Invited Review

Advances in determining asteroid chemistries and mineralogies

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Abstract

Considerable progress has been made in the last few years in determining asteroid chemistries and mineralogies. Dedicated spacecraft missions have allowed mineralogical predictions based on ground-based data to be confirmed or refuted. These missions include NEAR-Shoemaker to (253) Mathilde and (433) Eros, Hayabusa to (25143) Itokawa, and Dawn to (4) Vesta and (1) Ceres, the upcoming Hayabusa2 to (162173) Ryugu, and the upcoming OSIRIS-Rex to (101955) Bennu. All of these missions have or will make significant advances that could not have been made through just Earth-based observations. The recovery of Almahata Sitta from 2008 TC₃ was a rare opportunity to recover meteorite samples from a spectrally observed body from a naturally occurring event. This review will discuss the importance of spacecraft missions to asteroids.

1. Introduction

Technological advances have increased tremendously our knowledge in all scientific fields. Asteroid studies are no exception. Significant breakthroughs in determining asteroid compositions have occurred in the last fifteen years through dedicated spacecraft missions to these bodies. These spacecraft missions can observe asteroids in parts of the electromagnetic spectrum (e.g., gamma ray, X-ray) that give considerable insight on the surface compositions of these bodies; however, photons at these wavelengths cannot penetrate through the Earth's atmosphere. For the longest time, asteroid mineralogies could only be determined through the analysis of ground-based reflectance spectra in the visible and near-infrared (~ 0.4 to ~ 2.5 μm) (e.g., Gaffey et al., 1989). One disadvantage of using this wavelength region for mineralogical interpretations is that many types of meteoritic mineralogies do not have diagnostic spectral properties. Another disadvantage is that processes (e.g., space weathering) may be occurring on the surfaces of asteroids to alter their non-diagnostic spectral characteristics (e.g., spectral slope, band depth, which complicates determining their mineralogies.

A fundamental property of asteroids and meteorites that cannot be determined from Earth-based or Earth-orbiting telescopes but is vital for understanding the geologic history of a planetary body is their elemental compositions. Different meteorite groups have long been known to be easily distinguished on the basis of elemental abundances (e.g., Hutchison 2004). The geologic history of a planetary body can also be interpreted from its elemental composition (e.g., Nittler et al., 2004). Meteoritic elemental abundances can be routinely determined in Earth-based laboratories using a variety of widely-used techniques. However to determine these elemental abundances for a planetary body, a spacecraft must measure particles (e.g., x-ray photons, gamma ray photons, neutrons) created through the interaction of high-energy radiation (e.g., x-ray photons, cosmic rays) with elements in the asteroid regolith. These techniques were first used on missions to the Moon (e.g., Adler et al., 1972) and Mars (e.g., Mitrofanov et al., 2003) to characterize the geologic histories of these bodies.

Why is it so important to compositionally characterize asteroids? Asteroids are thought to be either the remaining building blocks of the terrestrial planets (e.g., Leinhardt and Stewart, 2012) or a byproduct of planet formation (e.g., Johnson et al., 2015) and understanding their mineralogies allow us to decipher the composition of the solar nebula in which they formed from. These bodies can also strike the Earth and any deflection strategy would need to incorporate the mineralogy of any threatening near-Earth asteroid (NEA). Manned space missions may want to mine asteroids for important resources (e.g., water, metallic iron) necessary for survival.

We now truly believe that we can determine an asteroid's composition (elemental and mineralogical) remotely using both reflectance spectra and elemental characterization. This confidence has come from these dedicated spacecraft missions, which have confirmed and refuted mineralogical interpretations made from Earth-based observations. Also, samples returned to Earth allow ground-based laboratory equipment to fully analyze these samples with extremely high precision. These measurements then allow for Earth-based mineralogical predictions to be tested. This review will discuss the importance of characterizing elemental

compositions, the strengths and limitations of visible and near-infrared spectroscopy, the questions that are being answered, and the dedicated spacecraft missions to asteroids that have been launched and will be launched in the near future.

2. Classifying meteorites

Elemental abundances have long been used to classify meteorites (e.g., Urey and Craig, 1953; Wasson and Kallemeyn, 1988; Weisberg et al., 2006). The wide range of different meteoritic mineralogies is reflected in their vastly different elemental abundances (Table 1).

Elemental abundances in meteorites give us a wide variety of information concerning the early history of our solar system. CI chondrites have an elemental composition that best matches the solar photosphere (e.g., Lodders, 2003), implying that these meteorites are the best analog for the bulk composition of the solar nebula. However due to their fragile nature that does not easily allow passage through the atmosphere, CI chondrites are relatively rare in our meteorite collections. Chondritic groups are generally thought to have compositions similar but not exactly like the precursors for the different achondritic (differentiated) meteorites (e.g., Keil, 1989; Ford et al., 2008). The relatively narrow differences in bulk elemental compositions among the chondritic groups (Table 1) are primarily due to enrichments or depletions in refractory and volatile elements (e.g., Brearley and Jones, 1998; Weisberg et al., 2006).

Geologic processes (e.g., melting, hydrothermal alteration) on meteorite parent bodies can significantly alter elemental abundances (e.g., Nittler et al., 2004). For example, as melting occurs on a parent body, the elemental composition of a material changes as partial melts of heavier minerals sink and lighter ones rise. Ultimately, a basaltic crust, olivine-rich mantle, and metallic iron core are commonly believed to form on bodies that fully differentiate (depending on the starting composition). These general trends are shown in Fig. 1. Chondritic meteorites have roughly similar Mg (wt%) and Fe (wt%) contents compared to chondrites with meteorites in a particular chondritic group falling in distinct regions of the plot. As melting occurs, these two elements segregate as the melt moves and different minerals form. Samples of different regions of a differentially or a partially-differentiated asteroid will then have vastly different compositions compared to the chondritic precursor, which can be seen in the spread in the average Mg/Si, Al/Si, and Fe/Si weight ratios for the achondritic groups in Table 1.

3. Classifying asteroids

In contrast, asteroids are classified according to their spectral properties, which are reflections of their surface mineralogy and chemistry. The hope is that bodies that have similar reflectance spectra also have similar mineralogies. The most commonly used taxonomies are the Bus and Binzel (2002b) system for visible spectra and the DeMeo et al. (2009) system (Fig. 2) for visible and near-infrared spectra.

A reflectance spectrum of an asteroid is the relative fraction of light reflected as a function of wavelength that is measured by a detector using a telescope. The most commonly used wavelength regions for analysis are in the visible and near-infrared since the Sun emits a considerable amount of radiation (peaking in the visible) in these wavelength regions and the Earth's atmosphere is also relatively transparent out to $\sim 2.5 \mu\text{m}$. Fortunately, many minerals found in meteorites also have characteristic absorption features between ~ 0.4 and $\sim 2.5 \mu\text{m}$ (e.g., Salisbury et al., 1975; Gaffey, 1976). Near-infrared observations are now relatively routine with the advent of the SpeX instrument on the IRTF (NASA Infrared Telescope Facility) on Mauna Kea, Hawaii (Rayner et al., 2003).

The actual source of photons (the Sun) cannot be directly measured during the observations. Therefore, the flux measured for the asteroid must be divided by the flux measured for a standard star (or the average of a series of standard stars). These standard stars should have spectral properties similar to those of the Sun (G2 spectral type) and should have been observed at a relatively similar airmass and time as the asteroid. This division hopefully removes the flux distribution of the source (the Sun) and the effects due to atmospheric absorptions.

The absorption bands in meteorite and asteroid spectra tend to be due to electronic and vibrational transitions. Crystal field electronic transitions are due to the absorption of photons by electrons in the partially-filled inner (3d) orbitals of transition metal ions (e.g., Burns 1993). Due to the different crystal structure and different compositions of different minerals, the d-levels split into different energy levels for different minerals causing absorptions to occur at different wavelengths. The most important transition metal in asteroid studies is Fe^{2+} since this ion is prevalent in minerals in meteorites. Since olivines and pyroxenes are commonly found in meteorites and almost always contain Fe^{2+} (except for pure enstatite), absorption features due to these minerals (Fig. 3) are very prevalent in asteroid spectra (Fig. 2). Olivine has three bands at ~ 0.9 , ~ 1.1 , and $\sim 1.25 \mu\text{m}$ that form an asymmetric $1 \mu\text{m}$ feature. Pyroxenes tend to have two symmetric bands at $\sim 0.9\text{--}1.0$ and $\sim 1.9\text{--}2.0 \mu\text{m}$. Since both olivine and pyroxenes are compositionally solid solutions with varying amounts of Fe and Mg (and Ca in the case of pyroxenes), the position and strengths of the absorption bands will primarily vary according to composition. The common metallic iron minerals (kamacite, taenite) do not contain Fe^{2+} and, therefore, do not have any crystal field absorption features. Charge transfer electronic absorptions are where an electron absorbs a photon and the electron transfers from one ion to another ion. One example is a $\sim 0.7 \mu\text{m}$ band, which has been attributed to an intervalence charge transfer ($\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$) (e.g., Vilas and Gaffey, 1989; Cloutis et al., 2011b; McAdam et al., 2015) in hydrated silicates.

Vibrational absorption bands are due to the absorption at fundamental frequencies, which causes a vibration in the molecule. Water (H_2O) and hydroxyl (OH) has a number of vibrations (e.g., Gaffey et al., 1989; Rivkin et al., 2002) that can result in a deep absorption band at $\sim 3 \mu\text{m}$, which is difficult to fully characterize due to atmospheric absorption bands.

Determining mineral abundances and mineral compositions from a reflectance spectrum is not trivial due to a number of factors. For mineral mixtures, the strengths of the absorption

bands for a mineral does not directly correspond to its abundance, many of the absorption bands are overlapping, the low temperatures of asteroids may alter absorption band positions (e.g., Moroz et al., 2000; Burbine et al., 2009; Reddy et al., 2012c; et al., 2013), and spectral properties may be altered by processes (usually called space weathering) that include impacts, solar wind particles and galactic cosmic rays (e.g., Bennett et al., 2013). A variety of techniques (e.g., radiative transfer modeling, modified Gaussian modeling, curve fitting, empirical formulas) (e.g., Sunshine and Pieters, 1993; Gaffey et al., 2002; Lawrence and Lucey, 2007; Dunn et al., 2010) have been developed to determine mineral abundances and mineral compositions from reflectance spectra. All of these methods have been calibrated or tested using minerals and meteorites of known compositions. However for the longest time, it was impossible to know well the mineralogy of an asteroid could be determined from Earth-based observations.

4. Fundamental questions

Before dedicated space missions, considerable progress had been made in determining asteroid mineralogies. The asteroid that scientists thought they understood best was (4) Vesta, the third largest body in the asteroid belt. Since the 1970s, Vesta was commonly thought to be the parent body of the HEDs (howardites, eucrites, and diogenites) due its spectral similarity (Fig. 4) with those meteorites in the visible (McCord et al., 1970) and near-infrared (Larson and Fink, 1975). Mineralogically, eucrites contain primarily anorthitic plagioclase and low-Ca pyroxene with augite exsolution lamellae while diogenites are predominately magnesian orthopyroxene. Howardites are approximately 50:50 mixtures of eucritic and diogenitic material and are the conclusive evidence that all three types of meteorites come from the same parent body. HEDs are derived from the crust of a differentiated parent body with many eucrites having mineralogies consistent with terrestrial basalts.

Dynamical issues (Wetherill, 1987) concerning fragments of Vesta reaching meteorite supply resonances were erased with the discovery (Binzel and Xu, 1993) of small (~10 km or smaller) objects (usually called Vestoids) with HED-like spectra in the Vesta family and between Vesta and the 3:1 and ν_6 meteorite-supplying resonances. Hubble spacecraft images of Vesta taken using four filters found Vesta to be spectrally and geologically diverse (Zellner et al., 1997; Binzel et al., 1997) and consistent with rotational spectra (Gaffey, 1997) taken from Earth. Evidence was pretty convincing to most researchers, except for a few researchers (e.g., Wasson, 1995; Wasson, 2013), that Vesta was the parent body of the HEDs.

But there was still considerable discussion (e.g., Chapman, 1996) whether the most common type of meteorites (ordinary chondrites) (~80% of all falls) were related to the most common type of observed asteroid (S-complex asteroids), which were previously referred to as S-types). Ordinary chondrites and most S-complex asteroids (previously referred to as S-types) have absorption features due to olivine and pyroxene (Fig. 2). However, spectral differences between ordinary chondrites and S-complex asteroids have long been known to exist (e.g., Chapman and Salisbury, 1973; Chapman, 1996). S-complex asteroids tended to have redder spectra (reflectances increasing with increasing wavelength) and weaker absorption bands (Fig.

5) than ordinary chondrites. Ordinary chondrites are primarily composed of olivine, pyroxene, and metallic iron (e.g., Weisberg et al., 2006; Krot et al., 2014). Ordinary chondrites are divided into three classes: H, L, and LL. Among the ordinary chondrites, H chondrites have the lowest Fe contents in their silicates and the highest metallic iron abundances, LL chondrites have the highest Fe contents in their silicates and the lowest metallic iron abundances, and L chondrites have intermediate compositions. H and L chondrites are the most common meteorites to fall to Earth (Table 1) whereas LL chondrites are much less common.

Lunar-style space weathering has long been invoked to explain the spectral differences between ordinary chondrites and S-complex bodies. However, there was still some resistance to this idea (Bell, 1995) since the process of “space weathering” was not fully understood at the time. Some researchers (e.g., Bell et al., 1989) believed that S-complex bodies were igneous in nature and that the red spectral slope was due to metallic iron. Using lunar samples as a guide (Pieters et al., 2000), the prevailing idea became that the production of microscopic iron grains by micrometeorite impacts was causing these spectral changes on asteroids. Sasaki et al. (2001) carried out analogue experiments to what may have been happening in space in the laboratory by irradiating olivine samples with a nano-second-pulse laser, which produced nanophase iron particles. The laser irradiation was to duplicate the effects of micrometeorite impacts. Sasaki et al. (2001) concluded that such nanophase iron could have been produced on asteroid surfaces by micrometeorite impacts that would redden a spectrum and darken the surface. Alteration by the solar wind (e.g., Loeffler et al., 2008; Brunetto, 2009; Bennett et al., 2013) has been later argued by Vernazza et al. (2009) to be the prime mechanism of space weathering since the timescale for space weathering seems to be relatively rapid ($\sim 10^6$ years). Only the very rare Q-types [e.g., (1862) Apollo] (Fig. 2), which tend to be found in the NEA population, have a reflectance spectrum similar to ordinary chondrites.

Analyses of telescopic data support the interpretation that some fraction of S-complex asteroids has mineralogies similar to ordinary chondrites. Using mineral mixtures, Cloutis et al. (1986) showed that the Band I center and Band Area Ratio (ratio of the area of Band II to Band I) could be used to estimate the mineralogy of an olivine-orthopyroxene assemblage. The Band I center moves to longer wavelengths and the Band Area Ratio moves to smaller values with increasing olivine abundances. The Gaffey et al. (1993) study of S-complex asteroids using Band I centers and Band Area Ratios found that had a fraction of S-asteroids [called S(IV)-types] had interpreted mineralogical similarities to ordinary chondrites. Analyses of space-weathered lunar samples and laboratory space-weathered ordinary chondrite samples by Gaffey (2010) have shown that diagnostic spectral band parameters (e.g., Band I and II centers, Band Area Ratios) are not affected by space weathering.

Binzel et al. (1996) found that there was a continuum of spectral properties between visible spectra of Q- and S-complex NEAs and S-complex main-belt asteroids. Since NEAs have smaller sizes than observable main-belt asteroids, this continuum implies an alteration process that is age dependent since NEAs have much shorter surface ages. Vernazza et al. (2008) using radiative transfer modeling found that most S-complex and Q-type NEAs had interpreted mineralogies similar to ordinary chondrites. They did find that most of these

modeled NEAs had interpreted mineralogies consist with LL chondrites, which was contrary to the fall statistics where H and L chondrites dominate.

Before 2000, the only spacecraft that had flown by an asteroid was Galileo. On its way to Jupiter, the spacecraft flew by (951) Gaspra in October of 1991 and (243) Ida in August of 1993. Galileo observed these asteroids with a camera (solid-state imager or SSI) that had an eight-position filter wheel (~ 0.4 to ~ 1.1 μm) and a near-infrared mapping spectrometer (NIMS) with a wavelength coverage of ~ 0.7 to ~ 5.2 μm . Galileo also discovered a satellite around Ida, which was named Dactyl.

Using Band I centers and Band Area Ratios, Granahan et al. (1994) and Granahan (2011) interpreted Galileo's visible and near-infrared data for Gaspra as indicating two different spectral units on the asteroid. Both spectral units had higher interpreted olivine abundances than ordinary chondrites. Using Band I centers and Band Area Ratios, Granahan et al. (1995) and Granahan (2002, 2013) found that Ida and Dactyl had interpreted mineralogies similar to LL chondrites.

Evidence for space weathering was also evident from analyses of Galileo spectra of Ida. Chapman (1996) showed that there was an alteration trend when comparing the visible spectra of "typical" Ida terrains, "fresh" craters, and ordinary chondrites. The spectra of "typical" Ida terrains were redder than "fresh" craters, which were redder than ordinary chondrites.

C-complex asteroids (previously referred to as C-types) (Fig. 2) historically have been linked (e.g., Johnson and Fanale, 1973) with carbonaceous chondrites due to both types of bodies having low visual albedos and a lack of prominent absorption features from ~ 0.4 to 2.5 μm . These bodies tend to have very strong absorption bands in the ~ 3 μm region. Burbine (1998) noted the spectral similarity between some C-complex bodies with ~ 0.7 μm absorption features [e.g., [13] Egeria, (19) Fortuna] and CM chondrites. The ~ 0.7 μm absorption feature is due to a charge transfer transition between Fe^{2+} and Fe^{3+} that is only found in CM chondrites.

5. NEAR-Shoemaker

In 1996, the first mission to specifically target an asteroid (Near Earth Asteroid Rendezvous or NEAR) was launched. NEAR-Shoemaker flew by C-complex asteroid (253) Mathilde in June of 1997 and orbited S-type asteroid (433) Eros for a year starting in 2000. It was the second Discovery mission, which attempted to do "faster, better, cheaper" planetary missions. The mission was later renamed NEAR-Shoemaker after planetary geologist Eugene Shoemaker (1928-1997).

NEAR-Shoemaker was pioneering for many reasons. It was the first mission whose primary goal was to just study an asteroid. It was the first spacecraft to orbit an asteroid (Eros), which was found to be an elongated body with a peanut-like shape (Fig. 6), and the first to fly by a C-complex body. It was the first mission to do geochemical analyses of an asteroid by detecting and analyzing X-rays and gamma rays emitted from the surface. It was also the first spacecraft to land on an asteroid. Instruments on NEAR-Shoemaker included a multi-spectral

imager (MSI), an infrared spectrometer (NIS), a laser rangefinder (NLR), an X-ray/gamma ray spectrometer (XGRS), a magnetometer (MAG), and a radio transponder.

Long before the encounter, Murchie and Pieters (1996) analyzed ground-based rotational spectra ($\sim 0.3\text{--}2.5\ \mu\text{m}$) of Eros and concluded that Eros had distinctive rotational spectral variations. They interpreted the spectral data as indicating Eros had both a pyroxene-rich and an olivine-rich hemisphere. McCoy et al. (2000) interpreted the presence of these two distinct mineralogies as possibly indicating that Eros may be a partially differentiated assemblage.

However, these distinct spectral variations were not apparent when NEAR-Shoemaker went into orbit around Eros in 2000. NEAR-Shoemaker observations showed Eros to be relatively spectrally homogeneous in the visible (Murchie et al., 2002) and near-infrared (Izenberg et al., 2003). From its average Band I center ($0.962\pm 0.006\ \mu\text{m}$) and Band Area Ratio (0.51 ± 0.02), Izenberg et al. (2003) found that the best mineralogical analog to Eros was the L chondrites. They also discovered that the brightest areas on Eros were found on steep crater walls. These areas also had bluer spectral slopes and deeper Band I absorption features relative to the rest of Eros. This result is consistent with the steep crater walls being “fresher” and less space-weathered than downslope areas. Gravity would be expected to expose new material on the steep crater walls as material continually “falls” to the crater floor.

The XGRS measured X-rays and gamma rays emitted off the surface to determine elemental ratios. The emitted X-rays are due to fluorescence, which is due to the absorption of x-rays or gamma rays by inner orbital electrons of atoms that causes these electrons to be expelled from these orbitals. Since every element has orbitals with characteristic energies, the energies of the emitted X-rays are characteristic of a particular element. The flux of emitted characteristic X-rays is related to the concentration of the element. Elemental weight ratios were determined instead of actual abundances since ratioing the calculated abundances removes the effect of many of the geometrical factors in the production and the scatter of X-rays. However, complicating the analysis was the fact that one X-ray spectrometer on NEAR-Shoemaker that was designed to measure the solar spectrum failed and the other was not sufficiently calibrated before launch to be directly used without a considerable amount of modeling (Lim and Nittler, 2009). The sampling depth for the measured X-rays is less than $100\ \mu\text{m}$.

While in orbit, the XGRS had no trouble detecting a statistically significant flux of X-rays from Eros above the background flux but was not able to detect a statistically significant flux of gamma rays. This high gamma ray background was due to the gamma ray spectrometer not being located on a boom (Evans et al., 2001), which would have reduced the background gamma ray signal from the spacecraft that is due to cosmic ray interactions. The Galactic Cosmic Ray Flux averaged over a solar cycle was used as the excitation source for the calculations of the elemental weight ratios (Evans et al., 2001).

Gamma rays from an asteroid (Evans et al., 2001) are emitted through the excitation of nuclei (e.g., O, Si, Fe) by galactic cosmic rays or solar particles or from the radioactive decay of a number of isotopes (e.g., ^{40}K , ^{232}Th , and ^{238}U). To produce gamma rays through inelastic scatter excitations, the galactic cosmic rays or solar particles must strike nuclei, which emit

neutrons that collide with other nuclei (Prettyman, 2007). These nuclei become excited through these reactions and emit gamma rays when they return to their normal energy state. For Eros, abundances of O, Mg, Si, K, and Fe were determined by gamma ray spectroscopy. The sampling depth for the measured gamma rays is tens of cm.

Almost all of the elemental weight ratios derived from the X-ray measurements for major (Mg/Si, Al/Si, Ca/Si, Fe/Si) (Trombka et al., 2000; Nittler et al., 2001; Lim and Nittler, 2009) and minor (Cr/Fe, Mn/Fe, Ni/Fe) (Foley et al., 2006) elements are consistent with Eros having an ordinary chondrite composition; however, a number of meteorite classes could not be ruled out (e.g., acapulcoites/lodranites). This overlap with ordinary chondrites is seen in Fig. 7. To directly compare NEAR-Shoemaker results to meteorites, bulk chemistries of gram-sized samples are necessary since elemental compositions were determined for relatively large areas of Eros' surface. Eugene Jarosewich (1926-2007) produced the largest bulk meteorite dataset using wet chemistry and these analyses (Jarosewich, 1990) were vital for comparing the bulk elemental asteroid data to meteorites.

The exception was the S/Si ratio (0.005 ± 0.008), which is depleted relative to ordinary chondrite values [average of ~ 0.12 from Nittler et al. (2004) database]. This depletion is attributed to space weathering, which could devolatilize troilite (FeS) on the asteroid surface. This explanation was backed up through experimental work (Loeffler et al., 2008) using the impact of ions to simulate the solar wind and laser irradiation to duplicate micrometeorite impacts.

The landing on Eros allowed the XGRS to detect a statistically significant number of gamma rays from Eros' surface. A recent reanalysis of the XGRS data (Peplowski et al., 2015) found that the measured elemental composition derived from the gamma ray observations was consistent with L and LL chondrites. Peplowski et al. (2015) determined a hydrogen concentration (1100^{+1600}_{-700}) that was consistent with hydrogen concentrations measured in L and LL chondrites falls. They argue that the absence of any measured depletion found for volatiles such as hydrogen and potassium for Eros indicates that the sulfur depletion is a surface effect, consistent with space weathering. Elements that were detected on Eros (Trombka et al., 2000; Nittler et al., 2001; Evans et al., 2001; Foley et al., 2006; Lim and Nittler, 2009; Peplowski et al., 2015) by the XGRS are listed in Table 2.

McCoy et al. (2001) analyzed all the available compositional data that was obtained for Eros by NEAR-Shoemaker in an attempt to find the best meteoritic match for the asteroid. These interpretations included the olivine-pyroxene mineralogy derived from the MSI and NIS and the elemental weight ratios and abundances derived from the XGRS. Using a Venn diagram (Fig. 8), they found that the best meteoritic analog for Eros was an ordinary chondrite or a primitive achondrite derived from an ordinary chondrite precursor that underwent limited partial melting.

The fly by of asteroid (253) Mathilde before the Eros encounter confirmed a low-albedo C-complex asteroid (Veveřka et al., 1999). The measured density of Mathilde ($1.3 \pm 0.3 \text{ g/cm}^3$)

was extremely low compared to meteorites (Consolmagno et al., 2008) and was consistent with a rubble pile with a considerable amount of porosity (~50%).

The NEAR-Shoemaker Mission demonstrated that the geochemistry of an asteroid could be determined reasonably well by a spacecraft. All available data indicate that Eros appears to have a surface mineralogy consistent with an ordinary chondrite assemblage (most likely an L or LL), but a more specific classification is not possible with certainty on the basis of the data on hand.

6. Hayabusa

The Japanese Hayabusa spacecraft originally called Mu Space Engineering Spacecraft C or MUSES-C), was the first mission to return a sample from an asteroid back to Earth. Hayabusa is Japanese for peregrine falcon. Hayabusa rendezvoused with S-complex asteroid (25143) Itokawa in the Fall of 2005. Images of Hayabusa showed (Fig. 9), in contrast to other observed asteroids, a body with a lack of craters but numerous boulders. A relatively smooth area on the surface is called Muses Sea in honor of the original spacecraft name.

Ground-based visible and near-infrared reflectance spectra (Binzel et al., 2001b; Abell et al., 2007) showed that Itokawa has a typical S-complex spectrum (Fig. 5) with absorption bands due to olivine and pyroxene and a reddened spectrum relative to ordinary chondrites. Using Modified Gaussian Modeling (MGM) to fit Itokawa's absorption bands, Binzel et al. (2001b) found that the fits are consistent with Itokawa having a surface mineralogy similar to LL chondrites. Using Band I and II centers and the Band Area Ratio, Abell et al. (2007) interpreted their data as indicating possibly an olivine-rich primitive achondrite, an atypical LL-chondrite, or a previously unsampled oxidized Fe-rich chondritic-like assemblage. They had interpreted Itokawa as having an olivine:pyroxene ratio of 75:25 (± 5) and a pyroxene composition of $\text{Wo}_{14\pm 5}\text{Fs}_{43\pm 5}$. This olivine to pyroxene ratio is slightly enriched relative to LL chondrites (Dunn et al., 2010) while the interpreted pyroxene composition is much more wollastonite- and ferrosilite-rich than those found in LL chondrites.

Scientific instruments on Hayabusa included a camera (Asteroid Multi-band Imaging Camera or AMICA), a near-infrared spectrometer (Near-Infrared Spectrometer or NIRS), laser altimeter (Light Detection and Ranging altimeter or LIDAR)), and an X-ray spectrometer (X-ray fluorescence spectrometer or XRS). AMICA took images in four filters (0.430 μm , 0.550 μm , 0.700 μm , 0.950 μm). NIRS spectral coverage was only from 0.75 to 2.1 μm so it did not cover the full wavelength region of pyroxenes. The reflectance spectra that were obtained (Abe et al., 2006) are consistent with LL chondrites, but the X-ray results (Okada et al., 2006) were later retracted. A minilander (MICRO/Nano Experimental Robot Vehicle for Asteroid or MINERVA) was launched from Hayabusa; however, it missed its target. MINERVA would have hopped on the surface of Itokawa, taken images, and measured surface temperatures.

Two separate "landings" were performed on the smooth Muses Sea region of Itokawa to retrieve samples (Yano et al., 2006). These "landings" were designed to be quick touches on the

surface where Hayabusa's sampling horn makes a quick contact with the asteroid and a bullet is fired into the surface to eject particles into the sampling horn. However during these two encounters, technical issues caused the bullets not be fired into the surface. But there was hope that simple contact with the surface would eject material into the sampling container, which contained two compartments.

These hopes were confirmed after Hayabusa's re-entry capsule landed in the Australian desert in June, 2010. The sampling container contained thousands of particles but less than a milligram of material. Analyses of the grains showed that they had mineralogies consistent with equilibrated LL (LL4-LL6) chondrites (Nakamura et al., 2011; Mikouchi et al., 2014). Oxygen isotopic ratios of these grains (Yurimoto et al., 2011) are also similar to those of LL4-LL6 chondrites. Noble gas isotopic measurements (Nagao et al., 2011) showed large amounts of solar helium (^4He), neon (^{20}Ne), and argon (^{36}Ar), indicating that these grains resided in the regolith on the very surface of Itokawa where they were exposed to the solar wind.

Using a scanning transmission electron microscope (STEM), Noguchi et al. (2011) were able to identify a thin layer of iron particles on grain surfaces. Coupled with the reddening of Itokawa's spectrum relative to LL chondrites, this result proved that space weathering does occur on asteroid surfaces. Thompson et al. (2014) confirmed these results by also identifying nanophase iron particles on Itokawa grains.

Hayabusa was able to definitively determine that Itokawa had an LL chondrite composition confirming the ground-based prediction of Binzel et al. (2001). Hayabusa also confirmed that space weathering occurs on S-complex asteroids. These confirmations were only possible with returned samples that could be analyzed in a laboratory.

7. Dawn

The Dawn mission was the first spacecraft to orbit two main-belt asteroids [(4) Vesta and (1) Ceres]. It was also the first to visit an intact differentiated asteroid, an original planetesimal from the beginning of the solar system and not the fragment of such a body. Dawn was also the first spacecraft to visit a Dwarf Planet. Dawn orbited Vesta from July 2011 to September 2012 and started orbiting Ceres from March 2015.

Instruments on Dawn included a framing camera (FC), visual and infrared spectrometer (VIR), and gamma ray and neutron detector (GRaND). The FC covers seven wavelengths from 0.438 to 0.961 μm while VIR measured reflectance spectra from 0.25 to 5.1 μm . Dawn was the first mission to an asteroid to have a neutron detector, which is used to determine hydrogen abundances and, therefore, the water content.

Images of Vesta (Fig. 10) revealed a heavily cratered Northern Hemisphere and smoother Southern hemisphere. Two overlapping large craters are present at its South Pole with the 500-km wide Rheasilvia crater overlying the 400-km wide Veneneia crater. Diogenite regions are more abundant in the Southern Hemisphere (e.g., Reddy et al., 2012b; Thangjam et al., 2013),

which is consistent with deeper excavation in the Southern Hemisphere due to these large craters. Numerous troughs are also present on Vesta's equator.

Spectral reflectance measurements of Vesta are consistent with HED meteorites with some areas being more eucritic and some more diogenitic (e.g., De Sanctis et al., 2012a, 2013; Reddy et al., 2012b; Thangjam et al., 2013; Ammannito et al., 2013; Zambon et al., 2014). Vesta also has a number of terrains that are enriched in low albedo material (Reddy et al., 2012a; McCord et al., 2012). These dark areas are generally associated with impact craters and are spectrally similar to carbonaceous chondrites. They are believed to be due to an influx of carbonaceous material striking the surface. This was not a surprising result since HEDs are known to contain CM2-like and CR2-like inclusions (e.g., Buchanan et al., 1993; Zolensky et al., 1996). These inclusions contain abundant hydrated silicates. Dark material on Vesta also was found to have a feature at $\sim 0.7 \mu\text{m}$ (Nathues et al., 2014), which is consistent with CM chondrite material (Cloutis et al., 2011b).

One surprising result for Vesta is the relatively rare occurrence of olivine-rich ($> 40\%$ wt%) areas on the surface on the basis of the analysis of its FC data (e.g., Ammannito et al., 2013; Thangjam et al., 2014; Nathues et al., 2015). A number of filter reflectance ratios such as the band tilt ($R_{0.92\mu\text{m}} / R_{0.96\mu\text{m}}$), mid ratio $[(R_{0.75\mu\text{m}} / R_{0.83\mu\text{m}}) / (R_{0.83\mu\text{m}} / R_{0.92\mu\text{m}})]$, and mid curvature $[(R_{0.75\mu\text{m}} + R_{0.92\mu\text{m}}) / R_{0.83\mu\text{m}}]$, which are based primarily on the work of Isaacson and Pieters (2009) in analyzing lunar spectra, have been used to identify olivine-rich regions (Thangjam et al., 2013, 2014). [R_x is the reflectance at a particular wavelength (x)]. Differentiation of an asteroid is thought to produce a basaltic crust, an olivine-dominated mantle, and a metallic iron core. Large craters are present on the surface, which should have broken through the assumed thickness of the basaltic crust and exposed the olivine-rich mantle. It is possible that the crust is relatively thick on Vesta or an olivine-rich mantle did not form on Vesta (Nathues et al., 2015; Le Corre et al., 2015). Nathues et al. (2015) and Le Corre et al. (2015) argue that most of the olivine on Vesta's surface is endogenic and due to an influx of olivine-rich material striking the surface.

Reddy et al. (2013) discussed the accuracy of compositional interpretations for Vesta's surface based on ground-based and Hubble observations. Ground-based rotational spectra (Gaffey, 1997; Reddy et al., 2010) and Hubble Space telescope observations (Thomas et al., 1997) previously had noted deeper band depths for the Southern Hemisphere, which is consistent with the Dawn results. A region on the equator with a lower Band Area Ratio that was identified by Gaffey (1997) as being olivine-rich is now interpreted as being due to impact melt in the ejecta blanket around the Oppia crater (Le Corre et al., 2013).

Global Fe/O (0.30 ± 0.04) and Si/O (0.56 ± 0.06) weight ratios for Vesta derived from gamma ray measurements (Prettyman et al., 2012) are consistent with HEDs. (The Prettyman et al. (2012) gives these values as mass ratios, which are equivalent to weight ratios.) The Fe/Si weight ratio is 0.54 ± 0.09 . These values are also consistent with some angrites, ureilites, and the anomalous Shallowater aubrite; however, none of these meteorites have reflectance spectra similar to Vesta. Iron abundances also vary on Vesta's surface (Yamashita et al., 2013). Measurements of the high-energy gamma ray flux from smaller areas on Vesta's surface are also

consistent with HEDs (Peplowski et al., 2013) and so is the calculated K/Th weight ratio (900 ± 400) (Prettyman et al., 2015). Elements measured on Vesta by Dawn are listed in Table 2.

The neutron detector measures thermal (energies less than 0.1 eV), epithermal (0.1 eV-0.7 MeV), and fast neutrons (>0.7 MeV) from an asteroid's surface (e.g., Prettyman et al., 2011). As cosmic rays (primarily protons) bombard Vesta's surface, they collide with atoms and dislodge neutrons from their nuclei. These fast-moving neutrons can then collide with other nuclei and lose energy. The lighter the nuclei they strike, the more energy the neutron loses. Since hydrogen has the lowest atomic mass of any element, abundant hydrogen in the subsurface will significantly "slow" down the neutrons. The relative abundances of thermal, epithermal, and fast neutrons will be both a function of the amount of hydrogen and the average atomic mass of the elements in the surface. The hydrogen is assumed to be a constituent of H_2O or $-\text{OH}$. Water contents as high as 400 ppm were calculated for Vesta's surface (Lawrence et al., 2013). This result is consistent with dark carbonaceous chondritic material on the surface. This result also confirmed the Hasegawa et al. (2003) detection of a weak ($\sim 1\%$) $3\text{ }\mu\text{m}$ feature for Vesta, which indicated OH and/or H_2O -bearing minerals on its surface. Dawn also observed a $2.8\text{ }\mu\text{m}$ absorption due to OH on Vesta's surface (De Sanctis et al., 2012b). Curvilinear features on the walls of young craters have been proposed (Scully et al., 2015) to be due to the impact release of water from deeply buried ice deposits that are too deep to be detected by GRAND; however, there is supporting evidence that such ice deposits exist on Vesta. Analyses of the fast neutron data (Lawrence et al., 2013) are also consistent with an HED-like mineralogy on Vesta's surface.

Dawn confirmed that Vesta has an HED-like surface composition. Dawn also confirmed that impacts of carbonaceous chondrite projectiles were common and left debris of that composition on the surface. Most HEDs appear to have originated from Vesta and/or the Vestoids. However, a number of eucrite-like meteorites (Yamaguchi et al., 2002; Gounelle et al., 2009; Scott et al., 2009; Bland et al., 2009) have also been discovered with oxygen isotopic compositions distinct from "typical" HEDs, implying more than one body formed in the asteroid belt with a basaltic crust. One such asteroid is (1459) Magnya, which has a V-type spectrum (Lazzaro et al., 2000; Hardersen et al., 2004) and orbits the Sun with a semi-major axis of 3.14 AU. (Vesta is located at a semi-major axis of 2.36 AU.) Dynamically modeling shows that it is extremely difficult to derive Magnya from Vesta (Michtchenko et al., 2002). A number of other V-types bodies have also been identified in the middle and outer main-belt (e.g., Roig and Gil-Hutton, 2006).

Dawn is currently orbiting the dwarf planet (1) Ceres in 2015. The exact composition of Ceres has been debated for approximately 40 years (e.g., Johnson et al., 1975; Chapman et al., 1975; Rivkin et al., 2011) due to difficulties in finding meteoritic spectral matches in the visible and near-infrared. Ceres has long been known to have a $3\text{ }\mu\text{m}$ absorption band (Lebofsky, 1978), indicating the occurrence of hydrated materials on its surface. But the structure of Ceres's $3\text{ }\mu\text{m}$ absorption band has not been found to be a very good "match" for any particular carbonaceous group. Higher resolution spectra in the $3\text{ }\mu\text{m}$ region (Milliken and Rivkin, 2009; Takir et al., 2015) has been interpreted as indicating a mineralogy of hydroxide brucite, magnesium carbonates, and serpentines, which is unlike any known meteorite assemblage. However, Beck

et al. (2015) argues that the absence of a corresponding brucite band at $\sim 2.47 \mu\text{m}$ indicates that this feature on Ceres is not due to brucite. Water vapor has recently been identified (Küppers et al., 2014) around Ceres, apparently indicating water ice beneath its surface. Bright spots have been observed on the surface of Ceres could possibly be due to water ice (Reddy et al., 2015).

8. Almahata Sitta

One test of how well we can determine asteroid mineralogies unexpectedly occurred when the asteroid 2008 TC₃ collided with the Earth's atmosphere in October 2008 and fragments rained down over the Sudan (Jenniskens et al., 2009, 2010). This object was discovered twenty hours before impact. Before impact, a visible spectrum was obtained of the body. Spectrally this object had a very weak UV feature and a blue spectral slope in the visible. The visible spectrum was classified as an F-type, which is a class from the Tholen (1984) taxonomic system. More recent taxonomies (e.g., Bus and Binzel, 2002b) would classify this body as a B-type (Fig. 2). Prior to this event, this spectral type had been typically linked with thermally altered carbonaceous chondrite material (e.g., Bell et al., 1989; Hiroi et al., 1993).

Because the location of the atmospheric impact over the Sudan was known, an expedition commenced to recover fragments. Approximately 4 kg of material was recovered. Most of the recovered meteorites (called Almahata Sitta) were found to be polymict ureilites (Zolensky et al., 2010; Bischoff et al., 2010). Ureilites are composed of olivine and pyroxene (pigeonite, augite, and/or orthopyroxene) with a high concentration of carbon (e.g., Zolensky et al., 2010). Cloutis and Hudon (2004) previously had stated that ureilites were most similar spectrally to C-complex asteroids. Ureilites have spectra similar to carbonaceous chondrites with weak absorption bands and flat to blue spectral slopes (Cloutis and Hudon, 2004; Cloutis et al., 2010).

Measurements of the oxygen isotopic compositions of the fragments (Rumble et al., 2010) were also consistent with ureilites. However, the strewn field also contained a number of fresh fragments of ordinary, enstatite, and R chondritic material (Bischoff et al., 2010; Shaddad et al., 2010; Goodrich et al., 2015). These fragments are also believed to have been part of 2008 TC₃ since they were relatively unweathered and a few of them had detectable short-lived cosmogenic isotopes (Bischoff et al., 2010), implying they fell recently. Also, two of these samples had cosmic ray exposure ages and light noble gas concentrations similar to the Almahata Sitta ureilite fragments (Welten et al., 2011). One analyzed chondrite also had amino acid compositions similar to one of the ureilites (Burton et al., 2011). Goodrich et al. (2015) estimated that 2008 TC₃ contained only a few percent non-ureilitic material.

The presence of a ureilite mineralogy for a C-complex asteroid is evidence that not all C-complex bodies have carbonaceous chondritic mineralogies. This result should also give caution to interpreting any asteroid spectrum that does not have distinctive spectral features. Impact melt could also cause a body with mafic absorption bands to spectrally appear like a C-complex body (e.g., Reddy et al., 2014). Also, asteroids may incorporate a number of different meteoritic mineralogies that could not have all formed on the same parent body. Also, the discovery of 2008 TC₃ before impact, the ability to obtain a reflectance spectrum with short notice, and the

recovery of its fragments shows the importance of coordinating detection surveys with spectral studies and recovery operations.

9. Upcoming asteroid missions

Two upcoming missions will orbit two NEAs and ultimately return samples back to Earth. Hayabusa2 and the Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) will both visit C-complex NEAs. Hayabusa2 will encounter asteroid (162173) Ryugu while OSIRIS-Rex will rendezvous with asteroid (101955) Bennu. Both asteroids are expected to be carbonaceous chondritic bodies, as judged from their spectral characteristics (Fig. 11).

Hayabusa2 was launched at the end of November 2014 and is expected to reach its target in June 2018. It will leave Ryugu in December 2019 and return to Earth in December 2020. Instruments on Hayabusa2 include a laser altimeter (LIDAR), a multi-band telescopic camera (ONC-T), wide-angle cameras (ONC-W1 and -W2), a near-infrared spectrometer (NIRS3), a thermal infrared imager (TIR), a small carry-on impactor (SCI), a deployable camera (DCAM3), and a sampler (SMP) (Tachibana et al., 2014). NIRS3 will obtain spectra in the 1.8 to 3.2 μm wavelength region, and will fully cover the 3 μm band due to H_2O and OH. This spectral region is much larger than the wavelength range covered by the original Hayabusa spectrometer.

A lander (MASCOT) and three small rovers (MINERVA-II-1A, -1B, and -2) will also be part of the mission package (Tachibana et al., 2014). MASCOT has a multi-band wide-angle camera (CAM), a six-band thermal radiometer (MARA), a three-axis fluxgate magnetometer (MAG), and a hyperspectral microscope (MicrOmega). MicrOmega will obtain images of relatively small areas (a few mm^2) of the surface with a spectral coverage of ~ 0.9 to ~ 3.5 μm . MASCOT will hopefully function for at least 15 hours.

The Hayabusa2 sampler system is similar to the Hayabusa sampler (Tachibana et al., 2014), which was designed to fire projectiles into the surface. The plan is to retrieve at least 100 mg of material. A backup sampling method was also designed for the sampler so that it has teeth (like a comb) to dig into the soil during touchdown and ensure material is picked up. The sample catcher will then be placed into the sample container, which is located in the re-entry capsule that will return the sample to Earth.

Rotational visible spectra (Binzel et al., 2001a; Vilas, 2008; Moskovitz et al., 2013) of asteroid Ryugu and its albedo ($\sim 5\%$) (Ishiguro et al., 2014) are consistent with C-complex asteroids. Binzel et al. (2001a) classified the asteroid as Cg, which is a C-complex asteroid with a strong UV feature (Fig. 11) (Bus and Binzel, 2002b). Vilas (2008) identified Ryugu as having a spectrum consistent with either a Cg- or Cgh-type. Vilas (2008) noted a possible feature between 0.6 and 0.7 μm due to a charge transfer absorption between Fe^{2+} and Fe^{3+} that may indicate hydrated silicates. This feature is not present in any of the other visible reflectance spectra (Binzel et al., 2001; Moskovitz et al., 2013) and could possibly indicate that the surface has a heterogeneous distribution of hydrated silicates. Moskovitz et al. (2013) classified Ryugu

as a C-type from its visible and near-infrared spectrum.

OSIRIS-REx will be launched in September 2016, reach asteroid Bennu in 2018, orbit it for a year and a half, briefly touch down on the surface, and then eject a sample return capsule (SRC) that will return to Earth in 2023 (e.g., Lauretta et al., 2015). Instruments on the spacecraft include a laser altimeter (OLA), camera suite (OCAMS), thermal emission spectrometer (OTES), visible and infrared spectrometer (OVIRS), and a regolith X-ray imaging spectrometer (REXIS). The touch-and-go sample acquisition mechanism (TAGSAM) is a robotic arm with an attached sampler head. When TAGSAM touches Bennu, nitrogen gas will be released, which will cause regolith to be directed into a collector. As a backup, contact pads on the sampler head will also trap small particles. Up to three attempts will be made. The sampler head will then be placed in the SRC. The goal is to collect at least 60 grams of regolith.

Bennu is classified as a B-type asteroid (e.g., Clark et al., 2011; Binzel et al., 2015) due to its blue spectral slope in the visible and near-infrared (Fig. 11). This object also has a low visual albedo of 5% (Emery et al., 2014). Clark et al. (2011) found that the best spectral match to Bennu was CI and/or CM chondrites. The calculated bulk density of Bennu ($1260 \pm 70 \text{ kg/m}^3$) (Chesley et al., 2014) is also consistent with a carbonaceous chondritic rubble pile assemblage.

Samples from both of these asteroids will provide considerable insight on the mineralogies of C-complex asteroids. Predictions have been made on the mineralogies of the body, which will either be confirmed or refuted by the returned samples. One body (Ryugu) may have undergone some hydration, whereas Bennu may have a mineralogy similar to the most primitive meteorites. It will also be quite intriguing to find out if these two asteroids have mineralogies consistent with known carbonaceous chondrites.

10. Conclusions

Considerable progress has been made in confirming predicted asteroid mineralogies through dedicated space missions. Studying less than a milligram of returned Itokawa material by Hayabusa was able to conclusively prove that this asteroid is an LL chondrite and that space weathering occurs on asteroid surfaces. Through a relatively “lucky” set of circumstances, ureilites are now known to be found among C-complex bodies. Geochemical measurements indicate that Eros has an ordinary chondrite-like surface mineralogy and that Vesta, as expected, has an HED-like surface mineralogy. Two more sample return missions (Hayabusa2 and OSIRIS-Rex) will be flying in the next two years to answer questions on two C-complex asteroids and should prove or refute their postulated linkages with carbonaceous chondrites.

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Figures

- Fig. 1. Mg (wt%) versus Fe (wt%) for a number of whole rock analyses of chondritic and achondritic meteorites from Nittler et al. (2004). General melting trends are plotted. This figure is based on a plot in Nittler et al. (2004).
- Fig. 2. The spectral properties of the DeMeo et al. (2009) asteroid classes. The wavelength region is $\sim 0.4\text{--}2.5\ \mu\text{m}$. Plot made available by F. E. DeMeo.
- Fig. 3. Plot of the reflectance spectra of olivine (Clark et al., 2007) and low-Ca pyroxene (hypersthene) (Clark et al., 2007). Spectra are normalized to unity at $0.55\ \mu\text{m}$ and then offset in reflectance. Band I and Band II are indicated in the figure. Tangent lines between reflectance maxima that are used to determine the band areas for the Band Area Ratio are also shown.
- Fig. 4. Plot of the reflectance spectra of V-type (4) Vesta (squares) (Bus and Binzel, 2002a) and howardite EET 87503 (line) (particle size $< 25\ \mu\text{m}$) (Hiroi et al., 1994). Spectra are normalized to unity at $0.55\ \mu\text{m}$. Error bars are 1σ . Even though it's a main-belt asteroid, the near-infrared Vesta spectrum was taken as part of the the MIT-Hawaii-IRTF Joint Campaign for NEO Spectral Reconnaissance (e.g., Binzel et al., 2006). Strong pyroxene bands are apparent.
- Fig. 5. Plot of the reflectance spectra of S-type (25143) Itokawa (Hayabusa sample return target) (squares) (Binzel et al., 2001b) and LL4 chondrite Greenwell Springs (line) (particle size $< 150\ \mu\text{m}$). Error bars are 1σ . The near-infrared Itokawa spectrum was taken as part of the the MIT-Hawaii-IRTF Joint Campaign for NEO Spectral Reconnaissance (e.g., Binzel et al., 2006). Strong pyroxene bands are apparent. Bands due to olivine and pyroxene are apparent.
- Fig. 6. This image of (433) Eros is a mosaic of four images obtained by NEAR-Shoemaker immediately after the spacecraft's insertion into orbit. Image credit: NASA.
- Fig. 7. Plot of calculated average Mg/Si versus average Al/Si and average Fe/Si ratios derived from X-ray analyses of (433) Eros (dark circle) (Lim and Nittler, 2009) versus whole rock meteorite data (Nittler et al., 2004). Error bars are 1σ .
- Fig. 8. Venn diagram of meteorite linkages with (433) Eros with different meteorite groups (McCoy et al., 2001). This figure is based on a plot in McCoy et al. (2001).
- Fig. 9. Image of (25143) Itokawa. On the surface of Itokawa, there is a lack of craters but it does have a large number of boulders. Courtesy of JAXA-ISAS.

Fig. 10. This image of (4) Vesta is a mosaic of images taken by NASA's Dawn spacecraft. The surface is heavily cratered. The South Pole is at the bottom of the image. Image credits: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.

Fig. 11. Plot of the reflectance spectra of (162173) Ryugu (Hayabusa2 sample return target) (Binzel et al., 2001a) and (101955) Bennu (OSIRIS-Rex sample return target) (Clark et al., 2011). Error bars are 1σ . The near-infrared Ryugu spectrum was taken as part of the the MIT-Hawaii-IRTF Joint Campaign for NEO Spectral Reconnaissance (e.g., Binzel et al., 2006). The Ryugu spectrum has a very low signal to noise compared to the Bennu spectrum. The Ryugu spectrum also has a number of residual atmospheric absorption bands.

Table 1. Major minerals and bulk elemental ratios of chondrites and achondrites. The fall percentages are from Burbine (2014). Mineral compositions found in the meteorites are from Brearley and Jones (1998), Mittlefehldt et al. (1998), and Cloutis et al. (2011a, 2011b, 2012a, 2012b, 2012c, 2012d, 2012e). Average Mg/Si, Al/Si, and Fe/Si elemental weight ratios are from whole rock analyses used by Nittler et al. (2004).

Type	Fall Percentage	Abundant Minerals	Mg/Si	Al/Si	Fe/Si
<u>Chondrites</u>					
L	36.7	olivine, low-Ca pyroxene, FeNi	0.83	0.07	1.21
H	33.8	olivine, low-Ca pyroxene, FeNi	0.85	0.07	1.65
LL	8.1	olivine, low-Ca pyroxene, FeNi	0.83	0.07	1.09
CM	1.5	hydrated silicates	0.90	0.10	1.63
L/LL	1.1	olivine, low-Ca pyroxene, FeNi	0.80	0.06	1.05
EH	0.9	enstatite, FeNi	0.67	0.07	1.91
EL	0.8	enstatite, FeNi	0.71	0.05	1.32
CV	0.7	olivine, low-Ca pyroxene	0.94	0.11	1.48
CO	0.6	olivine, low-Ca pyroxene	0.91	0.10	1.59
CI	0.5	hydrated silicates, magnetite	0.88	0.09	1.75
CR	0.3	hydrated silicates, FeNi, olivine	0.94	0.08	1.75
H/L	0.3	olivine, low-Ca pyroxene, FeNi	-	-	-
CK	0.2	olivine, plagioclase, low-Ca pyroxene	0.95	0.10	1.48
CB	0.1	FeNi, olivine	0.75	0.06	1.51
K	0.1	low-Ca pyroxene, olivine	-	-	-
R	0.1	olivine, low-Ca pyroxene	0.83	0.06	1.49
CH	all finds	FeNi, hydrated silicates, olivine	-	-	-
<u>Achondrites</u>					
Iron ¹	4.7	FeNi	-	-	-
Eucrite	3.3	pigeonite, plagioclase	0.21	0.29	0.63
Howardite	1.5	pigeonite, plagioclase, low-Ca pyroxene	0.41	0.18	0.58
Diogenite	0.1	low-Ca pyroxene	0.64	0.03	0.54
Aubrite	0.9	enstatite	0.85	0.02	0.07
Mesosiderite	0.7	low-Ca pyroxene, FeNi, plagioclase	0.39	0.22	4.59
Ureilite	0.6	olivine, low-Ca pyroxene, high-Ca pyroxene	1.20	0.02	0.73
Pallasite	0.4	FeNi, olivine	1.49	0.00	6.43
Acapulcoite/Lodranite	0.2	olivine, low-Ca pyroxene, FeNi	0.99	0.04	1.39
Angrite	0.1	Al-Ti diopside, anorthite, olivine	0.35	0.31	0.78
Winonaite	0.1	olivine, low-Ca pyroxene, FeNi	0.83	0.06	1.42
Brachinite	all finds	olivine, augite	0.97	0.04	1.26

¹The Fe/Si for iron meteorites is extremely high.

Table 2. Elements that have been detected on asteroids by spacecrafts. All ratios are element weight ratios. Results from Hayabusa are not included since the Okada et al. (2006) paper was later retracted. Results for Ceres from Dawn have not been published yet.

Element	Asteroid	Detection Method	Value	Reference
H	Eros	gamma rays	1100^{+1600}_{-700} ppm	Peplowski et al. (2015)
H	Vesta	neutrons	$\sim 180\text{-}800$ $\mu\text{g/g}$	Prettyman et al. (2012)
O	Eros	gamma rays	$\text{Mg/O}=0.36\pm 0.14$	Peplowski et al. (2015)
O	Vesta	gamma rays	$\text{Fe/O}=0.30\pm 0.04$	Prettyman et al. (2012)
Mg	Eros	X-rays	$\text{Mg/Si}=0.753^{+0.078}_{-0.055}$	Lim and Nittler (2009)
Mg	Eros	gamma rays	$\text{Mg/Si}=0.84\pm 0.27$	Peplowski et al. (2015)
Al	Eros	X-rays	$\text{Al/Si}=0.069\pm 0.055$	Lim and Nittler (2009)
Si	Eros	X-rays	$\text{Mg/Si}=0.753^{+0.078}_{-0.055}$	Lim and Nittler (2009)
Si	Eros	gamma rays	$\text{Si/O}=0.43\pm 0.17$	Peplowski et al. (2015)
Si	Vesta	gamma rays	$\text{Si/O}=0.56\pm 0.06$	Prettyman et al. (2012)
S	Eros	X-rays	$\text{S/Si}=0.005\pm 0.008$	Lim and Nittler (2009)
K	Eros	gamma rays	~ 700 ppm	Evans et al. (2001)
K	Vesta	gamma rays	595 ± 35 $\mu\text{g/g}$	Prettyman et al. (2015)
Ca	Eros	X-rays	$\text{Ca/Si}=0.060^{+0.023}_{-0.024}$	Lim and Nittler (2009)
Cr	Eros	X-rays	$\text{Cr/Fe}=0.022\pm 0.006$	Foley et al. (2006)
Mn	Eros	X-rays	$\text{Mn/Fe}\leq 0.017$	Foley et al. (2006)
Fe	Eros	X-rays	$\text{Fe/Si}=1.678^{+0.338}_{-0.320}$	Lim and Nittler (2009)
Fe	Eros	gamma rays	$\text{Fe/Si}=1.19\pm 0.30$	Peplowski et al. (2015)
Fe	Vesta	gamma rays	$\text{Fe/Si}=0.54\pm 0.09$	Prettyman et al. (2012)
Ni	Eros	X-rays	$\text{Ni/Fe}=0.11\pm 0.005$	Foley et al. (2006)
Th	Vesta	X-rays	657 ± 59 ng/g	Prettyman et al. (2015)

Figure 1

Figure 2

S-complex

C-complex

X-complex

End Members

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

XGRS

MSI/NIS

HED

Mesosiderites

Angrites

Pallasites

Aubrites

EH

EL

CI

CM

CV

Figure 9

Figure 10

Figure 11