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Asteroids: Recent Advances and New Perspectives

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1. INTRODUCTION

Asteroids are thought to be leftover planetesimals that are closely related to the precursor bodies that formed both the terrestrial planets and the cores of the giant planets. The most primitive ones contain a record of the original composition of the solar nebula in which the planets formed. The organic matter and properties of water that some contain provide us with critical clues about how life started on Earth. Moreover, some of them cross the trajectory of our planet and therefore pose a risk to humanity.

The sizes, shapes, and rotational, internal, and surface properties of asteroids are the outcome of collisional and dynamical evolution that has molded them since they formed. Understanding the processes they experienced, how these mechanisms changed their properties, and how these factors in turn influenced their evolution can serve as a tracer to tell us the story of the solar system.

In 2005, the European Space Agency published its report *Cosmic Vision: Space Science for Europe in 2015–2025,* which contained two questions related to asteroid research: (1) what are the conditions for planet formation and the emergence of life? (2) How does the solar system work?

Similarly, in 2012, the committee on the planetary science decadal survey appointed by the U.S. National Research Council published a list of questions intimately related to asteroid research. We repeat here those that help put into context the work that is presented throughout *Asteroids IV*: (1) What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated? (2) What solar system bodies endanger Earth's biosphere, and what mechanisms shield it?

In addition, the decadal survey indicated the goals for research on primitive bodies for the next decade: (1) Decipher the record in primitive bodies of epochs and processes not obtainable elsewhere, and (2) understand the role of primitive bodies as building blocks for planets and life.

Important questions related to asteroids in various areas were then indicated, some of which include:

- Which classes of meteorites come from which classes of asteroids, and how diverse were the components from which asteroids were assembled?
- Did asteroid differentiation involve near-complete melting to form magma oceans, or modest partial melting?
- What are the internal structures of Jupiter's Trojan asteroids? Are there systematic chemical or isotopic gradients in the solar system, and if so, what do they reveal about accretion?
- Do we have meteoritic samples of the objects that formed the dominant feeding zones for the innermost planets?
- How did Earth get its water and other volatiles? What is the mechanical process of accretion up to and through the formation of meter-size bodies?
- Which classes of asteroids participated in the late heavy bombardment of the inner planets and the Moon, and how did the current population of asteroids evolve in time and space?
- What are the sources of asteroid groups (e.g., Trojans) that remain to be explored by spacecraft?

It is clear that the solutions to these questions will allow us to glean insights into many fundamental planetary science problems, in particular those connected to the formation and evolution of our solar system.

Since the last book in this series, *Asteroids III*, we have made tremendous advances in our knowledge of asteroids, thanks to the combined efforts of ground- and spacebased observations, space mission rendezvous and flybys, laboratory analysis of returned samples, and theoretical and numerical modeling. In *Asteroids IV*, major strides have been made in the long journey that will eventually lead us to a much deeper understanding of our planetary ancestors. In the words of the classic Californian science fiction radio show *Hour 25*, our progress has all of us now "standing on the verge of new worlds, new ideas, and new adventures."

This book reviews these major advances in 42 chapters, with the aim of being as exhaustive as possible while also remaining accessible to students and researchers who are interested to learn about these fascinating bodies and what they tell us about solar system history. Here we introduce the major concepts and topics of this book and highlight some of the major advances that have been made since *Asteroids III*. This introduction does not include references except from the chapters themselves.

2. ASTEROID FORMATION AND SOLAR SYSTEM EVOLUTION

Many major improvements have been achieved in solar system dynamical studies since *Asteroids III*. As discussed in the review chapter by Johansen et al., new modeling work on the very early phases of planetesimal growth, together with constraints derived from meteorites and protoplanetary disks, have inspired next-generation scenarios of how the largest asteroids originated. Simulations of the evolution of turbulent gas and dust in protoplanetary disks demonstrate that 100- to 1000-km-diameter asteroids may have formed directly from the gravitational collapse of small particles that organize themselves in dense filaments and clusters. Although many open questions remain, these models provide a potential solution to the long-standing issue regarding the passage from centimeter-sized particles to asteroidal bodies in planetary growth studies, bypassing the long-standing "meter-size barrier."

In effect, laboratory experiments have shown that micrometer-scale dust readily aggregates into millimeter- or even pebble-sized agglomerates. On the largest scales, impact simulations have shown that self-gravity among two colliding protoplanets ensures net growth, although the efficiency of two planetesimals combining is often less than 100% (see the chapter by Asphaug et al.). The situation is still murky for objects ranging in size from millimeters to kilometers. In fact, macroscopic dust particles (millimeter or larger) have poor sticking properties in particle-particle collisions, while gravity between the components is too low to act as a "glue" between them. Johansen et al. discuss how the self-gravity of a sufficiently massive particle clump may be capable of growing bodies in this size range.

Several dynamical scenarios have also emerged to describe the early phases of the solar system, with the observed properties of the asteroid belt acting as a constraint (see chapter by Morbidelli et al.). They indicate that the asteroid belt has been sculpted by one or possibly a series of processes, and that this evolution can be characterized by three phases.

The first phase starts during the lifetime of the gaseous protoplanetary disk when the giant planets formed. Here the giant planets may have undergone migration as they gravitationally interacted with the solar nebula. One of the new scenarios describing this phase, which involves the migration of Jupiter through the asteroid belt, is called the "Grand Tack." It is capable of producing dynamical excitation among the existing asteroids, forcing many out of the region where the main belt currently lies, while also introducing new low-albedo asteroids into the main belt from the Jupiter-Saturn zone. This could have left the population in a state similar to the observed main belt, with a low-mass population having a wide range of eccentricities, inclinations, and compositions.

The second phase occurs later, possibly as late as ~4 G.y. ago or nearly 500 m.y. after the removal of the gaseous protoplanetary disk. Once again, the giant planets became temporarily unstable, such that some of them may have strongly interacted with a large primordial disk of comet-like planetesimals located in the outer reaches of the solar system. This allowed the giant planets to migrate from an initial resonant and compact configuration to their current configuration. The instability may also have led to the additional loss of asteroids from the main-belt region. The so-called "Nice model" provides a description of this evolutionary phase. The strength of this model is that it naturally reproduces various observed constraints within a single model, such as the current semimajor axes, eccentricities, and inclinations of giant planets; the curious existence of Trojan asteroids, a population that is reviewed by Emery et al.; and the structure of the Kuiper belt beyond Neptune. The Nice model also provides a possible explanation to the origin of the so-called late heavy bombardment, which some argue produced numerous younger basins on the Moon and terrestrial planets.

The studies of these first two phases provide us with new insights into how and where planets formed, with implications for the dynamical history of the asteroid belt and the diversity of compositions observed in the relatively narrow ~1-AU-wide main asteroid belt, as reviewed by DeMeo et al. These new scenarios together describe an evolutionary process that could lead to a solar system with properties that are consistent with the observed one. The aforementioned constraints, however, are challenging, and it is possible that the new scenarios will founder as they are tested in detail. Therein lies the new science that will comprise *Asteroids V* in the decade or more to come.

The third phase, reviewed by Morbidelli et al., covers the interval between late giant planet migration until today. Potentially as much as half the asteroid population was lost via depletion taking place at unstable resonances with the giant and terrestrial planets, mostly during the subsequent 100 m.y. after late planet migration took place.

Additional constraints on these ideas come from models of the collisional evolution of the asteroid belt. As reviewed by Bottke et al., the latest generation of model results suggests that the main belt's wavy size-frequency distribution describes a primordial population dominated by 100-km-diameter and larger objects (see Johansen et al.) that undergoes sufficient comminution to create much of the observed population of <100-km bodies. The shape of the size distribution created in this process can then be considered something of a fossil-like remnant of a violent early epoch. This left the main-belt size distribution in a collisional quasisteady state, and it has possibly been that way for billions of years.

Insights from collisional evolution models, however, rely strongly on our understanding of the physics of collisional disruption events. Scaling laws are needed to define the results of two-body collision results, and precise expressions are needed to define the nature of the fragment size frequency and ejection velocity distributions. As reviewed by Asphaug et al. and Jutzi et al., numerical modeling has become an important method for studying global-scale impacts and asteroid collisions. Moreover, impact experiments remain an important activity that has greatly improved our understanding of the impact process at small scales.

Since *Asteroids III*, computational resources, numerical methods, and impact experiments have all led to a new understanding of the impact process at both large and small scales. Several material models introduced in shock physics codes, with some of their results validated by comparison with laboratory hypervelocity shot experiments, now allow us to better account for the diversity of asteroid properties that affect collision outcomes. In particular, porosity models have been introduced to account for the influence of microporosity in the fragmentation process. Porosity helps to dissipate a portion of the impact energy into the crushing of pores, which results in compaction. This makes porous asteroids more resistant to disruption against impact than expected (see Jutzi et al.). The importance of the shear strength, and its dependency on the confining pressure produced by asteroidal self-gravity, is reviewed by Asphaug et al. They find that when this kind of friction is introduced, the impact energy threshold for disruption can increase by a factor of 5 to 10. The disruption threshold further increases by a factor of 2 to 3 when the energy dissipation by compaction (pore crushing) is taken into account.

The implications of these results are that many collision events previously considered catastrophic, defined as half the combined mass of the projectile and target flying away at escape velocity, are instead more likely to produce a shattered target that remains in possession of much of its mass. As collisional evolution models begin to take these results into account, new possible evolutionary histories of the asteroid belt may reveal themselves.

3. ASTEROID DIFFERENTIATION

Another issue that has made major advances since *Asteroids III* is asteroid differentiation. It was originally expected that asteroids that formed early and large enough to heat up enough from the decay of short-lived radioactive isotopes such as ^{26}Al and melt would eventually form an iron core, olivine-rich mantle, and basaltic crust. Thus all differentiated bodies, large or small, would look like little Vestas. Observational evidence for the mantle material among the known asteroids was lacking, thereby raising the question of "Where is the missing mantle material?" Scheinberg et al. describe differentiation models, including the possibility of partial differentiation, whereby some asteroids may have experienced enough melting to form differentiated interiors but still preserve primitive surface layers. The salient point here is that not all magmas are buoyant; some are happy to reside at depth rather than propelling themselves to the surface. Thus, the old adage that one cannot judge a book by its cover may be particularly appropriate here.

The possible sources of asteroid heating in the early solar system are summarized by Wilson et al. They describe the physical transport of magma in an asteroid during the differentiation process. Because most of our evidence of and information about asteroid differentiation comes from meteorite fragments of differentiated asteroids, these samples can be used to establish a chronology for asteroid formation, differentiation, and subsequent disruption of these differentiated bodies (see chapter by Scott et al.).

4. ASTEROID FAMILIES

Collisional evolution models have various constraints that they must reproduce to be validated, as Bottke et al. discuss in their review chapter. A critical one is the number and precise nature of asteroid families. An asteroid family is a group of asteroids that share similar orbital and compositional properties. They have long been thought to originate from the collisional disruption of parent asteroids. It is only in the last decade, however, that the collisional origin of asteroid families has been directly demonstrated by numerical simulations, as reviewed by Michel et al. By including both physical and dynamical effects, such as fragmentation and the gravitational self-attraction of components after a disruption, runs from these codes show that the catastrophic disruption of bodies larger than a few hundred meters in diameter will lead to reaccumulation of debris and the formation of large gravitational aggregates. This potentially solves the mystery of how very large members within asteroid families might form. Without this reaccumulation process, family members produced solely by the fragmentation phase would tend to be very small because the impact energy needed to reproduce the observed ejection speeds is too high to create large monolithic fragments.

Numerical simulations also benefit from the identification of very young families whose properties are the direct outcomes of parent body disruption events. These properties can be directly compared with numerical simulation outcomes, while the dispersion of older families is affected more by post-collision and dynamical processes. Through a careful comparison, we can obtain constraints on the internal structure of family members and the initial state of the parent body from which they came, while also probing the initial dynamical state of the new family. The results of this exercise show that the outcome of a parent body disruption depends strongly on the nature of its internal structure.

Since *Asteroids III,* the inventory of asteroid families has been steadily increasing as surveys continue to find new main-belt bodies. At the same time, several dedicated programs and sky surveys have produced an abundance of physical observations; nearly 2 orders of magnitude more asteroids have been characterized in some fashion than had been done a little more than a decade ago. This has set the stage for huge advances in our knowledge of families, as reviewed in the chapters by Nesvorný et al. and Masiero et al. Progress includes the discovery of several very young families, new data to better understand the full reach of specific families, and new tools that allow us to determine the dynamical evolution of families by nongravitational forces and date their approximate age.

A key advance in this work has been the comprehensive measurements of asteroid colors by the Sloan Digital Sky Survey and albedos by the Wide-field Infrared Survey Explorer (WISE) infrared telescope. These spectacular datasets also allow us to search for how the surface properties of different family members might vary from object to object. This could help us identify heterogeneity in the composition of the parent body. More critically for impact simulations aiming to reproduce the initial size frequency and ejection velocity distributions of family members, diameter measurements lead to improved estimates of the size-frequency distribution of family members as well as estimates of the original parent body sizes. These data are a rich and diverse source of new information about this history of the main belt.

5. ACTIVE ASTEROIDS

One of the more remarkable observational discoveries of the last decade is that some main-belt bodies eject small particles that lead to transient, comet-like comae and tails. These peculiar objects are called active asteroids, and are discussed in Jewitt et al. They are particularly remarkable for being an entirely new population located in one of the closest and most intensively studied regions of the solar system.

There are many plausible causes of this activity. They include impact ejection and disruption, rotational instabilities, electrostatic repulsion, radiation pressure sweeping, dehydration stresses and thermal fracture, as well as ice sublimation. The evidence suggests that one size does not fit all, and a good physical mechanism for activity for one object may not be a good fit for another. We expect substantial advances will be made in this area over the years between the publications of *Asteroids IV* and *V.* These processes also imply that the difference between asteroids and comets in terms of surface activity may be smaller than previously thought, supporting the idea of an asteroid-comet continuum.

6. WATER IN ASTEROIDS

While the search for extraterrestrial water has always been a priority in solar system science, particularly with NASA's "follow the water" space mission priorities, it has only recently become a big topic in asteroid science. Even though evidence of aqueous alteration on asteroids has long been known, the direct evidence of water or ice has been limited. *Asteroids IV* has a number of chapters dedicated to recent advances in understanding the role of water on or in asteroids. As described above, the discoveries of activated asteroids covered by Jewitt et al. have great implications for better understanding the relationship between asteroids and comets. Rivkin et al. present observational evidence for water and hydration on asteroids detected from visible to mid-IR wavelengths. They also discuss possible explanations for the presence of water or hydroxyl detections on asteroid surfaces; these explanations include not only the formation of those asteroids in an ice-rich environment, but also space weathering processes and the delivery of exogenic material. Among chondrites that accreted ices during formation, the chapter by Krot et al. describes the degree of aqueous alteration among chondrite types, their implications for the likely locations of the snow line early in solar system history, and the probable location of chondrite formation relative to this snow line.

7. ASTEROID PHYSICAL AND COMPOSITIONAL PROPERTIES

The available data on the sizes and shapes of asteroids has grown by exponentially since *Asteroids III*. Mid-infrared surveys, including WISE, have provided diameter and albedo estimates for more than 150,000 asteroids, increasing the characterized population by orders of magnitude (see the chapter by Mainzer et al.). From these data, the first "albedo map" of the main belt was created.

The abundance of thermal infrared data motivated advances in asteroid thermophysical modeling. This modeling has not only improved albedo estimates but has also constrained thermal inertia and surface roughness among different bodies. These parameters in turn constrain the grain sizes at the surface, as discussed in the chapter by Delbo et al. Moreover, a new mechanism for regolith production has been identified: thermal cracking through repeated temperature changes on an asteroid surface. We also have identified more shapes of asteroids than ever before via radar studies (chapter by Benner et al.), direct asteroid imaging, lightcurve inversion into shape models, and the combination of multiple data sources (see the chapter by Durech et al.). So far, these shapes have proven to be reliable, as demonstrated by spacecraft imaging the same targets.

In their review chapter, Reddy et al. review revised equations to constrain mineralogy and describe diagnostic features in the mid-infrared spectroscopy of asteroids, for which there were little data in previous books. Belskaya et al. discuss how our growing sample of polarimetric measurements has helped constrain the refractive index, particle size, packing density, and optical heterogeneity. Advances in photometry were led by spacecraft observations as well as theory and laboratory measurement (see the chapter by Li et al.).

For three decades we have sought to understand why the most common meteorite type, ordinary chondrites, does not spectrally match the most common asteroid taxonomic type, the so-called S-type asteroid. This has been known as the ordinary chondrite paradox. It was the Hayabusa mission returning samples from (25143) Itokawa that finally settled and resolutely revealed that these two sets are in fact a compositional match (see chapters by Yoshikawa et al. and Brunetto et al.). Significant progress has been made in understanding the primary cause of the spectral mismatch, i.e., the space weathering process. Brunetto at al. review what we have learned about space weathering over the past decade. Vernazza et al., in light of the link between ordinary chondrites and S-type asteroids, review the compositions of ordinary chondrites and what they tell us in the context of the formation and evolution of S-type parent bodies. It has been scientifically rewarding to resolve this longstanding puzzle with the first sample return mission to an asteroid.

8. ASTEROID GEOPHYSICS

Before the first asteroid images were sent from space, our knowledge of asteroids relied entirely on groundbased observations, meteorite analysis, and analytical/numerical modeling studies. Now, *in situ* images from flyby and rendezvous missions have revolutionized our knowledge of their physical properties. Since *Asteroids III*, space missions have closely studied an extreme range of asteroid sizes. For example, NASA's Dawn mission, reviewed by Russell et al., orbited (4) Vesta, the second largest asteroid (530 km diameter), and is now orbiting (1) Ceres, the largest (950-km diameter). These two worlds provide potential windows into the nature of the protoplanets that accreted into the terrestrial planets and perhaps those strange large bodies found today in the Kuiper belt.

On the opposite end of the size distribution, Japan's Hayabusa mission visited a 320-m-sized near-Earth asteroid (NEA) named (25143) Itokawa, which turns out to be a rubble pile, and successfully returned a sample to Earth, as reviewed by Yoshikawa et al. The European Space Agency's (ESA) Rosetta mission performed flybys of the E-type asteroid (2867) Šteins, discovering that it had the shape of a "diamond in the sky," and the M-type asteroid (21) Lutetia, which was found to have an intriguingly high density of 3.4 g cm^{-3}. Rosetta then continued on to Comet 67P/Churyumov-Gerasimenko, where it successfully performed the spectacular and successful landing of Philae. These encounters, as well as that with the contact binary (4179) Toutatis by China's Chang'e mission, are reviewed by Barucci et al.

Finally, Murchie et al. discuss what we have learned about Phobos and Deimos, two bodies in orbit around Mars. These satellites have several traits in common with low-reflectance bodies, and they arguably resemble some of the typical denizens found in the outer asteroid belt. The origins of Mars' satellites have long been debated. Some believe their physical properties point to them being captured asteroids. The problem is that the low inclinations of Phobos and Deimos are hard to match by any known capture mechanism. Instead, it can be argued they are more likely to be the byproduct of a disk of debris formed near Mars by some potential mechanism (e.g., similar to the preferred theory of the formation of Earth's Moon). Comparisons between Phobos/Deimos and what is known about low-albedo asteroids may ultimately provide us with solutions to this longstanding problem.

These missions showed us that asteroids are not only incredibly diverse in size, shape, structure, composition, and rotational properties, but have also been subjected to a wide range of processes. Each encounter/rendezvous provided us with a taste of how granular mechanics, landslides, earthquakes, faulting, and impact cratering affect worlds of many different sizes. The way in which matter behaves on an asteroidal surface, as well as the way in which the surface material will respond to different processes, depends drastically on a body's surface gravity. It is therefore no surprise that the 34-km-long asteroid (433) Eros, the primary target of the Near Earth Asteroid Rendezvous (NEAR) mission, and the 535-m-long asteroid (25143) Itokawa have very different surface properties, despite the fact that they are the same taxonomic type.

Over the past decade, remote and *in situ* observations have revealed that the surfaces of asteroids are generally covered by loose unconsolidated material called regolith. Regolith is present on asteroids of all sizes, from the largest to those as small as a few hundreds of meters, such as Itokawa. As a result of the unique microgravity environment that the smaller (and most populous) components of the asteroid population possess, complex and varied geophysical processes have given birth to fascinating features that we are just now beginning to understand. These processes were first described through detailed spacecraft observations, but recently have been studied in detail using theoretical, numerical, and experimental methods that combine several scientific disciplines. Murdoch et al. provide a summary of what the scientific community has learned so far about granular materials on the surfaces of these small planetary bodies using both experimental techniques and numerical simulations. Studies of how regolith evolves and responds to different processes (e.g., impacts, shaking, etc.) in low-gravity environments are vital to our understanding of observations as well as the design of future space missions.

Other ubiquitous features of asteroid surfaces are impact craters. As discussed by Marchi et al., crater populations are a powerful tool to trace back an asteroid's surface history and constrain its age. Large craters excavate deep inside the asteroid and produce reverberating stresses that cause global surface modifications, massive faulting, and overturn. Of the known asteroid craters, only the ~500-km Rheasilivia and ~400-km Veneneia craters, the two largest craters on (4) Vesta (see the chapter by Russell et al.), show clear evidence for gravitational rebound and central peak formation. These two basins overlap in Vesta's southern hemisphere, providing a distinct challenge for modeling efforts (see the chapter by Asphaug et al.). Understanding the formation of these giant craters is critical to interpreting Vesta's history, the nature of its associated asteroid family, and the origin of the howardite, eucrite, and diogenite (HED) meteorites that are almost certainly samples from Vesta itself.

While many broad questions were posed in the *Asteroids III* chapter on asteroid interiors, we are now able to delve more deeply into these. In this volume, authors leverage what has been learned from observations across a huge range of asteroid sizes and from our greater understanding of the processes that contribute to their interior properties (see the chapter by Scheeres et al.). As an example, consider that giant craters act as probes of interior geology (see Asphaug et al.), while bodies smaller than 100 km in diameter may increasingly originate from cratering and disruption events among larger bodies (see Bottke et al.). Consequently, most smaller bodies should be fractured, shattered, or rubble-pile bodies. Moreover, according to simulations, all bodies larger than a few hundred meters extracted from a larger body through a catastrophic disruption experienced reaccumulation during the ejection/gravitational phase of the collision (see Michel et al.).

Along these lines, Scheeres et al. review our current understanding of asteroid interiors and morphology. This includes a discussion of the strength of asteroid materials as inferred from meteors and meteorites, the density and porosity of asteroids as derived from remote observations, global constraints on asteroid strength and morphology based on ground- and spacebased observations, analytical theories of asteroid strength and evolution, and the current state of numerical simulation techniques of asteroid strength.

Despite these efforts, however, it is clear that many issues and questions remain. For example, we do not yet have a clear and detailed view of how to define the interior of an asteroid, even though we can approximately infer its strength based on its spin rate and on how it evolves. We are also lacking a robust theory of tidal dissipation within such rubble-pile bodies, as well as a way to characterize the critical parameters of rubble piles (e.g., rigidity, tidal Love number). Compared to the extent of knowledge at the time of *Asteroids III,* major advances have been made, but we still have a long way to go. It is here that direct measurements of asteroid interiors using techniques such as radar tomography or seismic experiments could provide us with new and strongly needed insights.

9. YARKOVSKY AND YORP EFFECTS

During the current and relatively calmer phase of main-belt history (i.e., the last 3 G.y. or so), we have become increasingly aware of slow but steady dynamical mechanisms that contribute to the evolution of asteroid physical properties, the modification of the orbits of asteroid family members, and the transport of asteroids from the main belt to resonances that can take them into near-Earth space. Vokrouhlický et al. review recent progress in our understanding of the Yarkovsky and Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) thermal forces that modify the orbits and spin rates of small asteroids. At the time of *Asteroids III,* the Yarkovsky effect had been explored theoretically, but it had not yet been directly detected. (6489) Golevka was the first asteroid for which an unambiguous signature of the Yarkovsky effect was detected in its orbit. Other detections, as well as upcoming possibilities, are reviewed in the chapter by Vokrouhlický et al.

Additional progress has also been made concerning the "sunlight alters spin" mechanism called the YORP effect. Analyses of small-asteroid populations indicate clear evolutionary differences due to the YORP effect, both in rotation rate and obliquity. Vokrouhlický et al. discuss the direct measurements of this effect as well as how sensitive it is to small-scale surface topography. YORP can either decrease or increase an asteroid's spin rate. In the latter case, YORP spinup can lead to a fission event and/or to the formation of a binary system. For such a system, a variant of the YORP effect has been proposed, called binary YORP (BYORP), that can potentially cause interesting effects to the newly formed satellite. It has not been directly observed as of yet, although some predictions stemming from this effect have been confirmed.

Both the Yarkovsky and YORP effects have many implications for asteroid properties, family structures, distribution of asteroid spin properties, transport of asteroids out of the main belt, and formation of asteroid binaries (Walsh and Jacobson), and could be an intriguing tool to probe the nature of individual asteroids.

10. MULTIPLE SYSTEMS

Multiple systems (e.g., binary and triple asteroids) are a nonnegligible fraction of the asteroid population. Their formation and evolution have been the subject of intensive work and discoveries over the past decade. The observational aspects of these systems are reviewed by Margot et al., while Walsh and Jacobson review how they have been modeled to date.

Since *Asteroids III,* the number of known binary NEAs has also more than quadrupled, while the number of known large main-belt asteroids with satellites has doubled. Half a dozen triple asteroids have been discovered. Moreover, populations of so-called asteroid pairs, defined as asteroids that have lost companions, have now become a flourishing field of research. Even small main-belt binaries have been identified, which is quite an achievement given how difficult it is to study small main-belt asteroids of any type.

These systems provide a natural laboratory in which to study many different types of physical processes acting on asteroids and how their dynamics provide a valuable probe of their physical properties — otherwise only possible with *in situ* spacecraft missions. Observations of small binary systems (with diameters of the primary body <10 km) have motivated theoretical work showing that YORP torques can efficiently drive the rotational disruption of small asteroids. Constraints on the dynamical evolution of those systems have also been obtained; they account for the effect of tides, thermal forces, and rigid body physics. The split pairs have then pushed theorists to explore a wide range of evolutionary end-states.

11. NEAR-EARTH ASTEROIDS

Asteroids that cross Earth's trajectory pose a threat to humankind. The explosion of a 20-m bolide over Chelyabinsk in Russia on February 13, 2013, and the realization that even relatively small impact events can cause human injuries, served as a valuable reminder of this fact. The inventory of potentially hazardous asteroids (PHAs) has driven the development of mitigation strategies; there are very low probabilities of Earth impact in the near future, but if a large asteroid does hit, the impact could have major consequences for life on Earth.

The proximity of asteroids in the PHA class of bodies also offers us with the opportunity for exploration via robotic and human missions. Abell et al. review the current status of ongoing projects to fulfill the dream of a human mission to an asteroid by NASA and other space agencies. These asteroids may also be a potential source of rare minerals, although there is still much to learn and to be done before we can fully exploit them.

The recent advances in asteroid surveys are reviewed in the chapter by Jedicke et al. To date, the vast majority of the known asteroids have been discovered by dedicated surveys funded by NASA. The ability of these surveys to find small asteroids has also steadily improved, with 8× more near-Earth objects (NEOs) and 10× more main-belt asteroids found in the last 5 years than in the 5 years leading up to *Asteroids III.* In particular, the NASA directive to discover 90% of NEOs greater than 1 km in diameter is estimated to have been achieved, and now the new challenge is to do the same for the smaller NEOs, which still pose serious regional threats to Earth.

Once an object is discovered, its orbit must be computed. Despite a well-consolidated theory of orbit determination, the increasing number and ever higher quality of observational data, together with the goal of pushing forward the horizon for ephemeris predictions, pose new challenges in estimating asteroid trajectories. Farnocchia et al. review the methods currently in use to compute asteroid orbits, predict their evolutions, and assess the impact hazard to Earth. Considerable activity has taken place regarding the hazard caused by asteroids. The goals of these studies are to increase the number of identified potentially hazardous objects and better understand the efficiency of various mitigation techniques. International institutions, such as the United Nations (UN), have also begun to organize a response to this risk. These activities are reviewed in the chapter by Harris et al.

Another field that has flourished since the time of *Asteroids III* is the study of subkilometer-sized asteroids. There are more than 9000 of these that have been discovered to date among NEOs. Binzel et al. summarize the current understanding of NEO spectroscopic properties.

Another method that can be employed to study the smallest asteroids is the use of meteoroid observation networks, which detect and measure fireballs, typically centimeter- to meter-sized bodies that enter Earth's atmosphere. Emission measurements provide compositional information, and additional data is provided by the fireball's path, which can constrain the body's orbit prior to entry.

Spectacular fireballs from the past decade that have resulted in meteorite recovery include the Chelyabinsk and Almahata Sitta (2008 TC_3) events (see the chapter by Borovička et al.). The case of Almahata Sitta is particularly fascinating. As reviewed by Borovička et al., in October 2008, a small asteroid with a flat (gray) spectrum at 550–800-nm wavelengths and a weak pyroxene absorption band around 900 nm — asteroid 2008 TC_3 — entered the atmosphere and exploded over the Nubian desert, depositing material in a strewn field in northern Sudan. Searches to date have recovered >600 fragments, but the net collected mass is still <1% of the expected mass of the roughly 3–4-m-diameter bolide. Most of this missing mass was almost certainly lost in the atmosphere. These materials are collectively named Almahata Sitta (AHS), and represent the first recovered meteorites from a spectrally observed asteroid. The ensuing wave of work on AHS revealed an enormous diversity of components. None of this was predicted from the remote spectral observations of the asteroid in space, showing that our interpretation of asteroid physical and compositional properties from remote observations must always be treated with due caution.

Smaller bodies in the form of micrometeorites also reach Earth. Interplanetary matter falls to Earth at a rate of 10,000–40,000 tons per year, mostly in the form of meteoroids with sizes ranging from 10 μm to 1 mm. Most of this material appears to come from disrupted Jupiter-family comets, which would explain the dynamical signatures of these bodies as well as their predominately primitive compositions. Jenniskens reviews the considerable progress made in this area, as well as what we have learned in charting meteoroid streams at Earth and understanding the mechanisms of meteoroid stream formation and evolution.

Several ongoing fragmentation cascades of comets and primitive asteroids manifest themselves as multiple meteoroid streams at Earth. Evidence is mounting that recently released meteoroids fall apart on timescales of 100–10,000 years, breaking into smaller meteoroids that survive for another ~100,000 years to form the zodiacal dust cloud. Main-belt asteroids are thus thought to contribute only a small fraction of the cloud's material. For asteroid-like material, the active asteroid (3200) Phaeton is perhaps the most significant source of the infall to Earth of freshly ejected meteoroids.

12. PERSPECTIVES

During the next decade, our knowledge of asteroids should undergo major improvements and possibly substantial revisions, thanks to both current and future space missions, groundbased observations, and future advances in numerical and theoretical works.

Dawn's visit to (1) Ceres will be completed by the time this book is released, but most of the science learned from that part of the mission will be in the realm of *Asteroids V.*

Two sample return space missions — Hayabusa-2 and the Origins Spectral Interpretation Resource Identification and Security-Regolith Explorer (OSIRIS-REx) — will visit their respective asteroid targets at nearly the same time. The Japan Aerospace Exploration Agency's (JAXA) Hayabusa-2 mission, launched successfully on December 3, 2014, will arrive at the primitive C-type NEA 1999 JU_3 in 2018. It will orbit the body for approximately one year before returning a sample to Earth in 2020. A small lander, the Mobile Asteroid Surface Scout (MASCOT), will perform *in situ* investigations, while a small carry-on impactor will perform a 2 km s^{-1} impact and will create a crater on the asteroid's surface — allowing us to test numerical impact models and scaling laws on a real asteroid surface — in which a sample will possibly be collected in addition to at least one other sample in a different area.

The counterpart of Hayabusa-2, NASA's OSIRIS-REx mission, will be launched in September 2016 and will arrive at the primitive B-type asteroid (101955) Bennu in 2018. It will also orbit its target for nearly a year before collecting a sample. The samples will then arrive on Earth in 2023. These two missions will allow us to make huge strides in our understanding of primitive asteroids while also helping us place into context our knowledge of certain types of carbonaceous chondrite meteorites. It will also be novel to compare and contrast the physical nature and compositional properties of two different C-complex asteroids (or see if they are from the same parent family).

ESA and NASA are also now performing a Phase A study of the Asteroid Impact and Deflection Assessment (AIDA) mission. AIDA is a joint ESA-NASA cooperative project that entered into the 15-month Phase A in 2015 and aims to be the first kinetic impactor test if approved in fall 2016 for launch in 2020. The characterization of its target — the secondary of the binary NEA (65803) Didymos — by ESA and the kinetic impact test by NASA would take place in 2022 and would allow us to have a first direct measurement of an asteroid internal structure by radar tomography and an asteroid's response to an impact.

It is also hoped that a new Discovery-class mission will be selected with asteroids as a target. Several proposed projects intend to survey and discover asteroids, visit particular or several asteroids in the main belt, perform seismic experiments on a NEA, and visit Trojan or active main-belt asteroids. The Japanese are studying a sample return from a Trojan asteroid using a novel solar sail for propulsion.

The 2029 Apophis encounter at 5.6 Earth radii from Earth's center is close enough for the body's spin to be affected by tidal forces. This will be a grand experiment in asteroid seismology that nature is performing for us. It would thus be interesting to see if tidal effects are enough strong to trigger some kind of surface or interior motion. This opportunity is so unique that it may ultimately motivate a space agency or an international effort to devote a small space mission to it.

The next generation of groundbased and spacebased telescopes is also underway. The space mission Gaia (ESA) is an all-sky astronomic space survey launched in 2013 that will measure the positions and colors of all sources down to a magnitude of V = 20. By the end of the mission in 2020, Gaia is expected to provide absolute astrometric positions for 350,000 asteroids that will be 2 orders of magnitude more precise than currently exist. We will also gain huge improvements in the accuracy of asteroid orbit determinations, and the masses of the largest 100 asteroids will be well established. Using spectra in visible wavelengths, Gaia will also provide a more refined taxonomic classification for many asteroids. Overall shapes, spins, and pole coordinates for various asteroids will also be part of the Gaia output.

The Large Synoptic Survey Telescope (LSST) also promises to discover large numbers of NEOs and other small bodies in the solar system. The James Webb Space Telescope (JWST), scheduled to launch in 2018, is the successor to the Hubble and Spitzer telescopes; it will feature a 6.5-m primary mirror. The next generations of groundbased telescopes are also in design or at early stages of construction. These include 30–40-m-class telescopes such as the Thirty Meter Telescope (TMT) to be built in Hawaii and the Giant Magellan Telescope (GMT) and European Extremely Large Telescope (E-ELT) to be built in Chile. These telescopes will provide opportunities for research on asteroids not currently possible and will allow discoveries we have not yet imagined.

Finally, our knowledge of asteroids is crucial to understanding the surroundings of other stars. We now have discovered more than 1800 confirmed extrasolar planets, plus more than 4500 Kepler planet candidates. The number of discoveries regarding exoplanets and debris disks will only increase, although we will not be able to observe the detailed properties of these systems in the near future. Asteroids carry information that is key to understanding planetary formation, as explained in several chapters of this book. They, along with comets, are the closest analog we have to the types of objects involved in planet formation. By exploring how asteroids formed and evolved, we glean insights into the history and properties of debris disks and planetary systems around other stars. Asteroids are therefore fascinating not only because they tell us about our own solar system's provenance and evolution, but also because they can help us better interpret what is going on in newly discovered planetary systems.