10.15 Asteroids and Comets

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10.15.1 Introduction

10.15.1.1 The Basics

The importance of small bodies – asteroids, comets, and small satellites – to the overall picture of planetary formation and planetary evolution has been recognized for decades (see reviews by, e.g., Bottke et al., 2002b; Festou et al., 2004). Only since the 1990s, however, we learned enough about the small bodies and about solar systems in general to start to make detailed connections. Our advances have come mainly thanks to new opportunities in ground- and space-based telescopic observations of both our own solar system and other systems. Additionally, the multitude of spacecraft that have now visited a variety of small bodies have provided a wealth of detailed context. The 1990s, 2000s, and 2010s have brought incredible insight into the nature of the small bodies.

In this chapter, we will give a review of recent developments in our astronomical understanding of small bodies. To keep
the discussion manageable, note that we focus here mainly on comets and asteroids that are not in orbit around major planets; that is, we are excluding those small satellites that are likely captured comets and asteroids. Such satellites can inform and have informed our understanding of the general comet and asteroid population (see reviews by, e.g., Bell et al., 1993; Jewitt and Haghighipour, 2007; Turrini et al., 2009).

With this restriction, note that when we refer to 'small bodies' in this chapter, we will mean just comets and asteroids. In Section 10.15.1, we will discuss the historical and current definitions of small bodies and motivate their study by describing their scientific importance. In Section 10.15.2, we will describe the bodies' origins, their formation scenarios, their interaction with planets and with each other, and some of their dynamic processes. In Section 10.15.3, we discuss the nature of their surfaces, while in Section 10.15.4, we cover their interiors. Section 10.15.5 treats the composition of small bodies, and we finish in Section 10.15.6 with a summary of some of the big questions in and future directions of small-body research.

10.15.1.2 Definitions

Comets have been noted in recorded history for millennia, and asteroids have been known for over 200 years. For most of their observational history, the two groups of small bodies were thought to be clearly separate. More specifically, observational differences were assumed to translate directly to differences in the fundamental nature of the objects. Asteroids were point-like objects in the sky, mostly physically located between Mars and Jupiter in the asteroid belt (a.k.a. the main asteroid belt or just the main belt). Comets were extended sources – showing comae and tails that are generally much brighter than the solid-body source itself – and were either on parabolic or highly elliptical orbits that took them beyond the planetary region of the solar system or on short-period orbits that barely (if at all) went past Jupiter. Even the names given to the bodies revealed this dichotomy: asteroids were ‘minor planets,’ basically just smaller, fainter versions of the other planets that were seen to wander across the sky. Comets were entirely different beasts, historically not even recognized as astronomical phenomena (as opposed to atmospheric) until Tycho Brahe’s parallax studies in the sixteenth century. Even the physical explanation for why comets looked extended – that is, that they had dust – was not established until the nineteenth century by, for example, Bessel (1836) and Bredichin (1877). The early twentieth century saw further characterization of the composition of the two groups, which further reinforced the apparent differences. Cometary spectra showed emission lines from gas species on top of a continuum spectrum, while those of asteroids sometimes showed broad absorption features in the continuum.

One of the major advances since the early 1990s is the realization that comets and asteroids are in fact not clearly separate classes of objects but instead part of a continuum of composition (e.g., Weissman et al., 1989, 2002). Comets are relatively icy and asteroids relatively rocky, but there are many objects that are now recognized to populate everywhere in between. For example, objects in the trans-Neptunian region – nominally called asteroids because of their lack of activity – are icy and would show cometary activity if they were only closer to the Sun (e.g., Barucci et al., 2002; Prialnik et al., 2008); objects that have orbits that are clearly cometary in nature are seen to be inactive, suggesting that their volatile component is deeply buried or now absent (e.g., Ishiguro et al., 2011); and sustained activity that has been seen to develop from objects in the asteroid belt between Mars and Jupiter appears to be driven by volatiles, indicating that ice must still exist somewhere on such objects that have been in the same thermal environment for billions of years (e.g., Hsieh et al., 2010).

Hence, while the terms ‘asteroid’ and ‘comet’ are still commonly used in the small-body community, there is broad recognition that these terms no longer necessarily act as shorthand descriptors for their true physical nature. In this chapter, we will continue to follow common usage when talking about specific objects that are referred to as comets or asteroids, but it is important to recognize that such terms can occasionally be misleading.

For this chapter, we will limit ourselves to a discussion of objects within a range of diameters. At the low end, we will not be talking about dust in and of itself but only dust as it relates to macroscopic comets and asteroids. In this sense, our lower limit to the diameter is about 0.1 m, although in practice, the lower limit is a few meters since almost no small bodies on heliocentric orbits have been observed that are smaller than that. At the upper end, we will limit ourselves to objects that have not pulled themselves into a roughly spherical or spheroidal shape as a result of self-gravity. This is consistent with the IAU definitions of planets and dwarf planets (IAU, 2006); we exclude these bodies from consideration here. We will, however, discuss (4) Vesta as it pertains to asteroid phenomena, though it arguably could be called a dwarf planet and has many terrestrial planet-like characteristics (e.g., Keil, 2002; Zuber et al., 2011).

Finally, a discussion of terminology is in order. Among comets, short- and long-period comets (SPCs and LPCs) are those that have orbital periods less than and longer than 200 years, respectively. SPCs include those of the ‘Jupiter-family’ (JFCs) and of the ‘Halley-type’ (HTCs), the former referring to comets whose orbits tend to be strongly influenced by Jupiter, have aphelia near Jupiter’s orbit, are mainly in the ecliptic plane, and generally have orbital periods of about 6 years. HTCs are now thought to be dynamically evolved counterparts to the LPCs; they can have any inclination. This terminology is the traditional one; Levison (1996) discussed comet classification and his newer system is in use by some comet scientists. That convention divides the population into ‘ecliptic comets’ (ECs) and ‘nearly isotropic comets’ (NICs). ECs include not only the Jupiter-family but also a few other inner-solar system comets that have been decoupled from Jupiter. Furthermore, ECs can include the active ‘centaurs,’ which are objects orbiting among the outer planets beyond 5 AU and are in transition from the trans-Neptunian region to the inner solar system. NICs include the HTCs and LPCs and so dispense with the arbitrary 200-year boundary.

Among asteroids, most of the over 380,000 numbered asteroids known reside in the asteroid belt between Mars and Jupiter. Asteroids are assigned permanent numbers when their orbits are sufficiently well determined to be identified decades in the future without ambiguity. An additional 260,000 unnumbered asteroids are currently cataloged and may become numbered as new observations are made, and their orbits are better determined. Hundreds more asteroids are discovered in a typical month. Some objects are Mars crossers (MCs), coming closer to the Sun than Mars, and some objects
are Earth crossers, coming closer to the Sun than Earth. Some asteroids cross the orbits of Venus and Mercury as well. A Near-Earth asteroid (NEA) is any object with a perihelion distance less than 1.3 AU, and the NEAs are broken down into 'Amors,' 'Apollos,' 'Atens,' and 'Atiras.' Amors are not Earth crossers, staying outside the Earth’s orbit; Apollos and Atens do cross the Earth’s orbit, with the distinction being whether the orbital semimajor axis is larger or smaller than 1 AU; Atiras also do not cross the Earth’s orbit, staying entirely interior to it. While these definitions are still in use, it is important to note that many of these distinctions are no longer meaningful, as we now know that objects can easily move from one dynamic group to another due to both gravitational perturbations and non-gravitational forces.

A traditional dynamic distinction between comets and asteroids is the Tisserand parameter ($T_J$). In a solar system consisting of just the Sun, Jupiter on a circular orbit, and the small body (called the ‘restricted three-body problem’), this parameter is nearly constant (i.e., an ‘integral of the motion’ in classical mechanics parlance). In the real solar system, it is still nearly constant and useful since in general asteroids have $T_J > 3$ and comets have $T_J < 3$. This comes from the fact that SPCs tend to be dynamically coupled to Jupiter; the Tisserand parameter can be related to the encounter velocity of a small body with Jupiter. However, there are many asteroids with $T_J < 3$ and several comets with $T_J > 3$, so the distinction is not exact.

Some of the classification distinctions can be seen in Figure 1, which shows a plot of the semimajor axis versus eccentricity of many of the asteroids in the inner solar system. In particular, the curves 'EC,' 'MC,' and 'JC' indicate the curves that mark which asteroids can cross the orbits of Earth, Mars, and Jupiter, respectively. We will return to this

![Figure 1](orbital_elements.png)

**Figure 1** Orbital elements of the over 363,000 numbered asteroids (at time of writing), as represented in $a$–$e$ space, where $a$ is the semimajor axis in AU and $e$ is the orbital eccentricity. Note that 1 AU is currently defined as 149,597,870.7 km exactly and is very nearly identical to the average Sun–Earth distance. There is obvious structure in the asteroid belt, and there are regions of orbital element space that are favored. ‘NEA’ indicates the locus where perihelion distance $q$ is 1.3 AU, the defined boundary for near-Earth objects. ‘EC,’ ‘MC,’ and ‘JC’ indicate the Earth-, Mars-, and Jupiter-crossing boundaries, respectively. The two curves marked $T_J = 3$ show where the Tisserand parameter is 3.0 for two possible values of the orbital inclination. Vertical dotted lines indicate mean-motion resonances (MMRs) with Jupiter; the resonance is listed at the top of each line. Note that Jupiter’s semimajor axis is 5.20 AU; Mars’s is 1.52 AU.
10.15.1.3 Dynamic Relationships

Some of the subpopulations of the solar system’s small bodies are dynamically linked. In particular, the JFCs are linked to several other groups. The ‘scattered disk’ of the Kuiper Belt – containing objects beyond Neptune on high-eccentricity orbits – is thought to be the original source of these comets, and the objects progress in a dynamic cascade from beyond Neptune to the outer-planets region, essentially being handed off from the control of Neptune, to Uranus, to Saturn, and finally to Jupiter (Duncan et al., 2004). Jupiter-controlled comets have aphelia near 5 AU, and these are the JFCs we see today. As mentioned earlier, many members of the transitional population, the centaurs, have been discovered inhabiting the outer-planets region, and some of the centaurs show cometary activity. The timescale for an object to exist among the giant planets is only a few million years (Hörner et al., 2004; Tiscareno and Malhotra, 2003).

JFCs share some of their orbital parameter space with NEAs. Current work suggests that up to a few percent of the NEA population could be JFCs that have simply lost their surface volatiles (e.g., Bottke et al., 2002a; DeMeo and Binzel, 2008; Fernández et al., 2005).

The connection between Jupiter’s Trojan asteroids – objects in 1:1 resonance, but on average about 60° ahead or behind Jupiter in orbital longitude – and the JFCs is uncertain. It is possible that there is some leakage from the Trojan swarms to the comet population (Marzari and Scholl, 2002); however, no one has ever reported an observation of a Trojan having a comet-like coma or tail. Nor is it clear what would be an observational distinction between a JFC that originated in the Trojan swarm and one that originated in the Kuiper Belt. One possible distinction is that Trojans might be expected to have a lower D/H ratio than objects that formed in the outer solar system, depending on how much compositional radial mixing has occurred; we discuss D/H ratios in more detail in Section 10.15.5.

The existence of a link between the asteroid belt and the NEAs is well established, although the details of which dynamic process moves which asteroids are still under debate (e.g., Bottke et al., 2002a).

10.15.1.4 Relevance to Geology

The most obvious geophysical link between Earth and the small bodies is cratering. Many craters are visible around Earth today, and the only reason we do not see more of them is because the Earth’s surface is in constant change. Most – though not all – asteroids have numerous craters, and indeed, most of the larger asteroid surfaces are saturated with craters. The study of the abundant craters on other solar system objects can bring insight into the impact process and how an impact’s effects depend on the composition, density, and other bulk parameters of both the impactor and the target body.

Erosive processes that garden and turn over surfaces occur on most, if not all, small bodies. The main difference is that small bodies are airless bodies – none have an atmosphere in the same sense that Mars, Venus, and Earth (or even Mercury and the Moon for that matter) have atmospheres. The only thing that comes close is the gravitationally bound coma that sometimes appears around the largest cometary nuclei (e.g., Meech et al., 1997). But in general, no asteroid that we consider here has an atmosphere, and comets only have exospheres. The building up or tearing down of surface structures comes mainly from external effects (e.g., micrometeorite bombardment and impact cratering), though also perhaps from internal processes in the case of comets.

As will be discussed in later sections, the surfaces and interiors of small bodies can be quite different from those of Earth and the other terrestrial planets. Densities, porosities, compositions, collision histories, and surface processes can all be different from what we know on Earth. Yet all of these properties are crucial for understanding the geophysics of small bodies. Complicating our study of these objects is the fact that detailed geomorphology can only be obtained through the use of spacecraft or radar echoes, meaning that many comets and asteroids simply have not been studied in sufficient detail for there to be a true geophysical analysis. One important point to note is that spacecraft flybys of comets and asteroids have made it abundantly clear that we have not yet seen the full diversity of small bodies close-up.

10.15.1.5 Relevance to Meteorites

We know through laboratory or in situ sample analysis that only a small fraction of meteorites originate from the Moon and Mars; the vast majority are from asteroids. The meteorites thus give us important insights into the composition of the solar nebula from which the planets formed. A comprehensive review of meteorite studies is beyond the scope of this chapter and indeed is the subject of entire volumes (e.g., Lauretta and McSween, 2006). We rely heavily on the studies of meteorites to give us an understanding of the composition of asteroids while at the same time recognizing that the sampling of the asteroid belt may be extremely nonuniform. Attempts to link telescope spectra of asteroids with laboratory measurements of meteorites have shown that there is not a simple one-to-one correspondence and many asteroids do not seem to be represented in the meteorites we have. On the other hand, some links are considered very secure, such as the spectra of howardites, diogenites, and eucrites matching the spectrum of asteroid Vesta; these meteorites are considered to be samples of this asteroid (Binzel and Xu, 1993; Drake, 2001). The identifiable spectrum of Vesta has let us identify collisional fragments of previous impacts in the asteroid belt and among the NEAs (Binzel et al., 2004). However, other connections of specific asteroids to specific meteorites are not so clear.

Several asteroid taxonomies have been suggested to better understand the relationships between different asteroid spectral types, meteorites, and compositions. Tholen and Binzel (1989) gave a thorough review of the most commonly used taxonomic system based on photometry in the visible range.
(0.35–1.0 μm). Bus and Binzel (2002) used higher-resolution spectra over a slightly narrower spectral range (0.45–0.95 μm) to extend the Tholen taxonomy to include more specific spectral features. DeMeo et al. (2009) extended the spectral range from visible to near-infrared (0.4–2.5 μm), and this Bus–DeMeo taxonomy is now the most widely used. Three groups of spectral types, S-, C-, and X-complex, encompass the majority of the asteroids. Each complex includes several related taxonomic classes designated by one or two letters; the specific taxonomic class that an asteroid is assigned depends on the details of the spectral shape. Figure 2 summarizes the spectra of all the taxonomic classes in the Bus–DeMeo system; it shows both the average spectrum of each taxonomic type and some actual asteroid spectra. This figure shows the diversity of asteroid reflectances in visible and near-infrared wavelengths among all the taxonomic types. The S-complex asteroids are primarily pyroxene and olivine, and in some cases metallic iron. Ordinary chondrites (OCs) and other stony but largely undifferentiated meteorites are thought to be samples of S-complex asteroids. The C-complex asteroids are mostly low-albedo, flat featureless spectra except for a broad absorption band at 0.7 μm indicative of oxidized iron (Vilas and Gaffey, 1989) defining the Ch class. Various carbonaceous chondrite meteorites are thought to be samples of these types of asteroids, although the spectral matches are not perfect. The X-complex asteroids have been linked to many different meteorite groups such as aubrites, enstatite chondrites, and achenites. Links to iron–nickel meteorites are problematic; originally, these were thought to come from the so-called (in the Tholen system) M-type asteroids, but now, it is unclear if any of the large asteroids can be primarily iron–nickel (see, e.g., Shepard et al., 2010, submitted for publication, and references therein for detailed discussion). A few additional taxonomic classes such as A, V, and R are unusual or match specific asteroids. For example, the V types are most likely related to Vesta, as discussed in the succeeding text. Finally, the D-type asteroids have featureless and very red sloped spectra and match the outer belt asteroids and Jupiter Trojans but do not match any meteorites very well, except perhaps Tagish Lake (Hiroi et al., 2001). Interestingly, both of Mars’s moons are D-type objects; this is unusual since D types are not so abundant in the inner part of the solar system. For convenience in this chapter, and unless otherwise noted, we will refer to broad spectral groups of asteroids using the Bus–DeMeo taxonomy.

Figure 2 The range of asteroid relative reflectances as seen in the red and near-infrared. There are 26 spectra here, representing the 24 taxonomic classes for the near-infrared devised by DeMeo et al. (‘S’ and ‘X’ are shown twice); the taxonomic type is the letter at the right edge of each spectrum. The number after the type is the numbered asteroid that represents the prototype. Note that for clarity, spectra within a panel have been shifted vertically; reflectance is set at unity for a wavelength of 0.55 μm. Asteroids on the left all show the classic two-band (‘Band I’ and ‘Band II’) absorption features near 1 and 2 μm due to pyroxene and olivine. These types include the objects in the S-complex (S, Sa, Sq, Sr, and Sv). Asteroids on the right lack these absorptions, including objects in the C-complex (C, Cb, Cg, Cgh, Ch, and B) and X-complex (X, Xc, Xe, and Xk); indeed, many of the asteroids on the right lack distinguishing diagnostic absorption features, making determining their composition problematic. Reprinted from DeMeo FE, Binzel RP, Slivan SM, and Bus SJ (2009) An extension of the Bus asteroid taxonomy into the near-infrared. Icarus 202: 160–180, Figures 5–7, 11, and 14, with permission from Elsevier.
The connection between meteorites and comets is very sparse; no meteorite currently in hand is considered to have definitely come from a comet. Cometary meteorites are expected to be rare simply due to high entry speed (Campins and Swindle, 1998), although it is possible that some relatively slow meteor showers may provide meteorites that survive (Brown et al., 2013).

10.15.1.6 Relevance to Astronomy

The asteroids and comets we see today are the survivors of the planetary formation process that proceeded during the start of our solar system. The current dominant hypothesis is that the nebular cloud that formed the Sun also had a protoplanetary disk, from which the first planetesimals, and then planets, formed. The details of what the protoplanetary disk was like and the actual mechanical process that formed the planets are both major questions in astronomy that are the subject of significant research. Thus, the study of comets and asteroids is tied to some of the ‘holy grails’ of astronomy. The role of comets and asteroids in the history of our solar system’s planets has become even more important since the late 1990s and 2000s with the discovery of many other planetary systems in our galaxy.

One of the interesting results from the several hundred exoplanets that have been discovered is the fact that the architecture of our own solar system seems to be relatively unusual (e.g., Borucki et al., 2011; Udry and Santos, 2007). Our planetary system’s layout – with small terrestrial planets close to the home star and large gas- and ice-giant planets farther out – has not yet been seen in very many other systems. While observational biases and limitations have made it difficult to ascertain just how many terrestrial planets there are elsewhere, it is clear that there are a great many ways for giant planets to end up being distributed within a planetary system. This reality has motivated dynamicists to investigate possible modes of planetary migration. Some of this migration is influenced by the population of small bodies; essentially, the act of perturbing small bodies may transfer sufficient angular momentum (by the law of conservation) to change a planet’s orbit. Thus, the population of small bodies in the protoplanetary disk is a fundamental part of understanding the development of the planets’ final layout in the solar system. Furthermore, we are discovering other systems around older stars where clearly there are asteroid or comet belts with masses much larger than those we currently have in our solar system (e.g., Lawler et al., 2009; Lisse et al., 2007). These disks of material are not protoplanetary, since the parent stars are usually hundreds of millions or billions of years old. Two questions stemming from these observations are why some systems have such massive disks and whether our own solar system went through a similar stage in the past.

Another area of relevance that pertains to the solar system itself has to do with water and organic molecules. The existence and distribution of these substances are, of course, crucial things to understand since life on Earth (and so far, life as we know it) requires such compounds to exist. Both comets and asteroids contain water and organics in various forms and concentrations. Current thinking is that it is unlikely that Earth formed with its current water content, since it was likely too hot; most of the Earth’s water presumably was brought to it via small-body impacts (e.g., Drake and Campins, 2006; Mottl et al., 2007). The original organic component of Earth was likewise probably miniscule, with small bodies perhaps providing the bulk of the organics (Anders, 1989).

Lastly, small bodies have relevance today since they represent an impact hazard to Earth. The extreme case is the K–Pg mass extinction 65 million years ago, after which a large fraction of the Earth’s species became extinct in a geologically short time. Presumably, an important factor in instigating this extinction was the impact of an approximately 10 km wide object striking what is now the Yucatán Peninsula (Alvarez et al., 1980). Many other impacts have happened since that event, causing varying degrees of damage to local and regional ecosystems and in some cases whole biomes. A very recent and well-observed event was the arrival of the ~15 m wide Chelyabinsk bolide in February 2013. That asteroid, which was not known before the encounter, was possibly the largest object to strike the Earth’s atmosphere since the 1908 Tunguska event (Brown, 2013). Somewhere out there is the next devastating small body that will eventually collide with us; the questions are how big is it, and is it coming in a few years, centuries, millennia, or longer? Unlike the dinosaurs, we can actually attempt to answer this question and try to guard against catastrophe.

10.15.2 Origins

10.15.2.1 Basics

The traditional, fundamental compositional distinction between comets and asteroids is the ice content. The zeroth-order explanation for this distinction involves the existence of a ‘snow line,’ a distance from the forming Sun within the protoplanetary disk beyond which water could condense. While the term ‘snow line’ conjures up the idea of a sharp boundary in the protoplanetary disk, it appears (as mentioned in Section 10.15.1) that the reality is more complicated, with the disk having a trend of ice abundance that varied with time rather than a sharp falloff (see, e.g., the review by Encrarez, 2008). The most widely accepted idea is that the comets and asteroids we see today are the remnants of the planetesimals that formed by accretion within the protoplanetary disk.

The specifics of the accretion process still provoke a major ongoing research effort, most strikingly epitomized by the so-called meter barrier. While numerical modeling has been able to reproduce the accretion of solid-phase rock, metal, and ice grains into conglomerates up to submeter scales with the correct timescales, simulating the creation of larger bodies has been difficult. The main problem is that, in many simulations, a two-body collision between meter-size objects seems to result in a destructive collision rather than an accretion. One possibility is that the interaction between the meter-size boulders and turbulent gas in the disk can sufficiently affect the nature of the collisions so that kilometer-scale bodies can actually be created (e.g., Chiang and Youdin, 2010; Johansen et al., 2007).

There is evidence for a protoplanetary disk within which species aside from ice exhibited trends with distance from the Sun. The distribution of spectroscopic asteroid types is not randomly mixed, but instead follows a trend with heliocentric distance, which has been interpreted as a remnant of the solar nebula. This phenomenon has been known for decades (e.g.,
but a recent demonstration of the situation is shown in Figure 3. Thousands of asteroids observed by the WISE spacecraft (Masiero et al., 2011) show that asteroid albedos (and similarly, taxonomic types and compositions) are not uniformly distributed in the asteroid belt; more primitive (lower albedo) objects dominate farther out, while more processed (higher albedo) objects dominate closer in. The correlation of spectral types with distance motivates the idea that the asteroid belt can be used to better understand the conditions in the solar nebula and the material that formed the terrestrial planets. However, discoveries of extrasolar planets and other planetary systems have greatly broadened our notions of what is ‘normal’ and ‘typical.’ Also, increasing computation capabilities have allowed ever more realistic and detailed models of accretion and are now challenging long-held ideas of what we thought we knew about solar system formation. The asteroid belt and Kuiper Belt are important keys to constraining and testing these models.

The mass of the asteroids in the asteroid belt between Mars and Jupiter is about \(6 \times 10^{-4}\) times the mass of Earth, extremely depleted compared to a protoplanetary disk extending smoothly from 1 to 5 AU and likely originally containing many Earth masses of material (e.g., Morbidelli et al., 2012). The formation of Jupiter was long thought to be responsible for disrupting the formation of a planet in this region and for scattering material around the solar system. The asteroids remaining in the asteroid belt have dynamic signatures from Jupiter’s gravitational effect, such as the Kirkwood gaps — evident as the gaps in semimajor axis as seen in Figure 1. These gaps are created by mean-motion resonances (MMRs) with Jupiter, where the orbital period of the asteroid is a small-integer ratio of Jupiter’s; they are denoted at the top of Figure 1. An MMR tends to enhance perturbations from Jupiter and so helps kick the asteroid out of that region of orbital element space. The belt’s inner edge is controlled partially by Mars. This is also seen in Figure 1; most of the asteroids now in the asteroid belt do not cross the MC line. The belt is also sculpted by the \(n_6\) resonance — a secular resonance arising from when the asteroid’s longitude of perihelion has a precession frequency matching that of Saturn (see, e.g., Froeschlé and Morbidelli, 1994). This resonance is most noticeable in a plot of inclination versus semimajor axis, as in Figure 3; the reason the asteroids look confined to low inclinations is because the \(n_6\) resonance tends to kick out any asteroid with an inclination that is too high. The equivalent resonance with Jupiter, \(n_5\), operates at higher inclinations, so in this case, Saturn’s influence is stronger than Jupiter’s.

### 10.15.2.2 Recent Models

Recent modeling efforts to reconcile formation timescales of the outer planets have led to consideration of large-scale migration of the giant planets. The so-called Nice model (Gomes et al., 2005; Morbidelli, 2010; Morbidelli et al., 2005; Tsiganis et al., 2005) — named after the city in France where many of the model’s originators work — has come to be broadly accepted, although the details are still debated. Indeed, the model, while explaining many observed orbital properties of small bodies in our solar system, has only made limited observational
predictions and could not account for the small mass of Mars (compared with Earth and Venus).

The basic premise of the model is that the outer planets (Jupiter, Saturn, Uranus, and Neptune) started out in orbits much closer to the Sun than they are now. There was also a disk of material – forerunners to today’s comets – that was the remnant of the protoplanetary disk from which the four planets formed. Scattering of these small bodies (as mentioned in Section 10.15.1) caused the planets to migrate in semimajor axis, eccentricity, and inclination. Approximately 800–900 million years after the planets formed, Saturn and Jupiter happened to fall into a 2:1 MMR. This had a profound effect on the layout of the solar system, strongly perturbing the remaining small bodies in the outer solar system, as well as Uranus and Neptune themselves. There is even a possibility that Uranus and Neptune switched order; this falls out of some simulations and would nicely explain the long-standing mystery of why Neptune is more massive than the next planet closer in to the Sun. An example of the effects of the model is shown in Figure 4; small bodies in the vicinity are very rapidly scattered. The model can explain such other observables as the inclination distribution of the Jovian Trojan asteroids and the basic structure of the Kuiper Belt and would be the cause of the Late Heavy Bombardment seen in the lunar cratering record, about 3.9 billion years ago.

More recently, Walsh et al. (2011) had added an early, inward migration of Jupiter to 1.0 AU, which finally allows Mars to form with its small mass. However, this requires a complete reworking of our interpretations of the asteroid belt. The ‘Grand Tack,’ as this model has been called, is still being refined, but like the Nice model, it explains some long-standing mysteries in an appealing way. It too may be overturned, but at present, it provides a useful framework for understanding the asteroids that is substantially different from before. Morbidelli et al. (2012) gave a comprehensive review of the formation of the terrestrial planets, from nebular dust to present-day bodies. The asteroids are an important constraint, as the asteroid belt as seen today is not consistent with early Jupiter migration in the gas disk (Walsh et al., 2012) or the later outer-planet migration (jumping Jupiter) scenarios.

Figure 4  An example simulation of the Nice model. The four panels show the development of the four outer planets plus thousands of massless test particles through the use of a numerical simulation. Panel (a) represents the solar system 200 million years after the formation of the planets; panel (b), 879 million years; panel (c), 880 million years; and panel (d), 1080 million years. Jupiter and Saturn enter the 2:1 MMR at 880 million years, and the disk of test particles is quickly disrupted. Reprinted from Gomes R, Levison HF, Tsiganis K, and Morbidelli A (2005) Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. Nature 435: 466–469, Figure 2, with permission from Macmillan Publishers Ltd.
Finding dynamic models that can match the current inclination and eccentricity distribution of the largest asteroids is surprisingly difficult and serves as a sensitive measure of the dynamic evolution of the solar system.

Morbidelli et al. (2012) and references therein described how the original material in the asteroid belt would have been disrupted by inward migration of Jupiter, leaving only the inner asteroid belt intact and scattering some of these objects outward behind it as it moves. After Saturn moved into resonance with Jupiter, both began to migrate outward, and some of the scattered objects were scattered back into the asteroid belt region, along with many additional volatile-rich objects (C-type asteroids) that may have formed closer to 5 AU. This scenario solves the problem of having both high- and low-temperature materials side by side in the asteroid belt. However, it means that the compositional gradient with heliocentric distance is not primordial and allows a larger amount of radial mixing than is usually considered probable. The problem of linking meteorites to their asteroid parent bodies also becomes nearly impossible, since the current position of the asteroids may not be at all related to where those bodies formed. However, the observations that asteroid families, collisional fragments of once intact parent bodies, are nearly all spectrally uniform, while many meteorites clearly show that differentiation has occurred, is no longer an impossible situation. Differentiated objects can form closer to the Sun and be emplaced in the asteroid belt by Jupiter during migration. Undifferentiated objects form farther out and are scattered inward by Jupiter. Both can now exist side by side, but neither is representative of material that condensed at 2–4 AU. We may have little hope to identify primordial material, if this accretion model is correct.

The topic of the origin of the Kuiper Belt, which is likely the original source of the JFCs we see today, is discussed in detail in Chapter 10.19. Briefly, the orbital distribution of today’s belt can be a useful constraint on the historical dynamic effects that sculpted it. For example, the slow outward migration of the outermost planet may have swept up some objects into MMRs; Pluto, residing in Neptune’s 3:2 resonance, is the most famous example. But the belt also holds a ‘scattered disk’ of objects that were presumably scattered by Neptune into highly eccentric orbits. There is also a ‘hot’ classical disk that maintains relatively low eccentricity but is dynamically ‘hot’ in the sense of having higher inclination. In contrast, the ‘cold’ classical disk has lower-inclination objects. There seems to be some difference in origin of these various populations since there is some difference in their surface properties – namely, color (e.g., Romanishin et al., 2010; Sheppard, 2012), which is for the most part the only measurable property available for the vast majority of known Kuiper Belt objects. As mentioned earlier, the Nice model would suggest that Saturn’s 2:1 MMR crossing disrupted the primordial Kuiper Belt, and it would imply that we may have a difficult time disentangling primordial and evolutionary effects.

10.15.2.3 Size Distributions

The size distribution of the asteroids has been measured to increasingly smaller sizes, but is still not linked to the dust distribution with any confidence. Models and observations have finally come together and agree that below about 10 km in diameter, all main-belt asteroids are collisional fragments (e.g., Bottke et al., 2005). Asteroids bigger than 30–50 km are likely to be fractured from multiple collisions but have lifetimes of 4.5 Gy or more and could be survivors of the formation of the planets. However, if the source regions for the present-day asteroid belt are as broad as 1—6 AU or more, these limits may change. There is some observational evidence for waviness in the cumulative size distribution – that is, for a distribution that follows a power law but with a bump at certain sizes (e.g., O’Brien and Greenberg, 2005). The cumulative size distribution as shown in the review by Bottke et al. (2005) is shown in Figure 5. This waviness could be interpreted as being controlled by the strength–size relationship of the asteroids. However, the existence of the waviness, and its location in the size distribution, is still under debate (e.g., Gladman et al., 2009).

The current size distribution of comets is, compared with the asteroids, poorly known. Work on the JFCs has been done by several teams (e.g., Fernández et al., 2013; Meech et al., 2004) and suggests that there is currently a lack of sub-kilometer-size comets. Some recent estimates of the distribution are shown in Figure 6. Note that there is no expectation that the current observed distribution of comet sizes reveals the primordial distribution; the collisional environment in the Kuiper Belt is likely too violent (Farinella and Davis, 1996). The observational situation is even worse for LPCs. Using the current size distribution of comets to work backward and tease out the original size distribution is a very long-term project that will require having a much better understanding of collisions, of cometary mass loss, and of fragmentation.

**Figure 5** Main-belt asteroid size-frequency distribution, as shown in Figure 1 from the work of Bottke et al., 2005. This distribution is computed from the absolute magnitude $H$ distribution, transformed into diameter bins assuming an average geometric albedo $p_v$ of 0.092. For the fainter objects, those with $H > 12$ (i.e., a diameter less than 18 km for the average albedo), the data are from the Sloan Digital Sky Survey. For the brighter objects, with $H < 12$, the observational census is virtually complete and so the data are from the list of known asteroids. Reprinted from Bottke WF, Jr., Durda DD, Nesvorný D, et al. (2005) The fossilized size distribution of the main asteroid belt. *Icarus* 175: 111–140, with permission from Elsevier.
10.15.3 Surfaces

10.15.3.1 Background

Twelve asteroids and five comets have been imaged at close range by spacecraft through flybys and/or rendezvous, returning a huge number of disk-resolved images of these small bodies. Table 1 lists all small-body encounters within $10^6$ km. Some views of these flyby targets are shown in Figures 7–10.

These planetary exploration missions have fundamentally changed solar system small bodies from astronomical objects to geologic objects. Our knowledge about the surface morphology and cratering characteristics has been greatly expanded as a result of those planetary missions. We will discuss the surface morphology of comets and asteroids separately; both kinds of objects are affected by cratering, but cometary surfaces are also changed on much shorter timescales by outgassing and erosion due to sublimation.

10.15.3.2 Surface Morphology on Asteroids

The first ever spacecraft flyby of an asteroid was in 1991, when the Galileo spacecraft visited (951) Gaspra while en route to Jupiter (Belton et al., 1992; Veversa et al., 1994). This flyby marks the start of observational studies of asteroid geomorphology. Since then, 11 more asteroids have been visited through either flybys or rendezvous missions (Table 1). Among those asteroids, (9969) Braille, (5535) Annefrank, and (132524) APL were observed at relatively low resolutions that do not allow for detailed studies of their surface morphology. The remaining asteroids represent a considerable sample of the general morphological properties of asteroids, from a small size of about half a kilometer in the maximum dimension for (25143) Itokawa (Demura et al., 2006) to the second largest of all main-belt asteroids, Vesta (Jaumann et al., 2012), and from near-Earth population – (433) Eros and Itokawa – to main-belt asteroids.

Despite their small sizes and therefore much weaker surface gravities compared with planets, asteroids display a large variety of surface features, including craters, boulders, lineaments (grooves, troughs, and ridges), rough and smooth terrains, regolith, and landslides. Being geologically inactive, the surfaces of asteroids are usually dominated by impact craters. The surface features reflect the mechanical responses of the target asteroids to various impact energies under various geometric settings and therefore reveal their physical properties. We summarize the major geologic features found on asteroids in this section, compare different asteroids, and discuss the implications to asteroids' evolutionary history and properties.

10.15.3.2.1 Craters

The dominant geomorphological features on the surfaces of almost all larger asteroids are craters, most of which are of impact origin, although this is not entirely certain for the small asteroid Itokawa due to the different morphology of the ‘circular depressions’ (Hirata et al., 2009). After formation, craters on asteroids are subject to size-dependent degradation and removal processes, such as regolith movement, slope failure, and micrometeorite bombardment. Three collective properties of crater populations on asteroids separately; both kinds of objects are affected by cratering, but cometary surfaces are also changed on much shorter timescales by outgassing and erosion due to sublimation.
<table>
<thead>
<tr>
<th>Object</th>
<th>Type</th>
<th>Year</th>
<th>Spacecraft</th>
<th>Closest pass (km)</th>
<th>Best res. (m/pixel)</th>
<th>Dimension of object (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21P/Giacobini–Zinner</td>
<td>JFC</td>
<td>1985</td>
<td>ICE</td>
<td>7800</td>
<td>N/A</td>
<td>?</td>
</tr>
<tr>
<td>1P/Halley</td>
<td>HTC</td>
<td>1986</td>
<td>Vega 1</td>
<td>8889</td>
<td>~300</td>
<td>15 × 7</td>
</tr>
<tr>
<td>1P/Halley</td>
<td>HTC</td>
<td>1986</td>
<td>Vega 2</td>
<td>8030</td>
<td>~300</td>
<td>15 × 7</td>
</tr>
<tr>
<td>1P/Halley</td>
<td>HTC</td>
<td>1986</td>
<td>Giotto</td>
<td>596</td>
<td>130</td>
<td>15 × 7</td>
</tr>
<tr>
<td>1P/Halley</td>
<td>HTC</td>
<td>1986</td>
<td>Suisei</td>
<td>151,000</td>
<td>37,000</td>
<td>15 × 7</td>
</tr>
<tr>
<td>(951) Gaspra</td>
<td>MBA</td>
<td>1991</td>
<td>Galileo</td>
<td>1600</td>
<td>54</td>
<td>18 × 11 × 9</td>
</tr>
<tr>
<td>26P/Grigg–Skjellerup</td>
<td>JFC</td>
<td>1992</td>
<td>Giotto</td>
<td>200</td>
<td>N/A</td>
<td>?</td>
</tr>
<tr>
<td>(243) Ida</td>
<td>MBA</td>
<td>1993</td>
<td>Galileo</td>
<td>2400</td>
<td>25</td>
<td>60 × 25 × 19</td>
</tr>
<tr>
<td>(253) Mathilde</td>
<td>MBA</td>
<td>1997</td>
<td>NEAR</td>
<td>1200</td>
<td>200</td>
<td>66 × 48 × 46</td>
</tr>
<tr>
<td>(433) Eros</td>
<td>NEA</td>
<td>1998</td>
<td>NEAR</td>
<td>3827</td>
<td>363</td>
<td>34 × 11 × 11</td>
</tr>
<tr>
<td>(9699) Braille</td>
<td>Q NEA</td>
<td>1999</td>
<td>Deep Space 1</td>
<td>26</td>
<td>182</td>
<td>2 × 1 × 1</td>
</tr>
<tr>
<td>(433) Eros</td>
<td>NEA</td>
<td>2000–2001</td>
<td>NEAR</td>
<td>0</td>
<td>cm to m</td>
<td>34 × 11 × 11</td>
</tr>
<tr>
<td>(5535) Annefrank</td>
<td>NEA</td>
<td>2002</td>
<td>Stardust</td>
<td>3079</td>
<td>184</td>
<td>7 × 5 × 3</td>
</tr>
<tr>
<td>19P/Borrelly</td>
<td>JFC</td>
<td>2002</td>
<td>Deep Space 1</td>
<td>2171</td>
<td>47</td>
<td>8 × 2</td>
</tr>
<tr>
<td>81P/Wild 2</td>
<td>JFC</td>
<td>2004</td>
<td>Stardust</td>
<td>237</td>
<td>14</td>
<td>6 × 4 × 3</td>
</tr>
<tr>
<td>9P/Tempel 1</td>
<td>JFC</td>
<td>2005</td>
<td>Deep Impact flyby</td>
<td>700</td>
<td>10</td>
<td>8 × 5</td>
</tr>
<tr>
<td>9P/Tempel 1</td>
<td>JFC</td>
<td>2005</td>
<td>Deep Impact impactor</td>
<td>0</td>
<td>3</td>
<td>8 × 5</td>
</tr>
<tr>
<td>(25143) Itokawa</td>
<td>NEA</td>
<td>2005</td>
<td>Hayabusa</td>
<td>0</td>
<td>cm to m</td>
<td>0.5 × 0.3 × 0.2</td>
</tr>
<tr>
<td>(132524) APL</td>
<td>MBA</td>
<td>2006</td>
<td>New Horizons</td>
<td>101,867</td>
<td>~2000</td>
<td>2.3</td>
</tr>
<tr>
<td>(2867) Steins</td>
<td>MBA</td>
<td>2008</td>
<td>Rosetta</td>
<td>800</td>
<td>80</td>
<td>7 × 6 × 5</td>
</tr>
<tr>
<td>(21) Lutetia</td>
<td>C or M MBA</td>
<td>2010</td>
<td>Rosetta</td>
<td>3162</td>
<td>60</td>
<td>121 × 101 × 75</td>
</tr>
<tr>
<td>103P/Hartley 2</td>
<td>JFC</td>
<td>2010</td>
<td>Deep Impact</td>
<td>700</td>
<td>~7</td>
<td>0.7 × 2.3</td>
</tr>
<tr>
<td>9P/Tempel 1</td>
<td>JFC</td>
<td>2011</td>
<td>Stardust</td>
<td>181</td>
<td>12</td>
<td>8 × 5</td>
</tr>
<tr>
<td>(4) Vesta</td>
<td>MBA</td>
<td>2011–2012</td>
<td>Dawn</td>
<td>210</td>
<td>20</td>
<td>573 × 557 × 446</td>
</tr>
<tr>
<td>(4179) Toutatis</td>
<td>MBA</td>
<td>2012</td>
<td>Chang'e 2</td>
<td>3.2</td>
<td>10</td>
<td>4.6 × 2.3 × 1.9</td>
</tr>
</tbody>
</table>

Under 'Type,' 'HTC' refers to Halley-type comet; 'JFC,' Jupiter-family comet; 'MBA,' main-belt asteroid; 'NEA,' near-Earth asteroid. The letter before 'MBA' and 'NEA' refers to the taxonomic type; the types are discussed in Sections 10.15.1.5 and 10.15.3.3. Note that flybys of comets 21P/Giacobini–Zinner and 26P/Grigg–Skjellerup returned no imaging, hence we have put a '?' in the dimension column.

Figure 7 Montage of many of the asteroids that have had close spacecraft flybys, shown to scale. Note that the diameter of the largest object, Vesta, in this view is about 560 km, while that of the smallest object, Itokawa, is under 1 km. Courtesy NASA/JPL-Caltech/JAXA/ESA (Photojournal image PIA14316).
Figure 8  More complete montage of all small bodies that have had spacecraft flybys, except for Vesta, shown to scale. Each asteroid is as close to true color and albedo as possible. Note that the diameter of the largest object here, Lutetia, is about 100 km. Montage by Emily Lakdawalla. Data from NASA/JPL/JHUAPL/UMD/JAXA/ESA/OSIRIS team/Russian Academy of Sciences/China National Space Agency. Processed by Emily Lakdawalla, Daniel Machacek, Ted Stryk, Gordan Ugarkovic. Used with permission.

Figure 9  Higher-resolution views of some of the main-belt asteroidal flyby targets shown in Figures 7 and 8 (clockwise from top left): Mathilde, Ida, and Gaspra. White horizontal bar in each panel measures 10 km. All pictures courtesy NASA (Photojournal images PIA02477, PIA00135, PIA00118).
with porosity. Third, the depth-to-diameter ratio ($d/D$) is affected by many factors including impact energy, target strength, and the degradation processes and trend (e.g., Carr et al., 1994; Melosh, 1989; Sullivan et al., 1996) and is also an indicator of regolith depth (e.g., Vincent et al., 2012a, b). The $d/D$ on small bodies, however, is not well measured due to the uncertainties in reconstructing 3-D topography.

The cumulative SFD of craters on asteroids generally follows a power law with an index between $-2$ and $-4$, which is consistent with the SFD of main-belt asteroids from both observations (Jedicke et al., 2002) and theoretical modeling (e.g., Bottke et al., 2005; see Figure 5). This particular range of the power-law index is the expected result of asteroid collisional evolution (Davis et al., 2002). Starting from an asteroid population model, relative velocity, and the assumption of scaling laws, one can fit the SFD and density of craters on an asteroid or a region to derive its crater retention age, which is the time since the most recent resurfacing event (e.g., O’Brien and Greenberg, 2005; O’Brien et al., 2006). While generally this approach matches the crater size frequency on asteroids and allows us to derive these relative ages satisfactorily on, for example, (243) Ida, Dactyl (Ida’s moon), parts of (21) Lutetia, and parts of Vesta (Chapman et al., 1996a; Davis et al., 1996; Marchi et al., 2012a,b), most asteroids show obvious deviations from the models at various crater sizes.

Gaspra (Figure 9) has few, if any, large craters but is peppered with fresh, small craters of several tens to hundreds of meters that are saturated, that is, in an equilibrium state (Carr et al., 1994; Chapman et al., 1996b). The number of craters on an object is said to reach equilibrium when for every new crater that forms, another is lost or covered up, so that the total number cannot increase. On Gaspra, the lack of large craters is inconsistent with the abundance of smaller craters. This property is so far unique to Gaspra. Gaspra possesses a few flat facets, which might be the remnants of large impact craters of sizes approaching the size of the asteroid itself (Greenberg et al., 1994; Thomas et al., 1994). The lack of large craters on Gaspra indicates a young age of $\sim$250 My (Chapman et al., 1996b). However, Greenberg et al. (1994) and Chapman (1997) argued that the surface of Gaspra could be either much older or younger, if one assumes rubble pile structure (nearly strengthless) or monolithic structure (strong), respectively.

Unlike Gaspra, Eros (Figure 10) shows an extreme paucity of small craters of $<100$ m, while large craters $>200$ m are in an equilibrium state, similar to that of Ida (Chapman et al., 2002; Veverka et al., 2000). Richardson et al. (2004) and Michel et al. (2009) showed that the most likely reason for the paucity of small craters on Eros is seismic shaking erasure. The possibility that small impactors are preferentially removed by a size-dependent mechanism – that is, by the Yarkovsky effect, a thermal radiation force that causes objects to undergo semimajor axis drift due to asymmetrical radiation (Bottke et al., 2006) – has been considered but rejected (O’Brien, 2009).

Itokawa (Figure 10) and (2867) Šteins also show obvious depletion of small craters (Besse et al., 2012), probably also due to seismic shaking. The YORP (Yarkovsky–O’Keefe–Radzievskii–Paddack) effect (Bottke et al., 2006) – analogous to the Yarkovsky effect except it changes the asteroid’s spin state due to that asymmetrical radiation of thermal emission – might be responsible for regolith movement on Šteins (Marchi et al., 2010a), effectively ‘reshaping’ the asteroid in that sense. Alternatively, for Itokawa, the high abundance of boulders on its surface could have protected it from forming small craters, with impactors simply fragmenting the boulders rather than creating craters (Michel et al., 2009).

The most striking features on (253) Mathilde (Figure 9) are several large craters with sizes comparable with the size of the asteroid itself (Cheng and Barnouin-Jha, 1999). The number of those large craters exceeds the saturation density, suggesting to several authors that Mathilde may be composed of weakly bonded, porous, crushable material that absorbs impact shock efficiently without disrupting preexisting large craters (Asphaug, 1999; Housen et al., 1999). The population of small craters on Mathilde also saturates its surface, consistent with an old surface of perhaps several billion years (Davis, 1999), although the estimate varies depending on the internal strength.

Vesta and Lutetia are both large and each shows a complicated cratering record on their surfaces. Vesta is $\sim$560 km in diameter (Jaumann et al., 2012) and is large enough to trap...
sufficient radiogenic heat during its accretion to lead to the differentiation of its interior. Vesta is thus a differentiated protoplanet (e.g., Keil, 2002; Russell et al., 2012). On the other hand, the internal structure of Lutetia (~100 km across) is uncertain, but it is unlikely to be differentiated, so it represents an ancient planetesimal (e.g., Coradini et al., 2011; Sierks et al., 2011). The cratering morphology on both asteroids includes all crater preservation states and different crater densities from region to region, suggesting very different crater retention ages from hundreds of My to >3.6 Gy (Marchi et al., 2012a,b; Massironi et al., 2012; Schenk et al., 2012; Thomas et al., 2012). On the oldest terrain on Lutetia, a region called Achaia, the SFD shows a distinct flexure point at 4–7 km diameter, attributed to the presence of a stratified surface with fractured material overlying a more competent interior (Marchi et al., 2012a), similar to the case for Mercury (Marchi et al., 2011). The full analysis of cratering properties on Vesta from Dawn data is still ongoing as of the writing of this chapter. Readers are referred to, for example, Yin et al. (submitted for publication) and Williams et al. (in press) for the geology of Vesta.

The degradation states of craters can be gauged with the depth-to-diameter ratio ($d/D$), and the ratio can be also an indicator of the depth of regolith. Typically, the crater $d/D$ on these asteroids is between 0.12 and 0.15 (Gaspera, Ida, and Eros) (Carr et al., 1994; Sullivan et al., 1996; Veverka et al., 2000), although for large asteroids Mathilde, Lutetia, and Vesta, this value could have a large range of <0.1 to >0.2 (Jaumann et al., 2012; Veverka et al., 1999; Vincent et al., 2012a,b). The small asteroid Steins also has a large range of $d/D$ of 0.04–0.25 (Besse et al., 2012). The smallest asteroid Itokawa has much shallower craters with $d/D$ of 0.08 on average and a relatively narrow range of $\pm 0.03$, possibly due to the small size of the asteroid, the small number of craters with which to make the analysis in the first place, the incomplete formation of raised rims, and/or the infilling of crater by pebbles (Hirata et al., 2009; Michel et al., 2009). In contrast, the Moon, Mars, and Phobos typically have a depth-to-diameter ratio of about 0.2 (Shingareva et al., 2008). The wide range of $d/D$ values among all these bodies indicates that crater creation and degradation depend on the detailed properties of the targets themselves. A comprehensive understanding of the variety of depth-to-diameter ratios – and of asteroid cratering in general – is a project for the future; the study of cratering on asteroids is complicated by both observational and modeling limitations. The most obvious factors include the identification of secondary craters (formed by reimpact of ejecta), the existence of extremely degraded craters underlaying new craters, and the often irregular shapes of asteroids with complicated local topography. Crater chronology is almost always limited by our knowledge of the impactor populations, the mechanical properties of the surface (affecting scaling laws), and the removal process. The result is that surface ages are often strongly model-dependent.

**10.15.3.2.2 Boulders**

The visiting spacecraft imaged boulders on the surfaces of Eros, Lutetia, Vesta, and especially Itokawa. The surface of Itokawa is in fact dominated by boulders rather than craters (Barnouin-Jha et al., 2008; Fujiwara et al., 2006; Michikami et al., 2008). This is dramatically shown in Figure 10. The boulders on Vesta have not yet been thoroughly studied as of the writing of this chapter. Therefore, we will focus on the other three asteroids to discuss boulders. The shape of boulders on Eros and Itokawa is consistent with laboratory impact experiments (Michikami et al., 2010). The SFDs of boulders on all of them, as well as on Phobos, follow a power-law index of nearly ~3 within a few meters to 80 m (Michikami et al., 2008; Thomas et al., 2000; 2001), a steep slope of power index of ~6 for <10 cm size on Eros near its landing size (Thomas et al., 2001), and steep slopes of indexes ~5 for boulders >80 m for both Eros and Lutetia (Küppers et al., 2012; Thomas et al., 2001).

The origin of boulders is generally associated with impact breaking of the target material. Since boulders are subject to destruction by the bombardment of small impactors, the existence of a large number of boulders usually suggests relatively young ages of the associated impact craters. For example, Geissler et al. (1996) noted that the distribution of large blocks on Ida is consistent with ejecta from the impact that created Azzurra crater; Thomas et al. (2001) studied the spatial distribution of boulders and their characteristics on Eros and established the formation of Shoemaker crater as the probable source of most of its boulders; a similar study for Lutetia by Küppers et al. (2012) also showed that most boulders on Lutetia were generated by the formation of the central crater in the youngest region, Baetica. The boulders on Itokawa, however, show a global distribution. There are no large craters on this small asteroid, and the total volume of boulders accounts for ~25% of the total excavated volume of craters, much higher than that on Eros (~1%) and on the Moon (~5%) (Cintala et al., 1982; Thomas et al., 2001). These arguments led Fujiwara et al. (2006) and Michikami et al. (2008) to conclude that the bulk of boulders on Itokawa most likely originated from the disruption of the parent body and reaccumulated on the surface of Itokawa during its formation.

**10.15.3.2.3 Lineaments**

Lineaments were first seen quite prominently on the global scale on Eros (Thomas and Prockter, 2010). The term includes grooves, troughs, and ridges, and they can be local or global in scale. Examples of lineaments are shown in Figures 11–13. All the asteroids that are resolved at sufficiently high resolution – except for Itokawa, which is a rubble pile – show either local or global lineaments on their surfaces. They seem to be caused by propagation of stress or tension and indicate to some extent a coherent interior. Local-scale lineaments appear to be associated with strong impacts that formed large craters. Global-scale lineaments could be associated with either the global response to seismic waves during large impacts or the stress environment of being broken up from the parent bodies (Buczowski et al., 2008; 2012; Prockter et al., 2002; Sullivan et al., 1996; Thomas et al., 1994, 2002, 2012; Veverka et al., 1994). However, an intriguing alternate hypothesis for the Eros lineaments was given by Greenberg (2008), who suggested instead that the lineaments are near a vein of stronger rock (perhaps created by partial melt) that was more resistant to impact erosion. Grooves seen in the regolith are probably expressions of fracture within a more coherent substrate (Thomas et al., 1979) and may provide additional clues about the interior structure.
The most interesting lineament systems exist on Eros, Lutetia, and Vesta. Buczkowski et al. (2008) mapped more than 2000 lineaments on Eros ranging up to tens of km in length (Figure 11). They found that, except for the lineaments that are radial or circumferential to ~10 craters and obviously associated with those impacts, the majority of lineaments belong to three sets: parallel to meridian, encircling one end of Eros, and toward the other end. While interpreting the first set as due to impacts on the long side of the body, they proposed that the second and third sets could be due to the stress environment in its parent body. Nevertheless, the large number of lineaments on Eros on a global scale is not consistent with a rubble pile internal structure.
Lutetia shows an extremely complicated system of lineaments on the full globe except for the geologically youngest region near the north pole (Thomas et al., 2012), and not as systematically distributed and organized as on Eros. An example of the lineament system is shown in Figure 12.

While the full analysis of lineament systems on Vesta is still ongoing, the most striking features are two sets of long linear structures near the equator and on the northern hemisphere that almost encircle the whole body (Figure 13) (Jaumann et al., 2012). Buczkowski et al. (2012) categorized these linear structures as grabens. These grabens appear to be coplanar with the respective poles coincident to the centers of two large basins near the south pole, Rheasilvia and Veneneia. They concluded that the properties of the grabens are consistent with impact-induced, global-scale deformation of a fully differentiated body, completely distinct from the responses of small, undifferentiated asteroids to impacts.

### 10.15.3.2.4 Smooth deposits

Both NEAs visited by spacecraft, Eros and Itokawa, display apparently smooth regions, termed ‘ponds’ on Eros (Abe et al., 2006; Barnouin-Jha et al., 2008; Cheng et al., 2001; Robinson et al., 2001). The smooth areas on both asteroids are located in gravitationally low areas, indicative of movements of regolith with centimeter- to millimeter-scale particles. Cheng et al. (2002) proposed that the ponded deposits on Eros are consistent with fluidlike motion of dry regolith, possibly induced by seismic agitation from impacts, the same process that is responsible for preferentially removing small craters on both of these objects (Michel et al., 2009; Richardson et al., 2004).

### 10.15.3.2.5 Regolith

Regolith (defined as loose, fragmental debris, regardless of origin) was not originally predicted before the Galileo encounter with Gaspra because of the low gravity (e.g., Housen et al., 1979a,b), although other early work, including that of Veverka et al. (1986), indicated that regolith would accumulate on small objects. The surfaces of asteroids are now known to possess a substantial amount of regolith derived from impacts, and this regolith demonstrates considerable mobility. The depth of regolith is generally inferred from crater morphology and ejecta, distribution of smooth deposits, the morphology of...
geologic features such as boulders and lineaments, and spectrophotometric variations of the surface. In general, meters to hundred of meters thick regolith are inferred on asteroids, depending on the size of the objects (Barnouin-Jha et al., 2008; Besse et al., 2012; Carr et al., 1994; Chapman et al., 1996a,b; Prockter et al., 2002; Sullivan et al., 1996; Vincent et al., 2012a,b). The regolith on Vesta displays global variations from tens of meters to >1 km (Denevi et al., 2012; Jaumann et al., 2012) due to the complicated impact history.

Movement of regolith is evident from the localized smooth areas (as discussed in the previous section) and by mass wasting due to slope failure, as commonly seen on steep slopes of crater walls (e.g., Jaumann et al., 2012; Krohn et al., in press; Miyamoto et al., 2007; Thomas et al., 2012). The mobility and evolution of regolith are generally inferred from both geomorphological evidence and the optical maturity of regolith (i.e., from space weathering; see next section). For NEAs, the causes of mass movement are generally considered to be (a) seismic shaking induced by impact, (b) YORP spin-up, and (c) tidal disturbance from close encounters with planets. In binary asteroids, tidal effects of one body on the other can similarly move regolith around.

10.15.3.3 Space Weathering

Our knowledge about the mineralogy of asteroids is dominated by remote sensing observations of the spectral reflectance properties of asteroidal surfaces, supplemented by laboratory experiments of meteorite samples. It has long been recognized that the optical properties of silicate rocks are subject to change due to exposure in the space environment, caused by solar wind irradiation and micrometeoroid sputtering (Hapke, 1973). For the case of the Moon, the exposure causes the surface to darken, the spectral slope to redden, and the mineral absorption bands to weaken. Such optical phenomena and the associated processes are broadly termed 'space weathering.' The space weathering process on the Moon is well understood (see, e.g., Hapke, 2001; Pieters et al., 2000, for comprehensive reviews). Laboratory measurements and experiments of lunar samples showed clear evidence that vaporization of silicate minerals and redeposition of nanophase iron (npFe⁰) coat the surface of regolith particles (cf. Hapke, 2001). Because the sizes of metallic Fe particles are smaller than visible wavelengths, they strongly absorb incident light, and their absorption coefficient decreases as the wavelength increases, resulting in darkening and reddening of the regolith particles, and masking out mineral absorption bands (cf. Hapke, 2001). However, this process cannot be easily extended to asteroids in general (Gaffey, 2010). Chapman (2004) presented an excellent historical review on this topic. Our understanding of space weathering on asteroids has been severely limited by both the lack of direct samples and the limited high spatial resolution spectroscopic data. Because mineralogical identification on asteroids almost entirely relies on the spectral reflectance properties of asteroidal surfaces, understanding the space weathering processes is an important aspect of asteroid science. As we shall see in this section, the surfaces of asteroids display different manifestations of space weathering from that on the Moon. For the convenience of our discussion, we refer to the space weathering process on the Moon and its associated optical effects as 'lunar-type.'

Space weathering on asteroids was first proposed to explain the spectral difference between the most abundant samples in our meteorite collections, the OCs, and the most abundant type of main-belt asteroids, S types (cf. Section 10.15.1.3). Presumably, the S types were the sources of OCs, yet the spectral differences remained problematic. Under the assumption that no mechanical or mixing process should change the mafic band centers and their relative strength, Gaffey et al. (1993) studied the mineralogy of S-type asteroids and found that the spectra of a particular subclass (known as 'S(IV)') imply mineralogy similar to the known OCs, therefore providing a generic link between S types and OCs. However, the S-type asteroids show much weaker absorption bands and much redder spectral slopes than do OCs. On the other hand, in the NEA population, a small class of asteroids, labeled the Q types, with sizes of a few km, show similar spectral characteristics to those of OCs (Binzel et al., 2002; McFadden et al., 1984). This relationship is a good reality check because the OC meteorites were NEAs before falling to Earth, so one would expect that there would be a closer spectral match. Binzel et al. (1996, 2002) showed that nonprimitive NEAs show a continuous spread in their spectra from OC-like to S-like, implying a process that is continuously operating on the surfaces of one class and changing their optical properties to the other. Both observational (Binzel et al., 2010) and dynamic (Nesvorný et al., 2010) evidence suggested that tidal encounters to within ~5 planet radii of Earth and Venus could reset the weathered surfaces on small S-type asteroids, by exposing a relatively fresh unweathered surface and changing them to Q types.

To put it another way, S-type main-belt asteroids have highly weathered surfaces because they have been exposed to the space environment for ostensibly tens of millions to billions of years. Q-type surfaces, that is, those with little or no weathering, on the other hand would appear in the NEA population because NEAs are collisional fragments and relatively recent escapees from the asteroid belt; thus, their surfaces have only been exposed for millions of years or perhaps much less. Recent observations of small S-type asteroids in the main belt that are of comparable size with NEAs also show spectral variation, which is logical because these objects have fresher surfaces and may be on their way to becoming NEAs. Some of these small objects have spectra that match the OCs (Mothé-Diniz et al., 2010). Further studies of the colors of many S-type dynamic families in the main belt have shown that their red spectral slopes are clearly correlated with dynamic ages since breaking up, consistent with continuous weathering process on S-type asteroids (Nesvorný et al., 2005).

Recent asteroid missions have both confirmed the existence of space weathering on asteroids and raised more questions. The Galileo spacecraft flybys of two S-type main-belt asteroids Gaspra and Ida showed that the surfaces of Gaspra and Ida both have large variations in colors and at least a factor of two variation in the strength of mafic bands. While the overall spectra of Gaspra and Ida are typical of S-type asteroids, small, fresh craters and ejecta appear to be bluer, and the ridges with steep slopes tends to be bluer than other areas (Belton et al., 1992, 1994; Geissler et al., 1996; Sullivan et al., 1996).
Close examination of the spectral trend on Ida revealed that the geomorphologically freshest units have spectral intermediate between OCs and the S-type asteroids (Chapman, 1996). However, because the albedo variation on Ida is small, the space weathering process does not seem to have darkened the surface of Ida as much as it has of the Moon.

The clearest evidence of space weathering on Eros was identified in the large crater named Psyche, where brighter materials are exposed on the wall and darker materials are deposited at the bottom (Clark et al., 2001). The albedo variation from wall to bottom is a factor of several. The color of the bright crater wall is slightly bluer than that of the dark crater floor, consistent with, but much subtler than, lunar-type space weathering (Izenberg et al., 2003; Murchie et al., 2002). Therefore, the wall of Psyche crater was recently exposed due to mass wasting of the original regolith on the slope and is much less space-weathered than the crater floor. However, there are a number of inconsistencies in terms of space weathering on Eros. First, the color and spectral variations on Eros are remarkably uniform to within 2% (Izenberg et al., 2003; McFadden et al., 2001). The lack of color contrast between the supposedly fresh crater wall and the weathered crater floor certainly suggests different weathering processes on Eros than on Gaspra, Ida, and the Moon; this is represented schematically in Figure 14 (Gaffey, 2010). Second, the downslope movement of Psyche crater wall material had to be driven by, for example, other impacts after the formation of the slope. However, Psyche crater appears to be the youngest on Eros; none of the small craters on Eros appear fresh, that is, brighter and bluer than average surface. Cheng et al. (2002) considered that the shaking of Eros, probably induced by tidal forces during close approach with terrestrial planets, could induce mass wasting on slopes and the formation of ponds. In addition, ejecta blocks on Eros, mostly excavated by the impact that formed Shoemaker crater, show similar albedo and spectra to other areas on Eros, a relation that also indicates relatively mature surfaces.

The Hayabusa mission to Itokawa provided evidence of space weathering on this small (550 m) NEA from both spectroscopic observations and the first samples directly returned from known sites on an S-type asteroid. Hiroi et al. (2006) showed that a dark region on Itokawa has a spectrum clearly consistent with significant space weathering with accumulated npFe\(^0\) (nanophase metallic iron) with about 0.03–0.07 vol.%. Ishiguro et al. (2007) analyzed the spectral data of the whole surface of the asteroid to map the space weathering maturity on Itokawa and found that fresh materials are generally observed in regions of steep slopes and craters, whereas mature materials are ubiquitously distributed. Laboratory measurements of the Itokawa samples showed surface modifications on the rims of some particles, with sulfur-bearing Fe-rich nanoparticles, interpreted as a consequence of alteration by vapor deposition (Noguchi et al., 2011, 2014).

The presence of npFe\(^0\) is one consequence of space weathering that appears to be the same on both the Moon and asteroids. In addition to the evidence of npFe\(^0\) found in Itokawa regolith samples (Noguchi et al., 2011, 2014), nanosize metallic particles are also found in some OC meteorites (Longobardo et al., 2011; Moretti et al., 2005, 2006) and in the howardite (i.e., likely Vesta fragment) Kapoeta meteorite (Noble et al., 2010). Furthermore, extensive laboratory experiments of space weathering have been conducted to simulate the effects of micrometeoroid impacts through laser impulses and solar wind bombardment through plasma irradiation (e.g., Brunetto and Strazzulla, 2005; Brunetto et al., 2006; Dukes et al., 1999; Hapke, 1973, 2001; Loeffler et al., 2008, 2009; Marchi et al., 2005; Noble et al., 2007; Strazzulla et al., 2005; Yamada et al., 1999). The most significant result from these experiments has been the reproduction of the lunar space weathering effects by generating npFe\(^0\) coating on mineral grains (Keller and McKay, 1993). The timescale of space weathering due to micrometeoroid impacts has been estimated to be of order 10\(^8\) years (Sasaki et al., 2001).

For non-S-type asteroids, such as the more primitive objects in the C-complex, the effect of space weathering is not obvious. This lack of spectral detection might be because the dark, opaque, carbonaceous materials (which are thought to be the dominant composition of low-albedo asteroids like those in the C-complex) may obscure the effects of space weathering. Alternatively, a low abundance of Fe might suppress the formation of npFe\(^0\) and slow down the process of lunar-type space weathering.

Finally, we point out the puzzling case of Vesta, which resides on the opposite end of the traditional space weathering problem, that is, Vesta shows a lack of weathering, even though it is expected. McCord et al. (1970) found an exact match between the spectrum of Vesta and the spectra of the most abundant achondrite meteorite samples, the howardite–eucrite–diogenite (HED), leading to the conclusion that Vesta is the source of HEDs. Compelling evidence from almost every aspect confirms the HED–Vesta connection. Early evidence includes the identification of small (few km) spectrally similar

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**Figure 14** Comparison of space weathering across asteroids and the Moon. There are many manifestations of ‘space weathering,’ and the trends of albedo versus depth of an absorption band versus spectral slope can be different depending on the properties of the surface under study. Reprinted from Gaffey MJ (2010) Space weathering and the interpretation of asteroid reflectance spectra. *Icarus* 209: 564–574, Figure 4, with permission from Elsevier.
asteroids (now known as taxonomic type V) that provide a
dynamic pathway to transport meteorites from the asteroid
belt to Earth (Binzel and Xu, 1993) and the existence of
a large basin near Vesta’s south pole (Thomas et al., 1997a,b).
Recent observations by the Dawn mission confirmed the
mineralogical connection between Vesta, HEDs, and V-type aster-
oids (Ammannito et al., 2013; De Sanctis et al., 2012, 2013)
and confirmed a highly impacted surface with two large, over-
lapping basins near the south pole, with the youngest one
perhaps just ~1 Gy old (Marchi et al., 2012b; Schenk et al.,
2012). However, laboratory studies suggest that ion irradiation
on HEDs darkens and reddens the samples rapidly, corre-
sponding to a space weathering timescale of 10^3–10^6 years
(Fulvio et al., 2012). The lack of space weathering on Vesta
itself is thus a mystery (see summary by Pieters et al., 2006).
To explain it, Vernazza et al. (2006) postulated that Vesta has a
more cometary nuclei (cometary missions returning disk-resolved images of four
(Fulvio et al., 2012). The lack of space weathering on Vesta
Moon and S-type asteroids occurs on Vesta, Pieters et al.
whether the traditional view of space weathering on the
of such processes on the Moon, Eros, and Ida.

10.15.3.4 Surface Morphology on Cometary Nuclei
The encounters with comet 1P/Halley by ESA’s Giotto space-
craft (Reinhard, 1986) and the Soviet Union’s Vega spacecraft
(Sagdeev et al., 1986) marked the first close-up imaging of
solar system small bodies. During the close encounter, the
Halley Multicolor Camera (HMC) on board the Giotto space-
craft centered on the brightest part of the inner coma, showing
the silhouette of a large, solid, and irregularly shaped nucleus
and jet-like dust activity that was much brighter than the
nucleus (Keller et al., 1986). Due to the bright jets in the
foreground of the nucleus, it was difficult to see the surface
morphology of this cometary nucleus from these images.
Nevertheless, the solid nature of cometary nuclei as icy conglomerates as proposed by Whipple (1950) was directly proved
correct. And for the first time, the albedo of a cometary nucleus
was directly measured to be ~4%.

Since the P/Halley flybys, there have been five additional
cometary missions returning disk-resolved images of four
more cometary nuclei (Table 1). A montage (not to scale) of
the comets is shown in Figure 15. The imaging data from
those cometary missions have formed the foundation of our
current understanding of the surface morphology of cometary
nuclei. While the comets have a variety of overall morphologies,
there are many common features, including pits and pitted
terrains, smooth areas, icy patches, and numerous small, bright,
or dark spots.

Comets have numerous (nearly) circular depressions with or
without raised rims on their surfaces, generally termed ‘pits’
due to their completely different morphology from impact
craters on asteroidal surfaces. Pits are observed on all four
cometary nuclei with various sizes and morphologies
(Figure 15; Britt et al., 2004; Brownlee et al., 2004; Thomas
et al., 2007, 2013a,b). The associated pitted terrains usually
occupy a large fraction of a comet’s surface, except in some
regions where there are smooth terrains. The cumulative size
distributions of pits on comets 9P/Tempel 1 and 81P/Wild 2
have slopes between −1.7 and −2.1 (Thomas et al., 2013a),
significantly different from the size distribution of typical
impact craters on the Moon or asteroids (between −2 and
−4). Therefore, pits on comets either do not all originate
from impacts or have been modified after formation. The pits
on comet P/Tempel 1 are up to a few hundred meters in
diameter and up to 25 m in depth, mostly without flat floors.
Those on P/Wild 2 have larger sizes up to ~1.5 km, mostly
with flat floors and some with central peaks. The most distinctive feature on comet P/Wild 2 is the nearly vertical walls of the
pits, sometimes with overhangs. While some pits with raised
rims on some comets could have impact origins (such as the
two circular depressions bracketing the Deep Impact (DI) mis-
sion impact site on comet P/Tempel 1), most of them are
probably cryovolcanic collapse features associated with come-
tary activity (Belton and Melosh, 2009; Belton et al., 2008).
Belton et al. (2013) ascribed >90% of the pits to cometary outburst activity.

The apparently smooth areas on comets P/Tempel 1
(Thomas et al., 2007, 2013a) and 103P/Hartley 2 (Thomas
et al., 2013b) are probably one of the most intriguing features
observed; such areas are visible in Figure 15. These terrains
have smooth texture up to 30 m scale but most likely also at a
5 m scale, with slightly lower reflectance than the surrounding
terrains, and they are usually laterally confined. They occupy
topographic lows with slopes up to a few degrees, suggestive of
flows. The ‘mesas’ on comet 19P/Borrelly as termed by Britt
et al. (2004) appear to be similar to the smooth areas on comets
P/Tempel 1 and P/Hartley 2. Belton and Melosh (2009) pro-
posed a fluidized multiphase transportation of dust resulting
from the sublimation of material with higher volatility than
water, such as CO or CO₂, from beneath the surface as the
origin of the smooth areas on comet P/Tempel 1. No such
smooth area was observed on comet P/Wild 2. Belton (2010)
used the smooth areas to hypothesize an evolutionary se-
quence of the four comets, where the surface of comet P/Wild
2 represents the early stage in the sequence and has not
developed smooth areas that are large enough to be visible,
while the surface of comet P/Hartley 2 represents the latest
stage with the largest fraction of surface covered by smooth
areas.

From the Deep Impact flyby spacecraft images of comet P/
Tempel 1, Sunshine et al. (2006) for the first time unambigu-
ously discovered water ice deposits on the surface of a cometary
Similar water ice concentration was again observed on comet P/Hartley 2 (Sunshine et al., 2011). The icy patches cover less than 1% of the total surface areas of comets and only contain about 3–6% water ice, with typical particle sizes of ~30 \( \mu \text{m} \), much larger than those in ejecta observed by Deep Impact (~1 \( \mu \text{m} \)) (Sunshine et al., 2007) and in comet P/Hartley 2’s coma (Protopapa et al., 2014). Temperature measurements and thermal modeling suggest that the water ice deposits are thermally decoupled from the refractory dust on the surface (Groussin et al., 2007, 2013). The locations of the identified ice deposits on comets P/Tempel 1 and P/Hartley 2 are both near the morning terminators, suggesting that they are probably condensation of water vapor in diurnal cycles as opposed to ice exposed from the interior (which would have much smaller particle sizes, too; Sunshine et al., 2007). It is quite possible that the reason for water ice being definitively discovered on only two cometary nuclei is that only the Deep Impact spacecraft, among those having visited comets, is equipped with a spectrometer capable of detecting water ice. Therefore, it is reasonable to speculate that water ice patches are likely common on cometary nuclei.

In addition to the large-scale features discussed earlier, there are numerous bright and dark spots on all well-imaged cometary nuclei (Figure 16). Some of them appear to be albedo features, such as some bright spots on comets P/Wild 2 and P/Tempel 1. The spots could be water ice concentrated in areas due to topography, but it is not possible to determine their origins conclusively because of the limited resolution or the unavailability of spectroscopic data. On the other hand, some dark spots could be either small-scale albedo features or small, deep pits or holes (Nelson et al., 2004).

Cometary surfaces are under constant change due to outgassing activity. The second flyby of comet P/Tempel 1 by the NEAT mission in 2011 just one perihelion passage after the Deep Impact flyby in 2005 showed clear change in surface morphology (Figure 17; Thomas et al., 2013a), although no obvious change in photometry was identified (Li et al., 2013). The most significant change observed was the retreat of the scarp bounding the smooth area near the south pole by at least 50 m. In addition, at least two crudely triangular areas evident in 2005 disappeared by 2011, representing a backwasting along at least 1000 m of the boundary. It is estimated that
Figure 16  Examples of the bright and dark spots seen on cometary surfaces. Images are of P/Hartley 2, P/Wild 2, and P/Borrelly, from left to right. The P/Hartley 2 and P/Borrelly images are the same as those seen in Figure 15, but with better contrast to enhance the features. P/Wild 2 image is from the Stardust archive of data in the NASA Planetary Data System (Newburn and Farnham, 2008). Some of the bright spots could be footpoints to jets. The dark spots could be low-albedo features or actual pits.

Figure 17  Changes in the surface of comet P/Tempel 1 from one orbit to the next. The left image is from the Deep Impact flyby in 2005, and the right image is from the Stardust flyby in 2011. Various bright and dark spots have appeared and/or disappeared in the intervening 6 years. The edge of the scarp has clearly changed, losing up to 50 m of extent in some locations. This change is shown in the bottom three panels, with the right panel showing the traces of the scarp. Reprinted from Thomas P, A’Hearn M, Belton MJS, et al. (2013) The nucleus of Comet 9P/Tempel 1: Shape and geology from two flybys. Icarus 222: 453–466, Figure 9, with permission from Elsevier.
the total volume loss was about 2–4 × 10^5 m^3, corresponding to 8–16 × 10^7 kg, assuming an average density of 0.47 kg/m^3 (Richardson et al., 2007). It has also been noted that there is concentrated jet activity originating near the scarp (Farnham et al., 2013). In addition to the boundary of the smooth features, several small bright albedo spots (<30 m) in the region have changed in contrast and extent. However, due to their small sizes, the changing viewing geometry, and the different imaging instruments, it remains uncertain whether these are real changes or are due to the effect of different illumination and viewing geometries or instrument effects. Interestingly, no obvious ejecta blanket produced by the DI impact could be identified on the surface of comet P/Tempel 1 (Schulz et al., 2013).

The high-resolution images of comets P/Borrelly, P/Wild 2, and P/Tempel 1 reveal another common feature, that is, ubiquitous surface layering that possibly extends into the interior. Based on these layers, Belton et al. (2007) hypothesized a ‘talpas’ model or ‘layered pile’ model to describe the internal structure of JFCs. In this model, the nucleus interiors are composed of layers of different thicknesses, sizes, and possibly compositions that were accumulated during the primordial accretion phase of comets through low-speed collisions between cometesimals. This hypothesis presents a completely different internal structure from the classic rubble pile model for asteroids (cf. Richardson, 2002, and references therein). While the evolution of asteroids mostly occurred in the inner solar system and was dominated by intense collisions after their formation, leading to their rubble pile nature, the evolution of comets probably took a completely different path. JFCs we see today were frozen for ~4 Gy in the Kuiper Belt, that is, where they are thought to have formed, before being gravitationally perturbed into the inner solar system (e.g., Duncan and Levison, 1997; Duncan et al., 2004; Morbidelli and Brown, 2004). Comets in JFC orbits are active for only 7% of the orbit (Duncan et al., 2004). Therefore, the evolution of JFCs is first dominated by the collisional environment in the Kuiper Belt and then on their surfaces by volatile sublimation during repeated perihelion passages. If talps are primordial in JFCs, then their preservation seems to indicate a much more benign collisional history than the asteroids have undergone. Future cometary missions, especially the CONSERT experiment on ESA’s Rosetta mission that will use ground-penetrating radar to study the internal structure of comet 67P/Churyumov–Gerasimenko (Schulz, 2009), should provide definitive tests on the talpas model.

10.15.4 Structure, Interior, and Spin

10.15.4.1 Structure of Asteroids

From the discovery of the largest asteroid, (1) Ceres, in 1801 by Piazzi (Fodera Serio et al., 2002) until the 1990s, asteroids were largely unresolved point sources. Reflected light can reveal surface composition and perhaps some level of structure through the thermal properties, but the interiors of asteroids were largely inaccessible to study. As described in the previous section, spacecraft missions can reveal exquisite detail of a body’s surface structure and in some cases interior by means of gravity measurements. However, the number of missions will by necessity be limited, so studies of the population must rely largely on ground-based remote sensing.

Ground-based radar does reveal the shapes and surface details of NEAs at few-meter resolution and has led to some surprising discoveries about their structure. Ostro (1989) summarized the early efforts to study the shapes and outer contours of NEAs. The two planetary radar facilities, Arecibo Observatory and Goldstone Deep Space Network, are complementary in their capabilities and ability to study solid solar system bodies, primarily NEAs (Ostro et al., 2002 and references therein). Starting in 1998, the increased sensitivity of the Arecibo planetary radar system, along with the huge increase in the discovery rate of NEAs, has begun to reveal their detailed shapes. Some were the expected collisional fragments, with irregular facets, craters, and ridges. However, some were surprisingly spheroidal, even at sizes of only a few hundred meters. The self-gravity of such small bodies is not nearly enough to overcome the strength of the rock, so these must be strengthless rubble piles. However, other objects in the same size range were seen to be elongated, or rapidly rotating, which required a coherent rock. The diversity of NEAs is remarkable and indicates a variety of formation mechanisms (Nolan et al., 2005; Ostro et al., 2002).

Radar imaging is accomplished by sending a monochromatic signal to the asteroid and receiving the signal, which reflects from the solid surface. Because the precise timing and characteristics of the transmitted signal sent are known, the return signal reveals much about the body, depending only upon knowing the time and speed of light. We can use the time sampling and rotational velocity information to reconstruct an image of the asteroid, with some projection effects, and ambiguity in that several points on the asteroid surface may have identical distance and apparent velocity and thus map to the same location in the radar image (see Magri et al., 2007; Ostro, 1993, for more details).

The resolution of a radar image depends on the signal-to-noise ratio (SNR) of the signal reflected from the asteroid. The power of the transmitter, size of the telescope, and gain contribute to the SNR, but the dominant factor is usually distance from Earth. The SNR depends on the inverse fourth power of distance. The resolution of NEAs is given in several studies (e.g., Richardson et al., 2007). It has also been noted that there is a variety of formation mechanisms (Nolan et al., 2002). As described earlier, NEAs are collisional fragments of larger objects that are then perturbed into planet-crossing orbits (e.g., Bottke et al., 2002a). While some NEAs do indeed look like irregular collisional shards, many others do not. About 25% of the NEAs between 200 and 800 m are spheroidal, and another 10–15% are two spheroidal lobes joined together. Elongated objects, with axial ratios of 2:1 or more, comprise about 10% of the sample, while binary systems are another 15% of NEAs less than 10 km in diameter (Taylor et al., 2012). An asteroid less than 10 km can only be spherical from its own gravity if it is strengthless, although surface features such as craters and ridges can be supported by friction in the surface material. Surface features seen in radar images must
be interpreted with caution, because the image is not a spatial image, but it does map into a spatial image. A radar image is really distance from the observer in one dimension, and rotational velocity in the other dimension, or distance from the rotation axis. By convention, radar images always appear as if the object is viewed from the north pole, illuminated from 90° phase angle. From a single image, the location of a feature on the surface cannot be determined uniquely. However, a series of images over several days can be used to derive a shape model (e.g., Magri et al., 2011; Nolan et al., 2012; Ostro et al., 2005). More limited datasets can be used to identify surface textures and features that often reveal internal structure.

The sample of objects shown in Figure 18 includes some notable objects. Asteroid (153951) 2001 SN_{263} is the first triple asteroid system discovered among the NEAs, where the outer satellite is larger (below the primary in this image) orbiting in about 6.2 days and the smaller inner one (above the primary) orbits in about 16.5 h. The OSIRIS-REx mission will visit asteroid (101955) Bennu (formerly 1999 RQ_{36}), a 550 m spheroidal asteroid, which although rotating relatively quickly (4.2 h) does not appear to have a satellite larger than 10 m at the present time. Both (374851) 2006 VV_{2} and Bennu have one or more boulders on the surface larger than 10 m, perhaps similar to those seen on Itokawa and Eros. The population of NEAs is varied in size and shape, composition, and rotation, suggesting a variety of possible outcomes for the same formation conditions.

10.15.4.2 Spin of Asteroids

The rotation rate of an object can put constraints on its internal structure. Optical light-curve observations of asteroids and comets have been carried out by both amateur and professional astronomers for many decades and provide an extensive database with which to study the population of asteroids. The most reliable data from the asteroid light-curve database compiled by Warner et al. (2009) – and which is frequently updated at http://www.minorplanet.info – are plotted in Figure 19 for main-belt asteroids, with H magnitude on the x-axis and rotation frequency (rotations per day) on the y-axis. The H magnitude is the brightness of an asteroid at 1 AU from both Earth and Sun, and at zero phase angle, so is a proxy for the asteroid diameter. The plot shows that for about H < 20, a rotation frequency of 10, or about 2.4 h rotation period, is a limiting value for all asteroids. This corresponds roughly to the fastest rate at which a strengthless rubble pile structure can spin without flying apart (e.g., Pravec and Harris, 2000). Smaller asteroids (H > 20) can break this spin barrier and can rotate as

![Arecibo radar images of a variety of asteroids can reveal surface features as small as 7.5 m. Scale bars show the approximate size in the vertical direction. In each of these images, the distance from Earth increases from top to bottom (except for 2006 VV_{2}, where it is the opposite), and Doppler frequency or object rotation velocity in the line of sight increases from left to right. These are not spatial images, but for a rigid body, they map into a spatial image, and surface features can be interpreted readily with some projection effects.](image)
2000 (Margot et al., 2002) opened up a new window on the discovery of the first binary NEA, (185851) 2000 DP 107, in the main belt population in the few-kilometer-size range (Pravec et al., 2006). Yet another technique that works quite well for binary discovery in the main belt is direct imaging through the use of telescopes that have adaptive optics. Normally, the atmosphere distorts the wave fronts from an astronomical source that are collected by a telescope; turbulence in the atmosphere leads to the light coming through many cells of air that each have slightly different indices of refraction. When the telescope tries to bring all the light to a focus, the resulting image is blurry, usually far blurrier than would be expected from just considering the diffraction limit of the telescope’s optics. For example, a 10 m telescope at a good astronomical site, without the aid of adaptive optics, might normally achieve images with ~0.5 arcsecond resolution, whereas the diffraction limit (Rayleigh criterion) at visible wavelengths for such a telescope is about 0.01 arcsecond. ‘Adaptive optics’ is the term for the technological feat of having a deformable mirror in the optical path (after the secondary mirror) that deblurs the light by changing the light’s reflection just enough to cancel out the effects of the turbulent cells of air. The mirror is deformed and re-deformed many times per second. An example of the incredibly good resolution that can be achieved through adaptive optics is shown in Figure 20, where one can clearly see a triple asteroid system, (216) Kleopatra (Descamps et al., 2011).

Following the discovery of binary 2000 DP 107, several formation theories were put forth. Tidal effects due to planetary encounters, collisional debris, disruption by collisions and reformation as a binary, and rotational fission all seemed viable possibilities (Merline et al., 2002). However, after several more binary systems were observed, and their common features compared, it was clear that some of these formation theories could be ruled out. All NEA binary systems have a fast rotating primary body, usually close to 2.5 h, near the theoretical spin barrier for a rubble pile structure (see Figure 19). The angular momentum of the system was well above the stability threshold, suggesting that spin-up and fission had occurred. The size of the secondary is remarkably consistent, between one-third and one-fifth of the primary diameter, and the orbit falls within 3–5 primary radii away. Many of the satellites are in synchronous rotation, and most are in very circular orbits, suggesting substantial tidal evolution. However, a few systems are not in synchronous rotation, and some satellites have orbital eccentricities of up to 0.15; one system, (153958) 2002 AM31, has eccentricity near 0.45 (Taylor et al., 2013).

Figure 19  Distribution of the rotation rates of asteroids. Rotation rates are given as frequencies (left axis) and periods (right axis). The rates are shown as a function of diameter (top axis), which is estimated from the absolute magnitude (H; bottom axis) using an assumed geometric albedo of 0.20 (cf. Figure 5). Plotted here are the higher-quality observations (U’ parameter of 2 or 3) taken from the asteroid light-curve database (Warner et al., 2009), based on many nights of observation for each asteroid to determine the rotation rate from changes in the brightness of the object as it rotates. Note the sharp cut in the distribution at a rotation period near 2.4 h. This rate seems to be a limit for asteroids larger than H magnitude of about 21, which has been interpreted as being the fastest that a strengthless, rubble pile body can spin without breaking apart. Figure is courtesy Patrick Taylor.

rapidly as 30 s. This certainly requires some tensile strength, although some internal fractures and porosity can still be present. The spin limit depends on the material density, so it is slightly slower for icy bodies. No asteroids appear to be both small and rotating slowly, although these are difficult to measure using ground-based optical telescopes. Radar measurements should see small objects rotating slowly if they exist, but the distribution from radar observations matches the light-curve distribution very closely, despite having very different observational biases.

10.15.4.3  Binaries

The discovery of the first binary NEA, (185851) 2000 DP 107, in 2000 (Margot et al., 2002) opened up a new window on studying interior structure of asteroids. Radar images allow the sizes of both components to be observed so the mass of the primary body can be derived from the orbit. Searches for binary asteroids had been inconclusive prior to this time, even leading to theoretical searches as to why binaries did not exist and would not be stable (e.g., Gehrels et al., 1987). Light-curve measurements suggested binary systems existed for decades, but the possibility of two-lobed or contact binary objects could not be ruled out for most of the cases. Clear evidence of occultations and eclipses in asteroid light curves had not been confirmed prior to the discovery of 2000 DP 107. However, after the first radar detection of an NEA binary system, showing the clear separation of the components, the light-curve evidence was then considered much more convincing.

As of 2014, two-thirds of the approximately 50 known NEA binary systems have been discovered using radar, still the most powerful means of identifying binary systems. Light-curve detection continues to be an important contributor and is now showing binary systems are equally common in the main-belt population in the few-kilometer-size range (Pravec et al., 2006).
most important factor in forming binaries. Binary systems are found, for example, among S-complex objects, X-complex objects, and V types (e.g., 2006 VV2). In particular, some binaries share characteristics that point to formation by spin-up due to the YORP effect, in particular some V types and Xe types, especially those Xe types that are part of the Hungaria family (the high inclination, low semimajor axis, and high-albedo group seen in the upper left of Figure 3). Note that Xe types used to be known as E types in the Tholen system and may have enstatite surfaces.

The densities of NEA binaries, 1.0–2.0 g cm\(^{-3}\), imply porosity of 30–50% if the grain density is 2.5–3.2 g cm\(^{-3}\) for ordinary or carbonaceous meteorites assumed to be the parent body analogs for at least some of the S-complex and X-complex objects. Britt and Consolmagno (2003) measured porosities of meteorites and found that cracks and fissures on all scales give moderate porosities (20–30%) for seemingly solid samples. Asteroid porosities of 50% or even more are not inconsistent with many meteorite samples we have. A thorough compilation of asteroid porosities is given by Carry (2012) and shown in Figure 21.

The first asteroid shape model resulting from radar observations, that of (4769) Castalia (formerly 1989 PB), is a two-lobed structure, reminiscent of a molar tooth (Hudson and Ostro, 1994). Many more asteroids have since been seen to have this same basic shape, not only NEAs but also comet nuclei (Harmon et al., 2010, 2011; Magri et al., 2011). Unlike near-Earth binary systems, these contact binaries tend to be slowly rotating and have nearly equal mass lobes (Benner et al., 2008). Jacobson and Scheeres (2011) suggested that when an object splits into nearly equal mass lobes, a stable binary system is difficult or impossible to form. The equal mass systems, (69230) Hermes (Margot et al., 2003) and (90) Antiope, are rare in the near-Earth and main-belt zones. In the Kuiper Belt, binary systems of nearly equal mass are more common, but the discovery biases are quite different from those in the other regions, as are the size ranges observable. The conditions that would lead to the formation of a contact binary rather than a rapidly rotating binary with mass ratio 1:3 or more may not really be fundamentally different, but may instead be a stochastic process.

10.15.4.4 Cometary Properties

Comets lag far behind asteroids in terms of our understanding of ensemble properties of structure and rotation. There are fewer available targets for study by radar, and rotational studies at visible wavelengths can be complicated by the fact that often, the coma is much brighter than the nucleus. Radar delay-Doppler imaging of the sort that appears in Figure 18 has only been obtained on four comets: P/2005 JQ2 (Catalina) (Harmon et al., 2006), 73P/Schwassmann–Wachmann 3 (Howell et al., 2007), 8P/Tuttle (Harmon et al., 2010), and P/Hartley 2 (Harmon et al., 2011). This last comet is shown in Figure 22, and one can compare the radar image of P/Hartley 2 to those shown in Figures 15 and 16.

In addition to the delay-Doppler imaging, basic radar spectra have been obtained from 11 other comets total (Harmon et al., 2004, 2011), yielding constraints on nuclear sizes and rotation rates. In some cases, the radar echoes contain a wide (in velocity space) skirt of flux. Since the wavelength of the radar is cm scale, this skirt is thought to show echoes from very large grains (>2 cm diameter) in the near-nucleus coma. Typical cometary activity can only lift (through the drag force) grains up to cm size; larger grains are usually too heavy and do not reach escape velocity (Grün and Jessberger, 1990), although in the context of fragmentation, larger grains can be liberated (e.g., Howell et al., 2007). In any case, the radar echo
A review of cometary rotation is provided by Samarasinha et al. (2004), and from 2004 to 2014, there have been only a few new rotation periods found for comets. The existence of excited (nonprincipal axis) rotation states has been noted in a few comets (e.g., comet P/Halley: Belton et al., 1991), but it is not always easy to confirm such spin states. One important advance since the mid-2000s however has been the discovery that several comets change their rotation periods significantly on orbital timescales. This phenomenon was first confirmed for 10P/Tempel 2 (Knight et al., 2012; Mueller and Ferrin, 2014).

**Figure 21** Scatter plot of macroporosities and masses of various small bodies as compiled by Carry (2012). Shading of each circle indicates the approximate uncertainty of the porosity measurement; Carry (2012) quantized the uncertainty as 20%, 50%, and 'infinity' (i.e., very large). Most of these results are from the 1990s and later; it is only since then that we have come to realize that many small bodies have large porosity. Reprinted from Carry B (2012) Density of asteroids. *Planetary and Space Sciences* 73: 98–118, Figure 8, with permission from Elsevier.

**Figure 22** Radar echoes from and shape modeling of comet P/Hartley 2. One of the delay-Doppler images of the nucleus is shown at top left, along with a simulated image from a shape model of two joined ellipsoids at bottom left. That shape model itself for the nucleus is shown at right. The long axis of the nucleus is about 2.3 km. Compare the model to the spacecraft imaging shown in Figures 15 and 16. Radar observations prior to the flyby of the comet by the Deep Impact spacecraft helped to refine the position of the comet nucleus and were critical to the success of the mission. The radar image sequence also helped to refine the rotation state. This is an excellent example of how ground-based observations provide important context for spacecraft missions. Reproduced from Harmon JK, Nolan MC, Howell ES, Giorgini JD, and Taylor PA (2011) Radar observations of comet 103P/Hartley 2. *Astrophysical Journal Letters* 734: L2, Figure 2(b), ©AAS, with permission.
1996), although it might have been seen in other comets earlier (e.g., Schleicher et al., 1991). Recently, changes in the rotation period have been noticed in comets 2P/Encke, P/Tempel 1, and P/Hartley 2 (Chesley et al., 2013; Meech et al., 2011; Mueller et al., 2008; Samarasinha et al., 2011). The change is on the order of 0.1–1%. For P/Encke; the change is a few minutes per orbit; for P/Tempel 1 and P/Hartley 2, it is on the order of 1 h per orbit. The primary driver is a net torque exerted on the nucleus by the reaction force of its outgassing. The physical importance of understanding such short-term changes in the rotational state is that one can then try to understand how long it takes for the excited rotation state to damp out, an effect that depends on the bulk solidity of the nucleus itself – that is, how much different pieces of the low-density nucleus rub up against each other. In other words, studies of cometary rotation states provide a clever way to try to understand the physical nature of cometary interiors.

The rapid changes that a comet can make to its own rotation period mean that in general, a comet has no memory of its primordial spin state. An intriguing study – but likely only feasible far in the future – would be to look at the distribution of rotation states among LPCs that are each on their first trip in from the Oort cloud and before they actually turn on. In other words, how are the LPCs spinning before they feel any torques from their own outgassing? Such observations would likely give us a window into a more primordial spin state distribution or at least certainly a glimpse of what very long-term, evolutionary dynamic processes might affect the comets while they are in the Oort cloud, tens of thousands of AU from the Sun. The difficulty is that there are virtually no LPCs discovered that are new in the Oort sense that are inactive; such objects are simply too faint to detect with current technology.

Even such fundamental quantities as the mass and the density of a cometary nucleus have been exceedingly difficult to constrain. Spacecraft have in general been too far from each comet under study to have their trajectories gravitationally deflected. The ejecta cloud produced by the impactor experiment with the Deep Impact mission suggested that the density of comet P/Tempel 1 is very low, about 400 kg m$^{-3}$ (Richardson et al., 2007) although the quoted range is 200–1000 kg m$^{-3}$. The shape of comet P/Hartley 2’s nucleus, like two ellipsoidal lobes, suggests that it might be showing an equipotential surface; if that is the case, Thomas et al. (2013b) derived a density of 200–400 kg m$^{-3}$. Before these missions, the most common way to estimate a comet’s mass was through the use of its nongravitational parameters, that is, by making use of the changes to a comet’s orbit caused by the reaction force of its own outgassing. Not only does outgassing change the spin state (as discussed earlier), but also the orbit then deviates from a purely gravitational solution (Marsden et al., 1973). Some recent estimates have been made for P/Wild 2 (upper limit of about 600–800 kg m$^{-3}$; Davidsson and Gutierrez, 2006) and P/Borrelly (100–300 kg m$^{-3}$; Davidsson and Gutierrez, 2004). Other estimates using the fact that the density must be sufficient to keep a comet from splitting apart due to its rotation are in the range of about 200–500 kg m$^{-3}$ (Davidsson, 2001). While it is wise to keep in mind that some of these analyses are model-dependent, the results are consistent with the idea that cometary nuclei are underdense and very porous bodies.

### 10.15 Composition

#### 10.15.1 Basic Premises

It is commonly assumed that because the comets we see today have spent most of their lifetimes in an environment too cold for most geochemical processes to occur and are too small to differentiate or retain heat of formation, that to first order the gas that comes off pristine comets will tell us about the compositional and chemical environment of the young solar system’s protoplanetary disk. The situation is more complex for asteroids, which may have suffered more processing due to internal heat and in some cases differentiation, but some primordial information can still be inferred.

As discussed earlier, the comets we see today are vestiges of the icy planetesimals that were formed during the era of planetary formation. When such a planetesimal was created, while the primary component was water, many icy species (CO, CO$_2$, CH$_3$OH, CH$_2$O, etc.) were incorporated into its body. The relative amounts of these species were a direct sample of the chemical and thermal properties of the protoplanetary disk at that time and at that location (or perhaps the locations sampled by the planetesimal if scattering occurred while it was accreting).

Since the volatile content of asteroids in general does not outgas, but is locked in the minerals, it is much more difficult to ascertain compared with comets. Except in the case of sample return, asteroid composition is determined either by analysis of meteorites (which may have lost some of their volatiles during atmospheric entry or due to weathering after reaching the ground) or by modeling the compositional diagnostics in the reflectance and emission spectra of the surfaces. These multi-component fits are highly dependent on the typical grain size of the regolith on the surface, making it difficult to distinguish between, for example, adsorbed water in layer phyllosilicates, OH groups on hydrated silicates, and actual water on clay grains. Basically, most remote sensing observations – even by a spacecraft that might be considered to be in situ – are only sensitive to the topmost microns of an object’s surface, leaving most of the bulk of the object itself unsampled. Radio and radar observations can penetrate deeper – several wavelengths, so roughly a few decimeters – but there are fairly restrictive detectability limits in that wavelength regime.

As mentioned in Section 10.15.1, some asteroids have been observed to have outbursts of dust, showing something like a cometary coma and tail. While some of these objects have merely suffered a collision and thrown off dust as debris from an impulsive impact, several objects have been observed to have sustained dust production over weeks or months. Presumably, such activity is driven by water (although this has yet to have observational confirmation), and rather than the sharp classifications of icy comets and rocky asteroids, it seems likely there is a spectrum of compositions between the two endpoints. The active objects with asteroid-like orbits have been dubbed the ‘main-belt comets.’ The prototype MBC, with not only the comet designation 133P/Elst–Pizarro but also the asteroid designation (7968), is shown in Figure 23. Dynamic modeling of the long tail shows that the cause of the ejection of dust from the object could not have been impulsive; it must have lasted for months and therefore is likely to be water sublimation-driven. Furthermore, P/Elst–Pizarro has shown activity consistently now at
properties can yield, for example, the rotational state of the rate of gas production from the nucleus. Modeling of these comae, we can examine the distribution, composition, and studies of the coma. From observations of gas in cometary coma that is usually bright enough to make it difficult to approach the Sun, their volatiles begin to sublimate, likely increasing proportion with distance from the Sun. As comets nated by rock-forming minerals but should have volatiles in comets is dominated by volatiles, while asteroids are domi-

nearly the same orbital longitudes for four orbits (Hsieh et al., 2013). There are currently less than ten known MBCs, but surveys are ongoing and it is expected more will be discovered. Statistical analysis of asteroid populations has suggested there may be on the order of a few hundred to a few thousand MBCs (Bertini, 2011; Gilbert and Wiebert, 2010; Hsieh, 2009). The existence of these objects has already transformed the way we think about the formation of planetesimals and mixing in the early solar system (see, e.g., Bertini, 2011). As we move from the discovery phase to the determination of composition of these objects, they should prove to be a valuable tool in constraining protoplanetary chemistry.

### 10.15.5.2 Volatiles

As discussed in Section 10.15.1, the primary difference between comets and asteroids is that the composition of comets is dominated by volatiles, while asteroids are dominated by rock-forming minerals but should have volatiles in increasing proportion with distance from the Sun. As comets approach the Sun, their volatiles begin to sublimate, likely from the outer 1–2 m (Prialnik et al., 2004). This produces a coma that is usually bright enough to make it difficult to discern the nucleus itself from Earth-based observations. Thus, frequently, the nucleus’s properties are inferred from studies of the coma. From observations of gas in cometary comae, we can examine the distribution, composition, and rate of gas production from the nucleus. Modeling of these properties can yield, for example, the rotational state of the nucleus and lower limits on its size (e.g., Samarasinha et al., 2011; Schleicher and Woodney, 2003). Some gases sublimate directly from the nucleus (parent) and others are produced in the coma (daughter), either by chemical reactions or, more commonly, by photodissociation of the original molecules. As water is the most abundant volatile, all other volatiles in comets are typically measured by abundance relative to water or its direct photofragment OH.

The various volatile species found in comets have a wide variety of sublimation temperatures, which means they have the ability to begin outgassing at a variety of heliocentric distances. CO is the most volatile with a sublimation temperature of 25 K, though the somewhat more abundant CO₂ with its sublimation temperature of 80 K and ability to begin outgassing around 13 AU is believed to be the likely driver of most distant comet activity (Meach and Svoren, 2004). Water gradually takes over as the primary driver of cometary activity as heliocentric distance decreases. This variation in onset sublimation temperature leads to variations in abundance with heliocentric distance for some species (Figure 24; Biver et al., 1997, 2002). This is not the only reason abundances can vary with heliocentric distance, for instance, the variation in the HNC/HCN ratio has been shown to be due to chemistry in the coma (Irvine et al., 1998; Rodgers and Charnley, 1998).

Chemical abundances of volatiles vary from comet to comet, but when a large number of comets are observed, statistically significant groupings appear; thus, much work from the 1980s to the 2010s has gone into developing and understanding compositionally based taxonomies. The first of these was done with daughter fragments OH, NH, CN, C₆, and C₇ as these are readily observed in the optical, often with smaller aperture telescopes (~1–2 m), owing to their electronic transitions at visible wavelengths. A’Hearn et al. (1995) observed 85 comets, discovering that a significant fraction of JFCs (those originating in the Kuiper Belt) were depleted in carbon-chain molecules – C₂ and C₃ – relative to comets originating in the Oort cloud. This is shown in Figure 25, which is taken from the work by A’Hearn et al. As of 2013, this work has been extended to 101 comets, and principal component analysis continues to show that the carbon-chain depletion is not associated with evolution, but is primordial in nature (D. Schleicher, private communication). Additional optical surveys have been done spectroscopically. Those done by Fink (2009) and Langland-Shula and Smith (2011) also divide their comets into taxonomies and agree with the A’Hearn et al. results where they overlap on carbon-chain depletion.

To determine composition, one would ideally observe the species that sublimate directly from the surface – that is, the parent species – rather than the chemical fragments. Most of these species, however, only have spectroscopic transitions in the infrared (vibrational and rovibrational) and radio (rotational). Some important species – most significantly, CO₂ – have transitions that occur at wavelengths where the atmosphere is effectively opaque. Such species can only be observed from space. Emissions from many parent species at radio wavelengths tend to be faint enough that they can only be observed in the brightest comets. Despite these challenges, the database of observed comets at these wavelengths continues to grow and taxonomies of parent species are beginning to emerge. Figure 26 from the work of Mumma and Charnley (2011) shows all of the species thus far observed. Radio surveys...
of 14 different species, 10 of them primary, in more than 40 comets have revealed no significant groupings related to dynamic origin (Biver et al., 2002; Crovisier et al., 2009).

The late 2000s and early 2010s have seen a burst of detections of CO$_2$, in over 40 comets, thanks to spacecraft observations, both in situ and remote (e.g., Combes et al., 1988; Crovisier et al., 1997; Feaga et al., 2007; Ootsubo et al., 2010; Reach et al., 2013). The abundance of CO$_2$ relative to water varies from ~3% to 30% when measured within 2.5 AU of the Sun (i.e., where water-driven outgassing is most vigorous), and no abundance variation based on primordial origin is observed (Mumma and Charnley, 2011).

Many of the organic species shown in Figure 26 are seen, as mentioned, at infrared wavelengths through the use of high-resolution, cross-dispersed echelle spectrometers. Such instruments can observe the vibrational transitions of many species at once. This has the advantage of there being no uncertainties in relative abundances due to rotational variation. In the infrared, water, the species to which all others are compared, can also be measured directly. Species included so far in surveys are H$_2$O, CO, HCN, CH$_3$OH, H$_2$CO, CH$_4$, C$_2$H$_2$, C$_2$H$_6$, OCS, and NH$_3$ (Bockelée-Morvan et al., 2004; DiSanti and Mumma, 2008; Mumma et al., 2003). These surveys, which have included 26 comets so far, find three groupings based on organic abundances: organic-normal, organic-enriched, and organic-depleted. Interestingly, unlike the optical photofragment-based surveys mentioned earlier, there is no clear relation between composition and origin, since comets of both Kuiper Belt and Oort cloud origin occur in all groups. Work to increase the sample size and improve statistics is ongoing (Mumma and Charnley, 2011).

The isotopic ratios of a number of elements in comets are of interest because they are considered signatures of the environment in which the Sun formed. The D/H ratio is one of the most sought after due to the question of how much comets contributed to the Earth’s water. The six Oort cloud comets measured before 2010 all had D/H ratios much higher than Standard Mean Ocean Water (SMOW). The first measurement of a Kuiper Belt comet was made by the Herschel space telescope, and P/Hartley 2 was observed to have the same

![Figure 24](https://example.com/figure24.png)
D/H ratio as SMOW to within the errors (Hartogh et al., 2011). This detection was followed by an upper limit for another JFC, 45P/Honda–Mrkos–Pajdušáková, which was consistent with the low D/H observed in P/Hartley 2 (Lis et al., 2013). The enigma of these observations is that the deuterium in comets originating in the Kuiper Belt was expected to be enriched relatively to that of the isotropic comet population (Kavelaars et al., 2011). If the protosolar nebula began with enriched D/H similar to dense molecular clouds (~1 × 10^{-5}), Butner et al., 2007), and the reactions that reduce that ratio in the protoplanetary disk decrease with distance due to decreasing temperature, density, and turbulent mixing with distance (e.g., Aikawa and Herbst, 2001; Drouart et al., 1999; Mousis et al., 2000), then it would be expected that the D/H ratio would increase with increasing distance. While this led Hartogh et al. (2011) to conclude that it was possible that either these models could be incorrect or P/Hartley 2 could be an escaped Trojan (since Trojans possibly formed closer to the Sun where D/H ratios would be more depleted), the discovery of a second depleted JFC makes it even more important to measure the D/H ratio in a greater sampling of this population to determine whether this is a real taxonomic difference and also whether this can constrain our models of solar system formation. Additionally, this question has significant implications for the delivery of water to the inner solar system. A thorough review of D/H observations and challenges can be found in work by Mumma and Charnley (2011).

Since studies of comet composition make use of the coma and not the actual cometary nucleus itself, it is reasonable to wonder if the composition of the coma really can tell us the composition of the nucleus. More specifically, how do we know that the layer in the nucleus from which the coma gases originate is truly indicative of the interior composition? How much heterogeneity is there?

An important clue was provided by the Deep Impact spacecraft’s visit to comet P/Tempel 1. The mission used an impactor to excavate a crater, yielding an opportunity to compare the composition of typical outgassing from surface layers with that of freshly excavated deeper layers as much as 20 m below the surface (Richardson et al., 2007). Measurements from both the ground and the spacecraft showed to within the uncertainties no change in abundance in most chemical species between the typical near surface outgassing and the ejecta plume from the excavated crater. Parent species CO2 (Feaga et al., 2007), CO (Feldman et al., 2006), and HCN (DiSanti et al., 2007), as well as daughter fragments (photodissociation products of the larger parent molecules) NH, CN, C3H, NH2, and C2 (Cochran et al., 2007), all retained the same relative abundance to water. So at the 0–20 m depth level, the degree of heterogeneity in comets – at least in comet P/Tempel 1 – seems to be low.

The topic of heterogeneity came to the forefront again after the spectacular data returned by the Deep Impact spacecraft as it flew by P/Hartley 2. Heterogeneity is demonstrated in Figure 27, which shows various images of the comet as constructed from the extensive infrared spectroscopy that was obtained. By looking at specific wavelengths in the spatially resolved spectra, spectral maps could be created. This particular figure is from the work of A’Hearn et al. (2011). The maps show that the sublimation of water was predominantly coming from the central region of the nucleus, as seen in the bottom left panel labeled ‘H2O vapor.’ However, the reflected sunlight off the dust (top left) and the emission from organic species (middle right) are almost entirely spatially uncorrelated with

**Figure 25** Correlations between relative abundances of daughter species in the comae of comets. \( Q(X) \) refers to the production rate of species \( X \). The strong depletion of \( C_2 \) and \( C_3 \) in some comets – denoted by the open circles – indicates a significant heterogeneity in the comet population. For the ‘typical’ comets (filled circles), the abundance of \( C_2 \) and CN (relative to water) is about the same (left panel), with the abundance of \( C_3 \) about a factor of 10 lower (middle panel). The dichotomy of abundance ratios does not extend however to NH (right panel). Reprinted from A’Hearn MF, Millis RL, Schleicher DG, Osip DJ, and Birch PV (1995) The ensemble properties of comets: Results from narrowband photometry of 85 comets, 1976–1992. *Icarus* 118: 223–270, Figure 10, with permission from Elsevier.
the water vapor. Instead, they are strongly correlated with the CO₂ emission as seen in the top right panel, indicating that CO₂ at one end of the comet is driving much of P/Hartley 2’s activity. Indeed, the CO₂ is even pulling off chunks of water ice (bottom right panel) into the coma.

However, the heterogeneity question is not yet fully understood, since there is good evidence that some comets are homogeneous perhaps all the way through – in particular comet P/Schwassmann–Wachmann 3, which was observed extensively in 2006 after it had broken into several large pieces during the previous two apparitions in 1995 and 2001. The gas and dust compositions in the coma of the comet’s fragments were basically identical (Dello Russo et al., 2007; Sitko et al., 2011). There was no indication that the two main pieces of the comet (fragments B and C) had radically different makeup. Both comets P/Schwassmann–Wachmann 3 and P/Hartley 2 are JFCs, but the lack of heterogeneity in P/Schwassmann–Wachmann 3 suggests that the two comets could not have been formed from material that had experienced the same amount of mixing in the protoplanetary disk. Of course, there are few comets with detailed enough measurements to make a claim about heterogeneity, so this topic requires more data before broad generalizations can be justified.

The volatile content of MBCs is a new development that has taken on added importance with the claim of water ice on the surface of asteroids (24) Themis and (65) Cybele (Campins et al., 2010; Licandro et al., 2011; Rivkin and Emery, 2010). While it was certainly true that the primitive bodies in the outer main belt were thought to have appreciable water content, the observational results provide confirmation. Note however that the existence of water-bearing minerals on asteroids – as evinced by the 3 µm absorption band – has been known since the late

**Figure 26** Relative production rates of various volatile species in comets. All abundances are scaled to water, which is set at 100%. The red segment shows the range among all measured comets; the numeral at the right edge gives how many comets in which the production rate of that species has been measured. After water, carbon dioxide, carbon monoxide, and methanol are the next most abundant species. Note the large variation in diatomic sulfur. Reprinted from Mumma MJ and Charnley SB (2011) The chemical composition of comets—emerging taxonomies and natal heritage. Annual Review of Astronomy and Astrophysics 49: 471–524, Figure 4, with permission from Annual Reviews.
1970s, when it was first seen on Ceres by Lebofsky (1978). Interestingly, there is evidence of transient or variable OH coming from Ceres, first reported by A’Hearn and Feldman (1992) using IUE and then later by Küppers et al. (2014) using Herschel. In particular, the Herschel observations have shown evidence of OH while Ceres is near perihelion, and the amount is seen to vary with Ceres’s rotation, suggesting specific source regions on the surface. Detection of water and/or ice in the outer part of the asteroid belt has also motivated some theoretical work on understanding how volatiles – in particular, water ice – can survive in the asteroid belt for billions of years (e.g., Schorghofer, 2008). The key seems to be having low thermal inertia so that diurnal and annual heat pulses from sunlight simply cannot make it down deep into the interior of the bodies. Thus, the natal water ice can survive for long periods of time and is available when, for example, an impactor strikes the body, clearing away the topmost layers and exposing the underlying ice to space and to the telescopes of astronomers.

The longevity of water ice and the poor thermal coupling between volatiles and rocks are also exemplified by the findings of the Deep Impact spacecraft on both comets P/Tempel 1 and P/Hartley 2, where surface ice was seen to cover a small percentage of each nucleus’s surface in locations where ostensibly the local temperature of the rock was well above the water ice sublimation temperature (Groussin et al., 2013; Sunshine et al., 2006). While this ice is likely not primordial, but probably a recondensation of settled water that was formerly in the gas phase, it is remarkable that cold ice could so clearly be seen surrounded by much hotter rock. Furthermore, the fact that CO2 was so abundant in as small a comet as P/Hartley 2 – one might have expected such a highly volatile species to have been completely baked out of the comet – lends further credence to the idea of cometary ice being decoupled from cometary silicates, probably helped by high porosity.

Much of the water content of the asteroids is studied through its existence within hydrated minerals, largely phyllosilicates. Studying the hydration is important for understanding what was going on in the young solar system such that liquid water could actually be in the physical presence of some of these minerals. In particular, the absorption band near 3 μm has been studied extensively in many asteroids, as mentioned earlier, going back over 30 years (e.g., Lebofsky, 1980). The aqueous alteration of minerals is seen in many primitive asteroids, but it is important to note that not all of them have it (e.g., Barucci et al., 1998; Rivkin, 2012; Rivkin et al., 2002). Interestingly, some of the asteroids that show evidence of hydration – for example, the so-called M types (under the Tholen taxonomy) – were once thought to be largely metallic.
asteroids and to have been heated to quite high temperatures. The presence of hydrated minerals and the lack of FeO seem to contradict this scenario. Radar observations do not support most of the M types having significant iron metal, at least near the surface (Shepard et al., 2010, submitted for publication). However, iron–nickel meteorites must come from somewhere, and the parent bodies of these are still under debate (e.g., Emery and Lim, 2011). In the Bus–DeMeo taxonomy, the former M types now fall within the X-complex, distributed among several taxa, and are apparently a compositionally heterogeneous group.

10.15.5.3 Mineralogy

As stated in Section 10.15.1.5, Figure 2 has a sampling of the spectral diversity among the asteroids. Note that the figure is not exhaustive; the overall slope of an asteroid’s spectrum can change depending on how much weathering it has suffered, so in some cases, a single type of asteroid can actually encompass a range of spectral slopes.

In any case, the figure demonstrates that many asteroids have absorption features that are diagnostic of the surface composition; the most prominent and commonly seen ones are the deep features near 1.0 and 2.0 μm, commonly referred to as ‘Band I’ and ‘Band II,’ respectively. Both absorption bands are due to pyroxene, while olivine also contributes to Band I. The band centers and band areas can be used to place some constraints on the mineral abundances of Ca and Fe in the pyroxenes, of clin- versus orthopyroxene, and of olivine (e.g., Gaffey et al., 2002). However, it is important to note that the mixing of various different particle sizes and compositions can lead to nonunique interpretations of observed spectra.

Another frequently seen absorption feature occurs near 0.7 μm, which seems to arise in asteroids with phyllosilicates on the surface (Vilas, 1994). The oxidized iron within the hydrated mineral undergoes a charge transfer from doubly to triply ionized (i.e., Fe$^{3+}$ to Fe$^{2+}$). As might be expected, the existence of this feature is correlated with an absorption feature near 3 μm that is also indicative of hydrated minerals (e.g., Rivkin, 2012; Rivkin et al., 2002); the visible-wavelength feature however is much easier to observe.

Direct sampling of asteroid mineralogy has now become possible with the success of the Hayabusa mission, which returned samples from the surface of Itokawa. In particular, one major result was that the strongly suspected link between S-type asteroids and OCs was confirmed (Nakamura et al., 2011). Furthermore, the isotopic oxygen abundance suggests that Itokawa itself is one of the sources of the OCs (Yurimoto et al., 2011).

Comet mineralogy has largely been studied through the dust grains that are dragged into space by the sublimating gas. An excellent recent review has been given by Kelley and Wooden (2009). Typical grain sizes are on the order of 1 μm, which is small enough that emission features from silicates appear in the 10 μm region, a wavelength regime amenable to ground-based spectroscopy. One of the most intriguing results from the study of many comets is the existence of crystalline silicates. Such crystallinity is in contrast to interstellar silicates, which may start out crystalline but are amorphized on million-year timescales (e.g., Kemper et al., 2004). Thus, crystalline silicates within the comets must have been heated to crystallize before being incorporated into the comet. We discuss this further in Section 10.15.6.3.

The silicates themselves are most commonly olivines and pyroxenes, as evinced by the shape of the 10 μm silicate feature. The shape also can be used to derive the degree of crystallinity and also the relative amounts of Mg and Fe. Many comets seem to have Mg-rich olivines and pyroxenes, or at least roughly equal amounts of Mg and Fe. This is not universal, however, and among the comets in which it has been studied, there appears to be diversity in the Mg-to-Fe silicate abundance. (Pyroxenes with some fraction of calcium (e.g., diopside and hedenbergite) are not commonly seen in comets although there are some claimed detections, including in the Deep Impact ejecta.) This high average Mg-to-Fe ratio is interesting since in asteroids and meteorites, it is more common to see the Fe-rich silicates. This dichotomy is presumably related to the compositional gradients in the protoplanetary disk. The cometary silicate composition is also somewhat dependent on dynamic class, perhaps again revealing something about formation regions of these objects.

The existence of hydrated minerals in comets, as claimed in the Deep Impact ejecta, would have significant implications for cometary formation, since presumably, the hydration could only come from liquid water, that is, water heated out of the solid phase. Yet we know that comets must have retained most of their water ice and indeed even the more volatile and highly abundant species like CO and CO$_2$.

Our understanding of the mineralogy of comets was helped greatly by the success of the Stardust mission, which brought dust grains from comet P/Wild 2 back to Earth. A summary of Stardust’s major results in this regard has been provided by Bradley et al. (2009), and implications of the results have been reviewed by Wooden (2008). One major result from the enabled laboratory studies is that the high degree of crystallinity in the silicates – mentioned in the previous text as a result of telescopic observations – was confirmed. This was a direct laboratory measurement and so a nice corroboration of the telescopic data. Such materials must have been heated and then brought out past the snow line, potentially many AU away, in order to be incorporated into the icy comets.

The result is even more significant since it appears that the fraction within the Stardust sample of so-called ‘presolar’ grains – grains that condensed in the interstellar medium or around other stars before finding their way into our own protoplanetary disk – is lower than what was expected based on what is seen in primitive meteorites (Stadermann et al., 2008). At face value, this implies that the rocky component of comets is quite heavily derived from material that was in the inner solar system and flowing outward. However, there is some evidence that presolar grains were preferentially destroyed by the collection process (Floss et al., 2013), which may complicate the interpretation.

Yet another interesting aspect to the Stardust sample is the low abundance of chondrules and phyllosilicates (Nakamura et al., 2008; Zolensky et al., 2006). With the disk evidently cycling material outward to the comet-formation region fairly efficiently, one might expect that collisions among young asteroidal bodies in the inner solar system could deliver chondrules and aqueously altered materials to the region where comets...
could incorporate them. Chondrules and phyllosilicates are after all common, judging by the meteorite record and by asteroid spectroscopy. However, the P/Wild 2 grains contain few of either, suggesting that the parent bodies to today’s cometary nuclei are ‘preaccretionary,’ that is, formed before the epoch of chondrule formation (Wooden, 2008). While the details of the thermodynamics, transport, and chemistry in the protoplanetary disk are important for getting the right answer, the result can place constraints on disk evolution models.

10.15.6 Big Questions and the Future

In this last section, we summarize some of the significant problems with regard to small bodies that we think are the most pressing. We also provide some discussion of how such problems could be addressed. The study of small bodies has been recognized by the Planetary Science Decadal Survey (Committee on the Planetary Science Decadal Survey 2011) as a way to address some of the questions of the highest overarching importance in the field. What the small bodies lack in mass relative to other parts of the solar system, they make up for in importance to understanding solar system history and evolution.

There are several general points that are useful to keep in mind regarding observations of small bodies. (1) Discovery far outpaces characterization. There are over 600 000 known asteroids, almost 500 JFCs, and a few thousand known Halley-type and LPCs. It is far easier to discover such objects than to study them and discover their compositional, structural, and physical properties. (2) Many small bodies have no or only very weak spectroscopic features that can be used for compositional diagnostics. To put it another way, the jump from reflectance and thermal emission properties and taxonomy to composition and mineralogy is often not straightforward, nor unique. (3) Observations rarely sample an object deeper than a few microns; many datasets obtained on small bodies really are only addressing the topmost microscopic layer. This is especially unfortunate because it is that layer that is the most processed. Seeing deeper down into an object is very useful but often very difficult to do unambiguously. (4) While we know that the small-body populations are a diverse group, we have only begun to understand the full variety of comet and asteroid properties. In other words, we know we are ignorant, but we are not yet quite sure just how ignorant! (5) The meteorite collection is indeed vast, but a significant barrier to advancing our understanding of small bodies is the relative lack of samples with known context. At the moment, we only addressing the topmost microscopic layer. This is especially unfortunate because it is that layer that is the most processed. Seeing deeper down into an object is very useful but often very difficult to do unambiguously. (4) While we know that the small-body populations are a diverse group, we have only begun to understand the full variety of comet and asteroid properties. In other words, we know we are ignorant, but we are not yet quite sure just how ignorant! (5) The meteorite collection is indeed vast, but a significant barrier to advancing our understanding of small bodies is the relative lack of samples with known context. At the moment, we only have samples from Itokawa and from P/Wild 2.

10.15.6.1 Where Is the Water?

As discussed earlier, we know that water makes up a significant fraction of the mass of a comet, but its contribution to the masses of the asteroids is much more uncertain. An important clue is the fact that CI and CM meteorites can be up to 15% water by weight (Salisbury et al., 1991). The water content of asteroids is a vital question since it is important to know what kind of objects actually provided Earth with its water. Part of this investigation requires studying how much of the water is bound up in hydration of minerals. This is a fundamental chemistry problem and needs to be addressed if we are to understand how much water there actually was available in the protoplanetary disk. Recent discoveries of water, or at least OH, in somewhat nonintuitive locations such as the poles of Mercury and the surface of the Moon suggest that it is crucial to know the details of the thermal environment in order to understand where water can survive.

Observationally, one approach that could vastly improve the state of the art is to have a large spectroscopic census of the 3 μm region in many asteroids. This wavelength region contains a broad absorption feature due to overlapping vibrational overtones of water and OH. The spectrum of each object should have high enough signal-to-noise to be able to use the shape of the absorption feature to distinguish between water itself and water that is bound in a hydrated mineral. Such a census would let us find surface water abundance as a function of taxonomic type and heliocentric distance and thus give us some connection between water and the birth location of the object. To some extent, this project is already underway, but spectroscopy at these wavelengths is not trivial, requiring dry air with low precipitable water above the telescope. Preliminary results suggest that the distribution of hydrated asteroids is not related to asteroid size or orbital location in a simple way (e.g., Rivkin et al., 2002).

10.15.6.2 Where Are the Organics?

As with water, the key to understanding the organics is in spectroscopic studies of the 3.2–3.6 μm region. C–H bonds in organic species have stretching modes at those wavelengths. High signal-to-noise is needed to be able to differentiate between different sets of organics within an asteroid. Currently, one usually just sees a broad feature that can be difficult to assign to specific species, since the phase of the material is solid. Organic materials in meteorites have been studied extensively, but the relationship to specific asteroids or locations is lacking (e.g., Pizzarello et al., 2006 and references therein).

Fortunately, comets can provide more insight about organic abundances, for the icy bodies at least, since the cometary activity naturally dredges up interior volatiles, making them visible in the coma as discussed earlier in this chapter. The difficulty is determining which volatiles are native to the cometary nucleus itself and which are products of chemistry that can occur within the collision zone of the coma, within a few radii of the nucleus’s surface.

There has been a tremendous increase in the study of cometary organics since the late 1990s, owing to improvements in infrared spectrometers and to access to the large telescopes that are required. Thanks to these observations, a clearer picture is emerging of how various species – C2H2, CH3OH, C2H6, H2CO, etc. – are distributed among the comet population (Mumma and Charnley, 2011). Continued observation of comets – from all dynamic classes – is certainly warranted. The number statistics are still fairly low, so a census of the organics in even 10–20 more comets, both short and long period, would be very helpful to discern trends. The difficulty is that there are only a few comets per year that are bright
fers angular momentum to the disk, which induces an outward motion of the accreting star. The magnetosphere of the accreting star transmits material outward after it has had a chance to be heated close to the disk. This process is used to explain astrophysical phenomena such as disks and jets around young stellar objects. The model uses the magnetohydrodynamics of the star–disk interaction to fling material away from the star.

Small heated grains are transported to the outer solar system, and the Shu X-wind can explain the transport of material. These grains can be measured in cometary materials. Gradie et al. (1989), as was described in Section 10.15.6.3.

Recent dynamic modeling – in particular models like the Nice model and the Grand Tack model – have been used to study the evolution of the solar system. These models have shown that the formation of the outer planets was significantly influenced by the migration of the giant planets. However, the current understanding of the primordial compositional gradient is not easy to constrain. The goal, after all, is to find the primordial compositional gradient. Two main problems in understanding what the primordial gradients were like remain: (a) there is uncertainty in what dynamic mixing has happened, and (b) we do not have enough compositional data to begin with. Detailed compositional studies of a wide range of small bodies will be necessary if we are to address the situation, and naturally, the first step is understanding composition as a function of object type and object’s location in the solar system right now. We can then hope to make use of advances in our understanding of solar system dynamics to constrain the initial conditions.

Although it had been suspected earlier, strong evidence for tremendous mixing in the protoplanetary disk comes from the fact that Stardust brought back silicate dust grains from comet P/Wild 2 with a degree of crystallinity that could only have been formed in high temperatures (Zolensky et al., 2006). This result was discussed in Section 10.15.5.3. In fact, more than half of the Fe-bearing silicates show evidence of having been processed in the inner solar system (Ogliore et al., 2009).

There are several models that could explain the transport of small heated grains to the outer solar system. The Shu X-wind model (Shu et al., 1994, 2000) has been a leading hypothesis since it can explain astrophysical phenomena regarding disks and jets around young stellar objects. The model uses the magnetohydrodynamics of the star–disk interaction to fling material outward after it has had a chance to be heated close to the protostar. The magnetosphere of the accreting star transfers angular momentum to the disk, which induces an outward wind. While much of the wind blows along field lines out of the disk altogether, some grains that were heated in the stellar accretion region will be blown back into the disk at distances appropriate for cometary accretion. However, there are several significant problems with this scenario as the source of crystalline grains, including the possible lack of time to produce the inferred initial $^{26}\text{Al}/^{27}\text{Al}$ ratio (Boss, 2012; Desch et al., 2010).

Other possible explanations come from one- and two-dimensional hydrodynamic models of turbulent, viscous disks. These models can explain both the outward transport of grains through diffusion and/or midplane gas flows in the first 1–2 My of disk formation. These grains would have to be incorporated into icy bodies very early on, before they fell back to smaller radii (e.g., Hughes and Armitage, 2010). Additionally, in full 3-D models of ‘marginally gravitationally unstable’ (MGI) disks, the disk appears to evolve through one or more phases of gravitational instability, and self-gravitational torques can transport material both inward and outward (e.g., Boss, 2007). Each of these approaches has implications for mixing and heterogeneity in the disk at varying timescales.

In any case, one of the significant clues to the early protoplanetary disk lies in the solids with depleted initial $^{26}\text{Al}$ abundance. In meteorites, both chondrules and a fraction of the calcium–aluminum-rich inclusions show evidence for zero initial abundance, indicating they formed before or several million years after the event(s) that infused the disk with $^{26}\text{Al}$. According to Boss (2012), better Pb–Pb isochron ages for the depleted inclusions, as well as tighter constraints on the initial heterogeneity of short-lived isotopes $^{60}\text{Fe}$ and $^{26}\text{Al}$, will help us understand the initial conditions. Furthermore, measurements of the isotopic ratio of oxygen in molecules observed in protoplanetary disks will help us understand mechanisms for fractionation and spatial heterogeneity of oxygen isotopic abundances since these isotopes display evidence for mass-independent fractionation in our solar system (Boss, 2012; Clayton, 1993; Sakamoto et al., 2007).

While meteorites continue to be a source of samples, sample return missions represent a promising way to make further progress, since parent bodies can be chosen for their known composition and dynamic properties.

### 10.15.6.4 What Did Small Bodies Do to Earth?

The current dominant hypothesis is that Earth and the terrestrial planets likely formed too close to the young Sun in too warm a region to allow hydration at formation (Morbidelli et al., 2000). In simplistic terms, this was thought to indicate that there was a ‘frost line’ or ‘snow line’ in the protoplanetary disk that marked the boundary of where water could condense out of the gas phase. Recent work has shown this is indeed an oversimplification and that condensation in the real protoplanetary disk was more complicated, as well as time-dependent (e.g., Bell, 2010; Encrenaz, 2008; Morbidelli et al., 2012; van Dishoeck et al., 2014). While it has long been assumed that small bodies from the outer solar system brought water and organics to the Earth, this hypothesis has been supported by the discovery of glycine in Stardust samples (Elsila et al., 2009). We can then hope to use these samples to understand the initial conditions. Furthermore, measurements of the isotopic ratio of oxygen in molecules observed in protoplanetary disks will help us understand mechanisms for fractionation and spatial heterogeneity of oxygen isotopic abundances since these isotopes display evidence for mass-independent fractionation in our solar system (Boss, 2012; Clayton, 1993; Sakamoto et al., 2007).

While meteorites continue to be a source of samples, sample return missions represent a promising way to make further progress, since parent bodies can be chosen for their known composition and dynamic properties.
from impactors (e.g., Marty, 2012; Saal et al., 2013). On the other hand, the composition and isotopic ratios in the mantle have also been used to argue in favor of contributions by both asteroids and comets (e.g., Halliday, 2013). Greater knowledge of isotopic ratios of small bodies and of the history of fractionation in the solar system will be a key part of understanding the origin of the Earth’s water.

As discussed in Section 10.15.5.2, until 2010, the water D/H ratio in six Oort cloud comets showed that the D/H ratio was much higher than observed in the Earth’s oceans (i.e., in SMOW). This made having comets as a source of the Earth’s water problematic. Modeling suggested that if Jupiter were in a nearly circular orbit, then water could be delivered to the terrestrial planets by chondritic material from beyond the frost line (Raymond et al., 2004). The discovery that the JFC P/Hartley 2 has a water D/H ratio similar to SMOW (Hartogh et al., 2011) revives the possibility that comets could have delivered a significant fraction of the Earth’s water. Furthermore, two other recent results on the D/H ratio – (a) the D/H measurement of less than 1.5 times SMOW in the Oort cloud comet C/2009 P1 (Garradd) by Bockelée-Morvan et al. (2012) and (b) the finding of an upper limit to the D/H ratio in comet P/Honda–Mrkos–Pajdušáková that is consistent with that of P/Hartley 2 (Lis et al., 2013) – demonstrate a possible continuum in cometary D/H. Clearly, the D/H ratio in comets is a more complicated issue than was previously thought. In any case, given the success of the asteroid models at delivering water, the answer may be that the Earth’s volatiles were delivered by some combination of asteroids and comets – unless it turns out that the wet Earth hypothesis is correct. It is possible that we will need to develop and fly the technology to sample small-body noble gas isotopes before we are reasonably certain of the origin of the Earth’s water.

It is clear from both this question and several of the others posed in this section that understanding the dynamic evolution of the small bodies is critical to being able to reconstruct the protoplanetary disk. The current dominant model of large-scale planetary migration in our solar system, the Nice model mentioned in earlier sections, has done an admirable job of explaining many observed phenomena, but the difficult part is using it to make a prediction that both (a) is observationally feasible and (b) would make a strong test of the idea’s validity. Compositional information on the small bodies is one possible way – since, for example, the model would predict that one would see a similar primordial composition among the outer main-belt asteroids, Trojans, and trans-Neptunian objects. The difficulty is that it is still hard to interpret the surface composition due to a lack of diagnostic features. What is unknown is whether the surfaces would really be the same because of similar primordial condition or simply because of similar subsequent evolution. Sample return missions may be required before we know that answer.

Nongravitational forces are an important aspect to the dynamics of many objects, as it is now clear that over fairly short dynamic timescales, they can move asteroids and comets significantly around the solar system. In particular, for asteroids, the Yarkovsky and YORP effects need to be better understood – and this means understanding the thermal properties as well as the structural properties in the interior. This is important since the Yarkovsky effect affects the delivery of asteroids from the asteroid belt to near-Earth space, including those that could someday strike Earth. For comets, outgassing torques and forces – on the whole much stronger than Yarkovsky effects – can measurably change a comet’s orbital elements on month- or year-long timescales, thereby making it more difficult to gauge just how significant the cometary impact risk is for Earth.

10.15.6.5 Forthcoming Breakthroughs

The next decade should bring tremendous insight into our understanding of comets and asteroids. First, the Rosetta spacecraft will rendezvous with comet P/Churyumov–Gerasimenko in 2014 and observe it close-up for several months. Rosetta is primarily a European Space Agency mission but NASA has contributed some of its instruments. For the first time, we will be able to watch a comet turn on as its activity gets started. The spacecraft also has a lander, Philae, that will be able to study the surface directly, our first such opportunity to do so on a comet. The spacecraft will arrive at comet P/Churyumov–Gerasimenko in May 2014 – when the comet is 4.0 AU from the Sun, outside the zone where water could sublimate – and will stay with the comet at least until December 2015. The comet’s perihelion occurs in August 2015, when it will be 1.24 AU from the Sun.

Asteroid sample return should figure prominently in the next several years, with the United States, Europe, and Japan all potentially sending sample return missions to primitive asteroids. The Japanese mission, Hayabusa 2, is a follow-up to its successful Hayabusa mission that brought back samples from asteroid Itokawa in 2010. Hayabusa 2 will travel to (162173) 1999 JU3, which is a primitive asteroid. Launch would happen in 2014 or 2015, with asteroid arrival in 2018. The spacecraft will collect a sample and leave the asteroid in 2019, returning to Earth in 2020. The US mission, OSIRIS-REx, which stands for ‘Origins Spectral Interpretation Resource Identification Security Regolith Explorer,’ will retrieve samples from asteroid Bennu. This object is likewise a primitive asteroid. Launch would happen in 2016, with arrival to the asteroid in 2019. The spacecraft would study the asteroid for many months, departing likely in 2021 and getting back to Earth in 2023. Even if only one of these missions is successful, we can expect to have tremendous new insights into our understanding of primitive bodies in the 2020s.

10.15.6.6 Longer-Term Missions

In the farther future, significant scientific return can be obtained from robotic missions that visit Trojan asteroids, primitive main-belt asteroids, and dormant/extinct comets. In the United States, NASA has plans for human visitation of asteroids in the relatively near future, mid-2020s. However, it is unclear exactly what path toward that goal will be taken. Nonetheless, there are significant engineering obstacles to a successful manned mission to an asteroid that need to be overcome. Some of these obstacles – sometimes known as ‘strategic knowledge gaps’ – can be answered through telescopic observation and robotic visitation of the asteroids in question. Some of these questions include the following: Could astronauts actually operate in the nearly zero gravity
environment around an asteroid? How would the spacecraft rendezvous? What are the surface and immediate subsurface layers like? Can one grab onto the surface or is it too powdery? Could one anchor to it? What thermal variation would there be as the asteroid rotates in and out of sunlight? Is the asteroid in a principal-axis rotation state, or is it tumbling? How far down would one have to dig to get to more pristine material, if at all?

While these are difficult problems to solve, one cannot help but be excited about what secrets of the small bodies and of our solar system will be revealed in the coming years. The synergy of Earth-based telescopic observation (to provide the big picture about many objects) and spacecraft missions (to provide the detailed picture of a few key objects) is sure to continue to provide astronomers and geophysicists with new, thrilling insights.

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