Formation and Physical Properties of Asteroids

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Asteroids are the leftover precursors to the terrestrial planets. Before the first images of them were sent from space, our knowledge of asteroids relied entirely on ground-based observations and meteorite analysis. Spacecraft images revolutionized our knowledge and geological understanding of their physical properties. They also showed us that asteroids are subjected to various kinds of processes and are incredibly diverse in size, shape, structure, composition, and rotational properties. Therefore, space missions remain necessary to enhance our knowledge of the various components of the asteroid population. In addition, numerical modeling is required to interpret spacecraft images and improve our understanding of the physical processes asteroids experience over their lifetime.

Keywords: asteroid, impact, regolith, internal structure

Ground observations collecting electromagnetic radiation (X-ray, visible, infrared, etc.) provide crucial, but nonetheless limited, knowledge of remote objects. Photo credit: Gran Telescopio CANARIAS, Canary Islands, Spain (www.gtc.iac.es)

INTRODUCTION

About 4.56 billion years ago, the early Solar System consisted of a rotating disk of gas and dust, called the protoplanetary disk, revolving around the Sun. Planets formed from this disk, and different populations of small bodies, in particular the main belt asteroids between the orbits of Mars and Jupiter, survived as remnants of this era. The process by which dust grew into the first multikilometer-size planetesimals is not entirely understood. However, while the exact mechanism of planetesimal formation and the origin of the primordial asteroid size distribution is still a matter of debate (see, for example, Morbidelli et al. 2009; Weidenschilling 2011), it is clear that planetesimals did form in the inner Solar System. This likely occurred within the first ~5 My of Solar System history.

Once planetesimals grew large enough to gravitationally perturb one another, collisions between bodies on crossing orbits led to the growth of larger planetary embryos and eventually to the formation of planets. According to current models, the asteroid belt that remained at the end of these processes was probably very different from the current main belt; it perhaps contained an Earth mass or more of material in planetary embryos with masses similar to that of the Moon or Mars, as well as tens, hundreds, or thousands of times more bodies like the asteroid 4 Vesta and the dwarf planet 1 Ceres than are present in the main belt today. In addition, the orbits of the planetesimals had relatively low orbital eccentricities and inclinations compared to current values for the asteroid belt. It is during the next stage of evolution that the asteroid belt began to develop to its current state.

This primary architecture of the Solar System shaped a thermal and chemical gradient: solids in the inner part of the disk formed at a temperature high enough to prevent condensation and accretion of volatile species, whereas in the outer region, distant from the proto-Sun, ices and giant gaseous planets formed. In fact, the main belt population represents both a compositional and a temperature gradient that may record this primary architecture, with higher-temperature refractory materials condensing out and forming S-type asteroids in the inner part of the belt and lower-temperature carbonaceous materials and water ice condensing in the outer part, forming C-type asteroids (see later discussion of spectral types). However, recent studies suggest that the lower-temperature carbonaceous material present in the main belt formed in very different locations and then was scattered into the asteroid belt. Evidence of such scattering and radial mixing of bodies comes from both direct measurements and dynamical models (see, for example, Walsh et al. 2011).

High-temperature minerals that formed in the hottest regions of the solar nebula were identified in the samples returned by the Stardust mission (NASA) from the comet 81P/Wild 2, a periodic comet captured only recently from the outer Solar System into its current orbit. This finding resulted in a complete revision of our understanding of early-stage processes in the solar nebula and provided dramatic evidence for extensive radial excursions early on in the solar nebula (e.g. Brownlee et al. 2006). Then, the discovery of planetary systems beyond our own clearly demonstrated that radial excursions also occur at planetary scales; in these systems, giant, gaseous planets are detected very close to their central star, which requires that they moved from their more distant formation regions. Such observations led to increasingly sophisticated numerical modeling, with some models requiring an extraordinary revision of the early history of the Solar System. This is the case of the Grand Tack model, which involves the inward migration of Jupiter and Saturn and their penetration deep into the inner Solar System (down to 1.5 AU for Jupiter) before migrating outwards to their current locations (Walsh et al. 2011). According to this model, the primordial asteroid belt was mostly emptied by the inward migration of Jupiter. On its outward migration, Jupiter scattered some of that material back into the asteroid belt region (predominantly into the inner part of the belt), and, along with Saturn,

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the other giant planet, it scattered material formed farther out in the Solar System (beyond ~4–5 AU) into the outer part of the asteroid belt. As a consequence, the inner belt is dominated by material formed in the ~1–3 AU region and the outer belt by material formed beyond ~4–5 AU (Walsh et al. 2011), which would explain the observed distribution of spectral types in the main belt.

Although the asteroid belt lost most of its mass during this phase, another bombardment, called the Late Heavy Bombardment (LHB), proposed as the source of the large lunar basins, occurred several hundred million years later. According to the Nice Model, the LHB was caused by a sudden change in the orbits of the giant planets as a result of the gravitational perturbations by an outer disk of planetesimals. While the giant planets were reaching their final orbits, a large amount of material formed beyond the giant planets was injected into the inner Solar System and another fraction of the asteroid belt was dynamically depleted, causing large impacts. The lunar basins provide evidence of these impacts. Several mechanisms have been proposed to deplete the mass of the primordial asteroid belt (possibly in two successive phases) and to cause the dynamical excitation and radial mixing observed today. However, these mechanisms have different implications for the original birth location of asteroids of different types (see for example, O'Brien et al. 2007 and Walsh et al. 2011 for the first depletion phase, and Levison et al. 2011 and references therein for the second depletion phase).

Since this epoch and throughout its history, the asteroid belt has been shaped by collisional processes, such as cratering, disruption, and the generation of new asteroids as collisional fragments. The size-frequency distribution of the main belt is classically fitted with power laws, but it has a wavy shape (i.e. it is not a straight line in a log-log plot; Fig. 1), which is characteristic of a population that has evolved through collisions (see, for example, O'Brien and Greenberg 2003). The specific wavy shape of the size distribution results from the dependence of the strength of a body on its size and the transition between different strength regimes. Asteroids smaller than a few hundred meters are held together mainly by material strength and are expected to become weaker with increasing size due in part to the distribution of flaws within them; larger bodies are affected more by gravitational forces and become stronger with increasing size (e.g. Holsapple et al. 2002). As a reference, the number of asteroids larger than 1 km is estimated at about one million in the main belt (Fig. 1).

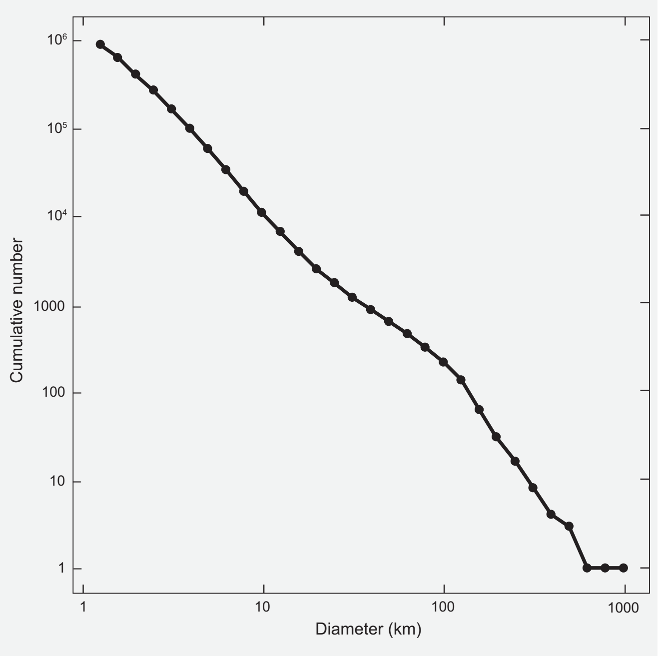

Figure 1 Cumulative size distribution of main belt asteroids (based on Bottke et al. 2005), showing that the distribution is wavy, with "bumps" near D ≈ 100 km and D ≈ 3–4 km.

Bottke et al. (2005) found that the current asteroid size distribution arose fairly early in the history of the asteroid belt. Once the belt was dynamically depleted and reached roughly its current mass, there was little further evolution of the size distribution, and hence Bottke et al. (2005) referred to it as a "fossil" size distribution. In its current state, collisions still occur in the asteroid belt, albeit at a reduced rate. The most obvious evidence for this is the formation of asteroid families, which are groups of asteroids whose members share similar orbital and taxonomic properties, suggesting that each of these families was formed by the disruption of a large parent body.

The collisional lifetime of bodies larger than a few tens to hundreds of kilometers in diameter is longer than the age of the Solar System, suggesting that most are likely to be primordial, while smaller bodies are probably collisional fragments. The exact size above which a body is more likely to be primordial is somewhat model dependent. Binzel et al. (1989), from the study of light curves, suggested that this transition occurs at a diameter of ~125 km. However, as this is a statistical measure, some smaller asteroids may still be primordial and some larger ones may have broken up in the past. Roughly 20 asteroid families have formed from the breakup of parent bodies larger than ~100 km in diameter (e.g. Bottke et al. 2005) over the last 4 billion years or so. In contrast, however, several hundred bodies currently exist in the 100 km size range, and most of these are likely to be primordial.

Despite our current understanding of how planets and small bodies formed and of how the asteroid belt evolved, we do not know much about the physical properties of asteroids. Such knowledge is fundamental for testing the validity of these scenarios and to extrapolate them to the future. Indeed, asteroids are subjected to various kinds of stresses (e.g. impacts, shaking) during their history. Their responses to these stresses depend on their physical properties. In turn, the processes that asteroids undergo during their history modify those properties. In order to achieve a more accurate picture of these bodies and their evolution, we need more information on their physical properties and we have to understand (1) how these properties influence the way they respond to different processes and (2) how these processes affect the properties.

PHYSICAL PROPERTIES OF ASTEROIDS

Knowledge from Ground-Based Observations

Asteroids are faint in the sky because they are small and only reflect sunlight from their surface. Therefore, knowledge of their physical properties from ground-based observations remains very limited.

One kind of information that can be obtained using optical telescopes is the visual magnitude of the asteroid. This is then converted into the absolute magnitude (the visual magnitude that it would have if it were at 1 AU from both the Sun and the observer), which gives a rough indication of the asteroid's size. Optical telescopes also provide light-curve measurements; collected over sufficient time, these allow the determination of the rotational period and possibly the pole orientation, and also permit a rough estimate of the object's shape.

Rotational periods have been determined for more than 1500 asteroids. Asteroid spin periods have a wide range, from several days to less than a minute for some small near-Earth asteroids (e.g. Pravec and Harris 2000). Spin periods are possibly related to the strength properties of the object. For bodies less than about 10 km in diameter, even a small amount of strength allows much more rapid spins than pure gravitational binding. This is the case of the so-called fast rotators. Analytical estimates suggest that even small amounts of strength or cohesion in a gravitational aggregate can render rapidly spinning small bodies stable against disruption. This interpretation implies that such bodies do not necessarily need to be fully cohesive or monolithic to survive with a fast rotation, but they cannot be pure cohesionless rubble piles either (Holsapple 2007). On the other hand, the spin rates of all bodies larger than about 10 km in diameter are limited to periods greater than about 2 h. This observation has been interpreted as evidence for a rubble pile (or gravitational aggregate) structure. This interpretation is actually flawed because the tensile strength of a monolithic body decreases with its size, and therefore in this size range (greater than several kilometers) the strength is so small that it does not permit higher spin rates than would be allowed for pure gravitational aggregates. Therefore these bodies may well be rubble piles, but their observed spin limits do not require it (see Holsapple 2007).

The spectral properties of an asteroid provide information about its composition. Visible-light to near-infrared spectroscopy has been used to place asteroids into multiple taxonomic classes based on the characteristics of their spectroscopic signature at different wavelengths (e.g. DeMeo et al. 2009). Asteroids of taxonomic type S (with a visual albedo $p_V \approx 0.15$ on average) are preferentially situated in the inner main belt. They are several times brighter than C-type asteroids (with a visual albedo $p_V \approx 0.05$ on average), which are mainly located in the outer main belt, and have distinct silicate absorption bands. S-type asteroids are probably made of similar materials to those of the most common meteorites, the ordinary chondrites, which are moderately evolved but unmelted chondritic rocks. In fact, the analysis of particles from the S-type asteroid Itokawa, successfully returned by the Japanese Hayabusa mission in 2010, shows that the particles came from materials like those in thermally metamorphosed LL-group ordinary chondrites and that the spectrum of Itokawa has been reddened by space weathering as a result of the exposure of its surface to micrometeorites and solar wind. The complete taxonomy of asteroids is obviously more complex and includes numerous subgroupings, such as the B, C, P, and D types, all of which correspond to dark, reddish asteroids. These asteroids are presumably made of the same materials as the most primitive meteorites, the carbonaceous chondrites, which include complex organic molecules, silicate minerals, and reduced iron and other metals. About 60% of the C-class asteroids, at heliocentric distances between 2.5 and 3.5 AU, are thought to have undergone some kind of aqueous alteration process (Barucci et al. 1998). D-type asteroids are particularly red at long-infrared wavelengths, may be rich in organic compounds, and have no clear relation with any kind of meteorite, with the possible exception of the Tagish Lake meteorite. A distinct class called M was originally thought to correspond to metallic fragments originating from differentiated planetary cores. However, mid-infrared spectroscopy (Rivkin et al. 2000) showed that the mineralogy of some M-type asteroids likely corresponds to hydrated silicate and not metal. So, our understanding of composition based solely on spectral observations remains limited and uncertain. The information provided by spectral observations tells us only about the first few micrometers of the surface and does not necessarily allow us to determine a possible overall heterogeneity.

Mid- to thermal-infrared observations, along with polarimetry measurements, are probably the only data that give some indication of actual physical properties. Measuring the heat flux of an asteroid at a single wavelength gives an estimate of the dimensions of the object; these measurements have lower uncertainty than measurements of the reflected sunlight in the visible-light spectral region. If the two measurements can be combined, both the effective diameter and the geometric albedo—the latter being a measure of the brightness at zero phase angle, that is, when illumination comes from directly behind the observer—can be derived. In addition, thermal measurements at two or more wavelengths, plus the brightness in the visible-light region, give information on the thermal properties. The thermal inertia, which is a measure of how fast a material heats up or cools off, of most observed asteroids is lower than the bare-rock reference value but greater than that of the lunar regolith; this observation indicates the presence of an insulating layer of granular material on their surface (Harris 2005). Moreover, there seems to be a trend, perhaps related to the gravitational environment, that smaller objects (with lower gravity) have a small regolith layer consisting of coarse grains, while larger objects have a thicker regolith layer consisting of fine grains. However, the detailed properties of this regolith layer are poorly known from remote observations. Moreover, the relation between thermal inertia and surface roughness is not straightforward, so one needs to interpret the thermal inertia with caution.

Finally, when an object comes close enough to Earth that detailed radar observations can be performed, a radar shape model can be produced. This allows one to probe some of the details of the body's surface properties, such as the potential presence of craters or large boulders (Fig. 2). The Arecibo Observatory in Puerto Rico, with a 305 m diameter dish, and the 70 m steerable dish at the Goldstone Observatory in California have been used with great success to obtain detailed images and dynamical information about near-Earth objects, as well as to characterize main belt asteroids (see, for example, Ostro et al. 2002). In addition, the great accuracy of the astrometry provided by radar observations allows for highly refined determinations of the orbital and rotational dynamics of an asteroid, which is crucial for assessing its risk as a threatening object.

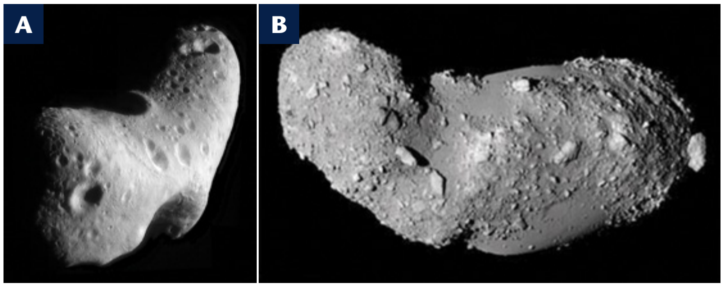

Figure 2 (**A**) Image of Eros (mean diameter 17 km) taken by NEAR-Shoemaker in 2000. (**B**) Close-up image of the asteroid Itokawa, taken by the Hayabusa spacecraft in 2005, showing an abundance of large boulders on its surface and the lack of cratering. Both bodies are of the same spectral type (S) but are totally different, in terms of not only size but also surface properties. Photo credits: NASA, JAXA

Knowledge from Space-Based Observations

Surface Properties

Ground-based observational programs, such as the Catalina Sky Survey (www.lpl.arizona.edu/css, University of Arizona), have been responsible for the discovery of the greatest number of asteroids, and they complement space-based programs. However, in principle, space-based observatories should detect a greater number of objects because a larger portion of sky is seen from space and because the atmosphere is absent. For example, the WISE space observatory took millions of infrared images. NEOWISE, the asteroid-hunting portion of the WISE survey, observed more than one hundred thousand asteroids in the main belt, in addition to at least 585 near-Earth objects (Mainzer et al. 2012). The Spitzer telescope has also observed more than 700 near-Earth asteroids (NEAs) (Trilling et al. 2010). From these observations, it was possible to estimate the sizes of most of these asteroids. However, such observations cannot tell us very much about the properties of the asteroids' surfaces, such as the size distribution of the grains that compose the regolith, as well as the regolith's depth, angle of repose, cohesion, and porosity. This information, as well as the detailed surface morphology/topography and distributions of craters and boulders on an asteroid's surface, can only be obtained by in situ investigations or sample-return space missions.

So far, only three space missions have been devoted to investigating asteroids from orbit, namely, the NEAR-Shoemaker mission (NASA), which orbited the 34.4 × 11.2 × 11.2 km size near-Earth asteroid 433 Eros (Fig. 2) for one year in 2000–2001; the Hayabusa mission (JAXA), which visited the 535 × 294 × 209 m NEA 25173 Itokawa (Fig. 2) for 3 months and successfully brought a sample back to Earth; and the Dawn mission (NASA), which investigated 4 Vesta, the second-largest asteroid at 530 km diameter, during one year in 2011–2012 (see McSween et al. 2014 this issue). Several other missions have performed asteroid flybys (e.g. the NASA Galileo and the ESA Rosetta missions), which are not discussed here due to space limitation, but they have contributed greatly to our current understanding of asteroids.

While Eros and Itokawa belong to the same S taxonomic class, their spacecraft-imaged surfaces show two drastically different worlds (Fig. 3). Eros's surface consists of a layer of regolith composed of very fine dust, with an estimated depth between 10 and 100 meters. Itokawa's surface contains both smooth and very rough areas and is covered by a layer of regolith whose average depth is estimated to be a few tens of centimeters. This layer is composed of unconsolidated gravels, which are typically piled on each other without being buried by fines (Miyamoto et al. 2007). The finest observed particles are centimeter-sized pebbles and are concentrated on smooth terrains.

If gravity is the discriminator, then Itokawa would be expected to be as different from Eros, geologically, as Eros is from the Moon (Asphaug 2009). This may explain their different geological properties despite their similar spectral type. On the other hand, both objects share an apparent lack of small craters compared with the number expected from their impactor flux histories. This lack of craters is interpreted as possible evidence of seismic shaking during small impacts, which can cause the regolith to move and erase small features (Miyamoto et al. 2007; Michel et al. 2009). A low-gravity environment can thus make small objects more sensitive to small events.

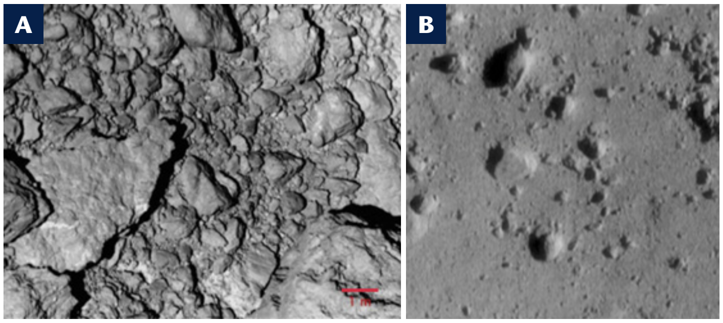

Figure 3 (**A**) Close-up image of the very rough surface of Itokawa (mean diameter 320 m), taken by Hayabusa (a 1-meter scale is indicated on the image); the surface is composed mainly of a thin layer of gravel and pebbles. (**B**) Close-up image of the surface of 17 km Eros, taken by the NEAR-Shoemaker mission from a height of 250 m (the imaged area is 12 m across); the surface consists of a deep layer of fine dust. Despite their drastically different regolith properties, Itokawa and Eros belong to the same taxonomic type (S). Photo credits: JAXA and NASA

So far, we do not have this level of detail for the surface of any dark, carbonaceous asteroid. These asteroids are believed to be the most primitive ones, and they dominate the population of the main belt (most of them reside in its outer part). The only images of a C-type object that we have are those of the 53 km diameter main belt asteroid 253 Mathilde, obtained during the NEAR mission flyby in 1997. They show five craters larger than 20 km, undisturbed by each other, which suggests that low-density asteroids (1.35 g/cm^3 for Mathilde) have a great ability to survive energetic impacts. These images, which were received with great surprise, opened an entire area of research regarding energetic impacts onto porous targets.

In summary, asteroid surfaces are very diverse, and each rendezvous or flyby with an asteroid has helped to improve our geological understanding of granular mechanics, landslides, earthquakes, faulting, and impact cratering. Future missions devoted to these small bodies will provide a great science return, and it is likely that some of our assumptions will need to be reconsidered.

Internal Structure

The internal structure of asteroids is inferred only from indirect evidence: bulk densities measured by spacecraft, the orbits of natural satellites in the case of asteroid binaries (Merline et al. 2002), and the drift of an asteroid's orbit due to the Yarkovsky thermal effect. A spacecraft near an asteroid is perturbed enough by the asteroid's gravity to allow an estimate of the asteroid's mass. The volume is then estimated using a model of the asteroid's shape. Mass and volume allow the derivation of the bulk density, whose uncertainty is usually dominated by the errors made on the volume estimate. These measurements indicate that dark bodies have a bulk density (typically about 1.0–1.3 g/cm^3; see, for example, Yeomans et al. 1997) that is lower than that of the bright asteroids (typically about 2.0–2.7 g/cm^3; see, for example, Abe et al. 2006).

The internal porosity of asteroids can be inferred by comparing their bulk density with that of their assumed meteorite analogues (Britt and Consolmagno 2000). Despite the small number of statistics from this comparison, it is clear that the interior of an asteroid generally has some degree of porosity. However, dark asteroids seem to be more porous (>40%) than bright ones. The nature of this porosity is unclear. Microscopic porosity is characterized by pores sufficiently small that their distribution can be assumed to be uniform and isotropic at the considered scale. In this case, the pore is typically smaller than the thickness of the shock front resulting from an impact. A rock like pumice has such microporosity. Macroscopic porosity, on the other hand, is characterized by pores whose sizes are such that the medium can no longer be assumed to be homogeneous and isotropic at the scale of the object. This porosity corresponds to large voids in an otherwise nonporous rock. While macroporosity may explain the difference in density between S-type asteroids and their meteorite analogues (ordinary chondrites), some microporosity may be needed to explain the lower bulk density of C-type asteroids.

Unfortunately, we do not have any direct evidence of the kind of porosity inside an asteroid, even in the cases of asteroids for which the density has been estimated. For instance, is Mathilde microporous, in the manner of cometary dust balls, as has been proposed to explain Mathilde's giant craters (Housen and Holsapple 2003)? Then, despite its possible microporosity, is Mathilde cohesive, as one might expect for microscale grain structure? Or does Mathilde, and the other primitive asteroids with comparable densities, possess huge voids, as one would expect from collisional disruption and reaccumulation of major fragments (Michel et al. 2001)? And at what size should asteroids be monolithic bodies (even with microporosity) rather than gravitational aggregates?

These questions do not have any clear answers yet, and only space missions aimed at probing the internal structure of an asteroid (for instance, by using radar tomography or by performing a seismic experiment) will provide them.

Knowledge from Numerical Modeling and Experiments

Collisions

Asteroids are continually involved in collisions. The outcome of these events depends on the physical properties of the colliding bodies, and the properties are, in turn, modified by these events. The collisional process is not fully understood, because we must still rely on poorly known asteroid-fragmentation physics. Nevertheless, numerical modeling of asteroid collisions has given results consistent with observations and has allowed us to make inferences about the physical properties of asteroids. Numerical simulations of the collisional disruption of large asteroids, including the fragmentation of the asteroid and the gravitational phase during which the fragments interact due to their mutual attraction, have successfully reproduced the formation of groups of asteroids sharing similar orbital and taxonomic properties (i.e. asteroid families) (Michel et al. 2001). The results showed that after a large asteroid is fragmented into small pieces by the impact of a projectile, subsequent gravitational reaccumulation of some of the fragments typically happens and leads to the formation of an entire family of large and small objects, whose properties are similar to those of the real family used as a comparison (Fig. 4). Moreover, in the models, all large family members (fragments larger than a few hundred meters) are made of gravitationally reaccumulated blocks (these bodies are called rubble piles or gravitational aggregates). This conclusion has great implications because it suggests that a large number of asteroids, in particular those originating from the disintegration of a larger body as a result of a collision, are rubble piles formed by reaccumulation.

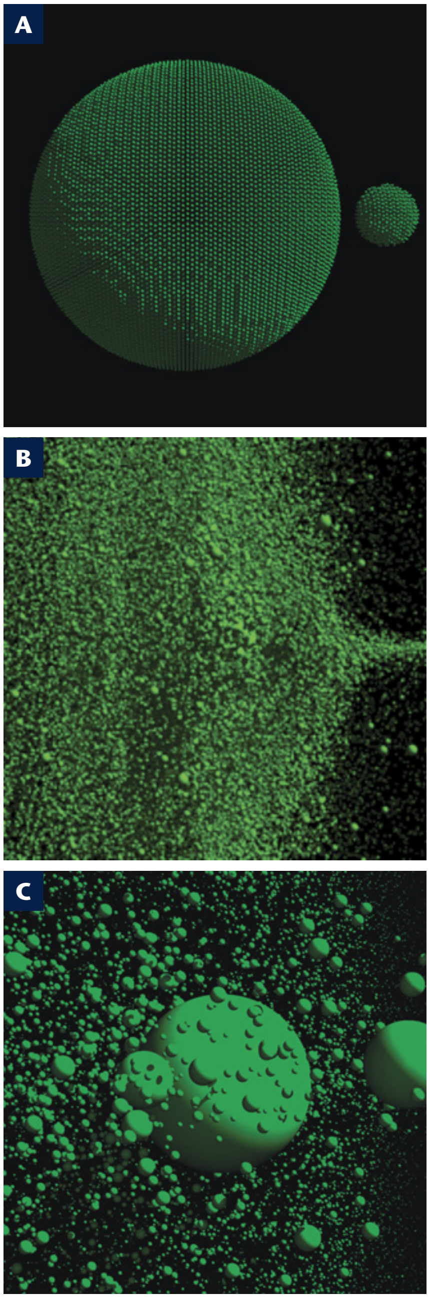

Figure 4 Snapshots of a numerical simulation of the catastrophic disruption of a 164 km monolithic asteroid, representing the formation of the Eunomia asteroid family. The middle and bottom frames are centered on the gravitational reaccumulation of the largest remnant. As a result of the impact (**A**), the parent body of the family has been fragmented into hundreds of thousands of kilometer-size fragments (small green dots in **B**), which interact due to their mutual gravitational attraction. The largest remnant (**C**) is an aggregate containing 54% of the mass of the original asteroid. Other aggregates are formed nearby, and the final outcome is an entire family of aggregates and smaller fragments, whose properties are similar to those of real asteroid family members. In these simulations, all fragments were constrained to be spherical, even after reaccumulation. Recent simulations (Michel and Richardson 2013) have begun to take into consideration the shapes of the reaccumulated bodies in order to compare them with real ones. Adapted from Michel et al. 2001

Most objects larger than 125 km are likely to be primordial. Although most of them have probably been affected by small collisions that occurred repeatedly, they did not experience catastrophic disruption and reaccumulation. Smaller bodies are thus probably more thoroughly shattered and are more porous than larger primordial bodies. This is consistent with the low bulk densities measured for some asteroids and has implications for their collisional lifetime and for the preparation of mitigation strategies aimed at deflecting a potentially dangerous asteroid.

Other Surface Processes

All observed bodies are covered with some kind of regolith. Knowledge about processes such as landslides, seismic shaking, and cratering can be used to infer the physical properties of asteroid surfaces observed by spacecraft. For instance, during impact-induced shaking, a form of segregation in granular material called the "Brazil nut effect" takes place, with the larger particles moving to the top. On asteroids, thorough shaking by nondisruptive collisions may activate the Brazil nut effect. This effect could thus contribute to the presence of large boulders on the surface of small asteroids like Itokawa (Miyamoto et al. 2007), although a recent study proposed that these boulders are the direct outcome of the reaccumulation that formed Itokawa (Michel and Richardson 2013). Nevertheless, the mechanism driving the Brazil nut segregation on asteroids is still under debate. Itokawa has long lost any internal heat capable of driving convection, which is a possible driving force for segregation. Asphaug (2007) suggested that the energy source was a granular thermal input associated with impacting meteoroids. However, new experiments in a parabolic flight environment have shown that gravity plays an active part in granular convection by tuning the frictional forces and that convective flow turns off under zero-gravity conditions (Murdoch et al. 2013). Therefore, a weak gravitational acceleration will likely reduce the efficiency of particle size segregation, and it is not clear yet whether the Brazil nut effect, if driven by convection, can be effective in a low-gravity environment such as that on Itokawa. However, it is likely that particle segregation does occur even in the reduced-gravity environment found on asteroid surfaces, but the process may require much longer timescales than would be needed in the presence of a strong gravitational field. This example demonstrates that we need more knowledge about the dynamics of regolith in low-gravity environments if we are to understand asteroidal surface properties and their evolution. This information is also necessary for designing efficient tools for human or robotic space missions to asteroids.

PERSPECTIVES

Ground- and space-based observations of asteroids have already allowed us to increase tremendously our knowledge of their physical properties, and they have shown us how diverse asteroids are in terms of size, shape, and surface properties. However, we do not have any details yet on their internal structure, and our understanding still relies on numerical models that need further testing. Moreover, although meteorites are fragments of asteroids, we are not sure if they are representative of the material composing the most primitive asteroids (especially the dark ones), and the only way to make the link between our meteorite collection and asteroids in space is to return samples to Earth (Libourel and Corrigan 2014 this issue).

Moreover, a particularly interesting and hazardous body, the 325 m diameter NEA 99942 Apophis, will come within 32,000 km of Earth in 2029. This might be an excellent opportunity for a space mission to determine its internal structure. Returning samples from different NEAs and probing their interiors using various techniques (e.g. radar tomography, seismic experiments) will give new insights into the physical properties of these leftovers from planet formation.

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