CAMBRIDGE
Cambridge University Press
978-1-108-47973-8 — Vesta and Ceres
Edited by Simone Marchi , Carol A. Raymond , Christopher T. Russell
Excerpt
More Information

Part I

REMOTE OBSERVATIONS AND EXPLORATION OF MAIN BELT ASTEROIDS

1

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 ~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 ~230 such bodies (see Table 1.1 for a complete list of D ≳200 km bodies and Table 1.2 for a complete list of D ≳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 μm 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, Cb, 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 objects that formed in situ, typically between 2.2 and 3.3 AU, but also bodies that were formed in the terrestrial planet region (Xe- 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 primordial 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 ≳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. (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

FU was supported by JSPS KAKENHI: grant nos. JP19H00725, JP20H00188, and JP20K04055. SH was supported by JSPS KAKENHI (grant nos. JP15K05277, JP17K05636, JP18K03723, JP19H00719, and JP20K04055) and by the Hypervelocity Impact Facility (former facility name: the Space Plasma Laboratory), ISAS, JAXA.

Table 1.1 *Volume equivalent diameter (Deq), geometric albedo, spectral type following the Bus-DeMeo taxonomy, semi-major axis (a), eccentricity (e), and inclination (i) for the largest (D > 200 km) Main Belt asteroids listed according to decreasing values of their size.*

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

Object	Deq (km)	Geom. alb.	Spectral type	a (AU)	e	i (deg)
1 Ceres	939.4	0.087	C	2.77	0.08	10.59
4 Vesta	525.4	0.404	V	2.36	0.09	7.14
2 Pallas	513.0	0.140	B	2.77	0.23	34.83
10 Hygiea	434.0	0.059	C	3.14	0.11	3.83
704 Interamnia	332.0	0.044	Cb	3.06	0.16	17.31
52 Europa	314.0	0.049	C	3.09	0.11	7.48
511 Davida	303.2	0.064	C	3.16	0.19	15.94
65 Cybele	286.3	0.049	Xk	3.42	0.11	3.56
87 Sylvia	280.0	0.043	X	3.48	0.09	10.88
31 Euphrosyne	268.0	0.047	Cb	3.16	0.22	26.28
15 Eunomia	267.3	0.196	S	2.64	0.19	11.75
107 Camilla	254.0	0.040	X	3.49	0.07	10.00
3 Juno	249.0	0.210	Sq	2.67	0.26	12.99
451 Patientia	242.9	0.069	C	3.06	0.07	15.24
324 Bamberga	232.9	0.061	C	2.68	0.34	11.10
16 Psyche	222.0	0.156	Xk	2.92	0.13	3.10
48 Doris	220.8	0.064	Ch	3.11	0.07	6.55
88 Thisbe	212.0	0.052	C	2.77	0.16	5.21
423 Diotima	211.2	0.053	C	3.07	0.04	11.24
19 Fortuna	211.0	0.048	Ch	2.44	0.16	1.57
13 Egeria	205.0	0.080	Ch	2.58	0.09	16.54
7 Iris	204.0	0.244	S	2.39	0.23	5.52
29 Amphitrite	204.0	0.185	S	2.55	0.07	6.08

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

Table 1.2 *Volume equivalent diameter (Deq), 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

Object	Deq (km)	Geom. Alb.	Spectral type	a (AU)	e	i (deg)
1 Ceres	939.4	0.087	C	2.77	0.08	10.59
2 Pallas	513.0	0.140	B	2.77	0.23	34.83
3 Juno	249.0	0.210	Sq	2.67	0.26	12.99
4 Vesta	525.4	0.404	V	2.36	0.09	7.14
5 Astraea	114.0	0.236	S	2.57	0.19	5.37
6 Hebe	196.0	0.220	S	2.43	0.20	14.75
7 Iris	204.0	0.244	S	2.39	0.23	5.52
8 Flora	140.0	0.226	Sw	2.20	0.16	5.89
9 Metis	168.0	0.189	K	2.39	0.12	5.58
10 Hygiea	434.0	0.059	C	3.14	0.11	3.83
11 Parthenope	154.5	0.186	Sq	2.45	0.10	4.63
12 Victoria	129.7	0.134	L	2.33	0.22	8.37
13 Egeria	205.0	0.080	Ch	2.58	0.09	16.54
14 Irene	149.7	0.239	S	2.59	0.17	9.12
15 Eunomia	267.3	0.196	S	2.64	0.19	11.75
16 Psyche	222.0	0.156	Xk	2.92	0.13	3.10
18 Melpomene	146.0	0.190	S	2.30	0.22	10.13
19 Fortuna	211.0	0.048	Ch	2.44	0.16	1.57
20 Massalia	140.8	0.229	S	2.41	0.14	0.71
21 Lutetia	98.0	0.184	Xc	2.44	0.16	3.06
22 Kalliope	161.0	0.171	X	2.91	0.10	13.72
23 Thalia	105.1	0.270	S	2.63	0.24	10.11
24 Themis	189.6	0.074	C	3.14	0.13	0.75
27 Euterpe	113.9	0.218	S	2.35	0.17	1.58
28 Bellona	122.7	0.187	S	2.78	0.15	9.43
29 Amphitrite	204.0	0.185	S	2.55	0.07	6.08
31 Euphrosyne	268.0	0.047	Cb	3.16	0.22	26.28
34 Circe	117.1	0.051	Ch	2.69	0.10	5.50
35 Leukothea	104.1	0.066	(C)	2.99	0.23	7.94
36 Atalante	111.5	0.060	Ch	2.75	0.30	18.43
37 Fides	110.0	0.182	S	2.64	0.17	3.07
38 Leda	116.1	0.063	Cgh	2.74	0.15	6.97
39 Laetitia	164.0	0.238	Sqw	2.77	0.11	10.38
40 Harmonia	116.7	0.209	S	2.27	0.05	4.26
41 Daphne	187.0	0.055	Ch	2.76	0.28	15.79
42 Isis	106.7	0.152	K	2.44	0.22	8.53
45 Eugenia	186.0	0.051	C	2.72	0.08	6.60
46 Hestia	126.0	0.051	Xc	2.53	0.17	2.34
47 Aglaja	142.0	0.064	C	2.88	0.13	4.98

Table 1.2 (*cont.*)

Object	Deq (km)	Geom. Alb.	Spectral type	a (AU)	e	i (deg)
48 Doris	220.8	0.064	Ch	3.11	0.07	6.55
49 Pales	161.3	0.052	Ch	3.09	0.23	3.17
50 Virginia	94.4	0.041	Ch	2.65	0.28	2.83
51 Nemausa	144.0	0.078	Cgh	2.37	0.07	9.98
52 Europa	314.0	0.049	C	3.09	0.11	7.48
53 Kalypso	110.7	0.044	Ch	2.62	0.21	5.17
54 Alexandra	143.0	0.066	Cgh	2.71	0.20	11.80
56 Melete	120.0	0.060	Xk	2.60	0.24	8.07
57 Mnemosyne	114.5	0.209	S	3.15	0.12	15.22
59 Elpis	168.0	0.043	C	2.71	0.12	8.63
62 Erato	97.0	0.063	B	3.13	0.17	2.23
65 Cybele	286.3	0.049	Xk	3.43	0.11	3.56
68 Leto	127.2	0.215	S	2.78	0.19	7.97
69 Hesperia	134.8	0.150	Xk	2.98	0.17	8.59
70 Panopaea	137.1	0.050	Cgh	2.61	0.18	11.59
74 Galatea	122.6	0.042	(C)	2.78	0.24	4.08
76 Freia	173.1	0.042	C	3.41	0.16	2.12
78 Diana	145.5	0.051	Ch	2.62	0.21	8.70
81 Terpsichore	124.0	0.042	C	2.86	0.21	7.80
85 Io	165.0	0.054	C	2.66	0.19	11.96
86 Semele	119.2	0.049	Cgh	3.11	0.21	4.82
87 Sylvia	280.0	0.043	X	3.48	0.09	10.88
88 Thisbe	212.0	0.052	C	2.77	0.16	5.21
89 Julia	140.0	0.172	S	2.55	0.18	16.14
90 Antiope	108.0	0.087	C	3.16	0.16	2.21
91 Aegina	109.0	0.042	Ch	2.59	0.11	2.11
92 Undina	121.0	0.280	Xk	3.19	0.10	9.93
93 Minerva	159.0	0.048	C	2.76	0.14	8.56
94 Aurora	199.0	0.041	C	3.16	0.09	7.97
95 Arethusa	144.5	0.062	Ch	3.07	0.15	13.00
96 Aegle	172.9	0.051	T	3.05	0.14	15.97
98 Ianthe	109.8	0.043	(Ch)	2.69	0.19	15.58
104 Klymene	127.8	0.054	Ch	3.15	0.16	2.79
105 Artemis	121.0	0.045	Ch	2.37	0.18	21.44
106 Dione	174.7	0.067	Cgh	3.18	0.17	4.60
107 Camilla	254.0	0.040	X	3.49	0.07	10.00
111 Ate	144.9	0.053	Ch	2.59	0.10	4.93
114 Kassandra	99.0	0.090	K	2.68	0.14	4.93
117 Lomia	158.6	0.048	(X)	2.99	0.03	14.90
120 Lachesis	170.2	0.050	C	3.12	0.06	6.95
121 Hermione	187.0	0.061	Ch	3.45	0.13	7.60
127 Johanna	121.7	0.053	Ch	2.76	0.07	8.24

Cambridge University Press
978-1-108-47973-8 — Vesta and Ceres
Edited by Simone Marchi , Carol A. Raymond , Christopher T. Russell
Excerpt
More Information

Table 1.2 (*cont.*)

Object	Deq (km)	Geom. Alb.	Spectral type	a (AU)	e	i (deg)
128 Nemesis	185.4	0.053	C	2.75	0.12	6.25
129 Antigone	126.0	0.147	Xk	2.88	0.21	12.23
130 Elektra	199.0	0.064	Ch	3.12	0.21	22.86
134 Sophrosyne	113.3	0.045	(Ch)	2.56	0.12	11.60
137 Meliboea	147.8	0.049	(C)	3.12	0.22	13.41
139 Juewa	167.2	0.047	(X)	2.78	0.18	10.91
140 Siwa	114.0	0.063	Xc	2.73	0.22	3.19
141 Lumen	136.4	0.050	Ch	2.67	0.21	11.89
144 Vibilia	141.0	0.051	Ch	2.66	0.24	4.81
145 Adeona	150.1	0.044	Ch	2.67	0.15	12.64
146 Lucina	134.5	0.052	Ch	2.72	0.07	13.10
147 Protogeneia	121.8	0.062	C	3.14	0.03	1.93
150 Nuwa	145.5	0.043	C	2.98	0.13	2.19
153 Hilda	186.6	0.055	X	3.97	0.14	7.83
154 Bertha	187.0	0.047	(C)	3.20	0.08	20.98
156 Xanthippe	113.6	0.048	Ch	2.73	0.23	9.78
159 Aemilia	130.0	0.059	Ch	3.10	0.11	6.13
162 Laurentia	98.6	0.055	(Ch)	3.02	0.18	6.10
164 Eva	107.7	0.039	(X)	2.63	0.34	24.47
165 Loreley	173.0	0.045	(Cb)	3.12	0.08	11.22
168 Sibylla	148.8	0.054	(Ch)	3.37	0.07	4.64
171 Ophelia	110.6	0.071	(Cb)	3.13	0.13	2.55
173 Ino	152.6	0.069	Xk	2.74	0.21	14.21
175 Andromache	110.8	0.071	Cg	3.18	0.23	3.22
176 Iduna	124.3	0.080	(Ch)	3.19	0.17	22.59
181 Eucharis	118.2	0.095	Xk	3.13	0.20	18.89
185 Eunike	168.2	0.057	C	2.74	0.13	23.22
187 Lamberta	131.8	0.059	Ch	2.73	0.24	10.59
190 Ismene	197.3	0.043	X	4.00	0.17	6.16
191 Kolga	102.3	0.040	Cb	2.89	0.09	11.51
194 Prokne	172.6	0.050	Ch	2.62	0.24	18.49
196 Philomela	148.8	0.195	(S)	3.11	0.02	7.26
200 Dynamene	133.4	0.050	(Ch)	2.74	0.13	6.90
203 Pompeja	111.3	0.045	(C-complex)	2.74	0.06	3.18
206 Hersilia	99.3	0.062	(C)	2.74	0.04	3.78
209 Dido	138.2	0.049	(Xc)	3.14	0.06	7.17
210 Isabella	85.8	0.048	Cb	2.72	0.12	5.26
211 Isolda	149.2	0.056	Ch	3.04	0.16	3.89
212 Medea	150.0	0.039	X	3.12	0.11	4.26
216 Kleopatra	121.0	0.145	Xe	2.80	0.25	13.10
221 Eos	105.6	0.139	K	3.01	0.10	10.88
225 Henrietta	119.3	0.042	(B)	3.39	0.26	20.87

Cambridge University Press
978-1-108-47973-8 — Vesta and Ceres
Edited by Simone Marchi , Carol A. Raymond , Christopher T. Russell
Excerpt
More Information

Table 1.2 (*cont.*)

Object	Deq (km)	Geom. Alb.	Spectral type	a (AU)	e	i (deg)
227 Philosophia	97.6	0.056	(X)	3.17	0.19	9.11
229 Adelinda	104.2	0.037	X	3.42	0.14	2.08
230 Athamantis	112.0	0.163	S	2.38	0.06	9.44
233 Asterope	106.0	0.157	Xk	2.66	0.10	7.69
238 Hypatia	151.4	0.042	(Ch)	2.91	0.09	12.39
241 Germania	178.7	0.052	C	3.05	0.10	5.51
247 Eukrate	147.0	0.051	(Xc)	2.74	0.24	24.99
250 Bettina	111.0	0.137	Xk	3.15	0.13	12.81
259 Aletheia	185.3	0.041	(X)	3.13	0.13	10.82
266 Aline	112.1	0.048	Ch	2.80	0.16	13.40
268 Adorea	148.9	0.040	X	3.09	0.14	2.44
275 Sapientia	110.9	0.042	C	2.77	0.16	4.76
276 Adelheid	123.9	0.046	X	3.12	0.07	21.62
279 Thule	124.9	0.043	D	4.28	0.01	2.34
283 Emma	142.0	0.032	C	3.05	0.15	7.99
286 Iclea	103.9	0.043	(Ch)	3.19	0.03	17.90
303 Josephina	103.4	0.052	(Ch)	3.12	0.06	6.87
308 Polyxo	147.3	0.045	T	2.75	0.04	4.36
324 Bamberga	232.9	0.061	C	2.68	0.34	11.10
328 Gudrun	120.1	0.045	C/Cb	3.11	0.11	16.12
334 Chicago	182.7	0.050	C	3.90	0.02	4.64
344 Desiderata	133.9	0.058	Xk	2.60	0.32	18.35
345 Tercidina	101.5	0.058	Ch	2.33	0.06	9.75
349 Dembowska	174.4	0.280	R	2.93	0.09	8.25
350 Ornamenta	114.3	0.063	(Ch)	3.11	0.16	24.91
354 Eleonora	159.9	0.187	A	2.80	0.12	18.40
356 Liguria	134.2	0.051	Ch	2.76	0.24	8.22
357 Ninina	104.6	0.053	(B)	3.15	0.07	15.08
360 Carlova	135.0	0.039	(C)	3.00	0.18	11.70
361 Bononia	150.5	0.041	D	3.96	0.21	12.62
365 Corduba	101.6	0.037	(C)	2.80	0.16	12.78
372 Palma	192.6	0.064	(B)	3.15	0.26	23.83
373 Melusina	98.7	0.042	(Ch)	3.12	0.14	15.43
375 Ursula	193.6	0.049	C	3.12	0.11	15.94
381 Myrrha	127.6	0.055	(Cb)	3.22	0.09	12.53
386 Siegena	167.0	0.053	(C)	2.90	0.17	20.26
387 Aquitania	97.0	0.171	L	2.74	0.24	18.13
388 Charybdis	122.2	0.044	(C)	3.01	0.06	6.44
393 Lampetia	121.9	0.064	(Xc)	2.78	0.33	14.88
404 Arsinoe	98.0	0.047	(Ch)	2.59	0.20	14.11
405 Thia	124.4	0.048	Ch	2.58	0.24	11.95
409 Aspasia	164.0	0.060	Xc	2.58	0.07	11.26

Table 1.2 (*cont.*)

Object	Deq (km)	Geom. Alb.	Spectral type	a (AU)	e	i (deg)
410 Chloris	116.6	0.058	(Ch)	2.73	0.24	10.96
412 Elisabetha	100.6	0.043	(C)	2.76	0.04	13.78
419 Aurelia	122.5	0.043	C	2.60	0.25	3.93
420 Bertholda	148.7	0.038	D	3.41	0.03	6.69
423 Diotima	211.2	0.053	C	3.07	0.04	11.24
426 Hippo	123.0	0.051	B	2.89	0.10	19.48
444 Gyptis	165.6	0.047	C	2.77	0.18	10.28
445 Edna	97.6	0.037	(Ch)	3.20	0.19	21.38
451 Patientia	242.9	0.069	C	3.06	0.07	15.24
455 Bruchsalia	98.5	0.052	(Xk)	2.66	0.29	12.02
466 Tisiphone	111.0	0.072	(Ch)	3.35	0.09	19.11
469 Argentina	127.4	0.039	(Xk)	3.18	0.16	11.59
471 Papagena	132.0	0.232	Sq	2.89	0.23	14.98
476 Hedwig	124.5	0.045	Xk	2.65	0.07	10.94
481 Emita	112.5	0.047	(Ch)	2.74	0.16	9.84
488 Kreusa	161.4	0.052	(Ch)	3.17	0.16	11.52
489 Comacina	138.8	0.044	(X)	3.15	0.04	13.00
490 Veritas	114.5	0.064	Ch	3.17	0.10	9.28
491 Carina	99.1	0.063	(C)	3.19	0.09	18.87
505 Cava	102.8	0.060	Xk	2.68	0.25	9.84
506 Marion	108.0	0.045	(X)	3.04	0.15	17.00
508 Princetonia	134.9	0.050	(X)	3.16	0.01	13.36
511 Davida	303.2	0.064	C	3.16	0.19	15.94
514 Armida	105.6	0.040	(Xe)	3.05	0.04	3.88
517 Edith	96.3	0.037	C	3.16	0.18	3.19
521 Brixia	118.9	0.060	Ch	2.74	0.28	10.60
522 Helga	97.2	0.044	(X)	3.63	0.08	4.44
532 Herculina	191.0	0.211	S	2.77	0.18	16.31
536 Merapi	159.5	0.042	Xk	3.50	0.09	19.43
545 Messalina	112.2	0.042	(Cb)	3.21	0.17	11.12
554 Peraga	102.9	0.039	Ch	2.38	0.15	2.94
566 Stereoskopia	167.0	0.042	(X)	3.38	0.11	4.90
570 Kythera	102.4	0.051	D	3.42	0.12	1.79
595 Polyxena	110.6	0.091	(T)	3.21	0.06	17.82
596 Scheila	114.3	0.038	T	2.93	0.16	14.66
602 Marianna	128.9	0.051	(Ch)	3.09	0.25	15.08
618 Elfriede	133.6	0.050	(C)	3.19	0.07	17.04
635 Vundtia	99.0	0.045	(B)	3.14	0.08	11.03
654 Zelinda	128.3	0.042	(Ch)	2.30	0.23	18.13
683 Lanzia	103.0	0.108	(C)	3.12	0.06	18.51
690 Wratislavia	157.9	0.044	(B)	3.14	0.18	11.27
694 Ekard	105.3	0.037	(Ch)	2.67	0.32	15.84

Table 1.2 (*cont.*)

Object	Deq (km)	Geom. Alb.	Spectral type	a (AU)	e	i (deg)
702 Alauda	195.0	0.056	C	3.19	0.02	20.61
704 Interamnia	332.0	0.044	Cb	3.06	0.16	17.31
705 Erminia	137.4	0.042	(C)	2.92	0.05	25.04
712 Boliviana	127.4	0.049	(X)	2.58	0.19	12.76
713 Luscinia	101.8	0.044	(C)	3.39	0.17	10.36
733 Mocia	102.6	0.041	(X)	3.40	0.06	20.26
739 Mandeville	111.2	0.054	Xc	2.74	0.14	20.66
747 Winchester	178.0	0.048	(C)	3.00	0.34	18.16
748 Simeisa	106.6	0.039	(T)	3.96	0.19	2.26
751 Faina	111.9	0.050	(Ch)	2.55	0.15	15.61
762 Pulcova	149.0	0.055	C	3.16	0.10	13.09
769 Tatjana	106.3	0.044	(C-complex)	3.17	0.19	7.37
772 Tanete	130.6	0.050	C	3.00	0.09	28.86
776 Berbericia	155.6	0.063	Cgh	2.93	0.16	18.25
780 Armenia	99.7	0.045	(C)	3.11	0.10	19.09
786 Bredichina	101.3	0.060	(X/Xc)	3.17	0.16	14.55
788 Hohensteina	119.2	0.060	(Ch)	3.12	0.13	14.34
790 Pretoria	159.1	0.045	(X)	3.41	0.15	20.53
804 Hispania	158.8	0.052	(C)	2.84	0.14	15.36
814 Tauris	111.0	0.045	(C)	3.15	0.31	21.83
895 Helio	134.2	0.049	(B)	3.20	0.15	26.09
909 Ulla	114.8	0.036	X	3.54	0.09	18.79
1015 Christa	100.6	0.043	(Xc)	3.21	0.08	9.46
1021 Flammario	101.0	0.045	C	2.74	0.28	15.87
1093 Freda	112.2	0.043	(Cb)	3.13	0.27	25.21
1269 Rollandia	108.2	0.045	(D)	3.91	0.10	2.76

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 ∼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' 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;