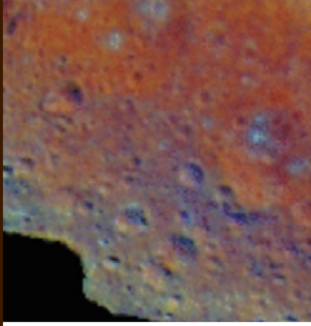

Establishing Asteroid–Meteorite Links

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Asteroids are arguably the most accessible remnants of building blocks of the early Solar System and an essential piece of the terrestrial planet–formation puzzle. Determining their compositions and physical properties can provide important and otherwise unobtainable information concerning the origin, structure, and dynamic history of the Solar System, as well as insights into the sources of materials from which the terrestrial planets were constructed. Our understanding of the compositional structure of the asteroid belt and of individual asteroids has advanced significantly since the 1970s. Strong associations between asteroids and meteorites are emerging thanks to multitechnique observations, the synthesis of observations and modeling, in situ measurements, and sample-return missions.

Keywords: asteroids, meteorites, Solar System evolution

INTRODUCTION

Understanding the origin and evolution of the Solar System is a fundamental scientific endeavour. Our planet, whose geology we are most familiar with because it is directly accessible to us, does not retain a readily readable record of its origins. Four and a half billion years of geological processes have largely obliterated this early record. To better understand the origin and early history of our planet and Solar System, we need to include information from outside the Earth.

Meteorites, which seemingly come to us for "free," can provide this crucial window into our origins. Meteorites come in different varieties, enabling us to sample different parts of the Solar System and different times in its evolution. The vast majority of meteorites originated from small parent bodies (asteroids); a small fraction of recovered meteorites (a few dozen of the tens of thousands of recovered meteorites) originated from the Moon and Mars (http://curator.jsc.nasa.gov/antmet/mmc/index.cfm), and possibly comets. A major shortcoming, which confirms the fact that nothing comes for "free," is that using meteorites to understand Solar System evolution is hampered by our lack of knowledge about their provenance. As on Earth, a rock with known spatial context is much more valuable than one collected at random. Thus, although we can date the formation of meteorites and often reconstruct their dynamical history, a priori knowledge of where these events occurred is lacking.

IMPORTANCE OF ASTEROID–METEORITE LINKS

If we can relate specific meteorites to either specific parent bodies or regions of space, we can start to address a range of important questions, such as:

- What kinds of dynamical processes operated in the early Solar System? (See Michel 2014 this issue.)
- What kinds of heating processes operated in the early Solar System? In other words, what controls the fact that meteorites range from fully primitive to highly evolved (completely differentiated)? (See Fig. 1.)
- What in situ resources are available on asteroids that could be economically exploited or used to facilitate extended human presence in space?
- What kinds of impact hazards does the Earth face? Asteroid composition and structure will determine what impact-mitigation strategies may be most effective.

The answers to these questions fall outside the scope of this article. However, to better understand Solar System history and begin to answer these questions, we need to study the when, where, and how of meteorite evolution. In this article, we focus on the where.

WHAT WE KNOW ABOUT ASTEROIDS

Our knowledge of asteroids dates back to 1801, with the discovery of the first main belt asteroid, 1 Ceres[4]. Over the ensuing years, many more asteroids were discovered, with the current inventory of discovered asteroids now numbering in the hundreds of thousands (www.minorplanetcenter.net). As the discoveries mounted, so too

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[4] Upon discovery, asteroids are given an alphanumeric preliminary designation, which is replaced by a purely numeric catalog number when the orbit becomes precisely known. Once assigned a permanent number, a name can be proposed.

have the physical observations that have yielded notable milestones in understanding the geology of asteroids. Some examples follow.

- The first indications that the asteroid belt is geologically diverse came in the 1920s with the discovery of color differences among asteroids (Bobrovnikoff 1929).
- The first and most strongly established mineralogical determination of asteroid surface composition and its meteorite association came about in 1970 for asteroid 4 Vesta (McCord et al. 1970).
- The first large-scale taxonomic studies, whereby asteroids were categorized into different spectral or color groups—suggestive of both mineralogical diversity and compositional groupings—emerged in the late 1970s and early 1980s (e.g. Bowell et al. 1978).
- The ability to firmly constrain or establish the surface mineralogy of spectrally distinctive asteroids began in the 1970s and was extended to more asteroids in the 1980s (e.g. Cruikshank and Hartmann 1984).
- Spectroscopic surveys of large numbers (hundreds) of asteroids began in the late 1970s (Zellner et al. 1985) and were expanded during the subsequent decades to include more asteroids, more detailed spectral resolution, and greater wavelength coverage (e.g. Xu et al. 1995; Burbine and Binzel 2002). Also during this period, Earth-based radar observations were used to determine shape, spin, and thus the history of asteroids.
- The mineralogical/spectral diversity across the surfaces of specific asteroids (e.g. Gaffey 1997) and within taxonomic groups (Gaffey et al. 1993) was discovered, and we acquired the ability to derive, or at least constrain, the surface mineralogy of spectrally distinctive asteroids (1990s).

Figure 1 Images of the interior surface of various meteorites. (**A**) The Allende CV3 carbonaceous chondrite, a primitive carbonaceous meteorite containing organic material, chondrules (melted droplets of preexisting minerals—round objects in the image); carbonaceous chondrites have been linked to various dark-asteroid classes. (**B**) The Seymchan pallasite, a differentiated meteorite or impact melt containing large grains of olivine in a metallic matrix; pallasites have been linked to A-class asteroids. (**C**) The Odessa differentiated iron meteorite showing the Widmanstätten pattern indicative of slow cooling; iron meteorites have been linked to M-class asteroids. (**D**) The Norton County aubrite, a high-temperature, highly reduced, differentiated meteorite; aubrites have been linked to E-class asteroids. (**E**) The NWA 869 L4-L6 ordinary chondrite breccia; darker regions are fragments of a carbonaceous chondrite, likely added as a result of an impact. Scale bars are in millimeters.

- Programs such as the Sloan Digital Sky Survey (www.sdss.org) and the NEOWise Space Infrared Survey (http://neo.jpl.nasa.gov/programs/neowise.html) carried out large-scale surveys of asteroids (thousands to hundreds of thousands) at a few wavelengths.
- Ground-based, telescopic spectral analysis predicted the LL ordinary chondrite composition of asteroid 25143 Itokawa (Binzel et al. 2001; the asteroid's original designation was 1998 SF36). Successful sample return by the Hayabusa mission gave ground-truth confirmation of the LL chondrite class (Tsuchiyama 2014 this issue) .

The earliest large-scale surveys suggested that the asteroid belt is radially stratified, with the presumed highest-temperature asteroids at the smallest heliocentric distances and the least altered asteroids farthest out. Since then, we have greatly refined our understanding of asteroidal mineralogical diversity and are strengthening mineralogical–spectroscopic linkages.

Some meteorites can be traced to specific regions in space or specific parent bodies. Sky-scanning cameras can detect meteorites entering the Earth's atmosphere as fireballs and we can back-calculate their orbits (e.g. Halliday et al. 1978). We were also fortunate recently to detect and study an asteroid prior to its encounter with Earth (2008 TC_3) and then recover pieces of the asteroid (Goodrich et al. 2014 this issue).

Although Earth- and space-based investigations can help us constrain asteroid surface compositions, there is no substitute for having a sample of known provenance in hand. Recently we directly sampled the near-Earth asteroid Itokawa (Tsuchiyama 2014). Asteroid sample-return missions are also scheduled for later in this decade (OSIRIS-REx, Hayabusa-2).

Compositional studies of meteorites indicate that they originated from at least many tens of distinct parent bodies (Keil 2000). It also appears that our meteorite collection is not representative of the compositional diversity of the asteroid belt (Burbine et al. 2002). A number of meteorite types must have formed in association with other types that have not yet been found. This is likely due to the biases and selection effects that are associated with the mechanisms that deliver meteorites from the asteroid belt to the Earth (e.g. Burbine et al. 2002). There are a number of asteroids whose mineralogy is reasonably well understood but for which we have no representatives in our meteorite collections (e.g. 44 Nysa, 349 Dembowska); conversely, there are meteorites for which we have no obvious parent body (e.g. GRA 06128/9). Complicating the determination of asteroid–meteorite links is the fact that the delivery of meteorites to Earth from the main asteroid belt is normally a multistep process with various biases (Michel 2014).

WAYS OF INVESTIGATING ASTEROIDS

We have a multitude of ways of investigating asteroids and forging asteroid–meteorite connections. Each method has advantages and limitations, and some methods can provide information on both physical properties and composition. Techniques that have been applied to the study of asteroids and that reveal something about physical properties (usually in conjunction with some constraints on composition) include gravitational interactions, stellar occultations, Earth-based radar imaging, optical and radar polarimetry, the acquisition of rotational light curves, and thermal-infrared observations. The derivable physical properties include size, shape, density, surface texture, presence or absence of regolith, rotation rate, and porosity. For most asteroids, one or a few of these parameters have been determined, leading to at least some constraints on physical and/or compositional properties. As the number of observational techniques applied to an asteroid increases, our understanding of an asteroid's physical structure necessarily improves.

Asteroid compositional determinations are also possible via multiple techniques. The major ways in which compositional properties can be determined or constrained include density determinations or constraints by gravitational interactions or radar observations, radar reflectivity to constrain metal content, elemental analysis using gamma ray or neutron detection, the measurement of a magnetic field (if present), optical polarimetry, reflectance spectroscopy, thermal emission spectroscopy, direct imaging, and dynamical correlations. As with the methods that can be used to constrain physical properties, these observational techniques probe asteroids to different depths and at different spatial scales, providing types of information that complement one another. Sample return provides the capstone of our understanding of asteroid–meteorite connections (Fig. 2).

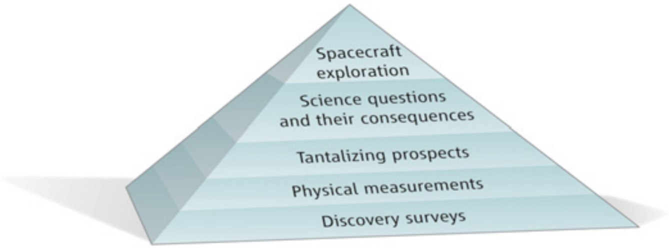

Figure 2 Pyramid building as an analogy to asteroid (and planetary) exploration. At the wide base is the discovery of the broad population, largely through telescopic surveys. Physical measurements are carried out on many, but not all, discovered objects, thus narrowing the pyramid. A still fewer number of objects are particularly tantalizing. Those objects for which our ability to answer significant science questions from Earth has reached its limit are then subjected to observational and theoretical study. The capstone represents spacecraft missions to the few objects whose study has the potential to deliver the most consequential breakthroughs. Image from Binzel (2012), reprinted with permission from *Science*

FORGING ASTEROID–METEORITE LINKS

By combining the results of multiple techniques, a more robust picture of an asteroid's properties emerges. Among the properties of interest, internal structure and composition are, not surprisingly, the most intractable. Different techniques probe asteroids to different depths, so any near-surface variations that may exist, such as those due to space weathering, are potentially recognizable. For example, apparent variations in the mineralogy of asteroid 433 Eros can largely be reconciled by invoking various surface-modification processes and the different interrogation depths of the instruments aboard the NEAR spacecraft (McCoy et al. 2001). Sending appropriately equipped spacecraft to asteroids also helps forge asteroid–meteorite links (Fig. 2).

Reflectance spectroscopy is the most widely applied asteroid-characterization technique. Many asteroids have reflectance spectra that seem to lack diagnostic absorption features. However, there are indications that what we believe to be spectrally bland asteroids may in fact have weak diagnostic absorption features that can be detected with high signal-to-noise observations (e.g. Vilas and Gaffey 1989). As data quality improves and other kinds of observational data become available, traditional asteroid taxonomic classes (such as the M class) may include mineralogically diverse bodies, ranging from primitive (wet) to evolved (dry) (Rivkin et al. 2000), thus increasing our ability to distinguish different materials.

A further issue that complicates establishing links is the dynamic nature of the asteroid belt. Once formed, asteroids do not serenely orbit the Sun, untouched. They are subject to various events and conditions: impacts over a range of sizes and energies, orbital perturbations, solar wind and galactic cosmic ray bombardment, the vacuum of space, and temperature excursions. Polymict breccias and the presence of xenoliths are the norm rather than the exception. Thus, when viewing an entire hemisphere of an asteroid, as is done for Earth-based observations, we are likely observing a diversity of terrains, both physically and compositionally. This further complicates our ability to relate a few grams of meteoritic material, which managed to survive a perilous journey to Earth, to a parent body exposed to the space environment.

The availability of meteorites and samples of known provenance (such as the Hayabusa samples from Itokawa and the Almahata Sitta samples from 2008 TC_3) is proving to be extremely valuable as we continue to establish asteroid–meteorite links. Although Itokawa samples yielded a previously predicted result (Binzel et al. 2001), the much more complex characteristics of the Almahata Sitta meteorite have demonstrated that, in other cases, samples can be more complicated than what is predicted from telescopic data. By combining asteroid observational data with models of asteroid orbital evolution and surface modification, as well as with meteorite data such as ejection and exposure ages, we are beginning to fill in the details on how we can better reconcile asteroid and meteorite observations. Our view of asteroids is also becoming more nuanced, with evidence pointing to these bodies having optically (and mineralogically) complex surfaces (Figs. 3, 4). The Dawn mission to Vesta is providing strong evidence of mixing of different meteorite types at large scales (McSween et al. 2014 this issue), complementing evidence of mixing of similar meteorite types at microscopic scales (Chou et al. 1976).

EXAMPLES OF ESTABLISHED ASTEROID–METEORITE LINKS

One of the first asteroid–meteorite links to be established was between 4 Vesta and howardite-eucrite-diogenite meteorites (McCord et al. 1970). Initially, their spectroscopic similarity was deemed dynamically dubious owing to the apparent lack of a plausible pathway from Vesta to the Earth. The discovery of the Vesta family of asteroids (or "Vestoids"; Binzel and Xu 1993) extending from Vesta to resonance delivery zones solidified the link. This link has stood the test of time and been confirmed by the in situ results provided by the Dawn mission to this asteroid (McSween et al. 2014). The return of samples from Itokawa by the Hayabusa mission (Tsuchiyama 2014) cemented the relationship between Itokawa and LL chondrites that was predicted prior to the spacecraft's launch. These are by far the strongest and most accepted asteroid–meteorite links, and they demonstrate the value of asteroid sample return and detailed spacecraft observations, and the capability of successful mineralogical interpretations by Earth-based observers.

Other links are less certain, and their reliability is often a function of an asteroid's "uniqueness." For example, as a group, the E-class asteroids are bright, and either they are spectrally featureless or they possess an absorption feature that is probably associated with the rare mineral oldhamite (CaS). Their brightness and the presence of oldhamite eliminate the possibility that these asteroids contain more than trace amounts of ferrous iron–bearing or opaque minerals. Only the aubrite achondrites satisfy these criteria. Asteroid Steins, an E-class asteroid, has high albedo, consistent with aubrites, but shows a prominent oldhamite-like absorption feature, suggesting that it represents a type of aubrite not represented in our meteorite collections, that is, an aubrite with a high-temperature, low-oxygen-fugacity mineral assemblage (Keller et al. 2010).

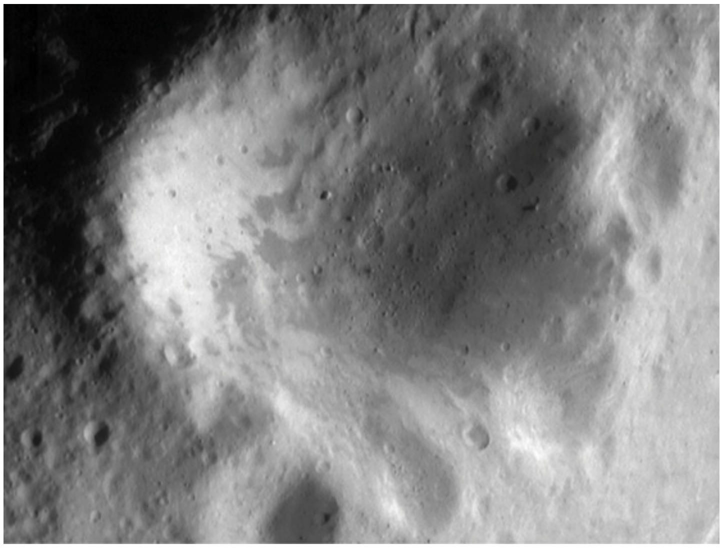

Figure 3 NEAR-Shoemaker spacecraft image mosaic of the 5.3 km wide crater Psyche on asteroid 433 Eros showing albedo differences in its wall. These may be related to differences in grain size and/or composition. Source: http://nssdc.gsfc.nasa.gov/planetary/image/near _ psyche _ mos.jpg

Another example is the strong link between A-class asteroids and olivine-rich meteorites, such as brachinites and pallasites. This association is based on a unique and diagnostic absorption feature exclusively attributable to ferrous iron–bearing olivine (Cruikshank and Hartmann 1984). At the other extreme, the Tagish Lake meteorite, a rare carbonaceous chondrite, has been associated with D-class asteroids; both Tagish Lake and D-class asteroids have reflectance spectra that are very dark in the visible-light region, becoming brighter toward the near-infrared, and they exhibit no recognizable absorption bands in their reflectance spectra (Hiroi and Hasegawa 2003). In other cases, such as the C-class asteroids, the lack of diagnostic spectral features suggests that this class may encompass multiple meteorite types and include compositionally diverse objects.

Meteorite–asteroid links can be enhanced when observational data are combined with other lines of evidence, such as the location of asteroids near "escape hatches" for delivery to Earth, clusters of meteorite exposure ages, and the spectral uniqueness of parent bodies. By building an internally self-consistent picture for specific asteroids, we can begin to home in on potential parent bodies for specific classes of meteorites. Such multidisciplinary approaches provide the strongest linkages. Multiple criteria have been used to link asteroid 6 Hebe and the H-type ordinary chondrites (Gaffey and Gilbert 1998), and 4 Vesta and the howardite-eucrite-diogenite suite of achondrites (McSween et al. 2014).

There are also abundant cases of asteroids for which no plausible meteorite analogues have been identified. These mostly include a number of the low-albedo, spectrally

FIGURE 4 Galileo spacecraft image mosaic of the ~31 km long asteroid 243 Ida and its ~1.4 km diameter moon, Dactyl. False colors have been used to highlight differences in reflectivity. These may be related to differences in grain size and/or composition. SOURCE: WWW.BOULDER.SWRI.EDU/CLARK/IDA.GIFL

featureless asteroids. Such spectrally featureless asteroids are assigned to the C spectral class and include a number of taxonomic subgroups that differ on the basis of their overall spectral shapes. Some recently identified asteroids exhibit absorption features diagnostic of ferrous iron–bearing spinel, and although spinel is present in a number of primitive carbonaceous chondrite meteorites, the inferred overall mineralogy of these asteroids is unlike that of any known meteorite (Sunshine et al. 2008). Interestingly, meteorites can sometimes be made to match asteroids, at least spectrally, by subjecting them to laboratory treatments, such as heating (Hiroi et al. 1996), further suggesting that the terrestrial meteorite collection is an incomplete representation of asteroid diversity.

It is worth reiterating that the terrestrial meteorite collection is not representative of the asteroid belt (Burbine et al. 2002). There are undoubtedly numerous asteroids and even asteroid taxonomic classes for which we have no recognized meteorites. The most numerous meteorites in our collections, the ordinary chondrites, are plausibly linked to only a small subset of characterized asteroids. Their dominance in current fall statistics may be attributable to relatively recent breakups of a few favorably placed parent bodies, as proposed for the asteroid Gefion and the L chondrites (Nesvorný et al. 2009). Underrepresentation is further hampered by ongoing uncertainties about how the space environment can affect the appearance of asteroids.

SPACE WEATHERING

Our long-standing inability to find good optical spectral matches between the most common meteorite types (ordinary chondrites) and their presumed parent bodies (expected to reside within the traditional S taxonomic class), as well as the large spectral differences between lunar regolith and rocks have made us realize that the exposure of asteroidal surfaces to the space environment can dramatically change their optical properties. This would result in a surface that is not representative of the bulk asteroid, potentially hiding expected meteorite parent bodies from view. The plethora of processes that can occur at the asteroid–space interface are collectively termed "space weathering" and include devolatilization/desiccation, solar wind implantation, sputtering, radiation damage, micrometeorite impacts, and thermal cycling (Hapke 2001). These are in addition to processes that may operate in the interior of asteroids, such as heating and aqueous alteration, as well as other processes such as impact-induced seismic shaking, rotationally induced movements of material towards the equator, and tidal stresses during planetary encounters (Binzel et al. 2010).

How space weathering operates on asteroidal surfaces is an area of active research. It appears to work in different ways on different asteroids (Gaffey 2010). A number of tentative explanations have been advanced to account for differences in perceived asteroid space weathering. Recent results from the Dawn mission to Vesta indicate that this body exhibits a style of space weathering quite different from that seen on other airless bodies (Pieters et al. 2012). There are likely multiple factors that can affect the style of space weathering. These include:

Heliocentric distance. This is likely the most important control on space weathering as it determines the solar wind density, impactor velocity, and the spatial density of potential impactors (higher in the main asteroid belt than near the Earth's orbit).

Size. Larger asteroids will provide a bigger target for potential impactors and will attract or perturb nearby asteroids (gravitational focusing) and will have greater ability to retain regolith.

Surface composition. Different materials will have different susceptibilities to space weathering. For example, the production of nanophase iron, which is an important modifier of the optical properties of the lunar regolith, requires an Fe-bearing target.

Magnetic field. The presence of a remnant magnetic field, such as may be present on Vesta (Fu et al. 2012), can deflect the solar wind, leading to less space weathering by processes associated with the solar wind.

Orbital inclination. This may play a secondary role, determining the spatial density of potential impactors, such as dust lanes in the main asteroid belt.

Date since the last major resurfacing relative to the time required for weathering or reweathering. An asteroid's surface can be "reset" by a major resurfacing event such as a large impact or intense seismic shaking. If the space weathering timescale is as short as 10^6 years (Vernazza et al. 2009), then surfaces young enough to appear "fresh" or "unweathered" are understandably rare since large-scale impacts occur, on average, on timescales greater than 10^6 years.

Variations in the appearance of space weathering on different asteroids likely reflect differences in the relative contributions of the same set of processes (Gaffey 2010). As an example, micrometeorite impacts on the lunar surface occur with an average speed that is a factor of ~4 greater than in the main asteroid belt. This could effectively lead to more impact melting on the Moon than on asteroids, where average speeds are lower.

Asteroidal-type space weathering, even though it affects many spectral properties, does not affect some that can be used to determine properties like the pyroxene/olivine ratio and mafic silicate composition, properties that can be used to discriminate ordinary chondrites from primitive or fully differentiated achondrites. Our understanding of space weathering, at least for near-Earth asteroids, has improved with the return of a regolith sample from Itokawa (Tsuchiyama 2014). Many, if not most, of Itokawa's mineral grains examined to date show evidence of space weathering, most notably in the form of nanophase iron and iron sulfides in the outer rind. Given our understanding of how nanophase iron and iron sulfides affect reflectance spectra, the spectral mismatch between Itokawa and LL chondrites can be largely resolved.

Some aspects of space weathering that can impact our ability to forge meteorite–asteroid linkages are still not well understood. For example: Does space weathering preferentially concentrate or deplete specific phases? What is the effect of space weathering on the composition of organic molecules and water-bearing minerals and on the distribution of fine-grained opaque minerals? Can space weathering "sandblast" metallic surfaces or grains? To answer these questions, a combination of work on samples recovered from the uppermost surfaces of asteroids, laboratory studies, and theoretical modeling is required.

ASTEROIDS AND THE ORIGIN OF THE TERRESTRIAL PLANETS

Remnants of the building blocks of the terrestrial planets are likely still present in the asteroid belt. As knowledge of the compositional diversity of asteroids and the compositional structure of the asteroid belt and near-Earth asteroids improves, we will be able to better address questions such as: Which models of Solar System evolution (some of which include large radial excursions of the giant planets) are consistent with compositional zonations in the main asteroid belt (Michel 2014)? Could the main asteroid belt have provided all the building blocks for the formation of the terrestrial planets? Where are the remnant building blocks of the terrestrial planets currently located? How do asteroids from the main belt evolve such that they develop Earth-crossing orbits, and how similar or different are main belt and near-Earth asteroids? What processes have affected asteroids since their formation?

THE FUTURE

Our ability to establish meteorite–asteroid linkages continues to improve, and the strongest connections are made when multiple observational techniques and dynamical models are combined to develop an internally consistent picture. Significant advances will be made by targeting sample-return missions to representatives of key asteroid taxonomic classes, such as the C spectral group, for which our understanding of composition is tenuous. The OSIRIS-REx asteroid sample-return mission is an important step in this direction. It will acquire both a regolith sample, to better understand how space weathering affects dark asteroids, and a bulk sample, which will help us relate the uppermost regolith to its overall composition. Future observations of asteroids using multiple techniques will gradually improve our view of the origin, structure, and composition of these important building blocks of our Solar System.

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