An Overview of the Asteroids: The Asteroids III Perspective

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1. INTRODUCTION: WHY WE STUDY ASTEROIDS

"We are now on the threshold of a new era of asteroid studies," wrote Tom Gehrels in 1971 (*Gehrels,* 1971). These words proved quite prophetic for the three decades of physical observations and theoretical understanding that followed. As the third century of asteroid research has begun in 2001, we can once again picture ourselves standing on a new threshold. This new century begins with asteroids no longer being starlike points of light in our telescopes, but resolved worlds with distinctly measurable, sizes, shapes, and surface morphologies. Each has a unique history to unravel, a history that begins at the time of formation of our own planet and the entire solar system.

The physical nature, distribution, formation, and evolution of asteroids are fundamental to our understanding how planet formation occurred and, ultimately, why life exists on Earth. In our current solar system, asteroids (and comets) are the most direct remnants of the original building blocks that formed the planets. As such, they contain a relatively pristine record of the initial conditions that existed in our solar nebula some 4.6 G.y. ago. The asteroids that have survived since that epoch, however, have experienced numerous collisional, dynamical, and thermal events that have shaped their present-day physical and orbital properties. Interpreting this record via observations, laboratory studies of meteorites, and theoretical/numerical modeling can tell us much about how the bodies in our solar system have evolved with time. In fact, even though asteroids represent only a tiny fraction of the total mass of the terrestrial planets, their large numbers, diverse compositions, and orbital distributions provide powerful constraints for planet-formation models. For example, in the inner solar system, the orbital and physical characteristics of the asteroid belt and the surfaces of the terrestrial planets scarred by asteroid impacts can be used to narrow the range of possible starting conditions that can conceivably create a planetary system similar to our own. While the dynamical properties of the terrestrial planets (e.g., masses, heliocentric distances, spin rates, obliquities) also provide valuable constraints, many of these characteristics may have been significantly influenced by large collisions and other stochastic events, potentially making it problematic to reproduce these traits in any modeling effort. Moreover, other useful constraints, such as a planet's geochemical and isotopic characteristics, are often difficult to interpret because each of the terrestrial planets has experienced differentiation and thermal evolution with unknown starting conditions. Thus, asteroids and other small body populations may provide the key pieces of the cosmological puzzle that allow us to decipher why at least one of the planets in our solar system harbors life.

Motivated by this theme, the planetary community's decadal survey recently published a list of three central questions raised by the structure and nature of various asteroid populations (*Sykes et al.,* 2002). These questions are intimately related to the need of finding an answer to a number of long-debated problems. We repeat them here, since they help put into context the work that is presented throughout *Asteroids III*.

I. What was the compositional gradient of the asteroid belt at the time of initial protoplanetary accretion?

- What is the population and compositional structure of the main asteroid belt today?
- How do dynamics and collisions modify this structure over time?
- What are the physical properties of asteroids?
- How do surface modification processes affect our ability to determine this structure?

II. What fragments originated from the same primordial parent bodies, and what was the original distribution of those parent bodies?

- What asteroid fragments are associated dynamically, suggesting a common origin?
- What objects are geochemically linked?

III. What are the early steps in planet formation and evolution?

- What are the compositions and structures of surviving protoplanets?

- What does their cratering record combined with the cratering record of younger surfaces reveal about the primordial size distribution of objects in the asteroid belt?
- What do meteorites tell us about formation and evolution processes of these bodies? How well do they sample the asteroid belt?

A second and perhaps more practical reason to study asteroids has to do with the fact that some of these bodies are capable of striking Earth with enough energy to produce severe or possibly catastrophic damage to our civilization. Over the last two decades, it has been convincingly argued that the impact of a multikilometer asteroid or comet 65 m.y. ago led to a mass extinction event that eliminated the dinosaurs (e.g., *Alvarez et al.,* 1980). Because events like this are increasingly seen as harbingers of things to come rather than anomalies, scientists from around the world are now employing a variety of techniques (e.g., remote sensing, numerical modeling, spacecraft missions) to detect bodies near Earth and understand their physical properties.

Since the publication of *Asteroids II* some 13 years ago, the asteroid community has made tremendous progress in addressing many of the diverse issues described above. To give the reader a sense of how far we have come over this time, recall that before the 1990s, we had yet to visit our first asteroid with a spacecraft, nor had asteroid satellites been directly imaged by groundbased observations. Detailed radar investigations of the shapes and surface properties of near-Earth objects (NEOs) were in their infancy, while the number of known NEOs was only ~100. Dedicated NEO surveys like Spacewatch and LINEAR were only beginning to come on line or were years away. Public awareness that impacting asteroids and comets posed a threat to life on Earth was almost nonexistent.

Now, when comparing the table of contents between *Asteroids II* and *Asteroids III*, one is immediately struck by the essential role that charge-coupled-device (CCD) technology has had in advancing our understanding of asteroid surfaces and rotations. CCDs have enabled the number of objects for which high-quality spectra are available to grow from hundreds to thousands (chapter by Bus et al.), to push the limits of rotation studies down to small sizes where complex rotation states are evident (chapter by Pravec et al.), to expand our observational sample of outer-belt asteroids (chapter by Barucci et al.), and to explore in detail the complex mineralogy that reveals the petrologic history of the asteroids (chapters by Rivkin et al. and Gaffey et al.). Improvements in radiometric techniques and the application of larger aperture telescopes have pushed forward our capabilities and understanding of the thermal properties of both main-belt and near-Earth asteroids (NEAs) (chapter by Harris and Lagerros). Astounding advances in radar imaging reconstruction techniques, coupled with the upgraded capability of the Arecibo facility, have allowed radar studies to blossom among a new generation of researchers, as summarized in the chapter by Ostro et al. Routine observations of asteroids from space platforms (chapter by Dotto et al.) plus our first *in situ* exploration of asteroids by space probes (chapters by Cheng, Sullivan et al., Chapman, and Farquhar et al.) have most strikingly propelled our knowledge forward by allowing us to explore asteroids as real places rather than as distant points of light.

The great strides made in exploring asteroids observationally have been matched by the tremendous progress made in simulating the nature and evolution of asteroids via numerical models. The advent of inexpensive, fast workstations and increasingly sophisticated numerical algorithms have allowed fairly realistic numerical experiments to become commonplace. It is now possible to track the orbits of planetesimals and planetary embryos for millions of years while including all relevant gravitational perturbations. We can also now model (with reasonable accuracy) what happens when kilometer-sized asteroids strike one another at speeds of several kilometers per second. To check the results of these "virtual laboratories," scientists must constantly compare their results with observational constraints. If the models are wrong, they must be refined or thrown out, as appropriate. This checks-and-balances system in asteroid research has produced a much deeper understanding of small-body evolution, such that many of the questions addressed by the decadal survey can now be attacked.

Our purpose for this chapter is to convey the current key points of understanding for the asteroids. In doing so, we hope to help map out the content of this book and point the reader to literature that has connections beyond this volume. Of course, the best purpose for reviewing our current understanding is setting the context for future asteroid investigations.

2. BRIEF HISTORY OF THE PRIMORDIAL ASTEROID BELT

2.1. Formation of Main-Belt Asteroids

The largest reservoir of asteroids in the inner solar system is the main belt, located between the orbits of Mars and Jupiter. The processes by which the main belt took on its current attributes are believed to be linked to planet formation, particularly the formation of the terrestrial planets and Jupiter. The sequence of planet formation in the inner solar system, which involves the gradual coalescence of many tiny bodies into rocky planets, can be divided into four stages: (1) the accumulation of dust in the solar nebula into kilometer-sized planetesimals, (2) runaway growth of the largest planetesimals via gravitational accretion into numerous protoplanets isolated in their feeding zones; (3) oligarchic growth of protoplanets fed by planetesimals residing between their feeding zones; and (4) mutual perturbations between Moon-to-Mars-sized planetary embryos and Jupiter, causing collisions, mergers, and the dynamical excitation of small-body populations not yet accreted by the embryos (e.g., *Safronov,* 1969; *Weidenschilling,* 2000). With the discovery and knowledge of numerous stellar disks and the detection of extrasolar planets (e.g., *Marcy et al.,* 2000), our understanding of the basic processes of accretion and planet formation has seen a broad and rapid growth beyond what is covered here. (Note: For a more detailed look at these processes, the reader is directed to the many excellent review chapters found in *Protostars and Planets IV,* published in 2000 by the University of Arizona Press).

Meteorites provide the clock for timing planetesimal formation. Several chronometers provided by short-lived radionuclides (e.g., ^{53}Mn decaying to ^{53}Cr; ^{26}Al decaying to ^{26}Mg) are described in the chapter by Shukolyukov and Lugmair. According to their high-resolution chronological studies, the calcium-aluminum-rich inclusions (CAIs) found in chondritic meteorites, considered the first condensates of matter in the solar system, have an estimated formation age of ~4571 m.y. Some 2 m.y. after the formation of the CAIs, asteroids with diameters $D > 10$ km had formed in the asteroid belt. Objects that had accreted significant amounts of ^{26}Al during this time were heated as ^{26}Al decayed into ^{26}Mg. In some cases, the heat budget on these asteroids was high enough to produce aqueous alteration, metamorphism, melting, or even differentiation.

The thermal evolution of large asteroids during this epoch is the subject of the chapter by McSween et al. Their modeling work suggests that there are several variables that determine how an asteroid might be modified over time by radiogenic heat: (1) accretion time, which determines the quantity and distribution of active ^{26}Al available to a given asteroid; (2) the composition of the accreted material, which changes with increasing heliocentric distance to include more water and other volatiles; (3) the thickness and thermal conductivity of an asteroid's regolith, which may regulate its ability to eliminate heat; and (4) the asteroid's ultimate diameter. Using these results, we can begin to interpret the surface properties and compositions of asteroids in the asteroid belt. For example, McSween et al.'s results point to a possible solution for this frequently-cited main-belt enigma: (4) Vesta, a $D = 530$ km asteroid in the inner main belt, has differentiated while (1) Ceres, a much larger $D = 930$ km asteroid in the central main belt, apparently has not. It is possible that objects in the inner main belt formed much more quickly than those farther out in the main belt, such that Vesta may have accreted more active ^{26}Al than Ceres. In addition, the presumed greater availability of volatiles in the outer main belt may have helped inhibit large-scale melting events. The observational search for water and aqueous alteration on main-belt asteroids is discussed in the chapter by Rivkin et al.

As far as we know, Vesta is the only remaining differentiated object in the main belt with an intact interior structure consisting of a core, olivine-rich mantle, and a basaltic crust. Assuming that Vesta is the ultimate source of the howardites, eucrites, and diogenite (HED) meteorites, a considerable amount of information can be inferred about Vesta's history. For example, Shukolyukov and Lugmair claim that differentiation ended on Vesta by ~4565 m.y., some 6 m.y. after the formation of the CAIs. In the chapter by Keil, the geologic history of Vesta is examined in detail. One of the interesting questions raised by their work is the hypothesis that the primordial main belt may, at one time, have held additional Vesta-like objects. Their claim is supported by evidence suggesting that 108 of the 135 asteroids sampled by meteorites were partially melted or completely melted and differentiated by postaccretionary heating events (e.g., iron meteorites and stony-irons like pallasites and mesosiderites). The possible existence of these bodies raises several important questions about the evolutionary history of the primordial main belt (e.g., What happened to these Vesta-like objects? Are there any meteoritical or asteroidal remnants from this population residing in the current main belt? What can these survivors tell us?), some of which are (briefly) addressed in the next section.

Additional constraints on this early period in solar system history come from the chapter by Scott, who investigates the effects of asteroid accretion, metamorphism, melting, and collisional evolution on various meteorite samples (e.g., chondrites, differentiated meteorites, breccias). Meteorites provide strong constraints for asteroid-evolution models, since they provide a physical record of real asteroid properties and the effects of impact damage. At the present time, however, many meteorite samples do not appear consistent with *Asteroids II*-era models of how the asteroid belt evolved over time.

2.2. Dynamical Excitation of the Primordial Main Belt

To decipher the timing and enigmatic processes of planet formation, it is useful to understand how the main belt reached its current state. As described in the chapter by Petit et al., the formation of Jupiter had significant repercussions for the evolution of the primordial main belt. We list the principal changes below:

1. *Large mass depletion.* Model results suggest the primordial main belt contained ~2–10 $M_\oplus$ of material, enough to allow the asteroids to accrete on relatively short timescales. The current main belt, however, is depleted of mass, such that it only contains ~5×10^{-4} $M_\oplus$ of material. The mechanism that eliminated the mass is constrained by the presence of Vesta's basaltic crust. If the main belt were massive for too long, Vesta's crust would have been obliterated by collisions.

2. *Strong dynamical excitation.* Initially, the eccentricities e and inclinations i of asteroids within the primordial main belt were low enough that accretion could occur. The median e, i values of asteroids in the current main belt, however, are high enough that collisions produce fragmentation rather than accretion.

3. *Radial mixing of asteroid types.* Asteroid thermal models suggest that the outer main belt should contain more "primitive" objects than the more heated/processed inner belt (chapter by McSween et al.). This trend is roughly reproduced in the current orbital distribution of the taxonomic classes, with S-type asteroids dominating the inner belt, C-

type asteroids dominating the central belt, and D-/P-type asteroids dominating the outer main belt. The boundaries between these main taxonomic types, however, are not sharp; some C and D asteroids can be found in the inner main belt, while some S-type asteroids can be found in the outer main belt. While it is difficult to produce this configuration using thermal models alone, it is plausible that some process (or processes) partially mixed the taxonomic types after their formation or that conditions at any one heliocentric distance changed while asteroids were forming.

Petit et al. claim that these characteristics are byproducts of a dynamical removal mechanism associated with the late stages of planet formation. Model results show that Jupiter's formation could have produced sweeping resonances and/or the scattering and excitation of large planetary embryos within the main belt, thereby eliminating most of the bodies from the primordial main belt shortly after Jupiter reached full size (i.e., presumably some 10 m.y. after the formation of planetesimals). This same dynamical excitation event should have scattered some asteroids away from their formation location, leaving the main belt in a condition comparable to its current state.

If this scenario is valid, we can postulate that Vesta is the lone survivor of a large population of similar objects that quickly disappeared from the main belt. Only a fraction of these Vesta-like objects was shattered by impacts before they were scattered out of the main belt, leaving behind an odd assortment of scraps that was then winnowed over 4.5 G.y. of comminution and dynamical evolution. Fortunately, remnants of this lost "Flying Dutchman" population may still exist in the current main belt or in our meteorite records (e.g., basaltic asteroid 1459 Magnya? olivine-rich A-type asteroids? numerous unusual types of stony-iron and iron meteorites? other?). These objects may be compelling targets for future rendezvous and/or sample return missions.

As an aside, we point out that the dynamical excitation of the primordial main belt may have provided Earth with most of its water. Model results by *Morbidelli et al.* (2000) indicate that collisions between large outer main-belt asteroid and Earth are capable of delivering nearly all of Earth's water budget. Comets, on the other hand, probably do not contribute more than 10% (*Morbidelli et al.,* 2000; *Levison et al.,* 2001). These results are consistent with the deuterium/hydrogen (D/H) ratio of terrestrial ocean water, which matches the D/H ratio of outer main-belt material [e.g., carbonaceous chondrites (*Dauphas et al.,* 2000)] but not that of observed comets coming from the Oort Cloud (e.g., *Meier et al.,* 1998). These results suggest that the outer main belt, which has not been extensively studied nor sampled by meteorites, is a fertile ground for new research projects and spacecraft missions over the next several decades.

2.3. Trojan Asteroids

The Trojan asteroids, the second largest reservoir of asteroids in the inner solar system, are located around the L_4 and L_5 Lagrange points of Jupiter. (We use the term "asteroid" here, although the compositional differences between outer-main-belt asteroids, Trojans, and dormant/extinct comets are thought to be subtle. For this reason, terms like "asteroid" or "comet" are ambiguous, such that both could be reasonably applied when these populations are discussed.) Even though the population of Trojans is thought to be only slightly less numerous than the current main belt (see the chapter by Jedicke et al.), the Trojans frequently receive far less attention then their next-door neighbor. The reasons probably have to do with the fact that Trojans are more distant and therefore are harder to observe and they lack the distinctive spectral features seen among many main-belt asteroids. Still, as described in the chapter by Barucci et al., the physical properties of the Trojans are an interesting counterpart to the diverse main-belt asteroids. Their spectra are featureless and reddish, indicating that they are probably covered by organic molecules. Most Trojans that have been examined closely appear to belong to the D-type taxonomic class, while their rotational properties appear to be similar to main-belt objects. The origin and evolution of the Trojans, as described by Marzari et al., are probably linked to the growth and evolution of Jupiter. As the gaseous envelope collapsed and accreted onto Jupiter's core and quickly increased its mass, the libration regions near the L_4 and L_5 Lagrange points would have readily expanded, capturing planetesimals that happened to be wandering near these zones. The more Jupiter increased its mass, the more the libration amplitudes of the captured planetesimals would shrink, forcing some objects into orbits consistent with known Trojans. Eventually, the planetesimals with large libration amplitudes and shorter dynamical lifetimes escaped, leaving behind the Trojan swarms observed today. Because this mechanism had a negligible effect on the eccentricities and inclinations of the captured bodies, it is possible, although unlikely, that the orbital distribution observed among the Trojans today is primordial. A more likely scenario is that some unknown postcapture mechanism produced the high inclinations observed among the known Trojans. Several potential mechanisms capable of increasing inclination values among the Trojan asteroids are discussed in the Marzari et al. chapter.

3. PRESENT STATE OF THE MAIN BELT

As described above, the evolution of the primordial main belt was characterized by numerous impacts, thermal processing, and substantial dynamical upheaval, all which occurred over a relatively short time span (on the order of ~100 m.y.). Once this dramatic epoch ended, however, the evolution of the remaining population occurred more slowly, with the dominant physical processes being collisions, now more infrequent than before, and several dynamical mechanisms capable of modifying the orbits of asteroids over time. To understand the evolution of main-belt asteroids, we need to understand how these processes operate. [We overlook for now the possibility that the main belt was significantly modified by the Late Heavy Bombardment (LHB). The LHB refers to an event ~3.9 G.y. ago where the inner solar system was ravaged by numerous impactors (e.g., *Hartmann et al.,* 2000). Evidence suggests that most lunar basins were formed at this time. Although the LHB's origin and length are unknown, numerical studies have suggested an intriguing possibility: The LHB may have been caused by a sudden dynamical depletion of small bodies in the primordial outer solar system some 600 m.y. after the birth of the solar system (*Levison et al.,* 2001). If this scenario is valid, the LHB would have had several consequences for the main belt: (1) Projectiles from the LHB may have disrupted main-belt asteroids. (2) Gravitational interactions between ejected outer solar system bodies and Jupiter may have caused Jupiter to migrate inward, such that asteroids could have been trapped, excited, or even ejected by sweeping jovian resonances. Even if the LHB scenario described in *Levison et al.* (2001) proves to be incorrect, it is clear that the history of the main belt (and the solar system) is intimately linked to our understanding of the LHB.]

The surface of an asteroid tells the story of what has happened to the body over time. To read that story, we must document an asteroid's morphological, orbital, and spectral properties, interpret how these factors relate to one another, and place them in context. *In situ* exploration and remote sensing observations help us estimate an asteroid's shape, surface spectral signature, size, rotation rate, cratering record, and bulk density. Other asteroid properties (e.g., internal composition, internal structure, chemical history) cannot be thoroughly assessed unless we land on the asteroid or bring back well-documented samples to terrestrial laboratories. Moreover, when interpreting available observations, we should take into account possible effects of space weathering due to long exposure of the surfaces to solar wind, cosmic rays, and micrometeorite impacts (see chapter by Clark et al.).

3.1. Collisions

Collisions are the principle geologic process occurring on asteroids today. Mutual collisions between asteroids have ground down earlier populations, processing their members into smaller and smaller fragments. In addition to being comminuted, asteroids are also scarred by impacts. The nature of the size distribution of the bombarding asteroid population is such that numbers increase strongly as size decreases. For this reason, asteroids are likely to experience numerous cratering events before eventually being disrupted by a more energetic impact. The records left behind by these events yield important information about the target as well as the bombarding population.

Though our understanding of high-velocity impact physics remains incomplete, we have made significant progress over the last decade. Recall that at the time of *Asteroids II*, no asteroid had yet been imaged by spacecraft. For this reason, much of our knowledge about asteroid internal structures was deduced from observations of ancient catastrophic disruption events among large asteroids (i.e., asteroid families) and laboratory impact experiments, where centimeter-sized projectiles were fired into targets at several kilometers per second. The conventional wisdom based on these inferences was that most small asteroids were monolithic shards produced by collisions. Consequently, their reaction to cratering and catastrophic disruption events was thought to be driven by their physical strength. As images of asteroids or asteroid-like objects [e.g., Phobos, (951) Gaspra, (243) Ida, (253) Mathilde, (433) Eros] were analyzed in the 1990s; however, it became apparent that we were missing something important. For example, each of these bodies had sustained a collision energetic enough to produce a multikilometer crater. In fact, in the case of Mathilde, the largest craters were comparable to the dimensions of the asteroid itself! The only way to explain the existence of these large craters was that some unexplored aspects of impact physics were allowing these objects to escape catastrophic disruption.

As described in the chapters by Asphaug et al., and Holsapple et al., these surprising results have been investigated using numerical hydrocodes, which can model the pressures, temperatures, and energies produced by asteroid-sized impacts with reasonable accuracy, and laboratory impact experiments, which can provide groundtruth for the complicated physics occurring when real objects collide at high velocities. Their results indicate that large asteroid craters form in the "gravity-scaling" regime, where the final size of the crater is controlled by the target's gravity. In contrast, small asteroid craters form in the "strength-scaling" regime, where the final size of the crater is governed by the strength of the target's surface. A collision in the gravity regime works in the following way. Imagine a body tens of meters in diameter striking an undamaged rocklike kilometer-sized asteroid. According to hydrocode modeling, the shock front launched by the collision pulverizes material at the impact site, such that crater excavation occurs in virtually strengthless material. Since weak material does not transport energy efficiently, much of the impact energy is deposited near the impact site. In this manner, craters formed in the gravity regime can be significantly larger than suggested by extrapolation of strength-scaling laws. In fact, a powerful enough shockwave may shatter the target asteroid, effectively creating a collection of gravitationally-bound components. This behavior provides insight into why multikilometer asteroids can have such enormous craters.

Until recently, hydrocode modeling of asteroid collisions had concentrated on relatively simple experiments: The target asteroids were assumed to be initially undamaged, the composition of the projectile and target asteroids was assumed to behave like basalt or other common terrestrial rocks, and the porosity of the target material was considered negligible. As our interpretation of asteroid and meteorite data has grown more sophisticated over time, however, it has become clear that these approximations do not address the full range of asteroid configurations. As described in the chapter by Britt et al., asteroid and meteorite density trends suggest that asteroids can be divided into three general groups: (1) asteroids that are essentially solid objects; (2) asteroids with macroporosities near 20% that are probably heavily fractured, and (3) asteroids with macroporosities >30% that may be considered gravitational aggregates. (Gravitational aggregates are commonly referred to in the literature as "rubble piles." Unfortunately, this term has led to several misunderstandings between geologists and numerical modelers, each of whom use the term "rubble pile" to describe a specific asteroid attribute. To avoid future entanglements, Richardson et al.'s chapter proposes new terminology in which a "rubble pile" describes the asteroid structure one might find if a bunch of rocks were dumped off a truck, while the term "gravitational aggregate" describes any object comprised of loosely consolidated material.) Although simulating impact events on model asteroids from the last two groups is challenging, many insights have already been gleaned from recent numerical and experimental data. Descriptions of the current state of the art can be found in chapters by Asphaug et al., Britt et al., and Holsapple et al.

These results led Richardson et al. to propose a new classification scheme for asteroid interiors, one that provides a more useful means for predicting how asteroids should react to short- and long-term stresses. Richardson et al. categorized the spectrum of possible asteroid configurations using two parameters, porosity and relative tensile strength (RTS). Porosity provides some measure of how asteroids react to impact energy. For example, since high-porosity objects are thought to absorb impact energy rather than transmit it, they should be more difficult to fragment/disrupt. On the other hand, RTS can be used to describe the structure of flaws inside an asteroid. Objects with high RTS, characterized as fractured or monolithic, should resist long-term stresses like planetary tidal forces, while objects with low RTS, characterized as highly fractured or shattered, are more susceptible to those same stresses. Using these parameters, it is possible to make some general statements about how different asteroids react to impacts:

1. Collisions on monolithic or moderately fractured asteroids (high RTS, low porosity) produce compressive waves that easily reach the farside of the object. The reflected compressive wave turns into a tensile wave that can produce damage and spalls. This structure may be a good description for <100-m asteroids.

2. Fractured or shattered asteroids (moderate RTS, low porosity) contain significant numbers of faults and joints that help to suppress the tensile wave, such that the object is more difficult to disrupt. This structure may be a good description for some S-type asteroids [e.g., (243) Ida, (433) Eros, and (951) Gaspra].

3. Asteroids with rubble-pile structures or highly porous structures (low RTS, moderate to high porosity) absorb impact energy via compression, with little to no tensile wave developed in the structure. When impact energy is damped, craters may form by compaction. This structure may be a good description for C-type asteroids like (253) Mathilde.

From an evolutionary standpoint, we expect collisions to eventually fracture or shatter most asteroids, ultimately turning them into gravitational aggregates. Observational evidence and numerical results described by several chapters (Richardson et al., Asphaug et al., Pravec et al., Britt et al., and Merline et al.) suggest that such structures may persist down to objects only a few hundred meters in diameter:

Asteroid spins. As described in the chapter by Pravec et al., the rotation rates of observed kilometer-sized and smaller asteroids indicate that relatively few are spinning fast enough to be in a state of tension. Moreover, the rotation period distribution of $D > 0.15$ km asteroids abruptly truncates at $P \gtrsim 2$ h, which is where gravitational aggregates of typical asteroidal density would begin to fly apart from centrifugal forces. Since solid objects should conceivably be able to spin at nearly any rate, the data suggests that most $D > 0.15$ km bodies lack tensile strength.

Binary asteroids in near-Earth space. Doublet craters, created by the nearly simultaneous impact of objects of comparable size, have been found on all the terrestrial planets. These craters were almost certainly formed by the impact of binary asteroids (see also the chapter by Merline et al.). To explain the quantity of observed doublets (i.e., ~10% on Earth), one must infer a steady-state population of ~15–20% binary asteroids in near-Earth space (see chapters by Pravec et al. and Merline et al.). A plausible way of producing such a large quantity of binaries in that region is to have gravitational aggregates undergo tidal disruption when passing close to a terrestrial planet, with some of the shed fragments entering orbit around the remnant asteroid. If this scenario is valid, we can infer that many near-Earth asteroids are virtually strengthless.

Asteroid densities. As described in the chapter by Britt et al., many S- and C-type asteroids have higher porosities (≥20%) that the average porosity values derived from various ordinary and carbonaceous meteorites (~10%). These results suggest many asteroids possess substantial macroporosity. The nature of this macroporosity (e.g., cracks between adjacent blocks? void spaces?) is an open question. Additional information about asteroid densities can be found in the chapter by Hilton.

Giant craters. Nearly every observed asteroid (e.g., Ida, Mathilde, Vesta, Eros) contains an impact crater on its surface that is comparable to the average radius of the body itself (see chapters by Chapman and by Sullivan et al.). The fact that these crater-forming impacts did not disrupt the target body implies the interior is highly fractured.

Studies of asteroid collisions via hydrocode and laboratory experiments can also be used to understand collisional evolution in the main belt. As reported in the chapters by Jedicke et al. and Davis et al., the cumulative size frequency distribution (SFD) of observed main-belt asteroids is wavy, with "bumps" at diameter D ~ 3–4 km and 100 km. These waves were something of a surprise, because *Dohnanyi* (1969) predicted that an asteroid population in collisional equilibrium should eventually evolve to a SFD with a cumulative power law slope index of –2.5. Dohnanyi's model, however, also made a number of assumptions: (1) His model asteroids were spherical and had equal densities, (2) the response of his model asteroids to impacts was size-independent, and (3) his model population had no lower cutoff in mass. In the real main belt, none of these assumptions can be considered valid: Asteroids have a variety of different collisional outcomes depending on their physical properties and the target/impactor size, while small bodies escape the main belt via Poynting-Robertson and Yarkovsky forces (see chapters by Dermott et al. and Bottke et al.). An important factor in negating Dohnanyi's assumption of self-similarity in the collision process is the transition between strength- and gravity-dominated scaling regimes that occurs near 100–300 m. As summarized in the Davis et al. chapter, gravity tends to make larger asteroids more difficult to disrupt. Ultimately, this perturbation introduces a wavelike effect into the main belt's SFD that produces the bumps observed at D ~ 3–4 km and 100 km.

3.2. Collisional Outcomes: Ejecta, Satellites, and Families

As described in the chapter by Scheeres et al., one common side effect of asteroid collisions is the production of ejecta and regolith. Data from asteroid polarimetric observations (e.g., *Dollfus et al.,* 1989) have suggested for some time that many large asteroids have regoliths. Interestingly, regolith has also been directly observed on asteroids Gaspra, Ida, Mathilde, and Eros as well as the martian moons Phobos and Deimos. The inferred existence of deep regolith (~10–100 m) on bodies with low escape velocities was unexpected, mainly because laboratory impact experiments had predicted that small rocky asteroids should lose nearly 100% of their ejecta in any given impact event. More recent modeling efforts have shown that the excavation phase of crater formation on a rocky asteroid is dominated by low velocities, such that a significant fraction of a crater's ejecta may remain gravitationally bound to the asteroid. Stranger results are found with porous media; laboratory impact experiments suggest that collisions into asteroids with this internal structure may produce craters primarily by compaction rather than excavation and that little ejecta is produced (see chapters by Britt et al., Asphaug et al., Richardson et al., and Holsapple et al.). These distinctive physical properties may explain why Mathilde's large craters, whose boundaries are adjacent to one another, somehow managed to avoid disturbing one another during their formation. Clearly our insights into these types of bodies will remain limited until we obtain more *in situ* observations of highly porous asteroids.

The fate of low-velocity crater ejecta launched from an asteroid depends on several factors: the asteroid's size, shape, density distribution, and rotation; the trajectory and velocity of the ejecta; and the launch location. Because irregularly shaped asteroids have irregular gravitational fields, orbital dynamics near the asteroid can be surprisingly complex. For this reason, numerical modeling is typically needed to interpret an asteroid's regolith or boulder distribution. Interestingly, these simulations can often be used to identify recent large impacts. For example, the subtle color/albedo variations observed across Ida's surface appear to be associated with the relatively fresh Azzurra Crater, while most of the house-sized boulders observed on Eros appear to have been ejected from the relatively fresh Shoemaker Regio Crater (see chapters by Scheeres et al., Sullivan et al., and Chapman).

Asteroid collisions may also produce asteroid satellites. As described in the chapter by Merline et al., asteroid satellites have now been observed around many main-belt asteroids, NEOs, transneptunian objects, and at least one Trojan asteroid. Several methods have been used to discover these binaries, including direct imaging (e.g., groundbased adaptive optics, HST, spacecraft), delay-Doppler radar techniques (see chapter by Ostro et al.), and sophisticated studies of lightcurve data. Most of the asteroid satellites discovered so far are small compared with their primary, although a few [e.g., (90) Antiope, (617) Patroclus] can be considered double asteroids. Interestingly, the majority of asteroids with satellites appear to be primitive in nature. Assuming this is not a selection effect, it would suggest that the physical properties of primitive asteroids (and their reaction to impacts) play a critical role in satellite formation. More data will be needed to draw a definitive conclusion.

Several possible mechanisms for forming asteroid satellites are discussed by Merline et al. and Paolicchi et al. Although planetary tidal disruptions may be responsible for creating many of the binaries found in near-Earth space (see chapter by Richardson et al.), the most likely scenario for producing binaries in non-planet-crossing populations involves collisions. There appear to be several ways that collisions produce asteroid satellites: (1) Bodies ejected from the impact site with similar trajectories may go into orbit around one another, and (2) gravitational perturbations or collisions between ejected fragments may change their trajectories enough for some fragments to enter into stable orbits around the primary (or each other). Tidal torques between the primary and secondary may also play a role, either by stabilizing orbits or by causing the secondary to crash back into the primary.

Another byproduct of asteroid collisions is asteroid families. As described in the chapter by Zappalà et al., a family is produced when a large asteroid undergoes a catastrophic disruption, leaving behind numerous fragments with similar proper semimajor axes a, eccentricities e, and inclinations i. Proper elements are of critical use in identifying families, since they are quasi-integrals of motion (i.e., they are nearly constant with time). The chapter by Knežević et al. discusses how new synthetic theories allow proper elements (and their errors) to be computed more precisely than previous methods. The means of identifying asteroid families using proper elements is discussed in the chapter by Bendjoya and Zappalà. The two most common methods used to determine family membership are (1) the hierarchical clustering method (HCM), which requires that a given asteroid be located within a given velocity difference, or cutoff velocity, to a neighboring asteroid in proper (a, e, i); and (2) the wavelet analysis method (WAM), which determines asteroid density concentrations within a proper (a, e, i) distribution. Once a family is recognized, the ejection velocities of the family members can be computed using the (a, e, i) differences between the inferred orbit of the original parent body and the current orbits of the family members. Note that this technique assumes that the orbits of the family members (particularly the semimajor axes) have been essentially constant since the family was created. As discussed in the chapters by Nesvorný et al. and Bottke et al., however, nearly all prominent asteroid families may have been spread in (a, e, i) since their formation via resonances and the Yarkovsky effect.

Zappalà et al. also discuss the size-frequency distributions of observed asteroid family members (typically with D > 5–10 km), which tend to have power-law indexes that are steeper than those measured for nonfamily asteroids. If this trend continues to smaller asteroids, it would suggest that families dominate the main-belt population at small sizes. The size-velocity trends measured from asteroid family fragments suggest that ejection velocities for multikilometer asteroids could be several 100 m s^{-1}. If true, family breakup events could potentially flood nearby resonances with fragments, possibly enough to produce an "asteroid" shower on Earth. Observations of asteroid family members, described by Cellino et al., suggest that most family members share similar, but not identical, spectral signatures. While this helps to verify the asteroid identification methods described by Bendjoya and Zappalà, it also suggests that no observed families were derived from the catastrophic disruption of a differentiated object (i.e., no asteroid association looks like it came from the core, mantle, and crust of a Vesta-like body). For this reason, spectral signatures may be used in the future to expand the membership of asteroid families by identifying those members that have evolved away from the family cluster over time.

3.3. Asteroid Geology

With this rudimentary understanding of how asteroids react to collision events, we can examine the geology of the four asteroids visited by spacecraft: Gaspra, Ida, Mathilde, and Eros. As described in the chapters by Sullivan et al., Chapman, Cheng, and Farquhar et al., all these bodies have shapes and surface morphologies shaped by collisions. We briefly review their characteristics below:

(951) Gaspra, an S-type member of the Flora family, has an elongated shape (18.2 × 10.5 × 8.9 km) characterized by broad, flat facets and shallow concavities several kilometers across. It has been suggested that some of these concavities may be ancient craters or spalls. The depth of Gaspra's regolith is at least a few meters, though some studies suggest it could also be significantly deeper. Observed grooves on Gaspra's surface suggest the asteroid may have originated as a single collisional fragment that was fractured or shattered by one or more collisions. The albedo, color, and photometric properties across Gaspra's surface are similar. The size-frequency distribution of Gaspra's craters is surprisingly steep (differential power law slope index of –4.3) and below saturation, such that Gaspra's surface may reveal the shape of the production population's size distribution.

(243) Ida, an S-type member of the Koronis family, is elongated (29.9 × 12.7 × 9.3 km) and has an irregular surface covered by impact craters as large as 12 km. Ida appears to be billions of years old, with its surface saturated in D < 1 km craters and several large craters showing signs of significant degradation. Observations of boulders, shallow mass-wasting features, grooves, and infilled craters all suggest that Ida possesses a substantial regolith, perhaps 50–100 m deep. The grooves themselves, some 4 km long, suggest that collisions have fractured or shattered the asteroid. Ejecta blocks can be found in several locations, with their distribution suggesting they are impact products derived directly from the largest craters or that they were swept up after an impact event by the leading rotational edge of Ida. Ida also has a satellite named Dactyl that has an average radius of 0.7 km. Color data and photometric modeling suggest Ida/Dactyl have similar compositions and surface textures.

(253) Mathilde, a C-type asteroid, was encountered by the *NEAR Shoemaker* spacecraft. Although only a fraction of Mathilde's surface was imaged, a best-fit ellipsoid suggests its shape is 66 × 48 × 46 km. Mathilde's surface is dominated by several large craters with diameters that exceed the asteroid's average radius. Despite this fact, there is no evidence that these craters ever interfered with one another; no ejecta blankets, ejecta blocks, or grooves have been observed. The density of Mathilde is ~1.3 g cm^{-3}, low enough to imply that this body may be highly porous (although it is not known whether it is macroporosity or microporosity). No spectral or albedo contrasts can be seen.

(433) Eros is an S-type near-Earth asteroid that was the final destination of the *NEAR Shoemaker* spacecraft. It has a curved shape and a length of 34 km. While the largest craters on Eros are Himeros (9 km), Shoemaker (7.6 km), and Psyche (5.3 km), most of the house-sized blocks observed on Eros's surface appear to have been produced by the Shoemaker impact. The entire surface is covered by regolith, although its thickness is uncertain. An examination of Eros' surface morphology and gravitational field suggests the asteroid was once a single ejecta fragment that was fractured or shattered by subsequent impacts. One of the most curious features on Eros is its ponded deposits, flat regions that cover the bottoms of some depressions. These deposits are concentrated within 10° of the equator. The mechanism that produced the ponded deposits is unknown, although seismic shaking and electrostatic levitation are the leading candidates. Most of Eros' impact craters were produced while it was a member of the main belt, since (1) Eros has only recently evolved out of the main belt, and (2) the impact flux on main-belt asteroids (or those crossing into the main belt) is several orders of magnitude higher than

impact rates on the Moon or those near-Earth asteroids collisionally decoupled from the main belt. The size distribution of Eros' D > 100 m craters is similar to Ida, while there is a notable deficiency of D < 100 m craters. The reason why Eros has so few small craters is unknown.

We believe this list could be readily expanded to include (4) Vesta, which has been closely examined both by HST observations and laboratory studies of HED meteorites (Dotto et al., Keil, Burbine et al., Scott), and several near-Earth asteroids extensively explored by radar (Ostro et al.). The power of various remote sensing techniques has reached the point that we are now capable of doing many things that were once the purview of spacecraft alone.

3.4. Dynamical Evolution of Main-Belt Asteroids

Since the publication of *Asteroids II*, our understanding of the dynamical evolution of asteroids has undergone significant advances. Propelled by the advent of symplectic integration algorithms and inexpensive but powerful workstations, numerical models are now capable of tracking the often chaotic orbital paths taken by test bodies for tens to hundreds of millions of years while including all gravitational perturbations produced by the planets. These timescales, which are orders of magnitude longer than the best integrations available a decade ago, have allowed us to develop a much deeper comprehension for how main-belt asteroids are transported to escape hatches that can take them out of the main belt and into the inner solar system.

Our advances in this field have come in two main areas:

1. *Effects of mean-motion and secular resonances.* As described in the chapters by Nesvorný et al. and Morbidelli et al., tremendous progress has been made in our understanding of how resonances modify the eccentricities and inclinations of main-belt and planet-crossing asteroids. It has been shown that test bodies entering several powerful mean-motion resonances with Jupiter (e.g., 3:1, 4:1, 5:2) can have their eccentricities pumped up to Earth-crossing values, usually over timescales of ~1 m.y. In some cases, orbital motion inside these resonances is chaotic enough that test bodies can be pushed directly onto Sun-grazing orbits. Similarly, the ν_6 secular resonance lying along the inner edge of the main belt is now seen as one of the primary sources of near-Earth objects (NEOs). Less dramatic but also important are the narrow mean-motion resonances produced by Mars and Jupiter and the three-body resonances produced by Jupiter and Saturn. These weaker but far more numerous resonances crisscross the main belt, such that most asteroids do not have to travel very far to interact with them. In some cases, these resonances can push main-belt asteroids onto Mars-crossing orbits, although over longer timescales than those described above (e.g., 10^7 to 10^9 yr).

2. *Effects of Yarkovsky thermal forces.* Nongravitational forces have been shown to play an important role in allowing asteroidal material to escape the main belt. As described in the chapter by Bottke et al., small bodies orbiting the Sun absorb sunlight, heat up, and reradiate the thermal energy after a short delay produced by thermal inertia. This emission, while tiny, produces a force that can lead to secular changes in the object's semimajor axis. This so-called "Yarkovsky effect" compels 0.1-m to 20-km bodies to slowly spiral inward or outward as a function of their spin, orbit, and material properties. A variant of this force called YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) is also capable of modifying the spin rates of asteroids.

Prior to these advances, it was generally believed that most NEOs and meteorites escaped the main belt by being directly injected by collisions into one of several powerful resonances (e.g., the ν_6 secular resonance or the 3:1 mean-motion resonance with Jupiter). As described by Bottke et al., however, this scenario is inconsistent with observations, numerical simulations of catastrophic collisions, and the cosmic-ray exposure ages of meteorites. A better scenario for how asteroids and meteoroids are delivered from their parent bodies in the main belt to the inner solar system (and Earth) is the following: (1) An asteroid undergoes a catastrophic disruption or cratering event and ejects numerous fragments; most are not directly injected into a resonance. (2) D < 20 km fragments start drifting in semimajor axis under the Yarkovsky effect. (3) These bodies jump over or become trapped in chaotic mean-motion and secular resonances that change their eccentricity and/or inclination. (4) Asteroids drifting far enough may fall into mean-motion or secular resonances capable of pushing them onto planet-crossing orbits. From here, they become members of the Mars-crossing and/or NEO populations.

At smaller size scales, Dermott et al. describes how interplanetary dust particles (IDPs) produced by asteroid collisions drift out of the main belt via Poynting-Robertson drag, a radiation effect that causes small objects to spiral inward as they absorb energy and momentum streaming radially outward from the Sun and then reradiate this energy isotropically in their own reference frame. Millions of metric tons of dust are delivered every year to Earth by this process. The interaction between these drifting IDPs and resonances can produce interesting effects. For example, both IRAS and COBE data have detected an Earth-resonant dust ring. It is produced when asteroid dust spiraling toward Earth becomes temporarily trapped in a co-rotation resonance near 1 AU. Eventually, the eccentricities of the dust particles get high enough to escape the resonance, allowing some to strike Earth.

4. THE NEAR-EARTH-OBJECT POPULATION

The near-Earth object (NEO) population, including both asteroids and active/extinct comets, are defined as those bodies having perihelion distances q ≤ 1.3 AU and aphelion distances Q ≥ 0.983 AU. Subcategories of the NEO population include the Apollos (a ≥ 1.0 AU, q ≤ 1.0167 AU) and Atens (a < 1.0 AU, Q ≥ 0.983 AU), which are on Earth-crossing orbits, and the Amors (1.0167 AU < q ≤ 1.3 AU), which are on nearly-Earth-crossing orbits. A population inside Earth's orbit (Q < 0.983 AU) is also expected to exist (see Morbidelli et al.). Evidence from the lunar cratering record suggests that the NEO population has been in steady-state for roughly the last 3 G.y. and has been comprised of bodies ranging in size from dust-sized fragments to objects tens of kilometers in diameter. Even so, temporary NEO showers following energetic collisional events in the main belt cannot be ruled out (Zappalà et al.).

Most NEOs are believed to be fragments of main-belt asteroids that, following ejection in a collision event involving a larger asteroid millions of years ago, evolved via resonances and nongravitational forces until reaching an Earth-approaching orbit. The rest are thought to be ejected members of comet reservoirs in the outer solar system, namely the Kuiper Belt and the Oort Cloud. In much the same way that rocks and sediments in a riverbed yield information on the types of material found upstream, the NEOs (and meteorites) can reveal a great deal about the nature of the bodies found in all asteroid and comet reservoirs. The majority of attention given to NEOs, however, is unrelated to their intrinsic scientific value; instead, it concerns the fact that a collision between a multikilometer asteroid/comet and Earth could potentially wreak regional-to-global devastation on our biosphere. For this reason, it is important that we understand the NEO population and the potential threat it represents to humanity.

4.1. Detecting Near-Earth Objects

The search for NEOs is described in the chapter by Stokes et al. Over the last decade, an increasing number of dedicated surveys (e.g., Spacewatch, LINEAR, LONEOS, Catalina Sky Survey, NEAT) have come on line to scan the skies for NEOs. In that time, the number of known NEOs has jumped from roughly 100 to well over 1000. At present, it is believed that over 50% of the objects with absolute magnitude H < 18 (i.e., roughly D > 1 km objects) have been discovered out to a semimajor axis a < 7.4 AU. This significant rise in productivity stems from several factors: a political recognition of the potential threat to Earth from NEOs, which in turn led to greater resources and more dedicated telescopes; a switch from visual detection via photographic searches to more sophisticated automated searches via sensitive CCD detectors; and an increase in available computing power. The immediate goal of these search programs is to find 90% of the kilometer-sized NEOs by 2008 (i.e., it is thought that an Earth impactor with a diameter larger than about 1 km could potentially produce global catastrophic consequences for human life on Earth; see chapter by Morrison et al.). Reaching that desired level of completeness, however, may be complicated by the fact that some NEOs are more difficult to detect than others.

Once a NEO has been detected, it is important to determine its orbit as precisely as possible and then compute whether the body has any chance of striking Earth in the near future. Chapters by Bowell et al. and Milani et al. discuss in detail the technical side of these issues.

4.2. Modeling the Near-Earth-Object Population

The remarkable progress made in finding NEOs over the last decade has also been accompanied by substantial numerical and theoretical work. Together, these advances give us a much more profound understanding of the orbital and size distribution of the NEO population than we had at the time of *Asteroids II*. In particular, advances in two areas have allowed us to compensate for a paucity of direct information on the nature of the NEO population:

1. *Observational biases.* Every NEO survey is limited by several factors: the orbits, sizes, and albedos of the bodies; the capabilities of the detector (e.g., limiting magnitude, degree of sky coverage); the software applied to sift asteroids and comets from the background; and factors related to the physical location of the site (e.g., weather, distance from city lights). The effects of these components on asteroid and comet detection are known as observational bias. As explained in the chapter by Jedicke et al., once these biases are understood and mathematically modeled, it is possible to take an observed population sampled by various surveys and deduce the properties of the actual population, even though many of the objects in that population remain undetected. Jedicke et al. describe the bias-corrected absolute magnitude distribution of several small-body populations: NEOs, main belt, Trojans, Centaurs, and the transneptunian objects.

2. *Dynamical pathways taken by near-Earth objects.* To determine the orbital distribution of the NEOs, it is important to understand how NEOs travel from their source regions to the observed orbits and their ultimate demise (i.e., elimination by striking the Sun, a planet, or being ejected out of the solar system). This type of modeling can be challenging, particularly because NEOs come from numerous regions inside (or adjacent to) sources like the main asteroid belt, transneptunian region, and/or Oort Cloud. As described in chapters by Morbidelli et al. and Weissman et al., tracking the evolution of thousands of test bodies from these source regions via numerical integration has allowed us to put together a picture of where test bodies from these regions are statistically most likely to spend their time.

By combining these components together, Morbidelli et al. and Weissman et al. explain how the evolution of asteroids and comets respectively can be used to compute a reasonably accurate model of the debiased orbital and absolute magnitude distribution of the NEO population as well as a measure of the relative importance of each distinctive NEO source region.

It is also possible to derive information on the NEO populations from the crater size-frequency distribution found on the terrestrial planets. As described in the chapter by Ivanov et al., the "wavy" shape of the crater size-frequency distributions found on the Moon and Mars are similar to the size-frequency distributions inferred for the main-belt population. This relationship suggests that (1) the planet-crossing object population may be dominated by asteroids (unless cometary impactors have a comparable size distribution to that found in the main belt) and (2) the planet-crossing objects are mainly replenished by bodies diffusing out of a main-belt population in collisional equilibrium. Using crater-scaling laws and estimates of the physical parameters and crater rates on the Moon and Mars, Ivanov et al. "back out" the shape of the planet-crossing asteroid population. To reasonable accuracy, their results appear to be consistent with estimates provided by more direct observational methods.

4.3. Near-Earth-Object Shapes

In the past decade radar studies of asteroids have provided accurate information on NEO shapes, surface properties, and rotation rates/states. The observational methods and results of radar astronomy are discussed in the chapter by Ostro et al. Most of the asteroids investigated in detail by radar are NEOs, primarily because the echo's signal-to noise ratio goes as (distance)$^{-4}$ (i.e., as the object approaches Earth, the radar return gets significantly stronger). If the target echoes are strong enough to get good resolution in both time delay (range) and Doppler frequency (radial velocity), it is possible to construct an accurate three-dimensional model of the object's shape as well as its precise spin state. These results indicate that asteroids come in all shapes and sizes, from featureless spherical balls to irregularly shaped objects with craggy, bumpy, and/or cratered surfaces. One main-belt object, (216) Kleopatra, even has the shape of a dog bone! Radar studies also show that some NEOs are in complex rotation states [e.g., (4179) Toutatis] and that a few have satellites (see chapters by Pravec et al. and Merline et al. for more information on these topics).

Additional information on asteroid shapes can be mined from photometric data. As described in the chapter by Kaasalainen et al., new lightcurve inversion techniques are making it possible to determine unique solutions for convex ("hull") shapes. These shape models mimic asteroid silhouettes in three dimensions, such that they provide reasonable facsimiles of asteroids like (951) Gaspra and (433) Eros. The future of this technique is very promising, particularly since it might be used to analyze nearly any asteroid that can be modeled as a triaxial ellipsoid.

4.4. Linking Meteorites and Near-Earth Objects to their Parent Bodies

An important goal of asteroid science is to link meteorites and their immediate precursors back to their parent bodies. To accomplish this task, we need to combine data from several different disciplines: dynamical modeling, spectroscopic observations, petrology, and mineralogy. It is difficult work, but enough progress has been made over the last decade that some positive connections can be described.

Spectroscopic observations tell us about composition of material on an asteroid's surface. Over the last decade, asteroid spectra have become an increasingly rich source of information on asteroid physical properties, particularly after CCD technology was incorporated into spectrographs. Understanding the detailed mineralogy derived from spectroscopic measurements has been a long-term goal and current progress and challenges are described herein by Gaffey et al. As reviewed in the chapter by Bus et al., survey results now suggest that the main-belt population contains some 26 different taxonomic types. Most of these taxonomic types can also be found within the NEO population. As discussed by Binzel et al., the NEO population appears to be, more or less, a representative sample of the taxonomic types found in the inner and central main-belt populations. These include V-type asteroids, which are thought to be derived from (4) Vesta, and E-type asteroids, which may be predominantly derived from the Hungaria asteroid region (i.e., the Hungarias are non-Mars-crossing asteroids with $1.77 < a < 2.06$ AU and $i > 15°$).

At present, roughly 80% of the NEOs with known taxonomic types are bright, S-type (or Q-type) bodies. As Binzel et al. point out, however, this value should be used carefully because dark C-type asteroids have lower albedos than S-types and thus are less numerous for a given absolute magnitude than their S-type counterparts. The fraction of observed NEOs with low albedos gradually increases as you move to larger semimajor axes, reflecting a comparable albedo gradient seen among the main-belt asteroids. NEOs residing in the Jupiter-family comet region are consistent with this trend; many are thought to be extinct comets. As discussed by both Weissman et al. and Binzel et al., extinct comet candidates generally have featureless spectra with flat to slightly increasing red slopes spanning the dynamic range between C- to D-type asteroids.

One of the major problems remaining since *Asteroids II* has to do with the mysterious source of the ordinary chondrite parent bodies. It has been suggested that ordinary chondrites, ordinary chondrite-like NEOs, and S-type asteroids are genetically related, primarily because they all appear to have similar spectral features. Evidence supporting this idea comes from observational work described in Binzel et al., where the spectra of several NEOs show a clear transition between S-type asteroid and ordinary chondrite-like spectra, and from the spectral features of (243) Ida, where ejecta associated with the relatively young Azzurra Crater appears to have spectral features that trend toward those of ordinary chondrites (see Scheeres et al., Sullivan et al., and Chapman). Still, the mechanism producing this transition has remained enigmatic. As described by Clark et al., a possible solution to this issue could be the surface modification processes commonly known as "space weathering." Space weathering is defined as any process that changes the spectroscopic properties on airless bodies. Processes that produce space weathering are impacts, solar-wind ion implantation, sputtering, and micrometeorite bombardment. Based on an analysis of lunar samples that show clear signs of space weathering, it has been suggested that space-weathering processes observed on asteroids may be caused by the deposition of condensates bearing submicroscopic Fe onto grain surfaces. The condensates are produced when the target material is vaporized, presumably by solar-wind sputtering and micrometeorite bombardment. For this process to work effectively, the target material must contain an abundance of Fe. Thus, asteroids with olivine-rich surfaces, like ordinary chondrites and S-type asteroids, are more likely to undergo optical maturation processes than those rich in pyroxene, like the HED meteorites or the basaltic crust of (4) Vesta. Other important factors may include (1) the impact energies of those micrometeorites striking the target, (2) the age of the surface, and/or (3) the ability of the object to retain regolith.

Finally, the chapter by Burbine et al. tries to put together the big picture and discuss whether various meteorite classes can be linked to specific parent objects in the main belt. For example, Burbine et al. presents the meteoritic and spectroscopic evidence (pro and con) that (1) ordinary chondrites are linked to the S-asteroids [i.e., specifically, the S(IV)-type asteroids], (2) CM chondrites were produced by the C-type asteroids, (3) iron meteorites and enstatite chondrites come from M-type asteroids, and (4) the HED meteorites come from (4) Vesta. Although several of the matches are compelling, Burbine et al. admit that most of the postulated parent bodies (with the possible exception of Vesta) do not have enough singular spectral features to conclusively link them with a meteorite class. In many cases, these issues may not be fully settled until spacecraft missions can return main-belt asteroid samples to Earth.

4.5. Impact Hazard

While many now recognize that the threat to life on Earth from impacting NEOs is real and important, it is less clear what we should do about it. From a policy perspective, one would expect that the resources devoted to this issue should be correlated with the perceived level of risk. Unfortunately, humanity has a mixed track record in dealing with the sometimes severe consequences that come solely from low-probability events (e.g., communities are often allowed to build homes on flood plains). For these reasons, the chapter by Morrison et al. reexamines the impact hazard issue and attempts to guide a path through the complicated policy issues that lie in front of us. Current estimates suggest that impacts capable of producing a global ecological catastrophe occur roughly twice per million years. The reaction to this perceived threat over the last decade has been remarkable; through hard work and persistence, scientists and issue advocates appear to have placed the impact hazard issue onto the radar screens of politicians from around the world. The outcome of this debate is still unclear, with budgetary constraints and competing priorities within the scientific community threatening to slow or even stop progress. Hopefully, by the time *Asteroids IV* is written, a much more complete picture of the asteroid and comet hazard issue will have emerged, enabling scientists, governments, and the public to deal with it effectively through international cooperation.

5. PREDICTING THE FUTURE

As the great baseball philosopher Yogi Berra reportedly said, "The hardest thing to predict is the future." With that in mind, we speculate on a few of the issues that might show up in *Asteroids IV*.

We believe it is likely that data from the least-studied portion of the main belt, namely the outer main belt and the Trojan populations, may become a major research goal as the search for the source of Earth's water budget becomes more extensive. The connection (or lack thereof) between these regions and the volatile content of the other terrestrial planets, particularly Mars, will also increase in importance. Several additional topics should also continue to stimulate inquiry among dynamical modelers, observers, and meteoriticists alike: (1) What can the current configuration of the main belt tell us about the processes that shaped planet formation? (2) What can the observed population of asteroids and/or meteorites tell us about the primordial asteroids that disappeared early in solar system history? (3) Was the main belt significantly shaped by the events producing the Late Heavy Bombardment, and/or was it an important source of impactors? (4) How have stochastic events (e.g., the breakup of a D > 100 km asteroid) changed the flux of material reaching Earth over time? (5) How do the physical properties of asteroids vary as a function of taxonomic type and how do they affect geologic processes like collisions? (6) What are the similarities and differences between outer main-belt asteroids, Trojan asteroids, and extinct comets? (7) How has the impactor flux of asteroids and comets varied with time? (8) How have asteroid and comet impacts affected the evolution of life on all the planets of the solar system?

From a numerical modeling perspective, we expect that faster computers and advanced codes will allow us to accurately simulate collisions between porous objects, such that impacts onto asteroids like Mathilde can be readily understood. They may also allow us to simultaneously track the collisional and dynamical evolution of millions of interacting bodies (with all appropriate physics included). These advances will eventually allow us to model the formation of the solar system (and main belt) without making too many oversimplifications. We also expect advances in several areas, including (but not limited to) such fundamental physics as the scattering of light by solid surfaces (see Muinonen et al.), the effect of nongravitational forces on the dynamical evolution of asteroids, and the inferred equilibrium shape of asteroids only partially dominated by gravity.

Our understanding of asteroid regolith properties may also be on the cusp of some important advances. Recent radiometric studies indicate that several small NEOs might exhibit radiometric-derived albedos that are unexpectedly high for their taxonomic class. These results, if confirmed, would suggest that the thermal and physical properties of asteroid surface regolith layers change as a function of asteroid diameter, possibly enough to have significant implications for the dynamical evolution of small bodies (e.g., Bottke et al.) and for our understanding of how asteroids scatter light (e.g., Muinonen et al.).

Spectroscopic observations of asteroids will be increasingly extended to near-infrared wavelengths owing to the development of increasingly sensitive detectors and a grow-ing cadre of larger-aperture telescopes. These advances in capabilities will allow asteroids at smaller sizes to be observed and allow increasing sophistication in the interpretation of their mineralogic and petrologic properties. With increasing knowledge of these properties, for example within asteroid families, we can look forward to advances in our revelation of the properties of asteroid interiors. Undoubtedly, these advances will also challenge our understanding of the early solar system evolutionary processes that are recorded within these remnant planetesimals.

Finally, we anticipate that data provided by the upcoming asteroid missions described in the chapter by Farquhar et al. will overturn at least some of the ideas proposed in *Asteroids III*. It is even possible that the upcoming *Dawn* mission to Ceres and Vesta will help to reestablish these objects as planetary worlds (e.g., *Stern and Levison,* 2002). Note that the chapter by Foderà Serio et al. describes how Ceres shortly held planetary status until it was demoted for unspecified reasons. *Asteroids IV* may also contain data from the first asteroid sample return mission. If so, we should be able to make our first direct links between several meteorite classes and their parent bodies in the main belt. Regardless, our understanding of asteroid physical properties will continue to grow by leaps and bounds as a consequence of both groundbased and *in situ* observations.

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