Part I

REMOTE OBSERVATIONS AND EXPLORATION OF MAIN BELT ASTEROIDS
Remote Observations of the Main Belt
PIERRE VERNAZZA, FUMIHIKO USUI, AND SUNAO HASEGAWA

1.1 INTRODUCTION

It might be no exaggeration to say that the history of asteroid science has always been driven by the history of research on the largest Main Belt asteroids (with diameters greater than \( \sim 100 \) km), with Ceres and Vesta being the most studied bodies. Because of their brightness and scientific interest due to their large size (between that of the most common asteroids and planets), the largest asteroids have always been privileged targets for every new generation telescope and/or instrument. Today, the asteroid belt contains \( \sim 230 \) such bodies (see Table 1.1 for a complete list of \( D \geq 200 \) km bodies and Table 1.2 for a complete list of \( D \geq 100 \) km bodies). Spectrophotometric observations have been carried out for all of these bodies in the visible and/or near-infrared range. Among the 25 spectral types defined within the Bus-DeMeo asteroid taxonomy based on principal components analysis of combined visible and near-infrared spectral data spanning wavelengths from 0.45 to 2.45 \( \mu m \) for nearly 400 asteroids (DeMeo et al., 2009), only \( O-, Q-, \) and \( Xn-\)type asteroids are absent among \( D > 100 \) km bodies. C-complex asteroids (\( B, C, Ch, Cg, Cgh, Ch \)), S-complex asteroids (\( Q, S, Sa, Sq, Sr, Sv \)), P/D type asteroids (low albedo \( X, T, \) and \( D \)-types), and the remaining types (1 \( A \)-type, 4 \( K \)-type, 2 \( L \)-type, 1 \( R \)-type, 1 \( V \)-type, 1 high albedo \( X \)-type, 2 \( Xe \)-type, 9 \( Xc \)-type, 15 \( Xk \)-type) represent, respectively, 61\%, 10\%, 13\%, and 16\% of all \( D > 100 \) km asteroids.

Early photometric observations of these bodies were key in establishing the existence of a compositional gradient in the asteroid belt (Gradie & Tedesco, 1982), with \( S \)-types being located on average closer to the Sun than \( C \)-types and \( P/D \)-types being the farthest from the Sun. On the basis of these observations, scenarios regarding the formation and dynamical evolution of the asteroid belt and that of the Solar System in general have been formulated (e.g., Gomes et al., 2005; Morbidelli et al., 2005; Tsiganis et al., 2005; Bottke et al., 2006; Levison et al., 2009; Walsh et al., 2011; Raymond & Izidoro, 2017). These dynamical models suggest that today’s asteroid belt may not only host object types that formed in situ, typically between 2.2 and 3.3 \( AU \), but also bodies that were formed in the terrestrial planet region (\( Xc \)- and possibly \( S \)-types), in the giant planet region (\( Ch/Cgh \)- and \( B/C \)-types) as well as beyond Neptune (\( P/D \)-types). In a broad stroke, the idea that the asteroid belt is a condensed version of the prymordial Solar System has progressively emerged. Notably, these observations along with those of more distant small bodies (giant planet trojans, trans-Neptunian objects) were instrumental in imposing giant planet migrations as a main step in the dynamical evolution of our Solar System. On the basis of these datasets, the idea of a static Solar System history has dramatically shifted to one of dynamic change and mixing (DeMeo & Carry, 2014). See Part III of this book for more details on this topic.

The study of the largest Main Belt asteroids is not only important because of the clues it delivers regarding the formation and evolution of the belt itself but also because many of these bodies are likely “primordial” remnants of the early Solar System (Morbidelli et al., 2009), that is their internal structure has likely remained intact since their formation (they can be seen as the smallest protoplanets). Many of these bodies thus offer, similarly to Ceres and Vesta detailed in the present book, invaluable constraints regarding the processes of protoplanet formation over a wide range of heliocentric distances (assuming that the aforementioned migration theories are correct).

In the present chapter, we review the current knowledge regarding large (\( D \geq 100 \) km) Main Belt asteroids derived from Earth-based spectroscopic and imaging observations with an emphasis on \( D > 200 \) km bodies including Ceres and Vesta. Our motivation is to provide a meaningful context for the two largest Main Belt asteroids visited by the Dawn mission (see Chapter 2) and to guide future in-situ investigations to the largest asteroids – that’s why small (\( D < 100 \) km) asteroids, which are essentially the leftover fragments of catastrophic collisions, are not discussed here.

1.2 SPECTROSCOPIC OBSERVATIONS OF LARGE MAIN BELT ASTEROIDS

Detailed reviews concerning the compositional interpretation of asteroid taxonomic types and their distribution across the Main Belt can be found in Burbine (2014, 2016), DeMeo et al. (2015), Reddy et al. (2015), Vernazza et al. (2015a), Vernazza et al. (2015b), Vernazza and Beck (2017), and Greenwood et al. (2020) and will not be repeated with the same level of detail in this chapter. Rather, we put the emphasis on the currently proposed connections between the various compositional classes present among the largest Main Belt asteroids and the two main classes of extra-terrestrial materials, namely meteorites and interplanetary dust particles (hereafter IDPs). The two largest asteroids, Vesta and Ceres, “heroes” of the present book, illustrate well the Main Belt paradox: some asteroids appear well sampled by meteorites (Vesta) whereas others don’t (Ceres). IDPs may be more appropriate analogues.
for these bodies. We first start by summarizing the results of Earth-based spectroscopic campaigns devoted to constrain the surface composition of Ceres and Vesta and then continue by summarizing current knowledge regarding the surface composition of D > 100 km asteroids.

1.2.1 Focus on Earth-based Spectroscopic Observations of Ceres and Vesta and Comparison to Dawn Measurements

1.2.1.1 (1) Ceres

In the 1970s, Ceres was identified as a carbonaceous chondrite-like asteroid based on a low albedo (~0.05–0.06) (Veverka, 1970; Matson, 1971; Bowell & Zellner, 1973) and a relatively flat reflectance from 0.5 to 2.5 μm (Chapman et al., 1973, 1975; Johnson & Fanale, 1973; Johnson et al., 1975). A few years later, a ~3.1 μm absorption feature was discovered in its spectrum (Lebofsky, 1978; Lebofsky et al., 1981) and was interpreted as indicative of the presence of hydrated clay minerals similar to those present in carbonaceous chondrites at the surface of Ceres. Subsequent work proposed ammoniated saponite (King et al., 1992) and water ice (Vernazza et al., 2005) as the origin of this band. The presence of water ice in the subsurface of Ceres was predicted based on the detection of OH escaping from the north polar region (A’Hearn & Feldman, 1992). Rivkin et al. (2006b) reported the presence of carbonates and iron-rich clays at the surface of Ceres based on spectroscopic measurements in the 2–4 μm range. This compositional interpretation was refined a few years later (Milliken & Rivkin, 2009) and an assemblage consisting of a mixture of hydroxide brucite, magnesium carbonates, and serpentines was proposed to explain Ceres’ spectral properties.

Recent observations with the AKARI satellite have revealed the presence of an additional absorption band in the 2.5–3.5 μm range that is located at 2.73 μm (Usui et al., 2019), while also confirming the presence of a band at 3.06–3.08 μm (Usui et al., 2019). Measurements performed by the VIR instrument onboard the Dawn mission have shown that the ~3.06 μm band assigned to ammoniated phyllosilicates by King et al. (1992) is the most

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<th>Spectral type</th>
<th>a (AU)</th>
<th>e</th>
<th>i (deg)</th>
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Table 1.2 Volume equivalent diameter (\(D_{\text{eq}}\)), geometric albedo, spectral type following the Bus-DeMeo taxonomy, semi-major axis (\(a\)), eccentricity (\(e\)), and inclination (\(i\)) for the largest (\(D > 100\) km) Main Belt asteroids.

The albedo and diameter values represent the averages of the values reported in Tedesco et al. (2002), Masiero et al. (2011, 2014), and Usui et al. (2011). Spectral types were retrieved from Bus and Binzel (2002), Lazzaro et al. (2004), and DeMeo et al. (2009). The spectral type in braces was determined using the Bus and Binzel (2002) taxonomy.

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Remote Observations of the Main Belt
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6 Vernazza, Usui, and Hasegawa
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plausible interpretation (De Sanctis et al., 2015), while the assemblage with brucite was not confirmed. The VIR instrument has further revealed the presence of water ice (Combe et al., 2016), carbonates (De Sanctis et al., 2016), organics (De Sanctis et al., 2017), and chloride salts (De Sanctis et al., 2020) at the surface of Ceres. See Chapters 7 and 8 for more detail.

Notably, a “genetic” link between Ceres and carbonaceous chondrites available in our collections has progressively been questioned with time (Milliken & Rivkin, 2009; Rivkin et al., 2011). First, the /C24 3.06 μm band present in Ceres spectrum differs from what is seen in carbonaceous chondrite spectra. Second, the band depth of the 2.73 μm band is shallower than that of CM-like (Ch-/Cgh-type) asteroids (Figure 1.1; Usui et al., 2019). Third, Ceres’s spectrum possesses a broad absorption band centered on ~1.2–1.3 μm that is not seen in spectra of aqueously altered carbonaceous chondrite (Figure 1.1). Vernazza et al. (2015a) and Marsset et al. (2016) have tentatively attributed this absorption band to amorphous silicates (mainly olivine), whereas Yang and Jewitt (2010) proposed magnetite instead. Observations in the mid-infrared wavelength range have further reinforced the existence of compositional differences between Ceres and carbonaceous chondrite meteorites (Vernazza et al., 2017, Figure 1.2). They have further revealed the presence of anhydrous silicates at the surface of Ceres in addition to phyllosilicates and carbonates.

### 1.2.1.2 (4) Vesta

It has been well known since the 1970s that Vesta possesses a high albedo (0.3–0.4) (e.g., Allen, 1970; Cruikshank & Morrison, 1973; Tedesco et al., 2002; Ryan & Woodward, 2010; Usui et al., 2011; Hasegawa et al., 2014) and that its surface is basaltic in composition (McCord et al., 1970; Larson & Fink, 1975; McFadden et al., 1977). Vesta’s spectrum displays two diagnostic absorption bands centered at ~0.9 μm and ~2 μm which imply the presence of pyroxene at its surface. A comparison of these observations with laboratory measurements of meteorites has revealed a spectral similarity between Vesta and that of the howardite–eucrite–diogenite (HED) achondritic meteorites (e.g., McCord et al., 1970; Feierberg & Drake, 1980; Feierberg et al., 1980;

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