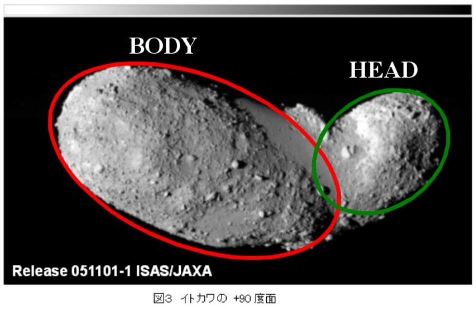


Figure 1: Itokawa with its two components highlighted

The ability of rubble pile asteroids to retain a characteristic shape in the presence of gravitational attraction of the other parts of the asteroid implies that they must have some internal strength. The ability of a rubble pile to sustain internal stresses is well established by the work of Holsapple [2], and thus there is no controversy with a body being a contact binary and for the different components of that body being rubble piles.

If two rubble piles can retain their characteristic, distinct shapes while in contact with each other, then they can also retain their characteristic shapes if shifted relative to each other or if they have slow impacts on the order of orbital speeds. Indeed, the stresses placed across the two components when in orbit will be lower than the stresses placed across them when they are in extreme close proximity – lying on each other.

Based on these observations, it is feasible to treat the geometrically separate components of observed asteroids as coherent structures, and model them as rigid bodies as a first approximation. Of course, such a model neglects the rubble pile structure of these systems at some level – but is supported by the basic observations that asteroids retain their coherent structure even when in contact with each other. On the other hand, if one rejects the rubble pile hypothesis for these NEA, or assumes that the components of a contact binary are indeed monolithic, then the rigid body assumption is uncontroversial.

External Perturbations to Angular Momentum The angular momentum of NEA are subject to changes over time, due to planetary flybys and solar irradiation [3,4]. Close flybys of planets can change the total angular momentum of an asteroid abruptly, causing it to spin much faster or slower and inducing tumbling, all over a time interval on the order of an hour. Such changes will provide discrete jumps in total angular momentum and energy that may induce an immediate response in the system. Conversely, the effect of solar irradiation can also influence the total angular momentum of an object, forcing it's spin to accelerate or decelerate depending on the details of its shape and obliquity. This leads to a gradual build-up or decrease in angular momentum, creating a system that may maintain its configuration beyond the point where it is no longer in a minimum energy configuration. If placed into such a situation it will be energetically unstable, and any small event or impulse such as an impact or distant planetary flyby may force the system to seek out a new configuration.

Energetics of Finite Bodies Given the above discussion, we apply our model of contact binary asteroids as composed of rigid bodies of finite size resting on each other. This current discussion only uses ideal shapes, such as spheres and ellipsoids, in order to make general observations. For real asteroid systems it is expected that local topography will play an extremely important role in constraining and controlling asteroid evolution.

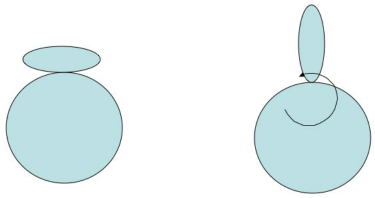
For simplicity we will consider a binary system consisting of a sphere of radius R and an ellipsoid with semi axes $\alpha_1 \geq \alpha_2 \geq \alpha_3$. Due to the symmetry of the ellipsoid, the relative equilibria that can exist between these two bodies can be easily enumerated. We define the mass fraction of the system to be $\nu = M_s/(M_s + M_e)$, $0 \leq \nu \leq 1$, where M_s is the mass of the sphere and M_e is the mass of the ellipsoid. If the components have equal density, the radius of the sphere is $R = (\alpha_1\alpha_2\alpha_3)^{1/3} (\nu/(1-\nu))^{1/3}$. We make no assumption about the relative size of the sphere and ellipsoid, and our discussion is relevant for the entire range of a small sphere and large ellipsoid to a large sphere and small ellipsoid.

For a sphere and ellipsoid resting on each other and uniformly rotating, the sphere must be located along a principal axis of the ellipsoid and the system must be rotating about one of the principal axes of the ellipsoid. We will generally assume that the system will rotate about the maximum moment of inertia of the system, which reduces the possible configurations to be considered. If the sphere rests on the α_3 axis, the system will rotate about the α_3 axis or the α_2 axis, depending on the mass fraction and ellipsoid parameters. If the sphere rests on either the α_2 or α_1 axis the system rotates about the α_3 axis.

To formally compute the stability of these different configurations is difficult, however since we have identified a discreet set of equilibria, it is possible for us to delineate the minimum energy configuration that such a system can have. We consider the energy of different configurations at a constant value of angular momentum to find the minimum energy configuration. Then we studied how this minimum energy configuration changes as the angular momentum is increased. Assuming an angular momentum, H, we can define the energy of the possible resting configurations. Then, as H changes we can identify the different configurations that result in a minimum energy.

At an angular momentum of $H = 0$ the minimum energy configuration has the sphere resting on the α_3 axis of the ellipsoid for any $\alpha_1 \geq \alpha_2 > \alpha_3$. This remains the minimum energy configuration when the system rotates slowly. Conversely, for large enough H (but less than the value for which the components orbit each other) the minimum energy configuration always consists of the sphere lying along the α_1 axis of the ellipsoid, the entire system rotating about the α_3 axis of the ellipsoid. This result holds for all values of ν and all $\alpha_1 > \alpha_2 > \alpha_3$.

For systems with $\nu \ll 1$, (small spheres on a large ellipsoid) these results are easy to imagine. When not spinning the minimum potential point on the body is always along the minimum axis. Thus small particles will preferentially move towards the polar regions. As the body rotates more rapidly, due to increases in its rotational angular momentum, the minimum energy point on the asteroid will shift at some point, in the limit always lying at the long ends of the spinning ellipsoid [5]. These energetic transitions are independent of the mass ratio, and thus for systems with $\nu \sim 1$, ellipsoidal rocks will move from resting on their minimum axis for slow rotation rates towards the sphere equator where they will stand on end as the angular momentum reaches a large enough value. For any of these cases, if the rotation rate increases to the fission limit, the components would naturally separate and the system would transition smoothly into an equilibrium orbital configuration. Such orbital configurations may be stable or unstable, depending on the mass fraction and shape of the ellipsoid.



Minimum Energy: H ~ 0 Minimum Energy: H large

Real-World Considerations For real asteroids it is implausible to assume that bodies will slide across each other into new minimum energy configurations once certain thresholds are crossed. Rather, surface topography and the rubble pile structure of these bodies themselves will hinder the system from smoothly seeking out its minimum energy state. Also, local concentrations of mass and deviations from such ideal shapes can change the minimum energy configurations in ways that have not been studied to date. Due to these considerations, under an increasing angular momentum load an asteroid may easily be pushed beyond its energetic threshold where it will be lying in a formally unstable state. The system would then be lying in a state similar to a "perched rock," waiting for a sufficient energy pulse to allow it to seek out its global minimum configuration. Such a transition could be initiated by a small impact or a relatively distant planetary flyby.

If the angular momentum is deposited by a close planetary flyby, it also coincides with a large scale jostling of the system which may precipitate a change of configuration into its minimum energy state at the same time that the system is given a new minimum energy state. For either scenario we can have global changes in the system configuration with components being transfered from one region to another. If these components are rubble piles, then as they move relative to each other they should also loose material from their surface leaving boulders and other debris from one component on the other. This would provide a surface mixture of rubble from both bodies. It will also expose previously covered material which would have been, by definition, in the interior and cover material that previously was on the surface.

Such reconfigurations can work in either direction, should the angular momentum of an asteroid be decreased due to YORP or a flyby the system can also collapse back into a low-rotation rate minimum energy configuration. Thus over long time spans it is possible for an asteroid consisting of multiple components to have them shift back and forth in a cycle of changing minimum energy configurations. This action would tend to mix material from the interior and surface regions, implying that when we look at an asteroid we look at its insides as well as its outsides. This is what we call global gardening.

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GLOBAL SEISMOLOGY ON IRREGULARLY SHAPED BODIES.

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Introduction: One way to obtain interior information from asteroids and comets is through seismology. Global seismological studies of Earth have a long history and many methods are highly developed but rely on the nearly spherical shape of our planet. To date, all small bodies that have been imaged are very irregular in shape. Work has been performed in doing seismology computations on irregularly shaped bodies and 433 Eros has been used as an example since the surface geometry was well characterized by the NEAR mission [1]. Computations with various assumed internal structures of Eros have produced different seismological output showing that different internal properties can be recognized through seismology. Of interest is the fact that the whole asteroid body can be "rung" and it is possible to determine the natural harmonic frequencies which are an aid to determining the internal structure.

Mission: An asteroid mission would include a satellite orbiting the asteroid for deploying the explosives and seismometers and controlling the experiment and relaying information back to Earth. Seismometers would be placed on the surface of the asteroid – attaching the seismometers to the surface is one of the research areas for a seismology mission. The asteroid would then be vibrated by an explosive. The produced seismic waves would shake the seismometers and that information would be transmitted to the orbiting satellite to relay the data to Earth ground stations.

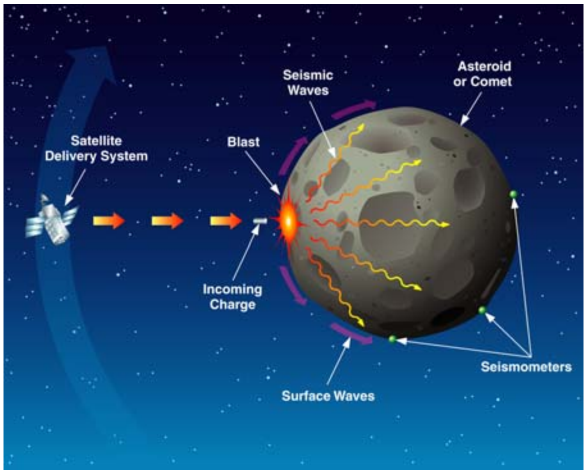

Figure 1. Schematic of a seismology mission.

Seismological Loading: Both explosives and impactors can be used to produce the seismic load. Computations with the hydrocode CTH were performed to compute loads transferred by both. One of the items investigated was the role of the surface material in the seismic loading. Four different materials have been examined: solid rock, fragmented rock, a lunar-surface-like regolith, and finally a low density distended material. The latter material was available as sophisticated material models have been developed to understand the impact damage caused to space shuttle thermal tiles [2]. The density of the material is 0.18 g/cm^3 and it is delicate and crushable.

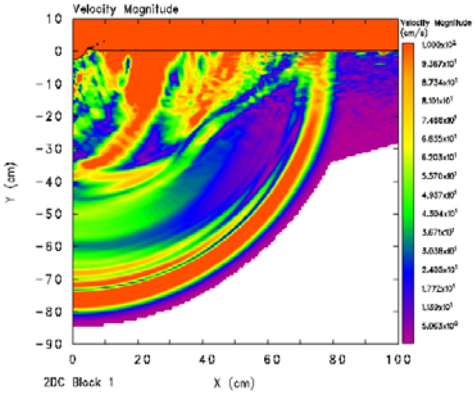

Figure 2. Velocity contours showing the spherically expanding seismic loading wave transferred to rock by explosive.

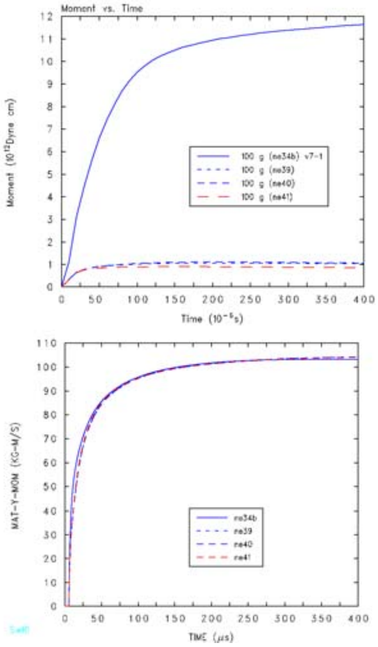

Figure 3. Top figure shows radial moment and lower figure downward momentum for loading of rock and regolith surfaces.

Asteroid Oscillations: The explosive loading computations performed in CTH require a zoning resolution that is not reasonable to maintain for the entire asteroid body (in particular, it is driven by the centimeters size of the explosive which is much smaller than the hundreds or thousands of meters size of the asteroid). Thus, the seismic source is quantified by downward momentum and the moment in the perpendicular directions or tangent plane. These values are then transferred to LS-DYNA, a finite element code where the whole body of the asteroid was modeled.

In previous work, geometrically simpler shapes (bricks and spheres) were computed and compared with known analytical solutions. Agreement between the computations and analytic results is excellent for the resonant frequencies computed through both the eigenvalue solver and through the Fourier transform of the seismometer traces. This agreement is a verification of the modeling technique.

For this work, a three-dimensional solid model of Eros was developed based on the surface shape as provided by NEAR data. The asteroid material was treated as elastic and the seismic wave propagation emanating from the source location and traveling throughout the asteroid body was computed. The loads were applied and the surface motion (accelerations, velocities and displacements) were examined at various locations as an indication of seismic data.

Of interest for a seismological mission is determining the interior structure and material properties of the asteroid. In particular, we wish to know the local density, strength, and cohesiveness. Three different internal structures for Eros were assumed and modeled as examples of possible structure. In the first case, Eros was modeled as a single solid rock, with isotropic and homogeneous material properties. As a second case, a large fracture near the center of Eros was assumed. As a third case, a regolith layer was placed on the surface of Eros. For these three geometries, seismic computations were performed.

The various acceleration traces and frequencies were compared, showing differences. The differences in seismic traces and in modal frequencies show that seismology can characterize the interior of Eros in particular and other asteroids in general. Though the inversion problem is not trivial (i.e., determining the internal structure from the seismic traces), what has been demonstrated is that current computational tools are able to address complicated irregular bodies and compute seismic propagation and normal mode vibration frequencies. Thus, the tools exist that will allow a detailed evaluation of seismic data from an asteroid. Those tools may also be used to design an optimal seismology experiment, including the distribution of the seismometers and loading locations based on a handful of assumed internal geometries. Such an approach to mission design could greatly aid in the return of useful data.

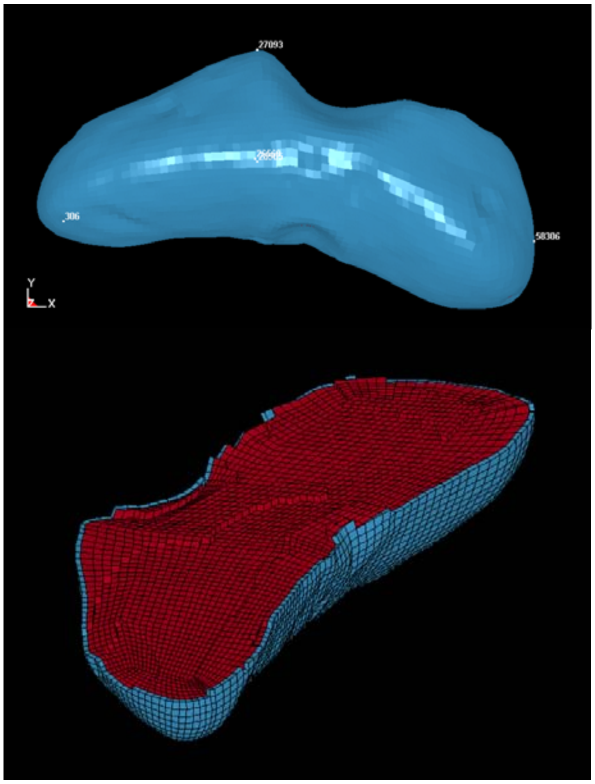

Figure 4. Two views of the model of Eros. The first is a surface view with numerical seismometer locations identified. The second is a cutaway of one of the models showing the surface regolith layer and then interior rock.

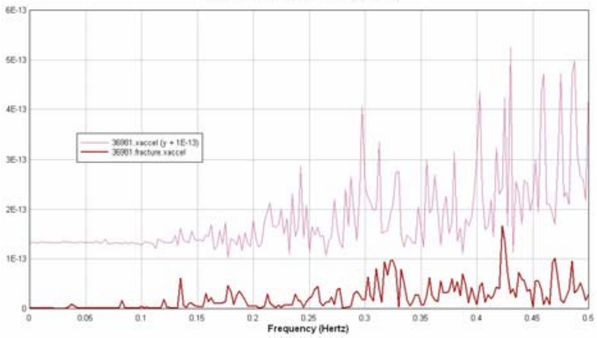

Figure 5. Fourier transform of one of the seismometer locations showing the solid Eros (offset) compared to the fractured Eros.

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SIZE DISTRIBUTION, STRUCTURE AND DENSITY OF COMETARY NUCLEI.

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Introduction: The physical nature of cometary nuclei remains one of the most important unresolved mysteries in solar system science. However, it is slowly yielding to investigations by ground-based observers as well as *in situ* observations by flyby spacecraft. The picture that is emerging is providing us with new insights into the nature of these primitive bodies.

Size Distribution: The sizes of cometary nuclei are estimated through a variety of techniques. These include: 1) direct imaging by spacecraft; 2) simultaneous visual and IR imaging that permits a solution for both the size and albedo; 3) IR imaging providing an estimate of the nucleus radius; 4) HST imaging of comets close to the Earth and subtraction of the coma signal; 5) CCD imaging of distant nuclei, far from the Sun where they are likely to be inactive, and using an assumed albedo of typically 4%; and 6) radar imaging.

Of these techniques, (5) is the most widely used, followed closely by (4). Although both techniques rely on an assumed albedo, the consistency of results from numerous observers as well as the confirmation of size and shape estimates from flyby spacecraft show that they are indeed reliable. Spacecraft have only imaged four cometary nuclei to date.

We have compiled a catalog of CCD, IR, HST, and spacecraft measurements of the dimensions of cometary nuclei [1]. The catalog contains 120 measurements of 57 Jupiter-family and 4 Halley-type comets. The data have been normalized to an assumed albedo of 0.04 except in cases where the albedo was directly measured. We find that the cumulative number of Jupiter-family comets (JFCs) at or larger than a given radius can be described by a power law with a slope of −1.73 ± 0.06 (Figure 1). This corresponds to a slope of −0.35 ± 0.01 for the cumulative luminosity function (CLF), similar to values found by other researchers [2-4], which range from −0.32 to −0.38, with the exception of [5] who found a slope of −0.53 ± 0.05.

Typical values of the CLF slope for Kuiper belt objects (KBOs) are −0.64 to −0.69 [6,7]. The shallower slope of the JFCs, which are considerably smaller than the observed KBOs, is likely due to a change in the slope of the KBO size distribution at the smaller sizes of JFCs [8]. The JFC size distribution may also evolve from its primitive value in the Kuiper belt due to physical evolution as the nuclei lose mass through sublimation and fragmentation.

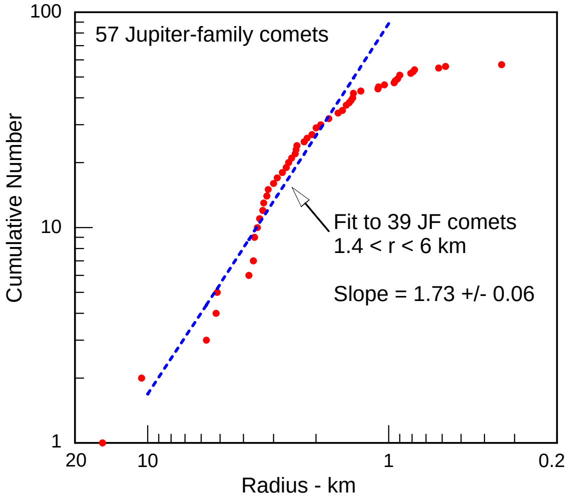

Figure 1. Cumulative size distribution of Jupiter family-cometary nuclei [1]. The least-squares fit is to the 39 nuclei with radii between 1.4 and 6 km. The data are observationally incomplete at radii < 1.4 km.

Nucleus Structure: The best models for the physical structure of cometary nuclei are the "fluffy aggregate" of Donn and Hughes [9] and the "primordial rubble pile" of Weissman [10]. These models suggest that comets are formed by the accretion of icy planetesimals at low encounter velocities, that did little to heat or crush the icy-conglomerate material. Since the comets are stored in low temperature environments and possess little self-gravity, this primitive, low density structure is believed to be preserved to the present day.

We now recognize that comets in both the Kuiper belt and the Oort cloud have likely undergone considerable collisional processing, *in situ* in the Kuiper belt in the case of ecliptic (Jupiter-family) comets [11], or during the ejection process from the giant planets region for the isotropic (Oort cloud and Halley-type) comets [12]. The consequences of this collisional evolution for the structure of present-day observed nuclei have not yet been explored.

The four cometary nuclei observed to date show vastly different shape and surface morphologies, though this may be due in part to the sharply different resolutions of the imagery for each nucleus. Comet 1P/Halley most clearly appears to be a rubble pile structure, with large topographic features and, at least, a binary shape. 19P/Borrelly also has a binary shape but has a smoother surface with less topography and some evidence of erosional processes.

Comet 81P/Wild 2 has a fairly spheroidal shape but a very unusual surface morphology, covered by numerous shallow and deep depressions that may be either eroded impact craters or sublimation pits, or some combination of the two. Large blocks protruding from the surface also suggest an underlying rubble pile structure. The orbital history of 81P/Wild 2 suggests that it may be a relatively young JF comet, new to the terrestrial planets region, and thus the surface may preserve features that are truly primitive.

The highest resolution images to date are of the nucleus of comet 9P/Tempel 1. These images reveal a complex surface morphology with strong evidence for erosional and geologic processes. There also appears to be two relatively well defined and large impact craters on the surface. Apparent layering in the surface images may be primitive, but more likely is further evidence of erosional processes acting on the nucleus. Some surface features on Tempel 1 resemble those on Borrelly and this may be consistent with both nuclei being older and more evolved, having had a long residence time in the terrestrial planets zone.

Nucleus Density: Densities of cometary nuclei are not well constrained. Most measurement methods are indirect, involving, for example, the modeling of non-gravitational forces on the nucleus based on its orbital motion and outgassing rate. These estimates have ranged from 0.1 to 1.5 g cm^{-3} [13-15]. The tidal breakup and re-assembly of comet Shoemaker-Levy 9 into ~21 major fragments in 1992 provided another means of indirectly estimating the bulk density of the nucleus, yielding values between 0.6 and 1.1 g cm^{-3} [16].

Most recently, the Deep Impact encounter with comet 9P/Tempel 1 obtained an estimate of the bulk density of the nucleus by observing the expansion of the dust plume resulting from the spacecraft impact. A value of 0.35 ± 0.25 g cm^{-3} was found [17]. This result is dependent on key assumptions about the impact event, namely that it was a gravity-dominated rather than strength-dominated impact.

Indirect lower limits on the density of nuclei can be obtained by studying their shape and rotational properties, if one assumes that they are strengthless rubble piles held together only by self-gravity. This method is analogous to that used for small asteroids, which shows a sharp cut-off in bodies > 150m diameter and with rotation periods < 2.2 hours.

A similar spin-period cut-off limit for cometary nuclei was first suggested by [18, 19], but at the longer period of 5.6 hours, which corresponds to a density lower-limit cut-off at 0.6 g cm^3. This continues to be supported as the cometary nucleus lightcurve sample continues to grow. Data on 20 cometary nuclei are shown in Figure 2 [20], along with contours of nucleus bulk density. Only one object shows a rotation period that would require a bulk density > 0.6 g cm^{-3} (rotation period < 5.6 hours). That object is 133P/Elst-Pizarro, which is in an asteroidal orbit and apparently a member of the Themis collisional family in the main belt. It is most likely that 133P is a volatile rich asteroid that has suffered a recent impact exposing buried volatiles.

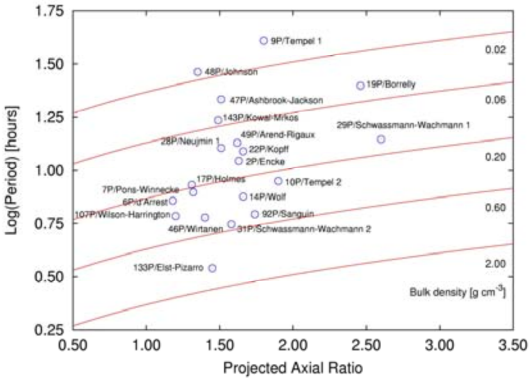

Figure 2. Measured rotation period versus axial ratio for 20 Jupiter-family nuclei [20]. If these objects are strengthless rubble piles held together only by their own self-gravity, then the data imply lower limits on the bulk density of the nuclei, shown by the contours.

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LOW-COST SMALL SPACECRAFT FOR MULTIPLE ASTEROID STUDIES.

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Introduction: Interest is growing in Near Earth Objects (NEO), particularly the class of Potentially Hazardous Asteroids (PHA). The U.S. Congress has mandated that NASA survey 90% of NEOs down to 100m size. However, telescopic surveys will be insufficient to characterize the full range of properties of these objects. This is particularly true if it becomes necessary to mitigate a threat. For the latter task detailed data, particularly on internal properties, is needed from in situ measurements.

NEOs are known to vary widely in their constitution, varying from loose agglomerations of rubble to more rigid structures of frozen volatiles to dense metallic bodies. Assessing the size, mass, and effective impact energy depends on these unknown mass and structural properties. The remote sensing surveys to date give us information on size/albedo properties of NEOs but are unable to measure the mass and structural properties. In situ measurements such as NEAR, Stardust, and Deep Impact do give us evidence to the mass, composition, and structural properties of NEOs, but to date have been too limited a sample size to characterize the broad population of NEOs observed in remote sensing surveys.

The first step is to develop a complementary, coordinated strategy of remote sensing surveys and in situ missions. This could leverage existing detection survey techniques, but would best be augmented by more extensive surveys using higher-resolution systems with spectroscopic capabilities. This detailed spectroscopic database would be complemented in parallel with statistically significant in situ sampling of the objects by impactors, orbiting missions, and landers.

What is needed is an affordable approach to sample in situ a large number of representative NEOs to build a database of their mass and structural properties. This in situ database could then be correlated with the much larger telescopic database to provide: 1) an improved statistical assessment of overall NEO risk, 2) an improved assessment of the risk associated with any specific NEO discovered to be on a likely path to impact the Earth, and 3) a better understanding of effective mitigation techniques.

Mission Possibilities: The recent Deep Impact mission showed the feasibility and effectiveness of this direct sensing approach to determine chemical constituents and structural properties. Additionally, we can assess the masses of NEOs by orbiting missions as was done by the NEAR spacecraft. With today's rather costly spacecraft approach it is likely that few, if any small NEOs will be studied in detail. The development of very small (10s of kilogram), low-cost (tens of millions of dollars US) changes this situation. The objective is to use the in-situ measurements on a fairly large number of bodies, say ten to twenty or so, to better determine mass and structural properties.

Small satellites and microsatellites, built to common specifications and produced in assembly line fashion, should be able to deliver the needed performance at an affordable price. To study a meaningful set of NEO objects, we would suggest at least ten objects, including one or more from each major class. This would require at least one, and probably several spacecraft per object. New technologies, including electric propulsion and high efficiency chemical micro-thrusters can enable a small spacecraft to have 2000 m/sec or more delta-v maneuver capability. These spacecraft could weigh as little as 20 kg and could be launched as auxiliary payloads on boosters carrying large satellites into GEO-transfer (or lunar transfer) orbits.

The small spacecraft could carry specialized instruments to image or measure infrared or radar characteristics of an object. From such data general mass properties and Yarkovsky-related parameters might be deduced. Two or more such spacecraft could enable an impact mission by one with the other able to measure results. The latter spacecraft could attach itself or kilogram-class nanosatellites to the surface to obtain detailed seismological data. Overall mission cost could be as low as $20M per asteroid. We propose that NASA consider beginning a series of low-cost NEO characterization missions as a key part of its new NEO program as mandated by the U.S. Congress.

Itokawa: a Sub-km, S-type, Rubble Pile Asteroid Investigated by Hayabusa. H. Yano[1], M. Yoshikawa[1], A. Fujiwara[1], and the Hayabusa Science Team. [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan, e-mail: yano@isas.jaxa.jp).

1. Mission Overview

Launched by the M-V-5 rocket on the 9th May 2003, JAXA/ISAS's engineering demonstration spacecraft "Hayabusa" arrived at the Gate Position, an altitude of about 20 km near the sub-earth point of the near-Earth asteroid 25143 Itokawa on the 12th September 2005. Then it moved to the Home Position for hovering at 7-km altitude from the surface to start scientific observations on the 30th September 2005. On the 8th to 28th October, the spacecraft departed to "tour" maneuvres to lower altitudes and various solar phase angles in order to acquire images of the polar regions, finer surface topography and with different light conditions. Based on the topographic and spectroscopic data for operational safety and engineering feasibility, as well as scientific significance, the smooth terrain "Muses Sea" was selected as the sampling site and the spacecraft attempted two touch downs on the 20th and 25th November, respectively [1-7].

Observational instruments onboard the Hayabusa spacecraft included a telescopic multi-band imager with filters (AMICA), a near-infrared spectrometer (NIRS), a laser ranging instrument (LIDAR), and a X-ray fluorescence spectrometer (XRS). A micro-rover "MINERVA", carrying a pair of stereoscopic imaging cameras and one other camera as well as thermometers was released toward Itokawa, but its landing was not successful.

Sampling during each touch down should have been made by shooting small projectiles onto the asteroid surface and collecting their ejecta through a 1-m long, funnel-like horn attached to the asteroid face of the spacecraft. However, it was found that the projectile firings during the first touch down was aborted while those during the second touch down have still not been confirmed due to the communication problem ocurred after the ascent. During the first touch down, the spacecraft hopped at least twice and stayed on the asteroid's surface for about a half hour. Thus it is plausible that some surface samples at slow, uplifted velocities reached inside the sample canister during this, unexpectedly long landing under the microgravity condition.

After the ascent from the second touch down, the spacecraft suffered from the difficulty with its attitude control capability due to leakage of reaction control system fuels in addition to malfunctions of two out of three reaxruib wheels. Yet the spacescraft is still capable of controlling three-axis stabilized attitude control with ion engines and Xe gas jet from neutralizers so that the return trip to the earth will start from February 2007. Hence the return of the spacecraft with the sampling capsule to the earth has been postponed from the original plan in June 2007 to June 2010.

2. Global Properties of Itokawa

Itokawa is an Apollo type asteroid. The orbital elements are a=1.324 AU, e=0.280, i=1.622 deg., q=0.953 AU, Q=1.695 AU, and the rotational period is 12.1324 hours. The spectroscopic type is S(IV). The dimension of Itokawa found by Hayabusa is 535 m, x 294 x 209 m. Pre-arrival, predicted values were confirmed by Hayabusa for the rotation period, its retrograde rotation and the spin pole orientation being approximately normal to the ecliptic. Mass,is estimated as $(3.510\pm0.105) \times 10^{10}$ kg by GM measurement from the spacecraft attitude with LIDAR and Doppler radio science. The three dimensional model gives the total volume of $(1.84 \pm0.092) \times 10^{7}$ m^{2}; hence the bulk density is estimated as (1.90 ± 0.13) g/cm^{3}.

The near infrared spectra show that are only slight differences in absorption band center position depending on respective locations. This result shows that there is not much difference in the constituent material as a function of location. This inference is also supported by the X-ray spectrometer data that shows no apparent difference in elemental abundance between the eastern or western sides. Results of both instruments are consistent with mineralogy and major compositions of ordinary chondrite meteorites. If we assume the grain density of LL chondrites for that of Itokawa, the macro-porosity of this asteroid becomes ~40 %, which is by far the largest porosity value among S-type asteroids observed so far and rather closer to C-type astreroids (Fig. 2).

Itokawa's global shape appears to be a contact binary composed of two parts called a "head" (smaller one) and "body"(larger one) of a "sea otter" (Fig.1). The surface of Itokawa exhibits a clear dichotomy divided into two distinct types of terrain: "the rough terrain", which exhibits rough topography mostly due to the existence of numerous, large boulders, and "the smooth terrain", which is mainly comprised of flat, smooth region.

3. The Muses Sea

The smooth region covers about 20 % of the total area and is distributed in two distinct areas: the "Muses Sea" is located between the head and the body and connected to the south polar region and the "Sagamihara" area surrounding the north polar region; these regions are filled with size-sorted, cm-order gravel in the lowest potentials. This is far larger than sub- mm regolith powders filling in ponds on (433) Eros. The Muses Sea holds a few boulders larger than several meters across, some of which are surrounded by dips or depressions. These rocks, tens of cm in size, often have rounded corners, flatter faces down and tend to flock together. All of the smooth terrains are concentrated in local lows of gravity-centrifugal potential and the Muses Sea has the minimum over the entire surface of Itokawa. These facts suggest a possible comminution and transportation process of regolith materials between the surrounding rough terrains and the Muses Sea smooth terrain. The boundaries between the rough and smooth regions are relatively sharp.

Large impact craters with typical bowl shapes are less than any other asteroids previously observed in the similar spatial resolutions. Some facets observed on Itokawa are probably of impact origin after the formation of Itokawa, and some could be surface features of the embedded large fragments.

These features might be due to relatively recent geological activities (e.g., seismic shaking) generated by external energy sources such as meteoroid impacts and planetary perturbation. This opens a new research area of "microgravity geology", which is crucial to better-understand connection between geochemical results of meteoritic analyses and geological features measured by spacecraft, especially for primitive, undifferentiated objects.

Due to the low escape velocity of Itokawa (i.e., 10-20 cm/s), most of the fine ejecta in cratering having higher velocities would have easily escaped from the surface. Only larger fragments with lower velocities than this escape velocity could have remained on the surface. This may explain why Itokawa's surface has relatively rough surface; several very large boulders were found particularly on the western side (the region of longitude 180-360 deg.) while no such large boulders exist on the eastern side (longitude 0-180deg.). The maximum boulder size is about 50 m near the terminator. Large pinnacles were also found in the "neck" region on the western side. An empirical relationship is known between the size of an impact crater and the maximum size of ejected fragments. The large boulders on Itokawa could not be produced from any of Itokawa's existing craters and hence these boulders are likely related to a large catastrophic collision event associated with formation of the present Itokawa.

On the19th November, the first touchdown (TD1) resulted in a cancelled projectile firing because the fan beam sensor apparently detected an obstacle and avoidance maneuver was conducted. The emergency ascent was autonomously cancelled and the spacecraft continued to free-fall to Itokawa's surface. At 21:10, the sampler horn touched and then rebounded on the asteroid surface. At 21:41 to 22:15, the spacecraft landed on the south west of the Muses Sea until an emergency ascent was conducted.

A temperature profile from the XRS thermal radiator was monitored during the TD1 phase. Its temperature increased by thermal emission from the asteroid surface as the spacecraft descended but it stopped increasing at 28±2 m altitude above the Muse Sea, the radiator temperature almost reached thermal equilibrium so that the emission temperature from the Muses Sea area below the spacecraft was estimated at 310±10 K. At the solar distance of ~1 AU, this result favors in brecciated rocks or/and a coarse-grain-filled surface with the thermal inertia ($\Gamma = 10^2 \sim 10^3$ $Jm^{-2}s^{-0.5}K^{-1}$) that is between monolithic rocks and powdery surface like lunar regolith.

4. Rubble Pile Structure

Major geological features of Itokawa discovered by Hayabusa include contact-binary appearance, high macro-porosity value, rough terrain filled with too large boulders uncovered by fine regolith, smooth terrain filled with cm-sized pebbles in local lows, no global ridges, and so on. All of these lead to a conclusion that Itokawa is the first convincing example of a rubble pile asteroid that spacecraft ever visited. Together with experimental and computational analyses, as well as information from retrieved samples (such as microporosity of samples) its internal structure can be investigated in detail.

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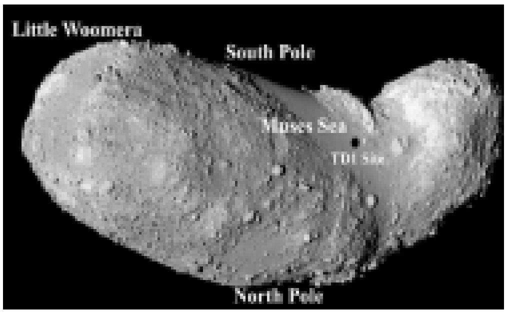
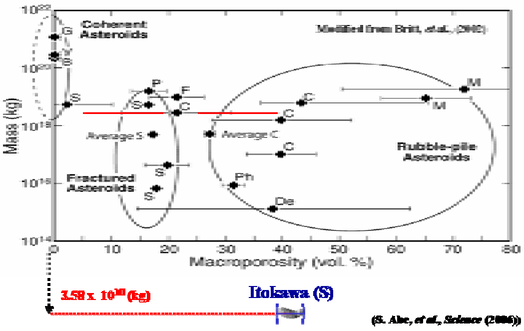


Fig.1: Itokawa's global shape



(S. Abe, *et al.*, *Science* (2006))

Fig.2: Mass-macroporosity plot by asteroid types

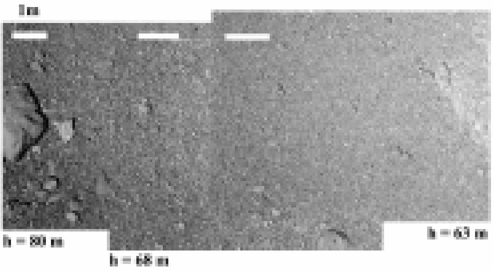


Fig.3. Close-up image of the Muses Sea field.

TECHNOLOGIES FOR FUTURE ASTEROID EXPLORATION: WHAT WE LEARNED FROM HAYABUSA MISSION.

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Introduction: Hayabusa spacecraft, which is the asteroid sample return mission of Japan, finally arrived at its destination Asteroid (25143) Itokawa in September 2005. We were surprised to see the image of Itokawa, because we found a lot of boulders instead of craters (Fig.1, left). We discovered many new things about the very small-sized asteroid Itokawa from the in situ observations. Also we have had many experiences and learned a lot about exploration of small asteroid. Although Hayabusa is still on the way to the Earth, we are now considering future asteroid sample return missions.

Hayabusa Mission Over View: Hayabusa was launched in May 2003, and after executing the Earth Swingby in May 2004, it arrived at Itokawa in September 2005. At first, Hayabusa observed Itokawa in detail by using four science instruments, the mass was estimated, and the shape model was created. Then in November 2005, several rehearsals descents and two touchdowns were done. First touch down was not performed as planed sequence, but second touch down was almost perfect. However, after this touch down, some troubles occurred and the departure from the asteroid was delayed. Therefore the return of Hayabusa to the earth is delayed three years, ant it will be in 2010. Although we are not sure whether some surface materials were collected or not, we are now working to send Hayabusa back to the earth.

Next Missions: We have been considering the post Hayabusa mission much before Hayabusa's arrival to the asteroid[1]. This is because we think that asteroid is the key object to understand the origin and evolution of the solar system. Since the results of Hayabusa were very impressive and important from the point of the planetary science, we are now attempting to start next mission as soon as possible. We call the next mission as Hayabusa-2. This spacecraft is basically the same as Hayabusa. Of course we modify several points where there were problems. But the model is almost same, so we can save time to manufacture it, and we are hoping that we can launch it in 2010 or 2011. The target is again small near earth asteroid but C-type. So we look forward to seeing how the small C-type asteroid looks like (Fig.1, right).

Also, we are considering another sample return mission, which we call it as "Hayabusa Mark-II" tentatively. Hayabusa Mark-II is not the copy of Hayabusa, but it is much-advanced mission both in the sampling and the remote sensing. For example, we want to challenge sampling with preserving depth profile and to get much more detailed data of the sampling sight. In addition, we also investigate the possibility of sample returns from two different asteroids by one spacecraft (Fig. 2).

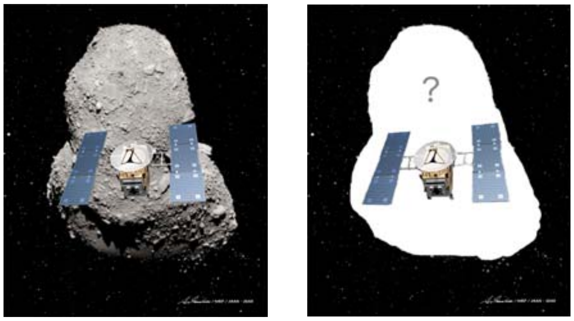

Fig.1 Composite image of Hayabusa and Itokawa (left), and Hayabusa-2 and a certain C-type asteroid (right).

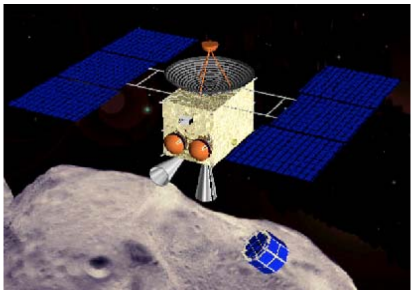

Fig.2 One of the examples of Hayabusa Mark-II.

We believe that the exploration of asteroids will provide us a lot of new discoveries and we are happy to discuss about the international collaborations for missions to small bodies in the solar system, because there are lots of them and we can know their real nature after we explore at least several of them.

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MICROGRAVITY ROBOTICS FOR SAMPLING AND IN-SITU SCIENCE MISSIONS.

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Introduction: Detailed exterior appearance, surface material compositions and key evidences to infer the interior of some of the asteroids and comets have been revealed by recent space robotic probes. Particularly in 2005, a couple of challenging attempts have been successfully conducted and then enlarged our view of minor bodies. One is *Deep Impact* mission to collide and create a crater on comet 9P/*Tempel 1*. The ejecta from the crater were observed from the spacecraft itself and a number of telescopes on Earth and in space, then their volatile compositions were quantified [1]. The other is *Hayabusa* mission to asteroid (25143) *Itokawa.* The target is a tiny S-type asteroid but after the close encounter observation, *Itokawa* turned out to be a rubble pile of loose-packed rocks that we have never seen closely before. *Hayabusa* also conducted a touch-and-go type of proximity operation. The purpose of the operation is to collect material samples from the surface and bring them back to Earth. To know the result of this challenging sample-return attempt, we have to wait until the spacecraft's safe return though, the robotics based navigation and sampling technology has been proven [2].

As technology candidates for follow-on minor body missions, there are a variety of designs studied in robotics community. One aspect of the study is the improvement of the impact sampling probe to conserve the geological stratigraphy of the target from outer surface to interior. Another aspect is a stable mobility on microgravity surface for in-situ observation and analysis on different locations specified by scientists.

In this paper, the author will make a quick review on the design consideration of the touch-and-go type of impact sampling selected for *Hayabusa* and the process of design evaluation. Then the focus will be extended to a possibility of surface locomotion by a robotic devise.

Sampling Strategies: Key consideration in the sampling on a minor body is versatility to microgravity environment and unknown hardness of the surface. As a general discussion, the strategies depicted in Figure 1 have been discussed as possible candidates for the *Hayabusa* mission [3]. (a) Drilling is a common idea to obtain core samples from surface to interior. However to achieve the drilling, the spacecraft must be anchored firmly on the surface to accommodate the reaction. Both drilling and anchoring will be possible on soft surface, such as the surface of a comet, but difficult on an asteroid. (b) Penetrating a sampling probe into the target from some distance can be a promising idea. If properly designed, samples will be packed in the penetrator keeping the geological stratigraphy, and if tethered they can be retrieved. In this strategy, the spacecraft needs hovering over the sampling site, then deploy and retrieve a tethered object, which will involve design complexity. (c) If a bullet or cannon-like projectile is projected with certain velocity, the surface will be crashed and fragments are ejected. An idea is to combine *Deep Impact*-like impact crash and *Stardust*-like dust collection technologies. But since the sample collection will be conducted at some distance from the impact site, the registration of the original sample location is difficult. (d) Another idea is to collect the crushed fragments on or at close vicinity of the surface. In this option, the spacecraft is required to make physical contact with the surface although, samples are efficiently collected from a specific point of interest on the surface. For the *Hayabusa* spacecraft we selected this strategy, and a number of tests were conducted to refine this design in terms of amount of sample collection and spacecraft safety in the *touch-and-go* maneuver [3].

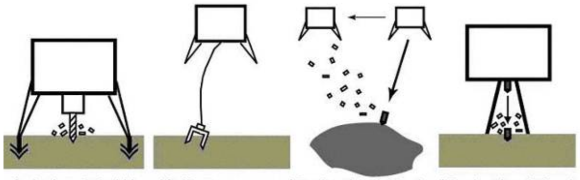
a) Anchor & Drill b) Hapoon & Penetrator c)Projection & Crush (distant fly-by) d)Projection & Crush (touch-down)

Figure 1: Sampling strategies on a minor body

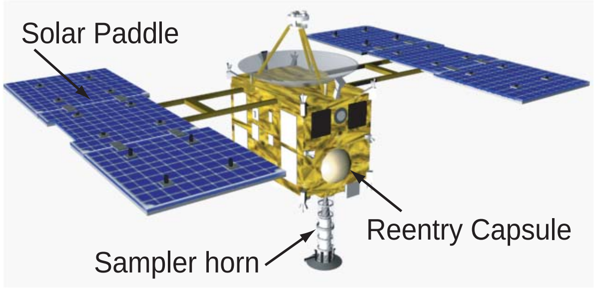

Figure 2: Design configuration of *Hayabusa* probe

Surface Mobility: As a challenging option, *Hayabusa* carried a tiny robotic system named *Minerva* that weighs less than 1 kg, yet capable to locomote on the surface of the target asteroid. The principle idea of the *Minerva* locomotion is to use an internal reaction wheel to tumble the robot body itself, then hit and hop over the microgravity surface. It has a drawback that the destination of each hopping maneuver is difficult to control, but this unique robotic devise must have provided amazing close-up pictures of the *Itokawa* surface. However, unfortunately, *Minerva* did not arrive on the *Itokawa* surface because of difficulty in the descending maneuver of *Hayabusa* on Nov. 12, 2005.

Another idea for surface mobility is to employ articulated mechanism like limbs of a human body or an insect or a spider. Those living creatures can hold on a rough surface and climb a rocky wall. This becomes much easier in microgravity environment [4]. Figure 3 describes a conceptual design and its hardware test bed. In the presented design, the rock-climber robot has six articulated limbs. In principle, three limbs are use to hold the surface while another three can move toward arbitrary direction. Such a robotic system could offer more of proximity surface science opportunities in near future though, since the robot has 18 active joints, the complexity in design and control is a drawback that we have to solve as an engineering issue.

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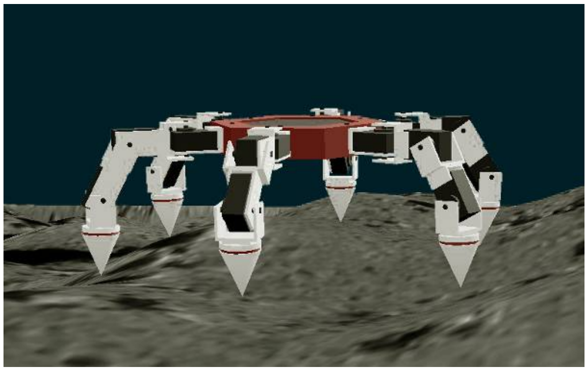

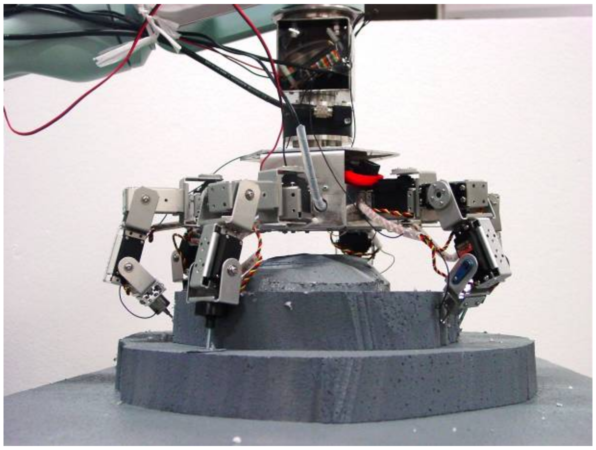

Figure 3: Conceptual design (top) and laboratory test bed (bottom) for a rock-climber type of articulated robotic surface locomotion system