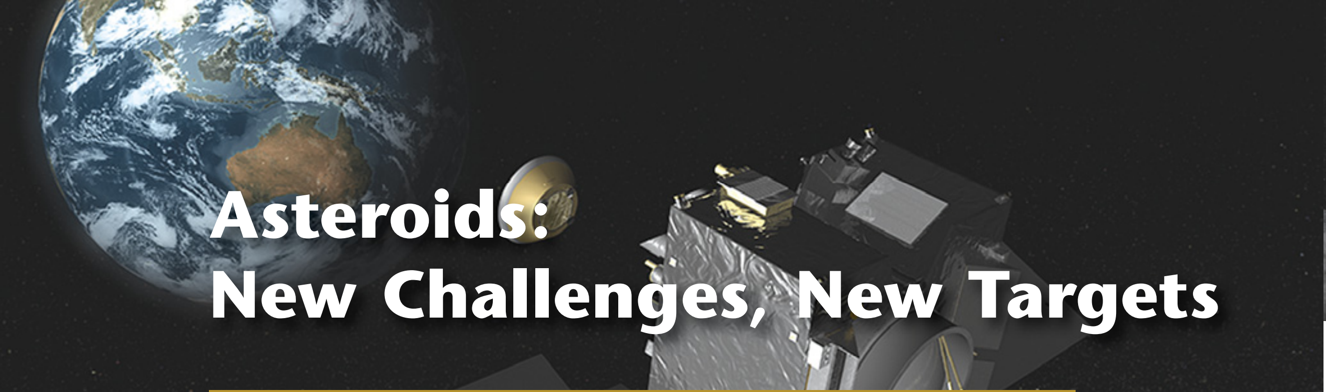

Illustrations (above and left) showing the OSIRIS-Rex spacecraft approaching asteroid 101955 Bennu and propelling the sample capsule back to Earth. Launch is planned for 2016. Artist's conception (NASA/Goddard/University of Arizona)

Asteroids: New Challenges, New Targets

Guy Libourel[1] and Catherine M. Corrigan[2]

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At present, we know of ~600,000 asteroids in the asteroid belt, and there are very likely millions more. Orbiting the Sun between Mars and Jupiter, they are thought to be the shattered remnants of small bodies formed within the young Sun's solar nebula that never accreted enough material to become planets. These "minor bodies" are therefore keys to understanding how the Solar System formed and evolved. As leftover planetary building blocks, they are of great importance in understanding planetary compositions. They may also provide clues to the origin of life, as similar bodies may have delivered organics and water to the early Earth. For these reasons, several international space agencies have funded sample-return missions to asteroids.

Keywords: meteorites, meteors, asteroids, minor planets, sample-return missions

THE CELESTIAL POLICE AND THE MINOR PLANETS

Over several nights in January 1801, Giuseppe Piazzi (Fig. 1), a professor of mathematics and astronomy at the University of Palermo in Sicily, tracked a faint stellar object that was moving against the background of stars. This object had an orbit that matched the orbit predicted by the Titius–Bode law of a missing planet between Mars and Jupiter. Such an object had long been chased by the "Celestial Police," a 19th-century international association of astronomers formed to find this missing planet; several astronomers were assigned to different sections of the ecliptic (plane of the Earth's orbit around the Sun). However, the object observed by Piazzi was not a planet—nor was it a comet, as he initially believed. Instead, the object was a minor planet—an asteroid—and was the first of its kind to be discovered. Piazzi named the asteroid Ceres Ferdinandea, after the Roman goddess of agriculture and fertility, and King Ferdinand IV of Naples and Sicily. 1 Ceres, as it is now dubbed by the Minor Planet Center (www.minorplanetcenter.net; MPC, a branch of the International Astronomical Union), is a body about 950 km in diameter, making it the largest asteroid. It is thought to be differentiated (Thomas et al. 2005), consisting of a rocky core and an icy mantle.

In March 1802, just over a year after Piazzi's discovery, Heinrich Wilhelm Olbers, a physician in Göttingen, Germany, discovered a second object, ~545 km in diameter, which he named Pallas. In 1807, he also discovered Vesta, a 525 km diameter differentiated body (see McSween et al. 2014 this issue). Pallas and Vesta are the only asteroids that are visible to the naked eye (Ceres is too dark, with an albedo of less than 10%). Pallas is now hypothesized to be closely analogous to primitive carbonaceous meteorites, although it is not clear if Earth has received any material from this body or if it is even possible for Earth to intercept meteorites from Pallas. Vesta is the source of the HED meteorites (for howardites, eucrites, and diogenites), of which we have many in our collections.

It took less than a decade for Ceres, Pallas, and Vesta, "the big-3 asteroids," to be discovered. Many new asteroid findings followed, and by the middle of the 19th century, approximately 100 asteroids had been located. Credit for this is mainly due to the use of astrophotographic techniques developed in 1891 by Maximilian Wolf (University of Heidelberg, Germany) to automate the discovery of asteroids. A total of 1000 asteroids had been found by 1921, 10,000 by 1981, and 100,000 by 2000 (source: MPC). Modern asteroid survey systems (LINEAR, CATALINA, LONEOS, SPACEWATCH, NEAT, PAN-STARRS, WISE) use automated means, so that new asteroids are being located in ever-increasing numbers. Currently, over 200 asteroids are known to be larger than 100 km in diameter (of which 26 are more than 200 km in diameter). A survey in the

Figure 1 Giuseppe Piazzi and 1 Ceres. Oil portrait painted in 1803 by Giuseppe Velasco, the author of many portraits in the Palermo Observatory collection. Courtesy of the Palermo Astronomical Observatory

1 Observatoire de la Côte d'Azur, BP 4229
06304 Nice Cedex 4, and CRPG, CNRS UMR 7358
Université de Lorraine BP20, 54501 Vandœuvre les Nancy, France
E-mail: libou@oca.eu

2 Smithsonian Institution, National Museum of Natural History
10th St. and Constitution Ave. NW, MRC 119
Washington, DC 20056, USA
E-mail: corriganc@si.edu

infrared wavelengths (Tedesco and Desert 2002) suggests that the cumulative number of main belt asteroids with diameters greater than 1 km is $1.2 \pm 0.5 \times 10^6$. The number of asteroids increases markedly with further decrease in size, and the existence of about 25,000,000 objects with a diameter of ~100 m has been inferred from mathematical models.

Asteroids revolve around the Sun in elliptical orbits that are characterized by the three Keplerian orbital elements: the semimajor axis (one-half of the longer dimension of the ellipse), the eccentricity (degree of elongation of the ellipse), and the inclination with respect to the ecliptic plane. Most asteroids have orbits that are more eccentric and more inclined (in general, up to 30°) than those of the planets. Telescope photometric observations provide information on the rotation of asteroids. While most have a regular rotation around a fixed axis, very small asteroids with an irregular shape have complex tumbling rotations. Asteroids smaller than 150 meters in diameter usually have rotational periods shorter than 2 hours (down to a few tens of seconds for those with a diameter around tens of meters). Asteroids above 150 meters in size generally have rotational periods ranging from 2.3 to 20 hours. Superslow rotators with periods longer than 30 days also exist. Some bodies are known to have a small companion moon or two moons. There are also cases in which two equally sized asteroids orbit each other.

Asteroids are categorized with respect to their distance from the Sun (Fig. 2). Those that have orbits that closely approach Earth are called near-Earth asteroids (NEAs; see below). Asteroids whose orbits lie between those of Mars and Jupiter, with semimajor axes between 2.1 and 3.3 astronomical units (AU; the average Earth–Sun distance) form the main belt, also called the asteroid belt. The Trojan minor bodies are farther away from the Sun, with an average semimajor axis of about 5.2 AU. They are seated on the two Lagrangian points (L4 and L5) of Jupiter's orbit (that is, the stable points on Jupiter's orbit where the centrifugal and gravitational forces from Jupiter and the Sun balance): the L4 Trojans (about 60° ahead of Jupiter) are called "Greeks", and L5 Trojans (about 60° behind the planet) are more specifically termed "Trojans" (Fig. 2). The Jupiter Trojans, being more similar to trans-Neptunian objects (those beyond 30 AU) than to asteroids, are not discussed in this issue.

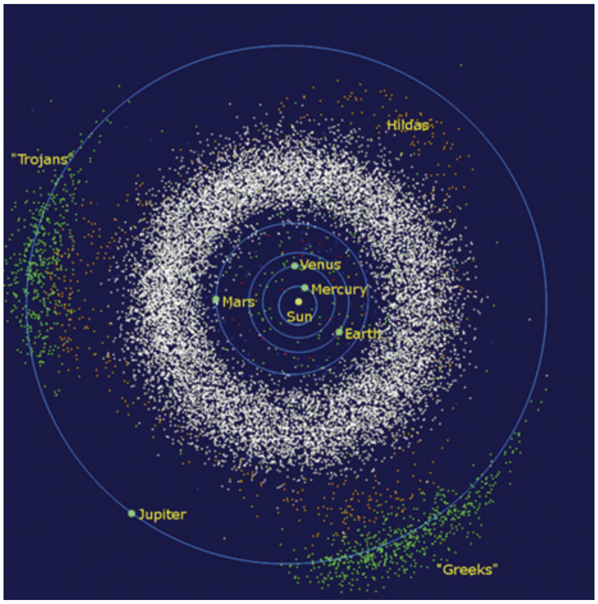


Figure 2 The asteroid belt or main belt is located between the orbits of Mars and Jupiter. Jupiter Trojans co-orbital with Jupiter are also displayed. The Trojans include the "Trojan" and "Greek" families.

As illustrated in Figure 2, the main belt houses the greatest number, and largest mass, of asteroids. The total mass of the main belt is estimated to be between 2.8×10^{21} and 3.2×10^{21} kilograms, which is approximately 4 percent of the mass of the Earth's Moon or less than 1/1000th of the mass of the Earth. The four largest objects, 1 Ceres, 4 Vesta, 2 Pallas, and 10 Hygiea, make up half the mass of the main belt, with about 30% accounted for by Ceres, 9% by Vesta, 7% by Pallas, and 3% by Hygiea (Fig. 3). For comparison, the total mass of the Trojans is estimated to be one-fifth the mass of the whole asteroid belt, and the total mass of the NEAs is negligible with respect to that of the main belt. Although the main belt contains a vast number of asteroids, the asteroids themselves are spread over an enormous volume of space. As a consequence, and contrary to popular conception, the asteroid belt is relatively empty. Thus, the idea of a spacecraft constantly dodging asteroids belongs only in science fiction movies and video games. In fact, there are too few pebble-sized asteroids distributed at this scale to pose a serious threat to a space mission (Dawn mission, http://dawn.jpl.nasa.gov/mission/journal_11_27_09.asp).

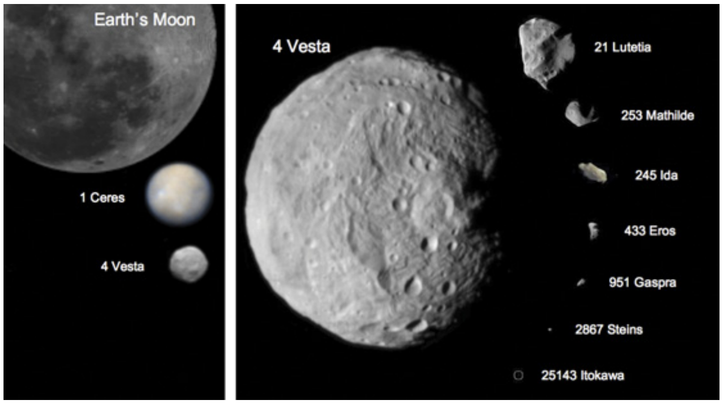


Figure 3 (**Left**) A composite image of the largest asteroids 1 Ceres and 4 Vesta, scaled to the Earth's Moon. (**Right**) High-resolution images of asteroids, scaled to 4 Vesta. Images from NASA/JPL-Caltech/JAXA/ESA (http://dawn.jpl.nasa.gov/multimedia/images/571372main _ pia14316-43 _ 800-600.jpg)

Naming Asteroids

The process of naming asteroids is complex. Since the convention was put in place in 1925, an asteroid is given a "provisional designation" before its official "formal designation" is determined. These designations are overseen by the Minor Planet Center, a branch of the International Astronomical Union. Provisional designations are a combination of numbers and letters that designate when during a particular year the asteroid was found. The first four numbers are the year it was discovered, and the following letters (and possibly numbers) indicate when during the year it was found. Formal names of asteroids are given once the official orbit is confirmed. This name consists of a number (giving the order in which it was discovered) and a name (which could be its discoverer, but is often the same as its provisional designation). Example: 101955 Bennu [previously known as (101955) 1999 RQ36]

CELESTIAL MECHANICS

In his seminal work on celestial mechanics, Pierre-Simon Laplace showed that orbital resonances occur when two bodies have orbital periods that are a simple integer ratio of each other. Such resonances may lead to the destabilization of one of the orbits, particularly for small bodies. Within the main belt, objects that have orbital periods in resonance with the orbital period of Jupiter are gradually ejected into different, random orbits with a larger or smaller semimajor axis. For example, at the 4:1 (2.06 AU), 3:1 (2.5 AU), 5:2 (2.82 AU), 7:3 (2.95 AU), and 2:1 (3.27 AU) mean-motion resonances with Jupiter, known as Kirkwood gaps, gravitational perturbations caused by the planet have led to the removal of asteroids from these regions (corresponding to empty zones in Figure 4). Another important resonance is the "ν6 secular resonance" between asteroids and Saturn, which is linked to the precession of the perihelion (closest point to the Sun) of the orbit of an asteroid and that of Saturn. This resonance forms the inner boundary of the asteroid belt at around 2.15 AU, with inclinations of about 20° (Fig. 5), and is responsible for delivering asteroids into planet-crossing orbits (see below). Asteroids approaching the ν6 secular resonance have their eccentricity slowly increased until they become Mars-crossers (Fig. 5), at which point they are usually ejected from the asteroid belt due to a close encounter with the gravitational field of Mars. If the "Mars-crossers" fail to interact with Mars, their orbital semimajor axis is gradually reduced and they become NEAs.

Asteroids that are nudged by the gravitational attraction of nearby planets or have significant inclination and eccentricity may collide with other bodies traveling along different orbits. Even if the impact probability is low, collisions between asteroids are not rare on astronomical timescales. Depending on the relative impact velocity between the bodies and on their sizes, collisions result in (1) the fragmentation of a parent asteroid into several large pieces and/or (2) the formation of fine, micron-sized asteroidal dust, which is partly responsible for the zodiacal light we see before sunrises and after sunsets. A collision between large asteroids brings into play both fragmentation and gravitation (see Michel 2014 this issue). The asteroids are partially to totally shattered, and subsequent gravitational attraction between fragments leads to reaccumulation, which finally forms an entire family of large and small objects (see below). Accordingly, most of the smaller asteroids are thought to be piles of rubble held together loosely by gravity (Michel and Richardson 2013; see also Tsuchiyama 2014 this issue). The largest asteroids (those larger than ~100 km), however, are probably primordial objects that were never disrupted (Asphaug 2009).

After almost two centuries of observations, ~600,000 asteroids have been discovered. Sustained accumulation of ground-based spectroscopic data and space mission thermal infrared data have allowed for the physical composition of the main belt to be constrained (Masiero et al. 2011). The composition of an asteroid can be inferred from several parameters: (1) the albedo, or the reflective power of a surface (defined as the ratio of radiation reflected from

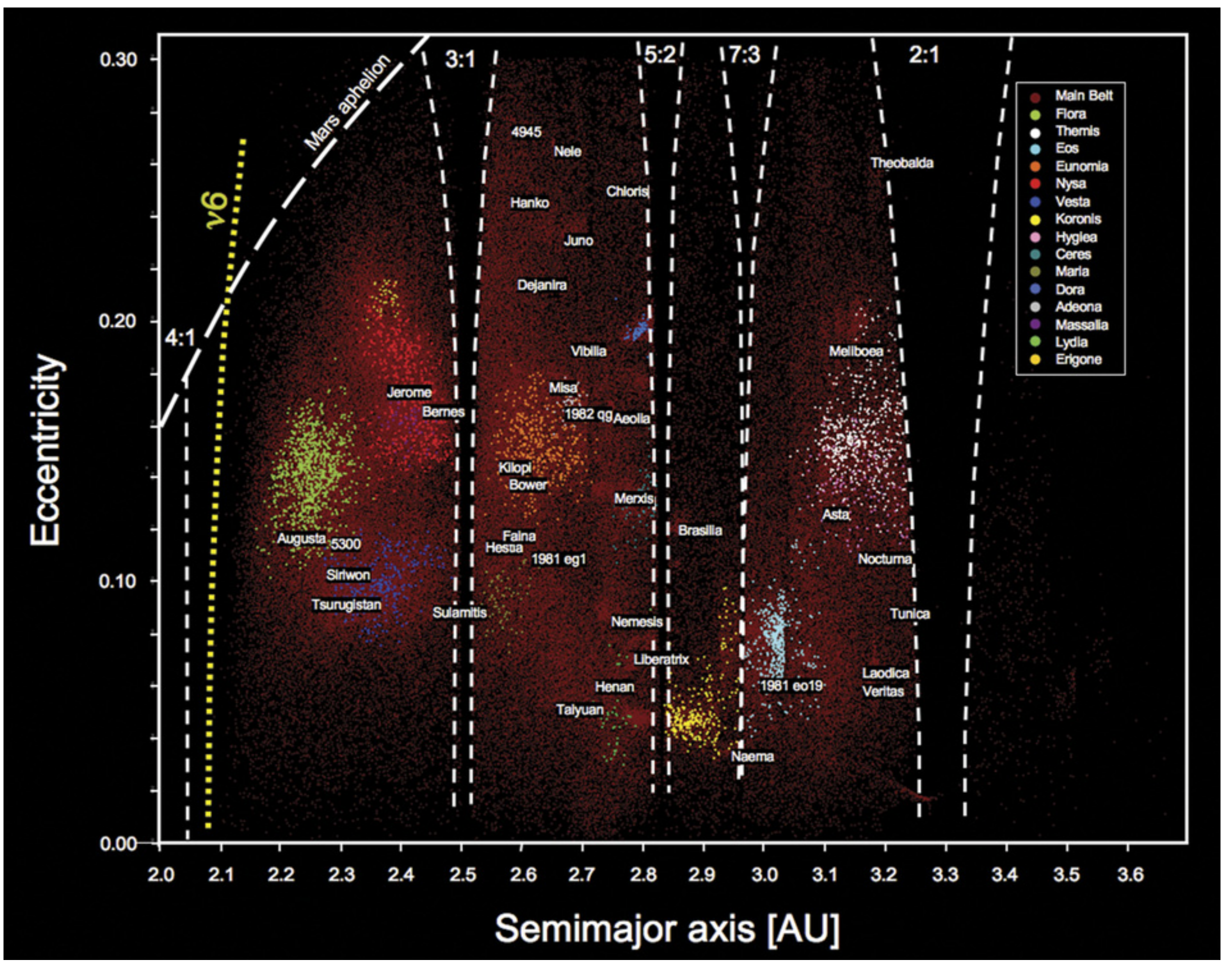
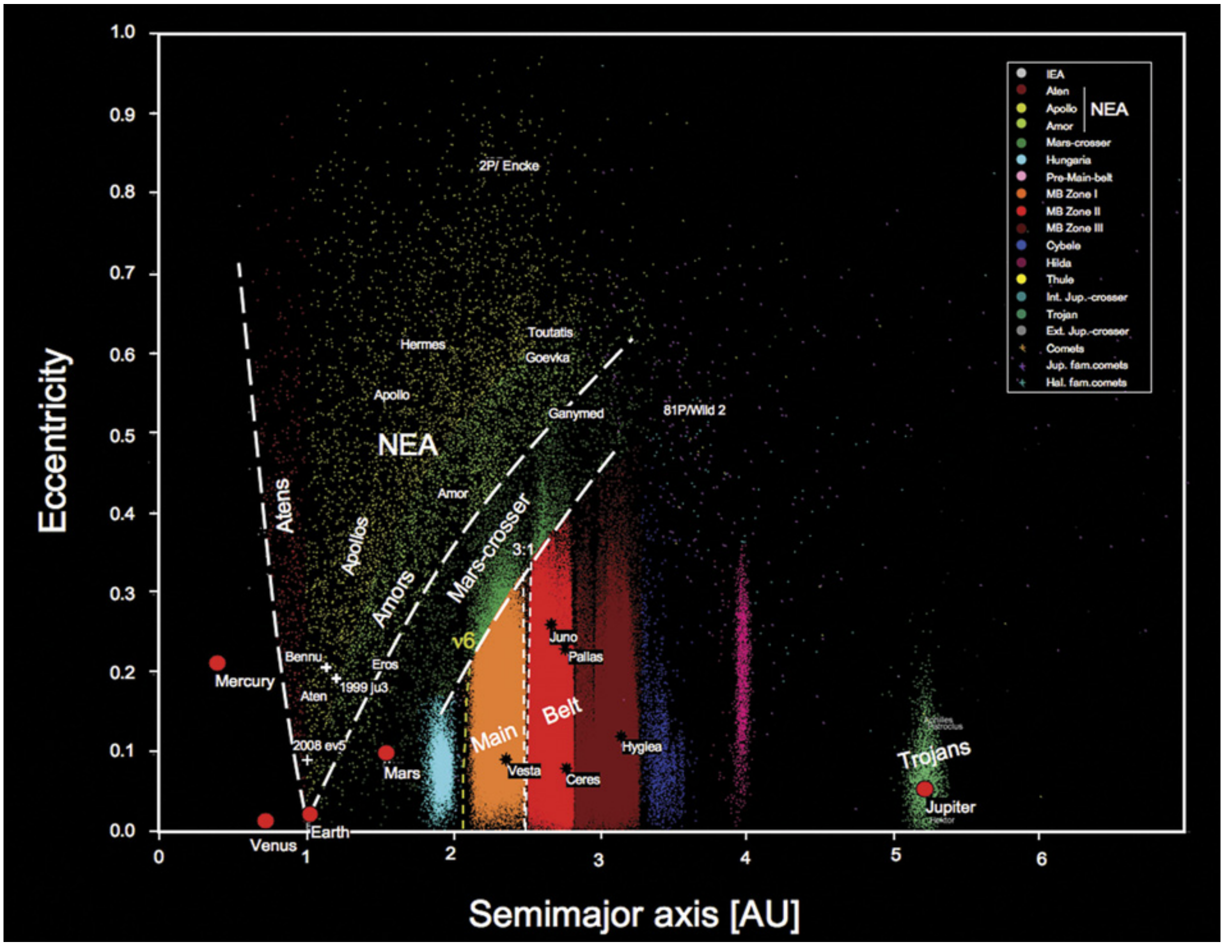


Figure 4 Asteroids of the main asteroid belt (red dots) showing their eccentricity versus their semimajor axis dimension (in astronomical units). The main Kirkwood gaps at 4:1 (2.06 AU), 3:1 (2.5 AU), 5:2 (2.82 AU), 7:3 (2.95 AU), and 2:1 (3.27 AU) mean orbital radii are indicated, and the main asteroid families (color coded) are shown, together with the names of some asteroids (adapted from Petr Scheirich 2005; http://sajri.astronomy.cz/asteroidgroups/ groups.htm).



the surface to incident radiation upon it, expressed as a percentage; the albedo varies between 0% for a totally absorbing surface and 100% for a perfect mirror); (2) the spectrum of the sunlight reflected by the asteroid surface; and (3) the bulk density of the asteroid. From these observations, we now know that the main belt consists of objects with a great diversity of compositions, with surface reflectances of small bodies revealing carbon-rich, silicate-rich, metal-rich, or basaltic compositions, and in some cases more complex features. Despite such diversity (e.g. Tholen and Barucci 1989), three categories of asteroids dominate the main belt. C-type or carbonaceous asteroids, with a generally low albedo (~5%), represent 75% of the known asteroids; S-type or silicate asteroids, which are relatively bright and have an intermediate albedo, account for 20% of the known asteroids; and M-type, metallic asteroids, as well as other bright objects, account for the rest. Bordering on S-type, V-type asteroids or vestoids have spectra similar to that of 4 Vesta (see McSween et al. 2014). Approximately 6% of main belt asteroids are vestoids. The observed distribution in the main belt suggests that the inner part of the belt is formed preferentially by the highly common S-type asteroids, which orbit nearer to Mars than the 3:1 Kirkwood gap (2.5 AU), while the outer part of the belt is formed by those asteroids orbiting close to Jupiter's orbit and is dominated by C-type asteroids; M-type asteroids are scattered throughout the central part of the belt (see Cloutis et al. 2014 this issue). Even if the Nice model (Tsiganis et al. 2005; Morbidelli et al. 2005) and the more recent Grand Tack model (Walsh et al. 2011)—that is, models in which the migration of gas-giant planets early in the history of the Solar System scattered the asteroids inward and outward in the Solar System—may explain part of this distribution, the full explanations for such a peculiar distribution of asteroids in the main belt and the small size of the mass in the main belt still remain to be determined. The scarcity of olivine-dominated, metal-free mantle materials in our asteroid observations (Burbine et al. 1996) is also not well understood, particularly if one assumes that complete or near-complete differentiation of pristine chondritic material results in an object with an Fe–Ni core and an olivine-dominated mantle.

Figure 5 Orbital elements for the inner Solar System, showing semimajor axis dimension (in astronomical units) versus eccentricity for some well-known objects and different types of asteroids, including near-Earth asteroids (NEAs), main belt (MB) asteroids, Trojans, and comets. Modified from Petr Scheirich (2005); http://sajri.astronomy.cz/asteroidgroups/groups.htm

In the main belt, several groups of asteroids of different size share similar orbital elements, such as semimajor axis, eccentricity, and orbital inclination. In addition, each group of asteroids is recognized as having similar spectral features within the group. Thus, such asteroids are considered to belong to the same asteroid family. Examples are illustrated in Figure 4. Asteroid families are thought to be the result of the disruption of a single parent body. Following a breakup event, fragments are launched into orbits that are distinct from, but similar to, the orbit of the original parent body. Smaller fragments are typically launched with higher velocity, creating a size-dependent spread in orbital elements that allows for the identification of asteroid families within the belt (see, for instance, Walsh et al. 2013). Several tens of families have already been recognized. Flora, Themis, Eos, Nysa-Eulalia-New Polana, Eunomia, Koronis, and Vesta are some of the most prominent, with each consisting of more than 100 known small bodies (Fig. 4). The boundaries of the families are somewhat vague because, at the edges, they blend into the background density of asteroids in the main belt (Fig. 4). While the largest families (Eos, Koronis, and Themis) seem to be compositionally homogeneous, interlopers from the background population are frequent in most of the asteroid families. In other cases, observed heterogeneity within families (e.g. the Vestan asteroids) may result from the fragmentation of a differentiated parent asteroid, which may be stripped of its crust, mantle, or iron core (see McSween et al. 2014).

HOW DID METEORITES FROM ASTEROIDS REACH EARTH?

Asteroids are currently thought to be quite mobile during their several-hundred-million-year lifetime inside the main belt (Bottke et al. 2006). Due to asteroid collisions and the Yarkovsky effects (thermal forces changing an asteroid's semimajor axis over time), main belt asteroids migrate and may end up crossing one of the aforementioned orbital resonances, eventually becoming a planet-crosser, that is, an asteroid whose orbit crosses the orbits of Mars, Earth, Venus, and Mercury (Fig. 5). A main belt asteroid becomes a near-Earth asteroid when its orbit brings it within 1.3 AU of the Sun or within 0.3 AU of the Earth's orbit. NEAs are grouped into three categories: Atens, representing 8% of the total number of NEAs, with orbital semimajor axes less than 1 AU; Apollos (54% of NEAs), which are Earth-crossing asteroids with orbital semimajor axes greater than that of the Earth (>1 AU), and Amors (37% of NEAs), which have orbital semimajor axes greater than 1 AU. Amors approach the orbit of the Earth but do not cross it; however, most Amors are Mars-crossing asteroids. Collectively, NEAs do not have stable orbits because they evolve rapidly in the Keplerian orbital space due to close encounters with terrestrial planets and resonance with the giant planets. For these reasons, NEAs have short lifetimes, on average only about 10 My (Gladman et al. 2000). NEAs become potentially hazardous asteroids (PHAs) when their orbits are within 0.05 AU (7.5 million kilometers) of the Earth's orbit (known as the Earth minimum orbit intersection distance, or MOID) and when their diameters exceed 100–150 m. Once this happens, there is a greater possibility of colliding with Earth and impacting the surface.

By definition, a meteor is an asteroid that enters the Earth's atmosphere. Due to their high entry velocity (several kilometers per second), meteors are heated to high temperatures as they are slowed by the atmosphere. This produces a visible path, and the meteor is then known as a fireball or shooting star. If the meteor survives its plunge through the atmosphere and lands on the surface, it is classified as a meteorite. The difference between an asteroid, a meteor, and a meteorite was nicely exemplified on February 15, 2013, when the asteroid NEA 2012 DA14 (45 m diameter) passed within 27,700 km of Earth. On the same day, an unrelated superbolide meteor (NEA Apollo group; $D \approx 15$ m) entered the Earth's atmosphere and descended over the Ural Mountains in Russia. It exploded at altitude in a massive blast captured on cameras, and it produced meteorite fragments that fell in and around the city of Chelyabinsk (Fig. 6). Interestingly, as asteroid NEA 2012 DA14 passed by Earth, its orbital period decreased, moving the asteroid from the Apollo group into the Aten group of near-Earth asteroids (Fig. 5). Thus, this asteroid serves as an example of how the orbital elements of an asteroid might change during its lifetime. As of February 2014, 10576 near-Earth objects (NEOs) have been discovered: 97 are near-Earth comets and 10480 are near-Earth asteroids. Approximately 1450 NEOs are classified as potentially hazardous (source: MPC; see also NASA's NEOWISE).

From these orbital and dynamical arguments, it is believed that most meteorites do indeed come from the asteroid belt and are therefore samples of asteroidal materials (Gounelle 2011). However, several factors bias the population of meteorites arriving on Earth and therefore limit our sampling of the asteroid belt. For instance, dynamical models (Bottke et al. 2000) have shown that the predominant source of NEAs is a narrow zone of the asteroid belt bound by the ν6 secular resonance at around 2.15 AU and the 3:1 Kirkwood gap resonance at 2.5 AU (Fig. 5). Therefore, it is quite likely that most meteorites on Earth are samples of the less primitive material of the inner main belt, and are not samples of the outer part of the belt, which is richer in low-albedo, carbonaceous asteroids. The cohesive strength of an asteroid/meteoroid is another important selection factor, which is related to the survivability of impacts in the main belt or collisions in the near-Earth region. The cohesive strength of asteroidal material also makes a great difference when considering its putative delivery to Earth, as evidenced by the frequent preservation of durable iron meteorites but the rare occurrence of fragile carbonaceous chondrites, which are more likely to be reduced to dust (see *Elements'* Cosmochemistry issue, February 2011).

Figure 6 On 15 February 2013, an Apollo-group near-Earth asteroid entered the Earth's atmosphere and became the Chelyabinsk meteor (upper panel), which was captured on cameras over the southern Ural region (Russia). The impact sites of some of the fragments of the Chelyabinsk meteorite have been found near Chebarkul Lake (bottom-left panel; credit to http://en.ria.ru/images/18103/10/181031043.jpg). Meteorite samples were recovered around Chelyabinsk by a Russian scientific group from the Vernadsky Institute of the Russian Academy of Sciences, including Marina A. Ivanova (bottom-right panel), Cyril A. Lorenz, Dmitriy D. Badyukov, Svetlana I. Demidova, Konstantin M. Ryazantsev, and Dmitriy A. Sadilenko.

Although meteorites most likely sample asteroidal materials, linking meteorites to their parent asteroid is a complicated issue. Owing to the lunar missions and more recently to NASA's Dawn mission to 4 Vesta (see McSween et al. 2014) and JAXA's Hayabusa mission to the near-Earth asteroid 25143 Itokawa (see Tsuchiyama 2014), we now know that the spectral characteristics of the regolith (Binzel et al. 2004) (the surface material of an asteroid) can be strongly altered by its long-term exposure to space weathering—impacts, solar wind ion implantation, sputtering, and micrometeorite bombardment—changing the surface of asteroids (for example, by mineral amorphization and precipitation of iron metal nanophases; see also Tsuchiyama 2014) so that they appear different from meteorites (Clark et al. 2002; Cloutis et al. 2014). Therefore, it is important to recognize that preferential sampling of Earth-bound materials and space weathering processes introduce biases of unknown magnitude when attempting to link asteroids and meteorites. Ultimately, this limits the usefulness of the meteorite collection, both as a true representation of the asteroid belt (see Goodrich et al. 2014 this issue) and as a proxy for understanding the early history of our Solar System.

WHY SHOULD WE GO THERE?

"Greed, fear, and love of knowledge send us to the asteroids," said Martin Elvis, a senior astrophysicist from the Harvard-Smithsonian Center for Astrophysics (the Smithsonian's Stars Lecture Series, December 2011), and he is likely right. Most people fear asteroids as a threat to life on Earth (Bottke et al. 2007; McSween 2012). Scientists' love of knowledge drives them to check out the material our planet grew from, including the oceans; find clues to the origin of life; and, maybe, find exotic materials we cannot make on Earth. And a few visionaries have long argued that the mineral wealth in asteroids is huge. According to John S. Lewis, author of the space-mining book *Mining the Sky*, an asteroid with a diameter of one kilometer would have a mass of about two billion tons and would contain 30 million tons of nickel, 1.5 million tons of metal cobalt, and 7500 tons of platinum. The platinum alone would have a value of more than $150 billion! By 2020, only 19 asteroids will have been visited by spacecraft, while there are millions out there. The time has now come when advanced space engineering and new astronomical knowledge can be combined to make exploring the asteroids possible. Among the missions scheduled to visit asteroids in the near future (described below; Fig. 7), three are targeted to return samples from some of the most primitive carbon- and organic-rich asteroids.

Figure 7 Logos of missions scheduled to visit asteroids in the near future: Dawn (NASA), OSIRIS-REx (NASA), Hayabusa-2 (JAXA), and MarcoPolo-R (ESA)

MISSIONS TO ASTEROIDS

Dawn (http://dawn.jpl.nasa.gov)

During its nearly decade-long voyage, the NASA Dawn mission will study remotely the asteroids 4 Vesta and 1 Ceres, celestial bodies believed to have accreted early in the history of the Solar System. The asteroid Vesta and the recently categorized dwarf planet Ceres have been selected because, while both speak to conditions and processes early in the formation of the Solar System, they developed into two different kinds of bodies. 4 Vesta is a dry, differentiated object with a surface that shows signs of resurfacing. It resembles the rocky bodies of the inner Solar System, including Earth. 1 Ceres, by contrast, has a primitive surface containing water-bearing minerals and may possess a weak atmosphere. It appears to have many similarities to the large icy moons of the outer Solar System. Launched September 27, 2007, Dawn visited 4 Vesta from July 2011 to July 2012 (see McSween 2014) and is now en route to 1 Ceres, with arrival scheduled for February 2015. To carry out its flyby scientific mission, the Dawn spacecraft will carry three science instruments whose data will be used in combination to characterize these bodies. These instruments are a visible-light camera, a visible-light and infrared mapping spectrometer, and a gamma ray and neutron spectrometer. Radiometric and optical navigation will provide data relating to the gravity field and thus to the bulk properties and internal structure of the two bodies.

OSIRIS-REx (http://osiris-rex.lpl.arizona.edu)

NASA's New Frontiers 3 mission will return a sample from the spectral class B Apollo asteroid 101955 Bennu [previously known as (101955) 1999 RQ36] in 2023. This potentially hazardous Earth-crossing object is hypothesized to be a carbonaceous asteroid similar to CI or CM carbonaceous chondrites (Campins et al. 2010). The OSIRIS-REx acronym describes the mission objectives: origins, spectral interpretation, resource identification, security, regolith explorer. Central to the mission is the return of ≥60 g of pristine asteroid regolith for examination by the cosmochemistry and astrobiology communities. By determining the geological provenance of the sample, we (and future generations) will be able to constrain Solar System history in a manner that cannot be fully accomplished with meteorites. The data obtained, including those from the analysis of organics, will be used to test hypotheses on the preaccretion origins of planet-forming materials, the origin of prebiotic compounds, the geological activity that occurred after small-body accretion, and the dynamics of an asteroid that evolves from the main belt to Earth-crossing. Furthermore, the spacecraft instrument suite will permit ground-truthing of orbital and Earth-based telescopic observations. The mission will also constrain the Yarkovsky effect on this asteroid in order to better predict its future orbit and potentially hazardous nature.

Hayabusa-2 (http://b612.jspec.jaxa.jp/hayabusa2/e/index_e.html)

Following Hayabusa's successful return of the first asteroid samples to Earth, JAXA is planning another asteroid mission, Hayabusa-2 (2014–2020), which will return samples from the near-Earth carbonaceous-type asteroid (162173) 1999 JU3. Hayabusa-2 has the following scientific objectives: (1) to determine the thermal evolution from planetesimal to near-Earth asteroid, (2) to understand the destruction and accumulation of a rubble-pile body; (3) to identify the diversification of organics through interactions with minerals and water, and (4) to study material evolution in the early Solar System. The basic design of the spacecraft is the same as Hayabusa, but new technologies will be adopted. Onboard scientific instruments will include a laser altimeter, a multi-band camera, a near-infrared spectrometer, a thermal infrared imager, and a wide-angle camera. A small impactor will be carried aboard for an asteroid-scale impact experiment. The sampling device will be the same as on Hayabusa, and a 5 g tantalum projectile will be shot at 300 m/s to collect >100 mg of asteroidal material. The sampler has three projectiles, and the sample container has three separate partitions for sampling at three different locations. One of the collection locations could be the site of the artificial-impact experiment, where the goal would be to sample subsurface materials. The samples will be delivered to Earth in December 2020.

MarcoPolo-R (https://www-n.oca.eu/MarcoPolo-R)

This proposed sample-return mission will be to a primitive near-Earth asteroid. It was selected in the framework of the European Space Agency's Cosmic Vision (CV) program as an M3-class mission candidate (for launch in 2022–2024). The final selection will be made in February 2014. The mission will greatly contribute to answering the fundamental CV questions: how does the Solar System work and what are the conditions for life and planetary formation? The target is the primitive potentially hazardous asteroid (341843) 2008 EV5, which offers unique scientific value. The asteroid's reflectance spectrum hints at an absorption band at 0.48 µm (Reddy et al. 2012), typical of aqueous alteration (Cloutis et al. 2011), implying that the asteroid is a particularly primitive object whose parent body may have accreted in a volatile-rich region of space. Both the spectral behavior of 2005 EV5 and its albedo of about 10–12%, interestingly higher than the albedo of the targets of the OSIRIS-REx and Hayabusa-2 missions, suggest that MarcoPolo-R will sample a more primitive body. MarcoPolo-R will provide a unique opportunity to enhance our knowledge of the nature of a distinct population of primitive bodies. MarcoPolo-R will ensure that European laboratories involved in sample analysis are positioned at the forefront in this new era of sample-return missions. Moreover, the short mission duration (4.5 years) of MarcoPolo-R will bring the time of the sample analysis closer to the expected return times of the JAXA and NASA sample-return missions, allowing Europe to contribute in a timely manner to the international sample-return activities.

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