Interiors of small bodies: foundations and perspectives

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Received 29 November 2002; accepted 18 March 2003

Abstract

With the surface properties and shapes of solar system small bodies (comets and asteroids) now being routinely revealed by spacecraft and Earth-based radar, understanding their interior structure represents the next frontier in our exploration of these worlds. Principal unknowns include the complex interactions between material strength and gravity in environments that are dominated by collisions and thermal processes. Our purpose for this review is to use our current knowledge of small body interiors as a foundation to define the science questions which motivate their continued study: In which bodies do “planetary” processes occur? Which bodies are “accretion survivors”, i.e., bodies whose current form and internal structure are not substantially altered from the time of formation? At what characteristic sizes are we most likely to find “rubble-piles”, i.e., substantially fractured (but not reorganized) interiors, and intact monolith-like bodies? From afar, precise determinations of newly discovered satellite orbits provide the best prospect for yielding masses from which densities may be inferred for a diverse range of near-Earth, main-belt, Trojan, and Kuiper belt objects. Through digital modeling of collision outcomes, bodies that are the most thoroughly fractured (and weak in the sense of having almost zero tensile strength) may be the strongest in the sense of being able to survive against disruptive collisions. Thoroughly fractured bodies may be found at almost any size, and because of their apparent resistance to disruptive collisions, may be the most commonly found interior state for small bodies in the solar system today. Advances in the precise tracking of spacecraft are giving promise to high-order measurements of the gravity fields determined by rendezvous missions. Solving these gravity fields for uniquely revealing internal structure requires active experiments, a major new direction for technological advancement in the coming decade. We note the motivation for understanding the interior properties of small bodies is both scientific and pragmatic, as such knowledge is also essential for considering impact mitigation.

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Keywords: Asteroids; Comets; Interiors

1. Introduction

Asteroids and comet nuclei (which we collectively refer to as small bodies) are emerging from the domain of astronomers into the realm of geology and geophysics. Spacecraft have provided resolved images of 1P/Halley, 951 Gaspra, 243 Ida, 253 Mathilde, 433 Eros, and 19P/Borrelly while radar observations are allowing shape modeling for dozens of small near-Earth objects (NEOs) and main-belt asteroids. Thus, these bodies are no longer just “star-like” or dust/gas obscured points of light viewed through a telescope. They are becoming individual worlds that beg for detailed exploration, explanation, and geological/geophysical understanding.

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As our knowledge base and understanding of shapes and surface characteristics advance, we are naturally drawn to “deeper” questions about the nature of the interior. Exploring and understanding the interior properties of small bodies is challenging from a classical geophysics perspective because so many different formation and evolutionary processes are at work. For example, objects that we consider to be “asteroid-like” formed in the more dense and hotter regions of the solar nebula inside the orbits of the newly forming giant planets. More “comet-like” small bodies acquired increasing volatile content as they formed in the region of the giant planets themselves and even far beyond. Superimposed on this diversity of formation environments and compositions is the relentless role of collisions. Here again a diversity of outcomes is likely the rule. In the asteroid belt collisional outcomes may be the single most dominant factor in controlling present day interior structures. At further heliocentric distances, collisions can dictate not only the interior structure but can also modify the original pristine state of the volatile content.

The challenges and the complexities of understanding small body interiors relative to the vacuum of our knowledge is what draws us to their scientific study. We also recognize that the long-term survival of human civilization may also depend on our having sufficient knowledge of how to mitigate a potential impact. In these early stages, learning about these objects is the same thing as doing something about them. Herein, we focus on the scientific motivation for their study and organize our review by posing a set of fundamental science questions to serve as a basis for assessing the current foundation and limits of our knowledge as well as to identify prospects for advancement.

1.1. Terminology

Alas, in any emerging field there is often a proliferation of terms that are used to describe similar phenomena or structures. In an effort to promote convergence of terminology, we adopt (and extend, with new terms in quotations) the lexicon proposed by Richardson et al. (2002) to describe the full range of possible interior states. Monoliths are essentially wholly intact units having a strength that is effectively equal to the tensile strength (maximum force per unit area that a body can withstand before fracture or rupture occurs) of its constituent material. Bodies that are not monoliths are referred to as aggregates whose categorization is described in terms of decreasing coherence (increasing number of boundaries or interfaces between units) and increasing bulk porosity. A “primitive aggregate” describes a body for which the lack of connection between different units is the result of its primordial formation process, rather than the result of fractures propagated by collisions. Fractured bodies have a sufficient number of cracks or faults that their tensile strength is reduced, yet their original structure remains intact. Shattered bodies have interior structures that are even more dominated by an abundance of joints and cracks. The relative tensile strength (defined as the effective tensile strength divided by the tensile of its constituent material) may approach zero. As in the case of fractured bodies, the original structure may remain mostly in place. Bodies that are shattered with rotated components have been thoroughly fractured (by collisions or tidal stresses) such that original units within the interior have been somewhat displaced and reoriented. Rubble piles are bodies that have been completely shattered and reassembled, where the new structure may be completely disorganized relative to the original. If the units somehow become attached or cemented to one another, the resulting structure is a coherent rubble-pile. (More generally, Richardson et al. denote any aggregate structure that undergoes any re-attachment or cementing as a coherent aggregate.) A “thermally modified primitive aggregate” might also increase or decrease in bulk porosity and in effective strength. An increase in the strength of contact between units could be described as a “lithified primitive aggregate.”

2. Science questions

For small bodies, the answers to fundamental science questions can be greatly dependent on factors such as: size, composition, presumed formation location, homogeneity of the original body (in terms of both composition and structure), thermal history, collisional history, and dynamical (orbital) history. Here, we frame our science questions in a sequence that principally addresses objects from larger to smaller sizes, but in reviewing current answers and providing perspective we attempt to take into account all of these factors. Fundamentally we wish to understand in what cases “primitive aggregates” may still be found where the transitions may reside between bodies that have been and have not been affected by “planetary processes.” We also wish to know how to distinguish between those objects, unaffected by planetary processes, which retain primitive properties in their interior, i.e., “accretion survivors,” and those that are hopelessly modified by 4.5 billion years of collisional and thermal evolution. In order to achieve this, we take it as a given that the modification processes and their effects must be well understood and therefore intensively studied.

2.1. At what size scales do “planetary processes” shape internal structure?

Loosely, we define “planetary processes” as those that allow some degree of internal differentiation which may not necessarily culminate in core formation. Within the outer solar system, it remains only speculation on the degree to which the largest trans-Neptunian objects (TNOs) may have undergone some differentiation. Pluto–Charon have the most precisely determined diameters and densities (2350 ± 50 km, 1250 ± 50 km, 1.99 ± 0.07, and 1.66 ± 0.15, respec-
atively; Tholen and Buie, 1997) and models for their interiors (McKinnon et al., 1997) suggest some differentiation into a rock/ice core. The possible differentiation of Pluto (and Charon) may also be the result of the formation and tidal evolution of this binary system. We note with excitement that Pluto–Charon are not unique as binary objects in the outer solar system (e.g., 1998 WW31; Veillet et al., 2002).

The upper size limit for which volatile-rich objects have likely undergone any substantial differentiation remains unconstrained. (Kissel et al., 1986) did not find any evidence of anomalous $^{26}$Mg in comet 1P/Halley, which may simply indicate that comets formed after all the initial $^{26}$Al had disappeared. Measurements of the ortho- to para-hydrogen ratio in water lines and other hydrogenated species suggest that comets have been preserved at low temperatures, consistent with the analysis by Lewis (1971) that shows that objects smaller than 300 km should have internal temperatures of less than 25 K. The presence of the $S_2$ molecule is also considered as a clue that comet nuclei have been thermally preserved at very low temperatures.

Apart from primordial heating that may be experienced by volatile-rich bodies, substantial thermal evolution (and consequently internal evolution) can occur as a result of orbital evolution. The outcomes can be as fundamentally important as the classical case of planetary differentiation. For example, a body dynamically evolving from the Kuiper belt into an orbit typical for a Jupiter-family comet experiences both a seasonal thermal wave due to each perihelion passage, which ultimately couples to a secular increase in the interior temperatures. The details of this process are very sensitive to unknown parameters of cometary nuclei, but representative calculations suggest that the seasonal thermal wave propagates tens of meters below the surface (e.g., compare Podolak and Prialnik, 1996; Benkhof and Boice, 1996 for the case of P/Wirtanen’s orbit). These are the depths to which gaseous transport is expected to take place assuming appropriate porosity. Below this depth, temperature gradually increases to come into equilibrium with the temperature expected for a given semi-major axis but thermal conductivity in these layers is slower and the time scale might well be longer than the time scale for dynamical evolution. This thermal evolution can lead to differentiation of ices, phase changes in the ices (most notably a phase change from amorphous to crystalline ice at temperatures around 130–150 K), and formation of mantles due to the release of volatiles (Weissman 1990).

We also point out that thermal stresses can lead to the loss of the body. Weissman (1980) found that 10% of dynamically new comets from the Oort cloud split, while 4% of returning comets and 1% of short period comets split during any given encounter. These breakups tend to occur long before perihelion, so there is no known mechanism for explaining these random splitting events. Samarasinha (1999) has proposed expanding volatiles, propagating from the sun-warmed exterior to the interior of a coarsely porous comet, in order to explain the disruption of comet LINEAR (C/1999 S4) into a power-law distribution of fragments (cumulative slope 1.74; Mäkinen et al., 2001) prior to perihelion.

Thermal stresses may also affect asteroids, but in a different way. Besides the radiation forces (Yarkovsky and YORP) which provide gentle non-gravitational thrusts and spins to asteroids, as discussed (above/below) thermal expansion was postulated by Dombard and Freed (2002) as a mechanism for the production of pervasive fractures on Eros, as it moved from its place of origin in the main belt into near-Earth space.

For bodies formed in the transition region between Mars and Jupiter (classically the asteroid belt), our insights into differentiation processes are substantially more enhanced through the availability of meteorite samples. Cooling rates from iron meteorites generally suggest bodies in the diameter range of about 100 km and larger (though some rapid cooling rates suggest sizes down to ~ 20 km) were capable of undergoing substantial differentiation in the early solar system (Haack et al., 1990; Mittlefehldt et al., 1998). Vesta, with a 500 km diameter and basaltic (igneous) crust (McCord et al., 1970), appears to be the only “intact” surviving differentiated parent body within the asteroid region. Spectroscopic colors, albedos, and radar reflectivities (Gaffey et al., 1989; Ostro et al., 2000) are all consistent with objects such as 16 Psyche and 216 Kleopatra being 100–200 km remnant iron cores of subsequently demolished parent bodies.

Not all large asteroids appear to have undergone substantial differentiation, with the nearly 1000 km diameter Ceres displaying spectral and albedo characteristics consistent with a relatively primitive (unheated) class of carbonaceous chondrite meteorites (Gaffey et al., 1989). Ceres and other similarly common “C-class” objects in the outer regions of the asteroid belt may have accreted slowly enough for radiogenic heat (principally from $^{26}$Al) to have been adequately dissipated without differentiation. Particularly important for Ceres may have been the increasing abundance of volatiles with increasing heliocentric distance. These additional volatiles may have been essential for quenching (through the heat of fusion for water ice) the differentiation process within Ceres (Grimm and McSween, 1989, 1993). Certainly if accretion time scales and/or quenching proved sufficient to arrest differentiation within the outer regions of the asteroid zone, “single” (non-binary) Trojan asteroids and TNOs also would be expected not to be differentiated.

2.2. Which bodies are “accretion survivors”, i.e., bodies whose current form and internal structure are not substantially altered from the time of formation?

Here, we seek to understand which individual bodies or classes of bodies are observable today that provide actual windows back to the shapes and internal structures created
in the early solar system. In other words, are there currently observable remnants of the final outcomes of accretion?

As we discuss in the following section, it seems likely that virtually all asteroids have been thoroughly shattered by collisions over the age of the solar system. Intriguingly and perhaps counter intuitively, collisions that severely fracture the interior (without causing total disruption) may be essential for a body’s long-term survival. While Ceres, by virtue of its size and Vesta by virtue of its thermal evolution may be best termed as surviving “protoplanets”, asteroids in the intermediate size range (a few hundred km) are most likely shattered survivors from the time of their accretion. Evidence abounds that such survival is stochastic, as evidenced by the widespread number of asteroid families that are almost certainly the remnants of catastrophically disruptive collisions of parent bodies having originals sizes of less than 100 km to greater than 200 km (Hirayama, 1918; Zappala et al., 2002; Tanga et al., 1999).

Trojan asteroids at the L4 and L5 Lagrange points of Jupiter have long been suspected of being primordial remnants retaining structures from the time of their formation because of their dynamical isolation and their inferred (from extreme lightcurve variations) elongated or possible contact binary shapes (Cook, 1971; Hartmann and Cruikshank, 1978; Cellino et al., 1985). Intuitively, the “binary argument” is that a large pair (as opposed to “just” a primary with a small satellite) is easiest and most likely to form in an early accretion period when relative encounter velocities are low. Any substantial amount of subsequent collisional evolution is likely to disrupt or dislodge the binary pair, making binaries a telltale signature of survivors from the accretion epoch. If this logic holds, then the discovery by direct imaging showing the L4 object 617 Patroclus to be a ∼ 100 km binary pair (Merline et al., 2001) supports the presumption of the largest Trojans being accretion survivors. This survivor size range inferred from binaries is consistent with Trojan collisional evolution and population size distribution models by Marzari et al. (1997), who estimate that this transition occurs around 50–100 km.

Perhaps of greatest interest to planetesimal studies is identifying the smallest objects that may be accretion survivors. While we are observationally challenged to resolve or even detect km-sized bodies in the Trojan region, Kuiper Belt, and Oort cloud, comets in the inner solar system are in fact small-sized outer solar system representatives that are close enough for study. Their inferred strengths, or lack thereof, within their internal structure provides the clearest evidence for most comets being well described as accretion survivors having a “rubble-pile” structure (Weissman, 1986). From its tidal encounter with Jupiter, prior to its plunging demise, the separation of the components within comet D/Shoemaker-Levy-9 has given the basis for estimating not only its internal strength (as the maximal tidal stress at periapse was no greater than 1000 bars), but also its density and probable structure (Asphaug and Benz, 1994, 1996). Similarly, a low interior strength for comet LINEAR (C/1999 S4) is suggested by the breakup of this comet far from any massive body. The presence of fragments of sizes of order 50–100 m in diameter indicates that this body entered the inner solar system as a surviving accretion aggregate.

Thermal evolution of comets, primarily as a result of perihelion passages, complicate the inferences we may make on their formation process and interior structure from remote-sensing observations (e.g., Keller et al., 1986; Bell et al., 2000) or direct impact experiments (A’Hearn, 1999). The thermal skin depth is related to the rotation period of the nucleus, its thermal conductivity and its density. For pure water ice, the skin depth is only 20 cm and is probably lower in reality given the presence of an insulating layer of porous dusty material and not ice. The presence of a mantle probably makes the comet stronger against collisional disruption perhaps by providing an additional layer structure to render even more inefficient the propagation of impact shock waves.

2.3. At what characteristic sizes are we most likely to find: rubble-piles, substantially fractured (but not reorganized) interiors, and intact monolith-like bodies?

Understanding the complex interplay between strength and gravity is the basis for answering this question, where the answers are not necessarily intuitive for inhabitants of a gravity-dominated planet. In some ways, a small body may be thought of as a planet having a lithosphere extending into its deep interior. At present, we are generally left to infer the nature of this lithosphere through measurements of the bulk density, through observations of collisional outcomes (both in the laboratory and asteroid families), through observations of the consequences of tidal, rotational, or thermal stresses (cometary breakups), and through analytical and numerical simulations. The current wisdom on the overall collisional evolution of the asteroid belt (e.g., Davis et al., 1989, 1994, 1999, 2002) is that all sizable bodies are thoroughly shattered (Melosh and Ryan, 1997). What eludes us is an understanding of the arrangement or coherency of these interiors. Whether TNOs are shattered or not is less clear. Although collisions are as frequent in the inner Kuiper belt as in the asteroid belt, they generally occur at significantly lower velocities and thus are more likely to have their effects confined to the near-surface layers. Since the internal structure is also unknown, the threshold energy for “shattering” throughout is also unknown. Davis and Farinella (2001) argue that “many” of the TNOs are shattered.

Bulk density measurements require a determination for both the mass and the volume, parameters that have been historically difficult to determine. Classically, asteroid masses have been determined by their interactions with one another (e.g., Schubart and Matson, 1979; Viateau, 2000) while their volumes are inferred from direct measurements and from modeling of their albedos and diameters (e.g., Tedesco et al., 1992). Apart from using spacecraft in flyby mode to
Britt et al. (2002) find their solutions distinguishable into three rough groups. The first group, having effectively zero macroporosity is comprised by the three largest asteroids: Ceres, Vesta, and Pallas. With diameters near 1000, 500, and 500 km, respectively, these bodies appear to have sufficient self-gravity to eliminate any significant macroporosity. Their inferred nature as protoplanets surviving over the age of the solar system certainly implies they have experienced substantial collisions such that their interiors are either fractured or shattered (in the lexicon of Richardson et al.). However, the lack of macroporosity and the preservation of Vesta’s basaltic crust imply that these largest bodies are not rubble-piles.

A second group of objects has macroporosities ranging from 15% to 25% over a diameter range from about 30 to 300 km. Eros, the most thoroughly studied small body to date, falls in the middle of this range (macroporosity ~ 20%; Wilkison et al., 2002) and thereby provides the best opportunity for insight. All indications are that Eros is a heavily fractured or shattered body, but not one that was previously disrupted and reaccumulated as a rubble pile. Eros appears to have a highly homogeneous structure because the offset between the center of mass from the gravity and shape models only amounts to 30–50 m. (Miller et al., 2002; Zuber et al., 2000; Thomas et al., 2002). Even with its irregular shape (diameter dimensions ranging from 9 to 32 km) and relatively fast 5.27 h spin period, Eros’ interior is not in tension due to rotation or precession wobble as the spin axis and principal body axis are aligned within 0.02° (Miller et al., 2002). Even though the interior is likely heavily fractured or shattered, surface expressions of structural features (ridges, grooves, etc.) demonstrate that still Eros retains some significant degree of tensile strength (Prockter et al. 2002). Other evidence for structural coherence of Eros includes its high mean density, twisted platform, clustered regions of surface slopes above the angle of repose, subdued or missing crater rims, and the continuity of long grooves and fractures (Zuber et al., 2000).

A third group of objects, ranging in diameter between about 50–250 km (setting aside Phobos and Deimos, whose residence within the Mars gravity well may make them special cases), have macroporosities in excess of 30%. These appear to be the best candidates for “rubble-pile” objects that have been substantially disrupted and reaccumulated such that their original internal arrangement has undergone moderate or substantial displacement. Most bizarre is the inferred > 70% macroporosity for 16 Psyche (Vitaeau, 2000). Psyche, a ~ 250 km diameter object, has an M-type reflectance spectrum that is interpreted as being analogous to very strong and very dense (7.4 gm cm⁻³ grain density) iron meteorites. A very high radar reflectivity for Psyche (Magri et al., 1999) provides the highest weight evidence for an iron meteorite analog. A composition of such extremely strong material may be essential for maintaining such a high porosity, where for a value > 70% the volume is dominated by voids greatly exceeding the abundance of holes in Swiss
cheese. Belskaya and Lagerkvist (1996) note that there are possibly other compositional interpretations for M-type asteroids. If Psyche’s actual grain density is substantially lower than 7.4 g cm$^{-3}$, the inferred value for the macro-porosity would be correspondingly lower. High material strength may not be a prerequisite for achieving 40–50% macro-porosity values, as three of the other four objects in this Britt et al. grouping have C-type spectral properties. These objects are interpreted as likely analogs to weaker carbonaceous chondrite meteorites. 253 Mathilde (50 km diameter) is a prototype example with an estimated macro-porosity near 40%. Weaker strengths for carbonaceous-like material may contribute to their likelihood of being substantially disrupted into rubble-pile structures.

There appears to be no characteristic size range (within the present sample) for a transition between fractured/shattered objects and bodies whose rearranged interiors classify them as rubble piles. It appears that stochastic collision history and basic composition play a greater role than size. However, a characteristic size does seem to be revealed between shattered/fractured bodies and monoliths having tensile strengths. Asteroid lightcurve studies pushing to progressively smaller sizes through measurements of near-Earth objects (e.g., Pravec et al., 2000) have revealed a set of remarkably fast rotating objects with periods as short as a few minutes (as opposed to $\sim 2$ h for the previous short period record). An analysis by Pravec and Harris (2000) finds a transition near 100 m where fast rotations (periods shorter than $\sim 2$ h) are rare or absent for objects larger than $\sim 100$ m, although the mean tension $\sim R^2 \rho \omega^2 - G \rho$ across their plane of maximum stress is generally miniscule. This transition may represent a barrier where $> 100$ m bodies have such a high degree of fracturing (and a corresponding lack of tensile strength) that self-gravity is the dominant force for their coherency. This transition size is also found in numerical simulations which show that large remnants from a catastrophic disruption of a larger parent body are no longer monolithic fragments once the latter exceeds 100–300 m in radius (Benz and Asphaug, 1999).

Below $\sim 100$ m almost all objects observed to date rotate faster than this limit, requiring their internal structure to be governed by their tensile strength. But we note that this tensile strength still may be incredibly weak: for the $\sim 11$ min period and $\sim 30$ m diameter of 1998 KY26 (Ostro et al., 1998) the required tensile strength is $\sim 300$ dyn cm$^{-2}$ (assuming $\rho \sim 1.3$ g cm$^{-3}$ for this C-type), orders of magnitude weaker than snow. Nevertheless, it appears that $\sim 100$ m may represent a characteristic size transition between “intact” strength dominated monoliths and even weaker (effectively strengthless?) fractured/shattered or rubble-pile bodies predominantly held together by gravity.

3. Perspectives

Having set out a fundamental set of science questions and having briefly outlined our current understanding, we continue by examining ways in which we are likely to further improve our answers over the time scale of a decade or more. Most interesting, of course, are the findings we cannot predict—findings which completely revamp our current understanding and dramatically change our science questions and perspectives. We are well advised not to be presumptuous in our current knowledge. For example, an accounting of the difficulties and uncertainties arising in measuring a mass, deriving a volume, and interpreting a basic composition highlights the challenge for determining a bulk porosity as a starting point for inferring interior structure. To our advantage, however, we have a number of vantage points for trying to improve our understanding of small body interiors.

3.1. Outside looking in—the view from afar

Measuring and defining shapes and spin states, detecting binaries and satellites and measuring their orbital dimensions and periods, and inferring parent body interiors from the collisional remnants within asteroid families all provide opportunities for insights from a distant perspective. As discussed in the previous section, the $\sim 100$ m limit against the spin up of small bodies may be the most fundamental insight gained by rotation studies. The rate at which an object in a non-principal axis or “excited” state loses its rotational energy—i.e., the rate at which it relaxes toward its ground state (pure spin) is a strong function of the size of the object (Burns and Safronov, 1973) depending on the inverse square of an effective radius. Thus new insights may perhaps be gained through unveiling a boundary size below which excited spin predominates. The clearest signature of excited spin in lightcurve observations is the simultaneous presence of two independent periodicities. Unfortunately, nature is not always kind and the independence of the periodicities is not always clear. For example, in the case of 1P/Halley the periodicities seen in the lightcurve are, to the limits of accuracy, all harmonically related to the 7.4 day periodicity. Our certainty about the excitation of Halley’s spin state comes from spacecraft observations of the orientations of the nucleus at the Vega and Giotto encounters, not from the lightcurve. If we depended only on the lightcurve information it is almost certain that we would have convinced ourselves by now that Halley spin was fully relaxed with a 7.4 day period. Numerical calculations show why this can be the case. As the spin state evolves for an elongated object torqued by jet activity it is found that the evolution tends to get hung up whenever the precession and rotation periods in the spin become commensurable, i.e., harmonically related. In order to make full use of lightcurve information to analyze spin states of cometary nuclei, simultaneous information on nucleus shape and the distribution (i.e., coma morphology—orientations and curvatures of molecular and dust jets) and strength of coma activity is also required. For asteroidal bodies, the boundary
size and rotation rate below which such “tumbling” occurs provides a measure of the material properties of interiors, primarily rigidity and specific dissipation factor \( Q \). Still to be unraveled is the mystery of a separate population of very slow rotators (Harris, 2002). Functionally, this population fits a distribution like \( N(< f) \propto f \), rather than the 3D Maxwellian form that fits the main population of spin rates within the asteroid belt (Pravec and Harris, 2000). Insights into the interior structure and tidal dissipation capabilities might be gleaned if this subpopulation is a remnant of massive unstable binaries that gravitationally disintegrated, in the process using up most of the primary’s spin energy.

After decades, even centuries, of speculation and dubious claims, asteroid satellites (binaries) have at last gained a firm footing. As referenced above, binaries have been found among practically every class of small body, including NEOs, main-belt asteroids, a Trojan, and several TNOs. The holy grail within binary systems, of course, is to have sufficient measurements to accurately solve for the mass of the system (the most difficult step toward a density determination). In many cases, long-term measurements with large aperture telescopes (often utilizing adaptive optics system) are essential for yielding the prize of well-determined orbital parameters. Precise determination of the total volume of the bodies (allowing for the presence of concavities) is also a challenging step toward achieving density determinations. Given the rate at which new satellites and binaries are currently being discovered (e.g., Veillet et al., 2002 estimate that 1% of TNOs may be binary), over the next decade the greatest growth in the number of available density measurements will come from this area. Because the uncertainties that make precise density determinations difficult will persist, analyses for inferring interior properties (such as the rigidity parameter \( Q/k_2 \)) will be best accomplished on a statistical basis using a large sample.

Still to be unraveled, or even confirmed, is the appearance that the “average” properties of binaries in different orbital regions differ remarkably. NEO binaries tend to have similar-sized components, with moderate orbital separations. TNO binaries are likewise close to equal sized, but with huge orbital spacings. Main-belt asteroid satellites tend to be smaller relative to their primaries (with one remarkable exception, 90 Antiope, that is a nearly equal mass, nearly contact binary). One might ascribe these differences to observational selection effects (e.g., only nearly equal sized, widely spaced binaries could possibly be detected in the TNO region). However, if main-belt binary statistics were like either NEO or TNO statistics, binary asteroids would have been discovered a century or so ago from regular telescopic observations. Thus, some differences must be real, and therefore call for explanation. We are only just beginning to have a sufficient number of examples to attempt generalizations as to mechanisms of formation and evolution. At the moment we can offer only speculations to stimulate new insights into the formation and evolution of these bodies with implications for interior structure. These insights include:

- The greater relative abundance of NEO binaries may be the result of tidal disruptions (à la comet Shoemaker-Levy 9). If correct, this argues that many NEOs may have very weak rubble-pile structures that have been formed in the recent solar system.
- Main-belt binaries may be formed by collisional processes. A satellite such as Dactyl might plausibly have started out as a clump of unescaped ejecta from a major impact, with the orbit circularized and expanded by tidal dissipation before it could chance to reimpact the primary. Such an accumulated ejecta process for forming satellites would explain why satellites of main-belt asteroids tend to be small compared to their primary.
- TNO binaries may rely on the solar tide to provide the “second burn” to put collisionally disrupted components into orbit about each other. In any case, the huge dimension of the range of stable orbits is such that very little subsequent (tidal) evolution should have occurred.
- Time scales of tidal evolution may provide constraints on internal properties of rigidity and energy dissipation, and/or time since formation.
- The shape, spin and density of some asteroids (best determined for Eros, but almost certainly also the case for Ida) imply Roche lobes so closely hugging the present surfaces of those asteroids that almost anything dislodged from the surface would likely end up in orbit, at least for a while.
- For larger main-belt binaries, one can plausibly point back to the early solar system to explain their formation. For example, 90 Antiope might have formed as a blob of nearly dispersed ejecta, from some super-large collision, satisfying the Jeans criterion for coalescence into a single gravitationally bound system but with too much angular momentum to exist as a single body. Such a blob would have little choice but to settle into a nearly contact binary configuration of two similar mass components.

Having been produced by the catastrophic disruption of large parent bodies, asteroid families continue to present us with observable outcomes of natural collision experiments. By studying families we are probing the pieces of small body interiors. Still not yet understood in terms of early solar system accretion and differentiation processes is why asteroid families observed to date (Bus, 1999; Cellino et al., 2002) are remarkably uniform in their spectral properties, indicating little evidence for substantial differentiation. This contrasts with the remnant metal core interpretation for large M-type asteroids like 16 Psyche. Burbine et al. (1996) suggest an explanation that for families formed from differentiated parent bodies, the crust and mantle material may have been “battered to bits” over the age of the solar system—but the extent of this “battering” is constrained by their remaining a reasonable chance that Vesta’s basaltic crust has
survived. Probing the spectral properties to smaller and smaller sizes may reveal the missing pieces of disrupted differentiated parent bodies. Indeed the discovery of a small (15 km) basaltic asteroid located far from (and very unlikely related to) Vesta by Lazzaro et al. (2000) may be just the tip of the iceberg for understanding the diverse differentiation history of inner solar system bodies.

More directly related to inferring interior strengths and structures are the size and velocity distributions within families (Cellino et al., 1999; Zappala et al., 2002). In principle these are related to the energetics and geometry of the impact and the strain-rate release of the fragments during the break-up and dispersion process. Tantalizingly, we now view only the final state of this complex process. An additional challenge now being faced is the extent to which the ejection velocities of the fragments (inferred from their orbital displacement from the center of mass) is affected by other process which may spread their orbits. Understanding processes like the Yarkovsky effect (Bottke et al., 2000) have a direct bearing on our being able to utilize the potential information contained within asteroid families. Indeed, the observed size-proper elements relations seen in many families tend to suggest that properties of the original ejection velocity fields of the fragments are still recognizable in present families. In particular, the trend exhibited by the size (or absolute magnitude) versus proper inclination plots is something that is not expected to have been substantially influenced by the Yarkovsky effect.

3.2. Outside looking in—the digital view

Numerically simulating the properties of interiors, in particular their response to impacts, presents a powerful tool for applying and evaluating a variety of physical models. In principle, the simulation of a body’s response to a collision by means of numerical calculations is a straightforward procedure. Once the relevant elasto-dynamical conservation equations have been appropriately transformed into numerical code, initial conditions can be specified and the outcome of collisions computed. The entire procedure can be checked in detail by comparing numerical results to laboratory impact experiments (e.g., Fujiwara et al., 1989; Benz and Asphaug, 1995; Ryan and Melosh, 1998; Ryan et al., 1999). In practice, however, the procedure is considerably more complicated for several reasons: (1) the physics involved may not necessarily be described by simple laws (fractures, phase changes, rheology, etc.). (2) The equations may be difficult to make discrete. (3) The computing power available may not be sufficient to allow for the desired or needed resolution. Applying numerical models to real solar system bodies presents serious challenges, in particular when trying to infer the initial conditions of a body’s interior that have lead to the morphological and/or dynamical properties observed today. We are dealing with a classical under-determined inverse problem that is greatly in need of new constraints that can be best supplied by the types of experiments described in Section 3.4.

Given these difficulties, and while we await measurements providing new constraints, our present task is to understand the properties of classes of models rather than focus on specific details. As an example we can examine how pre-existing fractures and/or porosity on micro- or macroscopic scales affect the overall strength of a body or its ability to transmit shock waves (e.g., Asphaug et al., 1998). One of the most important perspectives these models are giving us is that the effective strength of a body strongly depends upon these characteristics. For example, a body large enough to be in the gravitational regime (greater than roughly 1 km), that is pre-fractured in a small number of pieces without much void between them is weaker (in the sense that it is easier to disrupt) than a similar-sized monolith. On the other hand, the same body thoroughly shattered with large amounts of voids is more difficult to disrupt than the corresponding monolith despite the fact that the shattered body is “weaker” in the sense that it has almost no tensile strength! Thus, “survival of the weakest” may be the rule of the collisional evolution jungle as the principal effect for a shattered and porous interior is to attenuate the stress wave generated in an impact. As a strong shock propagates through a porous target, the energy is inefficiently transferred across the fracture interfaces and pore spaces, effectively localizing the energy dissipation. Compaction may also be very effective in dissipating the energy in a porous target, as proposed for the large craters comparable to the radius of Mathilde (Veverka et al., 1999; Housen et al., 1999). Thus, our current perspective is evolving toward a view that the majority of small bodies are shattered survivors that become increasing difficult to disrupt as sub-catastrophic collisions effectively add strength by adding fractures and by possibly increasing porosity. Stated another way, thoroughly shattered and porous interiors, even to the point of rubble-pile structures, are the longest-lived state for small bodies and may be considered their natural end state—thus predicting that when explored, almost all small body interiors will be found to be thoroughly shattered and porous.

Particularly relevant toward unveiling the current interior structure of small bodies is how fragments from catastrophic collisions reaccumulate themselves after the blow, when the impact indeed proves energetic enough to catastrophically disrupt the target. Modeling results by Michel et al. (2001) suggest that the largest members of asteroid families are likely rubble-piles, composed of fragments dispersed from a catastrophically disrupted parent that are able to reaccumulate through their mutual gravitational attraction. If correct, this work points toward families as the best place to study the rubble-pile end state for small body interiors. Nature could be giving us a helping hand in resolving this question if there actually is a propensity for forming satellites within asteroid families (Davis et al., 1996; Durda, 1996; Doressoundiram et al., 1997; Michel et al., 2001).
3.3. Outside looking in—the NEAR and near view

Although a model of the geologic structure can uniquely define the gravitational field of a body, a model of the gravitational field cannot uniquely define the geologic structure that produced it. Even though we cannot achieve unique solutions, well-constrained solutions in terms of overall homogeneity are achievable with orbiting missions, as demonstrated by NEAR at Eros and discussed in Section 2.3 above. Promising new approaches based on alternative representations of the gravity potential (e.g., the direct calculation of the potential obtained by modeling the body as a polyhedron, Werner and Scheeres, 1997) could allow us to model interiors even for highly irregular shapes. Mixed approaches, using both spherical harmonics and polyhedral representations (e.g., Scheeres et al., 2000) could help to discriminate the presence of density layers with relative accuracies of the order of $10^{-9}$.

New missions on the horizon promise the exploration of interiors for a wide variety of small bodies. On the protoplanet scale, the Dawn mission to Vesta and to Ceres (Russell et al., 2002) will reveal the presence or absence of a core. CONTOUR’s intended close flybys of comets 2P/Encke and 73P/Schwassmann-Wachmann 3 (Bell et al., 2000) are examples for a low-cost mission to derive multiple comet densities. Rosetta’s flight path may include one or more asteroid flybys enroute to its cometary destination. Rosetta will send a lander to the comet’s surface to perform in situ measurements of its physical and chemical properties. The Rosetta spacecraft is planned to operate for 2 years within a short distance from the comet in a parallel orbit, providing data on the evolution of a comet nucleus during its approach to perihelion.

Detailed examination of small body interiors from orbital missions currently appears achievable through very accurate orbit determination by means of multiple frequency tracking in conjunction with an accelerometer to reduce the effects of non-gravitational perturbations on the orbit solution (particularly critical in the low gravity field of a small body). These techniques will be demonstrated on the BepiColombo mission to Mercury (Milani et al., 2001). The multiple frequency X and Ka band link of BepiColombo will provide tracking precision of the order of 10 cm in range and $10^{-5}$ mm s$^{-1}$ in range rate (RMS values). Simulations performed for the BepiColombo mission show that, together with the accelerometer data, this ultra-accurate tracking will allow the determination of the spacecraft position with an actual error of a few tens of centimeters. This will lead to an unprecedented accurate knowledge of the gravity field of a solar system body (beyond the Earth) and will firmly constrain the presently unknown nature of Mercury’s core (Milani et al., 2001). As a comparison, the Eros gravity field derived by NEAR is deemed reliable up to degree and order 6 (Miller et al., 2002) whereas a reliable field of Mercury up to degree 25 should be attainable. A similarly instrumented mission around a small body could employ the same techniques and yield an improved knowledge of the gravity field (in terms of spherical, or ellipsoidal harmonics). The result would be a better detection of lateral and internal inhomogeneities in the body and set the appropriate reference surface (analogous to the Earth’s geoid) to be compared with other representation methods (as stated above).

3.4. Up close and personal—active experiments

However clever we are with models and data interpretation of gravity fields, the interiors of small bodies will remain a mystery until we begin to probe inside directly through active experiments. Deep Impact (A’Hearn, 1999) will make the first such experiment in the most simple way: impacting a projectile of a known mass and velocity and observing the consequences. The selection of 9P/Tempel-1 as the Deep Impact target will directly address our pervasive lack of direct and detailed knowledge of the strength, structure, and composition of cometary nuclei.

Taking further steps toward directly studying small body interiors will require applying the tools of modern geophysical prospecting: radar reflection and transmission tomography, seismo-acoustic waveform inversion, magneto-telluric imaging, and good old-fashioned drilling and blasting. Some of these are at present more feasible than others, but the overall mission requirements involve spacecraft at least capable of rendezvous and in most cases landing. Radar reflection tomography may be the most cost-effective tool for learning about small body interiors, as it can be done from an orbiter without a lander. But, it is not likely to provide unambiguous characterization in the absence of ground truth. Furthermore, a small body with metallic flecks (a chondrite) may be opaque to radar, as may one which is clay rich. Radar plus grenades might be a better combination, especially for probing near-surface geology (fault expressions, crater roots, cohesion of “ponded” materials, etc.). Radar plus grenades plus a seismic network might reveal whole-body structural characteristics, and the requiredlanders would allow for radio transmission tomography (much like the Rosetta CONCERT sounding experiment) unless the material is too opaque or the body too large. Seismology on small bodies might prove very challenging if their near-surface layers are highly porous and strongly attenuative. Blasts are very poor seismogenic activators to begin with; they may create holes in the regolith and little more. A deep penetrator with seismic thumper and several deep-anchored receivers may be required for high-quality seismic imaging of larger objects—a very complex mission goal that may not be achievable for several decades. Due to the potential for strong attenuation of electromagnetic and seismic energy, the smallest objects may be the best first candidates for seismology and radar. NEOs derived from cometary source material up to a few km across may also be good candidates for radar. Where seismic imaging is challenging, radio imaging may be optimal, and perhaps vice versa. An ideal candidate may
be those objects near the transition size of $\sim 100$ m. One might fire large projectiles (à la Deep Impact) to reveal nearly global consequences. One might try to spin up an object, causing it to rotate so fast that it cracks or otherwise flings itself apart. The list of creative possibilities goes on and on.

Only the most simple entrees from the above menu of possibilities for directly measuring small body interiors are likely to fit within the cost envelope of Discovery class missions within the United States. Low-cost (Discovery class) missions with focused science goals in this area are likely to be competitive. More extensive and more expensive small body interior missions will find it increasingly difficult to compete for flight selection in the face of many compelling mission opportunities within all of planetary science. Feasibility studies for future missions to NEOs are being funded within ESA’s Aurora Program. The goal of these studies is to give preliminary findings relevant to preparing and developing a mitigation plan. The governments of ESA’s member countries will have the opportunity to select and to finance one of these missions. Among the mission concepts are those that deal with (i) the discovery and follow up of potentially dangerous objects, (ii) the knowledge of their bulk composition through the determination of the taxonomy of a large sample of the NEOs population, and (iii) the determination of the bulk physical properties (mass, density, surface composition, and microscopic and macroscopic roughness). Two other mission studies (named Don Quixote and Ishtar) are addressing understanding the detailed internal structure of select NEO’s. Don Quixote proposes to send penetrators with seismometers to perform tomography of the asteroid target by monitoring the response to shooting a known mass at the surface. Ishtar plans an in-orbit radar global survey of few small asteroids to characterize the internal structure together with their bulk geophysical properties. Overall, the natural evolution of our increasing science knowledge about small bodies and careful and rational (fact, not fear) assessment of the impact hazard provides the most likely path by which extensive interior investigations will become a reality.

3.5. Learning how to learn: the science role for mitigation

As we state in the Introduction, our motivations for the study of small body interiors are the science questions and the diverse range of answers that can give us broad new insights across the field of planetary science. We note that nearly all of the answers gained from the science questions are both fundamental and essential to the “practical” problem of mitigation, should an NEO be discovered on a decidedly hazardous trajectory. Fortunately, the odds greatly favor that there is no sizable threatening object (or objects) on course for impact within the next century or more. Yet, prudence dictates that we should search so as to be sure and that we should have an understanding of how to mitigate a hazardous object should it be necessary. One can argue that the only object we need to understand in great detail is the one that will cross our path. We disagree. From the standpoint of practicality, the science questions we address and the methods we employ to answer them are essential for learning how to learn about the structure and interiors of small bodies. Without a sound knowledge base gained by the scientific study of these objects, we have no context within which to formulate realistic mitigation strategies. While it is unlikely that an actual mitigation will have to be performed for generations, the advancement of our scientific understanding through the exploration of small body interiors is certain.

4. Conclusions

Although the study of small body interiors is in its infancy, we are able to begin to formulate fundamental scientific questions whose answers are as diverse as the solar system small body population as a whole. We have the opportunity to explore and understand objects ranging from differentiated protoplanets to unaltered remnant planetesimals. The same collision processes that are likely to have thoroughly weakened and shattered interiors, in some cases creating rubble-piles, may have effectively made their targets virtually impossible to destroy completely. These processes also may be responsible for creating satellites, whose orbital motions provide the first key for unlocking their interior secrets. Only the smallest bodies may physically behave as monoliths, but their interior structures are likely complex as well. Our spacecraft exploration of these worlds is only just beginning, with steps toward increasingly sophisticated experiments falling within our vision. The scientific motivations for the understanding of small body interiors, perhaps fueled by a practical need to understand the requirements for impact mitigation, put us on a new and exciting threshold for exploration and discovery.

Acknowledgements

We thank the International Scientific Workshop Center of the Observatoire de Paris at Meudon for hosting an “Interior Structures of Small Bodies” workshop 10–14 June 2002, which formed the basis for the synthesis and prospectus presented here.

References


