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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 TC_3 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.

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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 ele-

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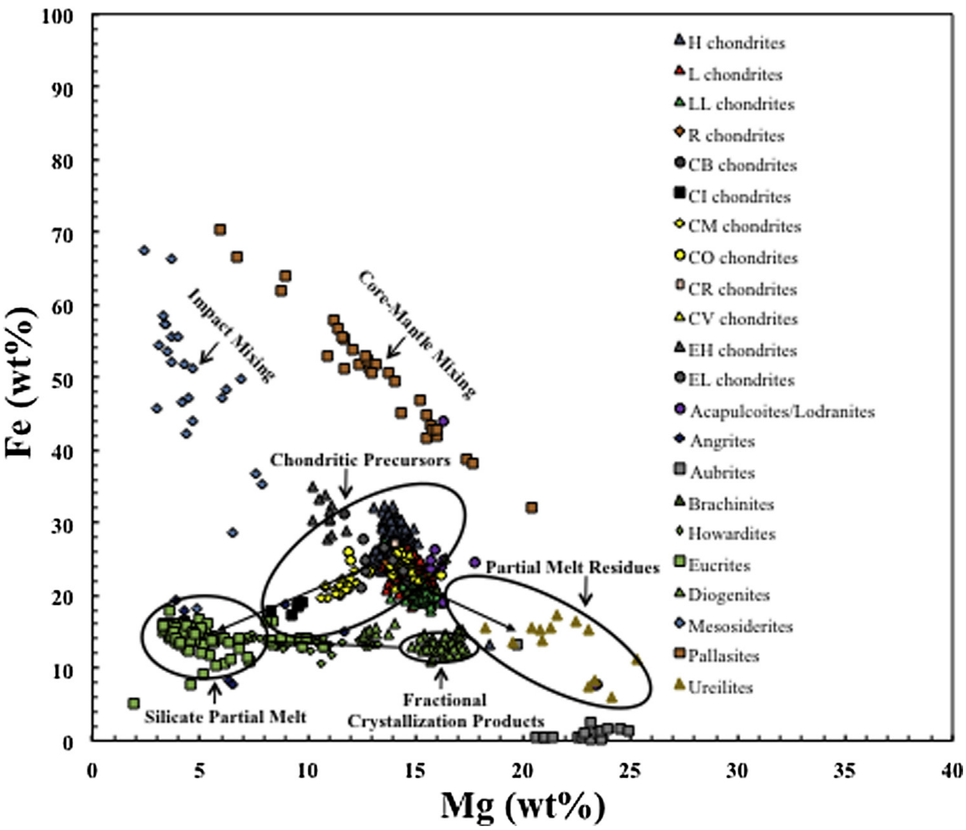

Fig. 1. Mg (wt%) versus Fe (wt%) for a number of whole rock analyses of chondritic and achondritic meteorites from Nittler et al. (2004). General melting trends are plotted. This figure is based on a plot in Nittler et al. (2004).

mental 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