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Invited Review: Physical Properties of Small Bodies from Atens to TNOs

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Abstract. Properties of small, heliocentric bodies in the solar system share many attributes because of their small sizes, yet vary in other ways because of their different locations of formation and the diverse subsequent evolutionary processes that have affected them. Our insights concerning their properties range from highly detailed knowledge of a few specific bodies (like Eros), to rich knowledge about unspecific bodies (meteorite parent bodies), to no knowledge at all (other than existence and rough limits on size) concerning much smaller and/or more distant bodies. Today's state of learning about physical properties of TNOs is analogous to that for main-belt asteroids 35 years ago. This invited review attempts to elucidate linkages and differences concerning these populations from the highly heterogeneous data sets, emphasizing basic properties (size, shape, spin, density, metal/rock/ice, major mineralogy, presence of satellites) rather than the highly detailed knowledge we have of a few bodies or their dynamical properties. The conclusion is that there are vital interrelationships among these bodies that reinforce the precept that guided the original ACM meetings, namely that we should all think about small bodies in an integrated way, not just about subsets of them, whether divided by size, composition, or location.

Keywords. comets: general, Kuiper Belt, minor planets: asteroids, planets and satellites: general, infrared: solar system

1. Introduction

In some ways, the physical properties of small bodies in the solar system is the largest topic in solar system research, if it can be considered to be a single topic at all. Besides being nearly infinite in numbers, small bodies have an enormous variety in physical properties, ranging from the nickel-iron alloys of metallic meteorites and asteroids to the underdense, volatile-rich bodies of the outer solar system, some with transient atmospheres. Their locations in the solar system range from perhaps inside the orbit of Mercury, although none of the hypothetical "vulcanoid" have yet been found, to the outermost reaches of the solar system; some would include the recently discovered tenth planet, 2003 UB313 ("Xena") at 97 AU distance from the Sun to be a "small body" (certainly its moon is). Diverse techniques are being utilized to divine the physical properties of small bodies, ranging from state-of-the-art laboratory examination of meteorites and interplanetary dust particles (IDPs), to groundbased astronomy (both passive [UV/optical/IR/radio] and active [radar]) utilizing the largest and most advanced facilities in the world, to orbital, *in situ*, and sample return studies of representative small bodies by spacecraft.

The breadth of this "meta-topic" under review was determined by the Organizing Committee of the ACM-2005 meeting, who also assigned it as the first talk of the first session. Inasmuch as it is impossible for me to prepare a definitive review of such an unwieldy topic and because many other invited reviews in this volume cover, at appropriate depth, subsets of this topic, this review should be considered as a "meta-review", summarizing some general themes to establish a context for many of the other contributions to this volume. Indeed, I must further delimit the scope of this review and treat some topics in only the briefest way. For example, a major branch of planetary science – meteoritics and cosmochemistry – is focused chiefly, though not exclusively, on measurement and interpretation of the physical properties of samples of small bodies, the meteorites. In view of the general astronomical orientation of ACM, however, I purposefully don't do justice to meteoritics in this review.

Let me begin by defining the various classes of "small bodies" whose physical properties are being researched. Although one might classify small bodies by composition, the two most useful classifications are (1) by distance from the Sun or, more specifically, by type of orbit, and (2) by size. By orbital type, one could list them roughly by increasing distance from the Sun: the still hypothetical vulcanoids, inner-Earth objects (IEOs, or Apoheles, of which three are currently known), Near Earth Asteroids (NEAs, including their subclasses the Atens, Apollos, and Amors), main-belt asteroids (including the Hungarias, Cybeles, Hildas, and others separated by large gaps from the densely populated main belt torus), Trojans (chiefly of Jupiter, but also of Mars and Neptune), Centaurs, Scattered Disk Objects (SDOs), Kuiper Belt Objects (KBOs, including Plutinos and classical Cubewanos), more distant objects that might be considered to be in the inner Oort cloud, comets (including Jupiter Family Comets [JFCs] and longer period comets, including those newly arrived from the Oort cloud; one might also include Damocloids, presumed dead comets), and planetary satellites. The term Trans-Neptunian Object (TNO) is often applied to the ensemble of outer solar system small bodies, sometimes including those that do not strictly adhere to the definition of having semi-major axes larger than that of Neptune. A final type of small body is a moon orbiting one of the other types. Rapidly increasing numbers of such moons have been discovered in the last few years orbiting NEAs, main-belt and Trojan asteroids, and TNOs. In principle, moons may orbit around small-body moons, although the first triple asteroid discovered (87 Sylvia) has two small moons orbiting around the main asteroid, not around each other. In this review, I concentrate on NEAs, main-belt asteroids, and TNOS, and largely ignore planetary satellites, even as the Cassini spacecraft is revealing a wealth of new information about the latter, including the fascinating interrelationships between small moons and Saturn's ring particles (which, of course, are small bodies – or conglomerations of small bodies – themselves).

One may also classify small bodies by size. In order of ascending size, there are IDPs, meteorites, and meteoroids at the small end; the middle range of diverse, astronomically observable small bodies roughly 10 m to 1000 km in diameter; and those larger than 1000 km, such as Pluto, 2003 UB313, Sedna, and the larger planetary satellites. In this review, I concentrate on bodies in the middle size range.

The kinds of information about physical properties that we seek to learn range from the very basic properties of size, density, and spin to the most highly detailed characterization of small-scale features (geology) and composition (chemistry, mineralogy). Generally, of course, we can determine or constrain some of the most basic properties for thousands or even tens of thousands of small bodies by simple telescopic observation from Earth whereas the most detailed physical characterization by close-up spacecraft studies can be done for only a few bodies. Disjoint from this spectrum of knowledge is the case of meteoritical studies, which measure in exquisite detail the isotopic, chemical, and mineralogical properties of small fragments of presumably hundreds of different small bodies; but almost none of this knowledge can be assigned to a specific small body, and assignment even to a class of small body (e.g. properties of ordinary chondrites to S-type asteroids) is fraught with uncertainty. The one likely exception is that there is a good case for believing that most eucrites, howardites, and diogenites (the HED achondrites) are derived, at least indirectly, from the asteroid Vesta.

Associated with the extreme range in specificity of knowledge of the physical properties of small bodies is the issue of observational biases and lack of representation. While it is elementary that objects that are bigger, closer to Earth, and have higher albedos are over-represented compared with small, black, distant bodies, there remains an unconscious bias towards "what-you-see-is-what-is-there" or, in the case of vulcanoids (notoriously difficult to find because of proximity to the brilliant Sun), "if you haven't found them we must presume that they don't exist." It is still not fully appreciated that the Jupiter Trojans are nearly as populous as main-belt asteroids. One must expect observational biases to be especially applicable to the TNOs and other outer solar system small bodies; indeed, apart from Pluto and Chiron, none of these bodies were known until 1992. Although more than 1,000 such bodies have been found in the subsequent 13 years, that places their statistics where the asteroids were in the 1920s, shortly after asteroid families were first recognized by Hirayama. Of course, the kind of detailed physical and compositional characterization of asteroids that can be done with modern astronomical techniques such as spectroscopy has so far been applied, to various degrees of precision, to only about 1% of the nearly 300,000 asteroids with reasonably well known orbits; although colors for tens of thousands of asteroids are being released by the Sloan Survey, the vast majority of asteroids still are characterized only by their orbital properties and rough apparent brightnesses. Because of the extreme faintness of most TNOs, considerable time on the largest telescopes is required to obtain physical data on even the brightest TNOs that is comparable to what is routinely obtained for asteroids. Thus TNO researchers must be particularly aware of the dangers of over generalizing results from a few well-observed bodies, over-interpreting noisy data, or ignoring potential observational biases.

The goals of astronomical observation of small body physical properties are to characterize size, three-dimensional shape, mass, spin rate and pole direction, albedo, spectral reflectance properties (from the UV into the infrared, perhaps revealing minerals or ices), thermal emission spectrum (mid-IR to radio), photometric and polarimetric properties, and temporal variations in many of the above (that might indicate spatial variations revealed by rotation or actual outbursts of dust or volatiles). Eventually, using radar on the closest NEAs but generally requiring spacecraft exploration, the goal is to observe bodies with sufficient spatial resolution (and even measure properties *in situ* or from returned samples) so that they are transformed from astronomical objects into geological/geophysical/geochemical worlds the way Mars is currently being studied by the numerous spacecraft orbiting or roving around on that planet. Because of their vast numbers, however, it will always remain the case that we will be able to study only a tiny percentage up close. So we will have to develop reliable ways to extrapolate our specific knowledge of the few to the general statistical population observable only from afar.

2. Colors and Spectral Properties

My first theme concerns "colors", by which I mean the approximate characterization of the spectral reflectance properties of the surfaces of small bodies. A highly precise and accurate reflection spectrum throughout the Sun's spectral range offers specific insight into the presence of some particular minerals and ices, but not of others. Even where useful absorption bands exist, the interpretation is sometimes ambiguous, and quantitative estimates of proportions of constituent materials are rendered difficult by uncertainties in surface particle sizes and other factors. In practice, however, spectral data are subject to further limitations due to signal-to-noise, variability in sky conditions, spectral bands where the sky is opaque, etc. There are further complications due to the fact that the optical surfaces of small bodies are subject to modification and damage due to "space weathering," caused by impacts of solar wind particles and micrometeorites. Thus the optical layers may not be representative of the bulk regolith on a body, let alone the material of which the body is predominantly composed. Still, such spectral reflectance data represent the best evidence we have about the composition of a distant body. For most small bodies, however, observational limitations restrict us to much lower photometric precision and much coarser spectral resolution than is required for determining specific mineralogy. Such "color" data nevertheless permit the development of a colorimetric taxonomy, and one may assume that members of a taxonomic group have the more specific characteristics of certain members of that group, which – because they are brighter or just happen to have been studied much more thoroughly – have available high-precision spectra.

By 1970, several dozen asteroids had been observed for UBV colors. Several researchers proposed that there were between 2 and 4 color groups, although hoped for correlations with meteorite colors were not apparent. By 1975, spectral reflectance data (for wavelengths shortwards of 1 micron) were available for a couple hundred asteroids, and UBV colors for many more. Some clustering was visible in color-color plots, and there were other statistically significant differences in color, whether or not there was an actual bifurcation into separate groups. Together with a statistically significant number of asteroids measured by 10-micron thermal infrared radiometry (yielding albedos), the database on spectra and colors permitted the development of the "C, S, M..." taxonomy, which has now consumed most of the letters of the alphabet. Such a taxonomy has been very useful for organizing the massive database on asteroidal physical properties. It has been augmented in recent years both by extension to beyond 2 microns as well as augmentation in sample size to several thousand asteroids. In 1975, the statistics were already sufficient to de-bias the data and start researching such statistical properties of asteroids as variation of taxonomic type with orbital elements, size distributions of taxonomic types, etc. The last comprehensive de-biased study of asteroid physical properties was in the late 1980s. Given the massive augmentation in the asteroid database since then, another comprehensive study is long overdue.

A currently exciting frontier is replicating for TNOs the kinds of studies that were being done three decades ago for main-belt asteroids. Beginning in 1998, it was proposed that colors of KBOs fell into two distinct groups, and debates ensued. The current situation is shown in Fig. 1, where clearly Centaur colors are bimodal, Plutinos are possibly bimodal, and SDOs and Cubewanos appear monomodal. The mean colors of the latter two groups differ from each other, however; it is not clear if their different colors are related to one or the other modes of the bimodal Centaurs. Weak correlations of colors of TNOs with different orbital properties are getting stronger as the sample increases. For example, it appears that there is a broad range of B-R colors for those with perihelion distance $q < 38$ AU whereas lower values of B-R are missing at larger q's, except for a group with inclination $i > 25°$. It is interesting that comet nuclei tend to have colors dissimilar from objects in their presumed source regions, which implies some kind of processing. Moderate resolution infrared spectra, obtained for a few of the largest TNOs, are revealing absorption bands characteristic of several types of ices (e.g. water, methane, nitrogen); already there appears to be considerable variety in surface compositions of TNOs. There is much discussion in the recent literature about the degree to which these studies reveal the inherent attributes of primitive bodies, or instead various kinds of processing, including ongoing space weathering.

Another arena of recent progress in spectral reflectance studies is NEAs. It is clear

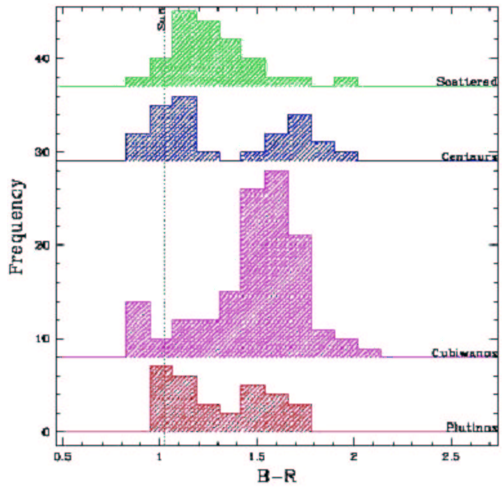

Figure 1. Histograms of B-R colors for Scattered Disk Objects, Centaurs, Cubewanos, and Plutinos, showing degrees of bimodality and monomodality. (From the database of Hainaut and Delsanti 2005.)

that larger NEAs share the diversity of spectral properties seen in the inner and middle parts of the main asteroid belt, consistent with recent dynamical research suggesting that NEAs should representatively sample large volumes of the inner and middle belt. However, at diameters smaller than 5 km (and especially < 2 km), the range in colors of the higher albedo NEAs (of S and Q taxonomic types) spreads to include shallower spectral slopes like those characteristic of ordinary chondritic meteorites. This appears to be consistent with the hypothesis that most common S-type asteroids are inherently of ordinary chondritic composition, but that the colors of larger bodies are often modified by space weathering processes. Larger asteroids tend to have two characteristics that would favor their surfaces being space-weathered: (a) larger asteroids have longer lifetimes against collisional disruption, thus would have a greater chance for space weathering to reach maturity, and (b) larger asteroids have greater gravity, thus facilitating the retention and processing of regolith, also enabling maturation of space weathering. The least reddened (space-weathered) NEAs have colors and spectral reflectances very similar to spectra of ordinary chondrites. While such spectra have not yet been seen in the main belt, few main-belt asteroids significantly smaller than 5 km diameter have been observed so far. It is plausible that some of the extreme colors and spectra seen among the smallest NEAs will eventually be found in the main belt, when objects of similar small sizes can be observed. Significantly, as many as 15% of NEAs exhibit D-type colors, common only in the outer main belt and beyond (e.g. among Trojans). However, the outer main belt remains understandably somewhat under-represented among NEAs, even after correcting for observational biases against low-albedos.

One theme of small-body research has been the search for heterogeneity in compositional properties. For example, it was once thought that many asteroid families contained members of several different taxonomic groups; that might imply processes of compositional differentiation (e.g. core formation due to heating and segregation of a mantle and crust). Recent, more comprehensive studies reveal, however, little evidence of such heterogeneity. On the contrary, the precursor bodies of most families appear to have been compositionally homogeneous. The erroneous earlier results mainly resulted from the presence of interlopers and less accurate approaches for calculating proper elements and family membership. Another approach to identifying heterogeneity is to watch for color or spectral changes as a body rotates. The very first asteroid whose reflectance spectrum was measured was Vesta, in 1929; indeed its rotation period was determined from temporal variations in its color, much more recently ascribed to an olivine-rich region in its otherwise basaltic crust. But most other reports of rotational color variations have been marginal and are doubtful. A famous instance was publication of confident conclusions that the NEA Eros had slightly different spectral properties on opposite sides; these were shown to be erroneous by the NEAR Shoemaker mission to Eros, which found an extremely high degree of spectral uniformity around the body. A recent interesting case involves a report of very different colors on Karin, the largest body in a sub-family within the Koronis family that was formed very recently, 5.8 Myr ago, in a catastrophic disruption; this report awaits confirmation. Initial results of searches for rotational color variations among TNOs reveals some showing no variations, but a couple of others hinting at variations.

3. Size Distributions

Sizes of small bodies can be estimated approximately from their apparent brightnesses. Combinations of visible and thermal-IR photometry, as well as other techniques, can yield reasonably accurate sizes for small bodies; their often irregular shapes limit ultimate precision. An individual size (or volume), when combined with a measurement of mass (e.g. from perturbations of nearby spacecraft, other nearby small bodies, or even planets like Mars...and, more recently, from the orbits of moons of some bodies), yields an important constraint on composition: density. In the aggregate, however, the statistics of sizes – when properly assessed from debiased observational data – provide fundamental information about collisional processes, either low-velocity accretional processes or subsequent catastrophic disruptions. Although the size distribution of NEAs was first inferred indirectly from the size distribution of lunar craters, the more reliable approach is to measure small-body sizes more directly.

While early theoretical work predicted a single equilibrium power-law size distribution for collisionally evolved systems, early studies of debiased main-belt asteroid sizes revealed a wavy pattern (i.e. the power-law exponent varies with size). The census of main-belt asteroids is now complete down to diameters of a couple tens of km, and debiased statistics of samples of smaller asteroids are valid down to about 3 km (Fig. 2). Relative to a single power law, there is an excess of asteroids about 100 km diameter. This is widely believed, as first proposed four decades ago, to be the collisionally unevolved remnant of the primordial population of asteroids. The relatively steep-sloping "tail" of the distribution for asteroids $<$30 km diameter is due to collisional evolution; these are the products of catastrophic collisions during the last 4 Gyr. (One issue that has not been revisited recently in any comprehensive way is late-1970s indications that different taxonomic types, and different dynamical groups of asteroids in and beyond the main belt, have different size distributions.)

Studies of the NEA size distribution incorporate not only astronomical data on NEAs but also statistics of fireballs and meteors as well as inferences from impact craters on the Earth and the Moon. The NEA size distribution differs noticeably from the main-belt case, probably due to size-dependent processes (like the Yarkovsky Effect) that extract NEAs from the main belt. It is slightly wavy, but the data are closely approximated by a single power-law exponent (the straight dashed blue line in Fig. 3); the data are inconsistent with attempts to match the lunar crater size distribution (red dashed and

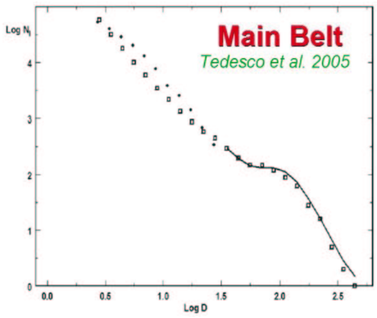

Figure 2. Incremental size distribution for main-belt asteroids larger than 3 km diameter, from the "Standard Asteroid Model" of Tedesco *et al.* (2005), shown as open squares. The dots are from an older model.

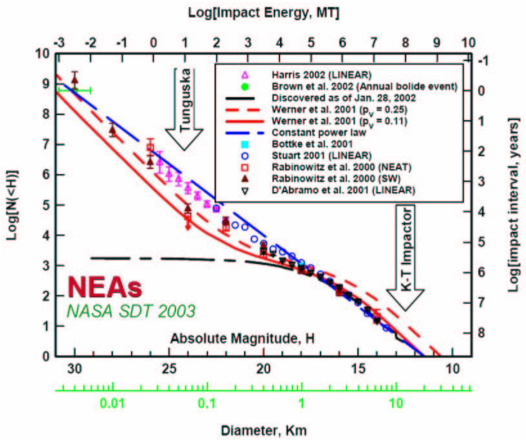

Figure 3. Cumulative size distribution for numbers of NEAs brighter than absolute magnitude H (Near-Earth Object Science Definition Team 2003). Equivalent axes for NEA diameter and Earth impact energy (in megatons) are shown. The data points are from astronomical observations; those based on LINEAR are more recent and reliable. The long-dashed blue line is a power-law that approximately fits the good data. The red curves represent unsuccessful attempts to fit a standard crater curve derived mainly from lunar craters, assuming two different albedos for NEAs.

solid curves), probably because most small lunar craters are produced by secondary ejecta from larger primary craters rather than by direct impacts by small NEAs.

The frontier of research on size distributions is in the outer solar system. It has been notoriously difficult to measure directly the sizes of comet nuclei, partly because of their activity. The latest results indicate that a power-law-like size distribution starts to become truncated at sizes <4 km diameter with very few comets smaller than 0.5 km. This is consistent with evidence for a paucity of small craters (except secondaries) on the surfaces of young satellite surfaces, like Europa, which are cratered predominantly by comets rather than asteroids. A recent discussion of the size distributions of various classes of TNOs is summarized in Fig. 4. There may be different size distributions for Cubewanos ("classical disk") compared to other TNOs. In any case, the slope of the power-law is relatively shallow below about 25 km diameter and steep at large sizes, crudely mimicking the excess of bodies $\sim$100 km diameter exhibited by main-belt asteroids. One can speculate that the 100 km "hump" reflects a primordial accretionary size distribution and that the different size distributions of comets and asteroids below 25 km

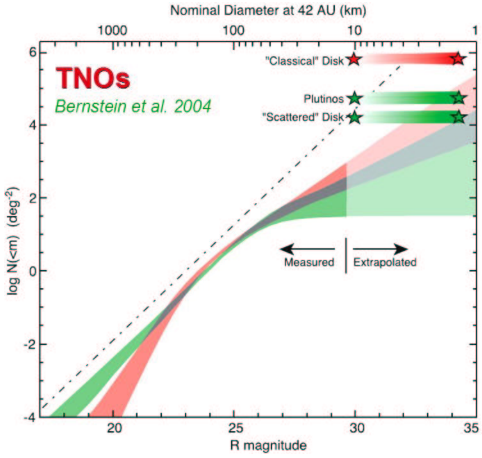

Figure 4. Limits on the size distributions of classical KBOs, shown in red, and "excited" (high inclination or resonant) TNOs, shown in green, fitting a double power-law to the data and extrapolating to smaller sizes. An earlier fit of a single power-law is shown by the dot-dash line. The horizontal bands represent theoretical estimates for three types of TNOs if they are sources for JFCs. Diagram from Bernstein *et al.* 2004.

(shallow versus comparatively steep, respectively) reflects different responses of the two types of bodies to collisions and other disaggregational processes.

4. Shapes, Satellites, and Geophysics

The mere fact that most small bodies exhibit double-peaked lightcurves implies that they are not spherical. In fact, some are highly irregular in shape, generally because the strengths of their constituent materials exceed the modest gravitational forces that would otherwise compress them into spheres, or into equilibrium figures for spinning bodies. Inversion of lightcurves ("photometric geodesy") yields fairly coarse constraints on three-dimensional shapes and requires time-consuming observations over many years to obtain diverse observing and illumination geometries. More recently, various additional techniques (high-resolution imaging by adaptive optics [AO] or from HST, radar delay-doppler mapping, stellar occultations, and close-up imaging from spacecraft) have greatly augmented our knowledge of the shapes of NEAs, other asteroids, and a few comet nuclei. Lightcurves of TNOs are beginning to suggest that they are commonly less spherical than comparably sized asteroids. This is especially true for one of the largest TNOs, 2003 EL61, which appears to be a highly elongated quasi-equilibrium figure (Jacobi ellipsoid) due to its very rapid rate of spin (just 3.9h); this body's length may exceed Pluto's diameter, although it has only one-third Pluto's mass.

Small bodies have a wide diversity of shapes and configurations (Fig. 5). One of the most profound changes in our gestalt of small bodies in the last dozen years has been the transformation from a perspective that few or none of them had satellites or were other than single bodies to the recognition that satellites or double configurations are extremely common. Despite unconfirmed earlier reports, not until 1994 was the first satellite of a small body discovered – Dactyl, orbiting around the main-belt asteroid Ida, found in images taken during the Galileo spacecraft flyby. Since then, satellites and/or double configurations have been discovered among most classes of small bodies from NEAs to TNOs. Numerous observational techniques are being used to address this issue, including AO and HST imaging, delay-doppler radar, and analysis of lightcurves (e.g.

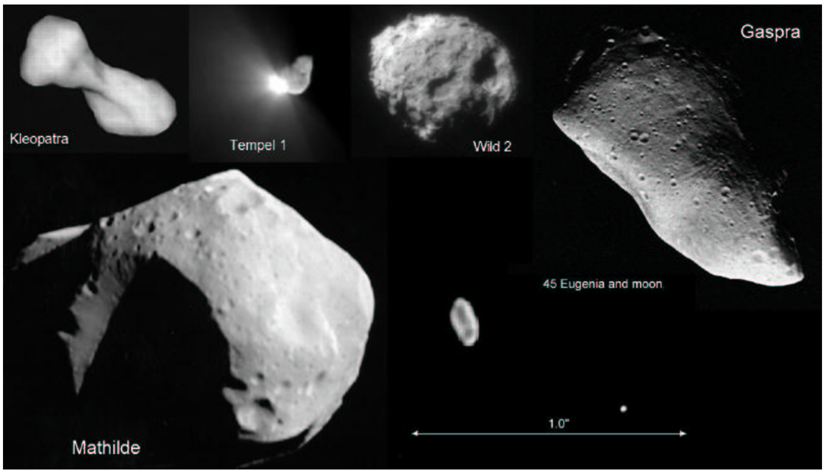

Figure 5. Pictures of diverse small bodies (not to scale) show a range of shapes, including the main-asteroid-with-moon configuration of Eugenia (lower right; from AO imaging with 1 arcsecond scale bar shown). Kleopatra is a double-lobed model based on radar delay-doppler imaging. Remaining images are from spacecraft.

"eclipsing binary" phenomena, dual-period lightcurves, etc.). At least 15% of NEAs have satellites or double configurations and widely separated satellites appear to be common among TNOs. There is every indication that percentages of bodies with satellites will increase as observational barriers are overcome (e.g. ability to detect smaller satellites near bright objects, or ability to detect closer satellites orbiting distant bodies). The common presence of satellites has the potential to dramatically improve our knowledge of the bulk densities of small bodies, from Kepler's third law, provided the volumes of the primaries can be determined fairly well.

There is great theoretical, and even *practical*, interest in the internal configurations of small bodies. Theoretical considerations of the efficiency of converting collisional kinetic energy into the kinetic energy that disperses fragments have long predicted that many small bodies are "rubble piles." The original use of this term envisioned that a collision would fragment a body into a size distribution of fragments; if the largest fragment has less than half the mass of the original body, and most of the fragments are lofted at less than escape velocity and thus reaccumulate into a conglomerate body, then the resulting rubble pile is dominated in mass by a few comparatively large bodies while the body also contains innumerable smaller fragments. Perhaps, after numerous sub-dispersive collisions, the largest components are themselves fragmented, although no physical process has been envisioned that yields a multi-component body in which all components are the same size, which has been convenient to model in computer simulations. The rubble pile concept has also been adapted to modelling comet nuclei, in which case the components of a rubble-pile nucleus might be original planetesimals gently accreted onto the growing nucleus or, alternatively, might be analogous to an asteroid rubble pile if comets are collisionally evolved.

There have been observational interpretations, for instance of large-scale geological features on Eros, suggesting a different kind of morphology, called the "shattered shard," in which it is envisioned that large-scale impacts have shattered the body but the remaining larger pieces have remained more-or-less in place. Computer hydrocode simulations of impacts, and of tidal deformation during close passages to a planet, have suggested that a variety of possible internal structures for small bodies may be produced. One clue about internal structure of NEAs has been the fact that, as of a few years ago, all NEAs >200 m diameter rotate with a period longer than 2.2h, a period at which a cohesionless rubble pile would barely fly apart by centrifugal force; smaller rapid spinners would then have to be monoliths (bodies with inherent tensile strength). Since then, exceptions have been observed. Also, it has been argued that large, natural bodies are inherently weak, even if they have not been physically broken by collisions. So it remains for future geophysical measurements by spacecraft missions to address the internal structures of small bodies, beyond the non-specific results of bulk density measurements (a low density may imply a large fraction of voids, but it doesn't specify whether the voids are microscopic or macroscopic in scale, and there is a wide range of inherent densities of materials of which small bodies are composed, at least spanning the range from ice to nickel-iron).

5. Geology

The first small bodies to be closely examined by spacecraft were the two moons of Mars. The distributions of craters, smooth areas, and cracks differ between the two. But it is difficult to generalize from such bodies buried deeply within the gravity well of Mars to the dominant populations of small bodies in heliocentric orbits. For example, ejecta from impacts on Phobos and Deimos enter "dust belts" encircling Mars that tend to reaccrete rapidly onto those satellites. Many satellites of the outer planets were imaged, generally at rather coarse resolution for the smaller ones, by the two Voyagers; a few, like Miranda, which presents an odd appearance, were seen at fairly high resolutions. Additional images have been obtained more recently by Galileo and Cassini. Ignoring the larger, planet-sized moons, one can nevertheless say that a reasonable geologic diversity is evident among many of these bodies, although impact craters are ubiquitous except on a few exceptional portions of a few bodies like Enceladus.

The first two heliocentric bodies to be seen close-up were the S-type, main-belt asteroids Gaspra and Ida (and Ida's moon). Geologically, they appear rather different, with Gaspra displaying an angular shape, perhaps configured by remnant "facets" of older large impact scars, and an under-saturated population of small craters while Ida's craters resemble much more closely the familiar saturation-cratered terrains of the Moon. Subsequent close-up imagery of other kinds of bodies, including C-type asteroid Mathilde, NEA Eros, and several comets, continues to reveal surprising diversity among them. Mathilde is dominated by huge craters on the scale of Mathilde's own radius. Global high-resolution imaging of Eros revealed a surprising dearth of small craters, an abundance of boulders, and wholly unexpected smooth regions colloquially termed "ponds". It is noteworthy that the surface of the much smaller NEA Itokawa, imaged by the Hayabusa spacecraft, strongly resembles Eros (smooth areas, numerous boulders, nearly craterless) at the same resolution (Fig. 6).

Although images of comets Halley and Borrelly were of too coarse resolution for detailed geological analysis, the higher resolution Stardust images of comet Wild 2 reveal a jagged, pock-marked surface apparently unlike the other comets. Deep Impact's images of comet Tempel 1 shows geological features, including a couple of smooth plains, very different from Wild 2; preliminary mosaics of images taken from the D.I. impactor itself, just before it struck, are shown in Fig. 7.

Additional spacecraft missions, either contemplated or already underway, may extend our examination of small bodies by focusing on *in situ* and sample return science. These approaches will surely begin to connect the "hand-sample" science of meteoritics to the "field geology and geophysics" of asteroids being revealed by fly-by and orbital missions, both of which may ultimately be extrapolated to the countless members of these popu-

Figure 6. NEA 25143 Itokawa, as imaged by the Hayabusa spacecraft in early October 2005. The 0.5 km diameter asteroid exhibits rocks and boulders, as well as smooth areas, but essentially no impact craters. Courtesy of JAXA.

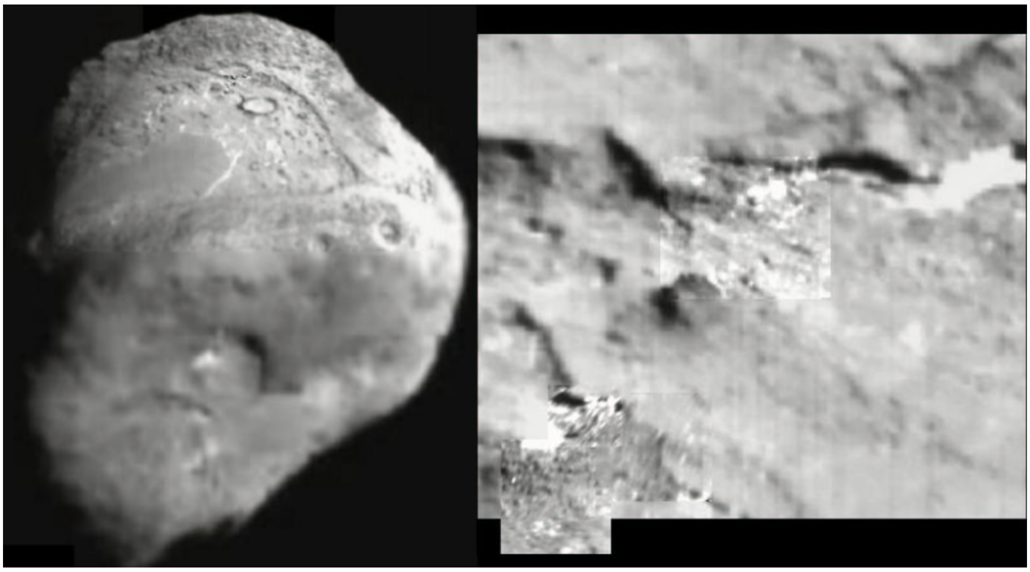

Figure 7. Preliminary mosaics of images taken by the Deep Impact impactor before impact. The nucleus of comet Tempel 1 is shown on the left. A mosaic of the final images is on the right; it is about the size of the uppermost of the two prominent craters near the top of the full-nucleus image, and is centered just below the lower part of that crater's rim.

lations observable only from a distance by astronomical techniques. Our appetite for the next phase of small body studies has been whetted by the NEAR Shoemaker mission, which actually landed successfully on Eros, although it was not designed to do so. Analysis, during the five years since the NEAR mission ended, of its comprehensive orbital remote-sensing data (especially from the X-ray spectrometer) has conclusively demonstrated that Eros is an L or LL type of ordinary chondrite. Of course, Eros is not the original parent body of these meteorites, since it is in a very transient orbit in the inner solar system, but the linkage appears largely to resolve the long-standing controversy about the nature of most S-type asteroids. Of course, S-type asteroids volumetrically constitute a tiny fraction of the main belt, which is dominated by low-albedo objects (C-, P-, and D- types). And it is presumed that we do not yet have terrestrial samples, other than IDPs, of the more volatile rich and presumably generally less-altered bodies from the colder, more distant reaches of the solar system. So the geology of small bodies is a topic in its infancy.

6. Relationship of Physical Properties to Other Issues

While this review of the meta-topic of small-body properties has attempted to summarize major elements of the study of physical properties of small bodies, it is appropriate to view physical properties in the context of small-body science as a whole. The other major meta-topic of this ACM meeting concerns the dynamics of small bodies. There is an intricate linkage between the two. I briefly consider four kinds of ways in which the topics are related.

First, dynamical processes *cause physical properties* to be the way they are. For example, it is becoming increasingly clear that effects related to the Yarkovsky Effect play a fundamental role in determining the spins and axis orientations of asteroids. Tidal interactions of small bodies with planets and with the Sun cause distortions, disruptions, and even disintegrations. Collisions and catastrophic disruptions, and the dynamics of ejecta, create families, rubble-pile structures, and satellites (determining initial spins and sizes). Second, physical properties help *elucidate dynamics*. For example, colors have helped define dynamical families of asteroids. Yarkovsky/YORP effects depend on albedo, shape, thermal inertia, spin, density, etc. Third, dynamical analysis can help *determine physical properties*. Mass, hence density, is determined by analysis of gravitational perturbations or from the orbits of satellites. I have already described how spins may, or may not, define whether a body is a rubble pile or a monolith. Non-gravitational forces constrain attributes of the physical properties of cometary nuclei. Fourth and finally, dynamical analysis helps us *study physical processes*. Precise, specific ages for asteroid families derived from dynamical analysis help us determine the rates of physical processes such as space weathering. The ways that small body perihelia evolve permit us to better understand volatilization of surface materials.

There are actually practical implications of physical properties of small bodies. Astronomy is a prime arena of ivory-tower science, solar physics being the chief exception (e.g. manifestations in electrical grids on Earth). About the only other topic in astronomy with potential practical effects are asteroids and comets. They present both a hazard, from their rare but potentially devastating impacts, and the most accessible sources of resources for use in space. Both in terms of "handling" a dangerous NEA in order to divert it from Earth impact and in terms of mining materials for use in space, the physical properties – especially surface and near-surface properties – are fundamental. How can one anchor onto the surface of a nearly gravitationless body...if it is made of solid metal, if it has a regolith, or if it has the consistency of "talcum powder," a term used in early descriptions of the character of comet Tempel 1 inferred from Deep Impact?

Consider the case of 320 m diameter 99942 Apophis, which at this writing has a 1-in-6000 chance of striking the Earth on 13 April 2036 by passing through a "key-hole" during its exceptionally close pass by Earth on 13 April 2028. Whether it passes through the keyhole depends, in part, on physical properties that determine how the Yarkovsky Effect will modify its trajectory. Its surficial properties would constrain our ability to attach a device (e.g. low-thrust ion engine) to its surface. Internal properties may affect how it responds to accelerations, explosions, or other approaches to averting the impact. Indeed, its physical properties will determine how it responds to Earth's strong tidal forces as it passes by below synchronous satellite altitude in 2028; calculations suggest that there may be dramatic changes to its spin state and perhaps internal readjustments, especially if it is a rubble pile. Even the consequences of an Earth impact are affected (although in a secondary way) by its density and structure; a tsunami, threatening the west coast of North America, roughly equivalent in magnitude to the South Asian tsunami of 2004, is envisioned if it were to strike in the Pacific Ocean, but detailed consequences might depend on Apophis' physical properties.

7. Concluding Themes

As I discussed at the outset, small bodies are difficult to study. They are small, distant, and extremely numerous – and their evident diversity means that seeing one is *not* like seeing them all. Many of them are dark and/or dimly illuminated. Some of them, like Apophis, are in resonant orbits that render them invisible much of the time. The past decade has seen revolutionary improvements in search techniques and in instrumentation that reveals physical properties even from our distant location on or orbiting Earth. But we are only scratching the surface. Whole new populations of small bodies may yet be discovered and studies of physical properties of outer solar system small bodies will continue to be exceptionally challenging.

There are subtler issues, however. Our remote-sensing observations, whether obtained from telescopes or spacecraft, almost all pertain to the very uppermost surfaces of small bodies. Virtually the entire volumes of these bodies remain hidden from our view. The presumption may be valid in many cases that surfaces are made of roughly the same materials as the interiors, but it remains a presumption. Beyond that, especially for these airless bodies, the surfaces that we remotely sense are the very same surfaces struck by solar wind particles, micrometeorites, ultraviolet and higher energy radiation, etc. that damage or modify grains on the immediate surfaces. So what you see is often *not* what you "get". Either we understand these space weathering effects and develop reliable theories of regolith processes, for example, or we extrapolate from surfaces to internal depths at our peril.

Another aspect of small bodies in which our intuition may fail us concerns their nearly gravity-free environments. Geologists, in particular, often interpret spacecraft data from other bodies in a "comparative planetological" approach, in which analogies from familiar terrestrial experience play a large role. Geology at almost zero-g can be very different. Transitioning from astronomical to geological perspectives of small bodies may be more difficult than it has been in the cases of the terrestrial planets.

I expect more surprises as we really learn about the structures of small bodies: their porosities, densities, strengths, etc. Why do so many comets disintegrate and vanish? Are they like "dust bunnies"? What are appropriate analogs for materials that accreted slowly and have never been heated or compacted? Styrofoam? Talcum powder? (And how does talcum powder behave at near-zero g? What are the roles of electrostatic or magnetic forces?) Are M-types stripped metallic cores? Spectral evidence suggests that many are not...then what are they? One issue we have to contend with is the enormous bias we have inherited from the physical characteristics of meteorites in our collections. The vast majority of even asteroidal materials, let alone cometary fragments (which have the added problem of higher velocity impacts), may not ever make it through Earth's atmosphere for collection. If most small body materials are granular, weak, or underdense, then we would have no direct evidence that they exist.

Yet another question about small bodies is "what are we missing?" Despite considerable efforts to locate additional Plutos, years went by before 2003 UB313 was discovered. It is in an unusually inclined orbit. To what degree are search programs biased, for example by competitive pressures to find "the most" objects, or to name them, etc.? It is difficult to suppress our preconceptions. Witness the radically different structures of extra-solar planetary systems, with their intra-Mercurian Jovian planets. Let us not prematurely rule out vulcanoids, or vast clouds of Trojans around other planets, or satellites of small bodies in places we haven't found them yet, just because they haven't yet been found. Louis A. Frank's mini-comets do not exist, but other populations of hypothetical small bodies (e.g. interstellar comets), or even populations never imagined, may yet exist and await discovery.

Finally, the science of extra-solar small bodies already is underway, even if we can never imagine studying an individual body at such an enormous distance. Asteroid belts, Oort clouds, and planetesimal swarms have already been interpreted to exist around some other stars, primarily from infrared astronomical detection of disks. The statistical properties of such disks may prove to be powerful counterpoints against which to consider small bodies in our own solar system.

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