INVITED REVIEW ABSTRACTS

ASTEROID INTERIORS

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The interiors of asteroids remain the subject of inference, based on surface observations and on measurements of density. This talk will begin with an overview of what has been learned over the past 20 years regarding internal structures, from the perspective of spacecraft and groundbased radar observations, theoretical modeling, and small-scale laboratory experiments. It will finish with an assessment of what might be learned prior to direct exploration of interiors, and prospects for the latter summarizing findings from the first Workshop on Spacecraft Reconnaissance of Asteroid and Comet Interiors (Santa Cruz, CA, October 2006).

One recent theoretical development, is how asteroid surface morphologies – crater statistics in particular – serve as expressions of the seismic properties of asteroid interiors. Asteroid craters may allow us to measure, to first order, how an asteroid responds to collisions and other high energy events through a quick examination of its largest craters. A first order analysis suggests that asteroids have a higher catastrophic disruption threshold than previously established, because their stress wave attenuation is lower than previously thought.

The critical crater diameter D_{crit} is defined as the minimum crater diameter on an asteroid whose formation disrupts, through distal shock and seismic effects, all previous craters D_{crit}.This threshold is computed by applying crater scaling relations and peak particle velocity attenuation relations. If the largest distinct crater observed on an asteroid is typically at or near this threshold size, it follows from this analysis that small asteroids (e.g. 25143 Itokawa) can have no sizable craters, relative to their diameter, while large asteroids (e.g. 253 Mathilde) are likely to have hemisphere-spanning craters.

Because D_{crit} can approach or even exceed the size of the target, the largest asteroids like Mathilde are likely to be saturated with hemisphere-spanning craters up until the size that the asteroid is a geologically active and gravitationally relaxing planet. This is because craters smaller than D_{crit}, however gigantic they might appear, do not broadcast globally.

Stress wave velocities on known asteroids, as parameterized by the model, are found to decay with the 1.3 power of distance for most asteroids (circles below plot the largest identified crater on each asteroid, while curves plot the parameterized stress attenuation). This is much less attenuative than strong shocks. This is consistent with expectation, because disturbances capable or destroying crater rims on asteroids are of very low particle velocity, and thus require stress waves lower in amplitude than typical lunar regolith cohesion. This is in contrast with most models for asteroid catastrophic disruption, which rely upon stronger attenuation or upon hydrocodes tuned to energetic blast events, assume much higher stress attenuation.? These models over-estimate particle velocity attenuation and thus over-estimate the threshold for catastrophic disruption Q_D^*.

COLLISION AND IMPACT SIMULATIONS INCLUDING POROSITY

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The Smooth Particle Hydrodynamic (SPH) method has been used extensively over the years to simulate impacts and collisions involving brittle solids. This approach has been tested at different scales. At the small ones, laboratory impact experiments have been used to validate the method. At larger scales, asteroid families have served as laboratory to test the approach in the gravitational regime. In all cases, the results of carefully carried out simulations have been shown to agree quite well with the experiments.

However, spacecraft missions and ground-based observations are providing increasing evidence that many or even most asteroids are porous. Porosity may also play an important role in the formation of planets as the dissipative properties of porous media will enhance the collisional sticking mechanism required to build planetesimals. Furthermore, the simulations of collisional asteroid family formation have also shown that the internal structure of the parent bodies involved plays a major role in defining the collisional outcome (fragment size distribution, fragment velocities, amount of material ejected, etc.). While large scale cracks and/or boulders can be modeled explicitly, small scale (smaller than the numerical resolution) porosity has to be modeled implicitly within a suitable model.

In order to account for these important effects related to material properties, we have extended the SPH method to render it suitable for the calculation of shock dynamics and fracture in porous media. Our approach is based on the so called P-alpha model which was adapted for implementation in our SPH impact code. We shall report some test results of this new approach and point out some generic difficulties facing these simulations.

ASTEROID FAMILIES

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Since they are the products of energetic collisional events, asteroid families provide a fundamental body of evidence to test the predictions of theoretical and numerical models of catastrophic disruption phenomena. The main difficulty to be faced is that of being able to retrieve from current physical and dynamical data the information directly related to the original events that produced families, and to separate and quantitatively assess the importance of evolutionary phenomena that have progressively changed the properties of families, as a consequence of physical processes that are not related to the original disruption events. Starting since the early 90s, there has been a significant evolution in our interpretation of family properties, as a consequence of the progressive development of new theoretical ideas, the development of numerical models, and the recognition and quantitative assessment of the influence of dynamical processes that had not been taken into account in preliminary studies, including primarily the Yarkovsky and YORP effects. A brief review of the current state of the art in ourunderstanding of asteroid families is presented, and a few likely directions for future developments are sketched.

FUNDAMENTALLY DISTINCT OUTCOMES OF ASTEROID COLLISIONAL EVOLUTION: ITOKAWA AND EROS

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The outcomes of asteroid collisional evolution are presently unclear: are most asteroids larger than 1 km size gravitational aggregates reaccreted from fragments of a 1parent body that was collisionally disrupted, while much smaller asteroids are collisional shards that were never completely disrupted? The 16 km mean diameter S-type asteroid 433 Eros, visited by the NEAR mission, has surface geology consistent with being a fractured shard. The Hayabusa spacecraft visited an S-asteroid smaller than $1km$, namely 25143 Itokawa. Here we report the first comparative analyses of Itokawa and Eros geology. Itokawa lacks a global lineament fabric, and its blocks, craters, and regolith are inconsistent with formation and evolution as a fractured shard, unlike Eros. Itokawa is not a scaled-down Eros, but formed by a distinct process of catastrophic disruption and reaccumulation.

POROSITY AND INTERNAL COMPOSITION OF ASTEROIDS

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A fundamental physical property of an asteroid is its density. One might naively expect asteroid density to be related to its composition, and thus it might be expected to be similar to the densities of meteorites thought to be derived from those asteroids. However, all but the largest asteroids whose densities have been measured appear to be significantly under-dense, with densities in some cases less than half the density of their suggested meteorite analogues. These meteorite analogues have only only about 10 percent microporosity, expressed primarily in microcracks resulting from shock events. Thus, if the proposed analogues are correct, asteroids commonly have very large macroporosity.

The observed power law of asteroid sizes, and studies of the collisional dynamics of the asteroid belt, have suggested a history of intense collisional evolution such that only the largest asteroids retain their primordial masses and surfaces. Asteroids below 300 kilometers in diameter should have been shattered by energetic collisions. After such events, some objects would reaccrete to form gravitationally-bound rubble piles, while the rest would be broken into smaller fragments, to be further shattered or fragmented.

Evidence from the densities are available only for a few dozen asteroids to date. However, the images of 253 Mathilde (whose density is only half the density of typical meteorite material) show six identified impact craters that are larger than the size necessary to shatter the asteroid. The only way that Mathilde could have survived these repeated huge impacts is if it were already a shattered rubble pile that dissipates much of the energy of large impacts in the friction of the pieces of rubble grinding against each other.

In terrestrial experience, significant porosity is possible only if the rubble is size-sorted, preventing smaller particles from filling the voids between larger particles. During the re-accretion, one might expect that the largest pieces, which would travel the least distance from the center of mass of the orbiting fragments, would be the first to re-accrete; smaller fragments would reaccrete later. Jostling within the rubble pile during the reaccretion might also provide such size-sorting. Given the very low gravity driving the collapse of these rubble piles, and the significant friction between between the fragments, this size sorting could be maintained.

Thus most asteroids may be shattered heaps of perhaps loosely bound rubble with significant porosity in the form of large fractures, vast internal voids, and loose fitting joints between major fragments. Thus it is not surprising that the average asteroid would have a very large porosity.

Finally, we note that the shock compression of very porous material during impacts should result in significant heating of that material. This could be an important source of the metamporphism seen in meteorites classes.

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This talk will summarize the presentations at CD7 in the context of the overall goals of these workshops. The emphasis will be on describing progress in understanding catastrophic disruption and its role in shaping the solar system.

ON THE "STRENGTH" OF SMALL BODIES OF THE SOLAR SYSTEM

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Comprised from rocks, ices and metals, the small bodies of the Solar System generally show features of strength, and that property played a major role in the formation and evolution of the Solar System. But the quantification of strength is generally difficult: that is a consequence of the fact that there are many different measures of strength, and those measures depend significantly on a bodies composition, previous history and size. Although it is at the root of our theories of disruption of at least all small bodies, our community has only recently begun to understand and come to grips with that issue. I will give a general review and overview of strength theories for geological-type materials, relating various different measures such as tensile, shear, and compressive strengths. I will present some recent results showing the effects of strength on the distributions of the spin states of the asteroids, which gives important clues about disruptions that w can use in our studies. And I will discuss major uncertainties about current scaling theories for the catastrophic disruptions of asteroids.

LABORATORY IMPACT DISRUPTION EXPERIMENTS - TOWARDS UNDERSTANDING THE IMPACT PROCESS OF POROUS BODIES

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Laboratory studies on the impact process of small bodies have been performed in recent decades using light-gas guns and other facilities (Holsapple et al. 2002). These experimental studies have provided quantitative data and insights into many aspects of centimeter-scale impact processes, especially for brittle solid targets. Close-up views of boulders on asteroid 25143 Itokawa showed that the boulders are strikingly similar to laboratory rock impact fragments in terms of shape and structure, despite the orders of magnitude difference in scale (Nakamura et al. 2007), encouraging experimental approaches.

However, since laboratory experiments are limited in scale, numerical simulation and scaling methods have been adopted in order to extend the laboratory results to the scales of small bodies. With such extended studies, the flaw statistics of the target body are a key parameters that determines the outcome of impact disruption. To date, the flaw statistics have been studied for a few target materials used in impact disruption experiments directly and indirectly (Housen and Holsapple 1999, Nakamura et al. 2006). With porous bodies, pores play important complicated roles in impact disruption: pores stop crack-growth, while they suppress the transmission efficiency of the impact energy throughout the body. It is therefore impact experiments using porous targets are required in order to understand the physical processes involved and establish a database that can serve as a useful reference for numerical modeling and the scaling approach.

We started impact disruption experiments of porous targets with different strength and porosity. The target materials used include sintered glass beads (Setoh et al. 2007), gypsum, and pumice. The porosity of the targets ranged from a few percent to 70% and the compressive strength ranged from under 1 MPa to over tens of MPa. The microscopic structures of the target materials differed from one another and was characterized using microscopic imaging. In parallel with the impact experiments, other studies have examined how materials lose their porosity under static compression (Hiraoka and Nakamura, this meeting). The results of the impact experiments of these targets will be briefly summarized.

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THE COLLISIONAL EVOLUTION OF SMALL BODIES IN THE SOLAR SYSTEM

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Collisions have played an important role in sculpting the populations of small Solar System bodies, namely the asteroids and trans-Neptunian objects (TNOs). Both populations were originally much more massive, and have evolved to their current state through the combined effects of dynamical and collisional evolution. There is a wealth of observational data concerning the size and orbital distributions of the asteroid belt, and there is also a reasonable understanding of its dynamical history [eg. 1,2], allowing for the development of fairly well-constrained models of its evolution [eg. 3,4,5]. These models suggest that dynamical effects, namely perturbations from massive planetary embryos, coupled with Jovian and Saturnian resonances, drove the primordial asteroid belt to its current low-mass state during the first ∼10 Myr of Solar System history. Most collisional evolution occurred early on while it was still massive.

In contrast to the asteroid belt, the size and orbital distribution of the more distant TNO population is not as well known, and much work is still being done to understand its dynamical origin. Models of its collisional evolution have generally focused on trying to grind an originally massive TNO population down to its current mass through collisional erosion [eg. 6-9]. However, new simulations that self-consistently incorporate both dynamical evolution and collisional erosion suggest that dynamical effects are primarily responsible for the mass depletion [10]. Further work, which self-consistently incorporates collisional accretion as well as collisional erosion and dynamical evolution, is necessary to better understand the relative roles of dynamics and collisions in the sculpting the TNO population [see 11 for a discussion].

This review talk will summarize the work to date on the collisional evolution of the asteroid and TNO populations, as well as other populations such as the Jupiter Trojans, in particular focusing on the interplay between dynamical and collisional evolution. I will highlight the outstanding questions and uncertainties that remain, and point out important directions for future work.

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ASTEROID ROTATIONS AND BINARIES

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Rotations of asteroids are determined by mechanisms and properties with importance varying with asteroid size. Asteroids larger than about 50 km are affected primarily by collisions. Their spin rate distribution close to Maxwellian suggests that they are either original bodies of the asteroid main belt, or their largest, collisionally evolved remnants. Rotations of asteroids smaller than 50 km are significantly affected by a non-collisional mechanism, with the most probable candidate being the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect that causes a radiative spin up or spin down of asteroids.

The YORP effect theory gives a consistent explanation for a few different features seen in the smaller asteroids population: 1) Excess of both fast and slow rotators. 2) Alignment of spin axes of members of the Koronis family. 3) Abundant population of small, close binary systems with a total angular momentum confined to values near critical.

Internal structure does not have a significant effect on rotations of larger asteroids which are in a gravity regime, but it is a key property for smaller asteroids. Asteroids in the size range 0.2 to about 10 km show a barrier against spins faster than 11/d that shifts to slower rates with increasing equatorial elongation. They are predominantly bodies with tensile strength too low to withstand a centrifugal acceleration for rotation faster than the critical spin rate. A scaled tensile strength of cracked but coherent rocks suggests that that a cohesionless structure is predominant among asteroids with $D = 0.2$ to 3 km.

The spin barrier disappears at sizes less than 0.2 km where most asteroids rotate too fast to be held together by self-gravitation only, so a cohesion is implied in them. They may be single fragments of the rubble that make up larger asteroids from which the smaller ones are derived.

An abundant population of binary systems has been found among asteroids in the size range 0.3 to 10 km in heliocentric orbits from near-Earth to the main belt. The fact that they appear exactly in the same size range where there is observed the spin barrier is not a mere coincidence, but the two things actually appear related. Primaries of the binary systems concentrate at fast spin rates, in a pile up just below the cohesionless spin barrier. Angular momentum content of the binary systems is close to the critical limit for a single body in a gravity regime, suggesting that they formed from parent bodies spinning at the critical rate by some sort of fission or mass shedding. The YORP effect is a candidate to be the dominant source of spin-up to instability. Gravitational interaction during close approaches to the terrestrial planets cannot be a primary mechanism of formation of the binaries, but it may affect properties of the NEA part of the binary population. For example, estimated short lifetime and its strong dependence on semi-major axis of the NEA binaries, together with the strength of the YORP effect being inversely proportional to the square of diameter, may be a reason that binaries in near-Earth orbits concentrate among NEAs with $D < 2$ km and that the fraction of binaries decreases among larger NEAs, as well as for their tendency to smaller relative separations (shorter periods) in comparison with main belt members of the binary population.

N-BODY MODELS OF AGGREGATION AND DISRUPTION

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N-body simulations, in which the equations of motion of N self-gravitating particles are solved approximately over discrete intervals in time, have been used for many years to model complex phenomena related to both aggregation and disruption of small solar system bodies. Examples include planetesimal growth leading to planet formation, asteroid family formation, and the formation of binary asteroids following collisional or rotational disruption of a larger body. Direct simulation permits investigation of collective behaviour, such as gravitational reaccumulation of fragments following catastrophic disruption (possibly leading to the formation of binary or higher-order systems), that would otherwise be difficult to predict. As algorithms and hardware have improved, so have the detail and realism of the simulations. This review will summarize the major types of N-body simulations that have been employed to study the evolution of small solar system bodies, with an emphasis on recent developments that have led to the most sophisticated models yet of asteroid family formation. New capabilities include modeling the gravitational and collisional evolution of complex shapes with variable tensile and shear strength.