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“Water” abundance at the surface of C-complex main-belt asteroids

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Abstract : Recently published space-based observations of main-belt asteroids with the AKARI telescope provide a full description of the 3- μ m band, related to the presence of OH bearing minerals. Here, we use laboratory spectra of carbonaceous chondrites obtained under controlled atmosphere (CI, CM, CO, CV, CR Tagish Lake) to derive spectral metrics related to the water content in the samples. After testing several spectral metrics, we use a combination of band depth at 2.75 μ m and 2.80 μ m that shows a correlation with [H₂O] in the sample determined by TGA, though with a high uncertainty (4 wt. % H₂O). This relation is used to determine water content at the surface of large C-complex main-belt asteroids and discuss the origin of the variability found. On average C-complex Main-Belt Asteroids (MBA) have water contents of 4.5 wt.% (volume average, (1) Ceres excluded), significantly lower than average CM chondrites. **The estimated water content for the most hydrated asteroids are lower than those of the most hydrated meteorites, a difference that could be attributed to space-weathering. An anti-correlation is also present between water content and overall spectral slope, which is opposite to expectation from laboratory simulations of space weathering on dark carbonaceous chondrites. This suggests that part of the variability in the surface hydration among the different C-complex asteroids is not due to space-weathering, but to the composition of surface material.** When applied to Ceres, the hygrometer presented in this work enables us to estimate that at least 1.22 wt. % of the hydrogen is present in the form of organics. This richness in organics strengthens the connection between Ceres and cometary materials.

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1. Introduction

The Solar System hosts a population of small objects but with large scientific value, the so-called small bodies (a denomination regrouping asteroids, comets, centaurs and trans-neptunian objects). **Despite all these objects being small, they show a diversity of** orbits, colors, densities or Vis-NIR spectra (Masiero et al. 2011, Vernazza and Beck, 2017, DeMeo and Carry, 2013, 2014; Carry, 2012). Among small bodies, main-belt asteroids (MBAs) are of particular interest since they are expected to be a major source of meteorites (Morbidelli and Gladman, 1998). Conversely studying meteorites may help to understand the nature of the main-asteroid belt population, and overall is a gateway to understanding the small bodies population as a whole. Among main-belt asteroids, the so-called S spectral-type have been linked successfully to ordinary chondrites (Nakamura et al., 2011), a family of meteorites that dominates the flux of meteorites since at least a few million years (Drouart et al., 2019). About half of the main-belt is composed of so-called **C-complex** asteroids (DeMeo and Carry, 2013), which have been connected to the less frequent carbonaceous chondrites group. More details on the link between the two groups will be provided by the two C-complex asteroid sample-return missions, Hayabusa2 (JAXA) and OSIRIS-REx (NASA).

While the S-complex asteroid / ordinary chondrites connection seems to be well established, the relation between carbonaceous chondrites and C-complex are more blurred. One of the key difficulties is the lack of strong absorption in the Vis-NIR for C-complex, with the exception of the 0.7 and 0.9 μm absorption bands, **that have typical band depths of 5 % (Fornasier et al., 1999) and** are attributed to Fe^{2+} - Fe^{3+} bearing hydrated minerals. Many **C-complex** are devoid of these bands and their nature has been discussed whether as geologically processed (through thermal metamorphism, Hiroi et al., 1996) or as primitive (Interplanetary Dust Particles (IDP) rich, Vernazza et al., 2015). Because of their connection to carbonaceous chondrites, and the detection of signatures of hydrated minerals on some of them, **C-complex** asteroids are expected to be H_2O -rich. Carbonaceous chondrites do also show evidence of the presence of hydrated minerals in **varying** amounts depending on the carbonaceous chondrite class.

While absorption bands are faint on **C-complex** asteroids in the Vis-NIR, deep bands can be found in the 3- μm region where fundamental, harmonic and combination modes of $-\text{OH}$ occur. These bands have been used to discuss the relations between carbonaceous chondrites and **C-complex** asteroids (Lebofsky et al., 1981, Hiroi et al.; 1996, Miyamoto and Zolensky, 1994, Sato et al., 1997, Osawa et al. 2005, Bates et al., 2020, Takir et al. 2013, Beck et al., 2010, 2018, Potin et al., 2019, 2020, Rivkin et al., 2003, 2015, 2019). The comparison between laboratory spectra and telescopic observation has several complexities related to i) the contamination of laboratory data by terrestrial water, ii) the atmospheric absorption that masks the 2.6-2.9 μm region in ground-based observations, where the maxima of $-\text{OH}$ absorption are typically found, iii) observation geometry effects, when comparing disk integrated observations to laboratory measurements.

Here, the approach is in essence similar to Rivkin et al. (2003) but we build on significant progress in these issues. First, **reflectance of chondrite meteorites** under asteroidal conditions have been obtained for about 40 samples (Potin et al., 2020b; Eschrig et al., 2020), and the effects of observation geometry on the 3- μm band have been recently quantified (Potin et al., 2019). Second, recently published space-based observations by the Akari telescope offer a full description of the 3- μm feature for

93 several tens of Main-belt asteroids. This new laboratory dataset enables us to define
94 metrics for remote quantification of water that are applied to derive the amount of
95 water present at the surface of hydrated MBAs.

96 97 98 2. Methods

99 2.1 Reflectance datasets

100 The reflectance spectra used in this work have been published in previous
101 articles. All these spectra were acquired with the same setup, the SHADOWS instrument
102 (Potin et al., 2018), coupled to the MIRAGE environmental chamber. Unlike most
103 instruments used to study reflectance in the 3- μ m region, the SHADOWS system is not
104 based on FTIR but uses a monochromatic light source and an InSb detector (Potin et al.,
105 2018). Also, the SHADOWS instrument measures bi-directional reflectance spectra
106 unlike most-systems that are biconical. All spectra are accessible through the SSHADE
107 database (www.shade.eu).

108 The spectra of the CI Orgueil, Tagish Lake and CM chondrites are taken from
109 Potin et al. (2019) and Potin et al. (2020b). The spectra of CO and CV chondrites are
110 taken from Eschrig et al. (2020). Spectra of the Paris meteorite were presented in Bonal
111 et al. (2019). All samples were measured under vacuum at 80°-100°C, with the exception
112 of a few CO chondrites and the Paris lithologies, that were measured during an early
113 measurement campaign under vacuum and 25°C. Details are provided in Table 1.

114 115 116 2.2 Quantification of equivalent “water”

117 Within meteorites, “water” may occur in several forms. Firstly, water may be
118 present as molecules, in the form of adsorbed water, mesoporous water, structural
119 water such as in hydrated salts (sulfates for instance) or fluid inclusions. Secondly,
120 “water” may occur as -OH groups in the form of hydroxylated silicates, or hydroxides
121 (Fe or Mg). In the later case, this not really water but can be somehow considered as
122 water from a geochemical perspective, since they result from the interaction of
123 anhydrous minerals and water in the parent body, and that molecular water will be
124 released upon thermal decomposition of these minerals.

125 A largely used method for water and -OH quantification, used in Earth Sciences on
126 geological samples, is infrared spectroscopy. However, this approach is difficult to apply
127 to carbonaceous chondrites that are a complex mixture of complex phases. The
128 techniques applied to derive water abundance in carbonaceous chondrites include X-
129 Ray Diffraction (XRD) to estimate the amount of phyllosilicates (Howard et al., 2009,
130 2011, King et al., 2015, 2017), pyrolysis-based mass spectrometry (Alexander et al.,
131 2012, 2013), thermogravimetry (Lee et al. 2016, Garenne et al. 2014, King et al. 2015,
132 Gilmour et al. 2019, Bonal et al. 2020) as well as Karl-Fisher titration. Each of these
133 techniques has pros and cons. The water abundances used for the present work were
134 derived from thermo-gravimetric analysis (TGA, Garenne et al. 2014, Bonal et al., 2020),
135 on the same sample or same batch of sample that was used for reflectance spectroscopy.
136 This is an important point since many carbonaceous chondrites are breccias (Bischoff et
137 al., 2006), and different fragments of the same meteorites may show contrasted water
138 contents (Beck et al., 2014b). One of the disadvantages of TGA is that, except when it is
139 coupled with mass spectrometry or infrared, it is not compound specific. This means
140 that from TGA data we do not know if the mass loss is due to water, or if other
141 compounds contribute (i.e. carbonates and organics). Still, they probably only contribute

142 in a minor way since the TGA data (Garenne et al., 2014) were found to show a good
143 correlation with H content determined independently (Alexander et al., 2012, 2013), as
144 well as with IR spectroscopy (Beck et al., 2014a, Eschrig et al., 2020). In this work we
145 used TGA data obtained in earlier studies (Garenne et al., 2014; Bonal et al., 2020). The
146 mass analyzed are typically 30 mg of samples for TGA measurements, and 30-50 mg for
147 reflectance spectra. The H₂O content is taken as the 200-770° mass loss as used in
148 Garenne et al. (2014) for CI and CM and as the 200-900°C mass loss for CO, CV and CR as
149 used in Bonal et al. (2020). Note that this definition is different from that of King et al.
150 2015 that suggested to use 200-800°C for CI phyllosilicate dehydration.
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153 3. Remote quantification

154 3.1 Lessons from transmission IR spectroscopy

155 Because OH bonds have a high dipolar moment they are active in infrared
156 spectroscopy. The bending mode of water has a fundamental vibration around 6 μm
157 while the OH stretching modes have fundamental vibrations around 2.7 μm for water
158 and sometimes at higher wavelength for X-OH (where X is a transition metal).
159 Combination and harmonic modes can be found in the vis-NIR (1.05, 1.4, 1.9, 2.1-2.3)
160 and around 3-μm. The so-called 3-μm band is a composite feature extending from 2.7 to
161 about 4-μm with contributions from fundamental, harmonic and combination of
162 stretching and bending vibration.

163 Transmission spectroscopy is sensitive to water related absorptions and can be
164 used to quantify water abundance down to ppm levels (for example in tektite; Beran and
165 Koeberl, 1997). In previous works, we studied water “speciation” and abundance of
166 OH/H₂O within carbonaceous chondrites (bulk sample: Beck et al., 2010, 2014, matrix:
167 Bonal et al., 2016, 2020) and micrometeorites (Battandier et al., 2018). These works
168 revealed that under ambient conditions adsorbed terrestrial water contributes
169 significantly and contaminates the 3-μm region (Beck et al. 2010). They also showed a
170 change of the position of the absorption maximum (Beck et al. 2010) for CM chondrites
171 and a correlation between the intensity of the 3-μm band (normalized to the silicate
172 feature intensity) and hydrogen content (Beck et al., 2014).
173

174 3.2 Complexities associated with reflectance

175 While transmission infrared is efficient to quantify water content, the use of the
176 3-μm band in reflectance is more challenging. Reflectance spectroscopy involves both
177 absorption and reflection, and the resulting spectrum is controlled by composition
178 (absorption properties) and physical properties (refractive index, grain sizes, porosity)
179 and observation geometry. Detailed work by Milliken and Mustard (2005) has revealed
180 some of the complexities in defining a unique water abundance calibration curves based
181 on the 3-μm band.

182 To illustrate some of the difficulties, synthetic mixtures of an -OH bearing phase
183 with a dark component were modeled using Hapke (2012) theory. A dark and spectrally
184 flat component was mixed with a brighter component to which an -OH absorption
185 feature was added in the form of an exponentially modified Gaussian (Potin et al.,
186 2020a)(Fig. 1). Simulations were run so that the volume fraction of the -OH free and -
187 OH bearing compounds were kept constant, implying that the amount of water in the
188 mixture was constant. However, the relative grain size between the two constituents
189 was changed. Calculations showed that the band depth could vary by a factor of ten, in
190 the grain size range investigated (diameter ratio varying between 0.05 and 500, and the

191 diameter of the bright grain being 10- μm). When the dark grains are large, the mixture
192 is relatively bright and the dependence of band depth on the size of the dark grains is
193 modest. When the size of the dark grains is smaller than the size of the bright grains,
194 then the mixture is dark and the dependence of band depth to the size of the dark grains
195 is high. Note that these calculations do not apply to grain sizes that are much smaller
196 than wavelength and should follow a different regime of radiative transfer.

197 In this model case, the band depth alone is found to be a degenerated parameter,
198 which will fail in retrieving water content: samples with the same water content have
199 different band depth. Applying radiative transfer models that try to reproduce not only
200 band depth but also absolute reflectance may help in this matter, since they can provide
201 constraints on grain size and remove some of the degeneracy. However, they rely on a
202 certain number of parameters (nature and intensity of the opposition effect, shape of the
203 single particle phase function, optical constants,...) that may be difficult to constrain and
204 often need an a priori hypothesis. Another approach that may be used is to analyze
205 samples that can be seen as simulants of asteroids surfaces, namely meteorites.

206 207 208 3.3 Calibration curve

209
210 Using meteorites as simulant of asteroidal surfaces has shown great success in
211 predicting the composition of S and V type asteroid (Nakamura et al. 2011; DeSanctis et
212 al. 2012). Even if the meteorite is not exactly made of the same material as the surface of
213 the asteroids, it may provide a good analogue in terms of grain size, texture and
214 mineralogy, and can then release some of the degeneracies associated with reflectance
215 spectroscopy.

216 Several metrics to quantify water abundance from reflectance spectra have been
217 defined and investigated in the past, in particular in Milliken and Mustard (2005) and
218 Pommerol and Schmitt (2008). Metrics specific to carbonaceous chondrites have been
219 discussed in Rivkin et al. (2003), Kaplan et al. (2019), Garenne et al. (2016) and Beck et
220 al. (2018). The specificity of the work discussed in the present article is to try to define
221 metrics that are applicable to different classes of carbonaceous chondrites, and to use
222 newly acquired spectra on CR, CO and CV chondrites. Here, we tested several of those
223 metrics. We will discuss them in the next paragraph.

224 One of the difficulties in ground-based investigations of small bodies in the 3- μm
225 region is the presence of water-vapor and ice in the earth-atmosphere that mask a
226 significant portion of the absorption, including the absorption maximum for most
227 phyllosilicates. A method that has been used to circumvent this problem is to use a
228 combination of band depth at 2.9 and 3.2 μm (Sato et al., 1997; Rivkin et al., 2002), outside
229 of the Earth's atmospheric absorption. A good correlation between these two band
230 depths was found previously (Sato et al., 1997, Takir et al., 2019) as well as in our
231 dataset obtained on carbonaceous chondrites (Figure 2). Within this array the CM
232 chondrites appear to define a line offset from that defined by CV, CO and CR chondrites,
233 which can be explained by different shapes of the 3- μm band. The CM chondrite (as well
234 as the CR1 GRO 95577) have a band with a maximum of absorption around 2.7-2.80 μm
235 while CO, CV and CR tend to have an absorption maxima in the 2.85-3.0 μm range
236 (Eschrig et al., 2020). Figure 3 presents the relation between carbonaceous chondrites
237 water content and the band depth at 2.9 μm . This graph shows a strong dispersion in the
238 dataset and that the different classes of carbonaceous chondrites show different
239 relations between water-content and band depth at 2.9 μm . More specifically the slope

240 of the band depth vs H₂O content seems to be lower in the case of CM chondrites than in
241 the case of CV-CO chondrites. This can be explained by the fact that OH may be present
242 in the form of oxides in some of the samples (CV) rather than in phyllosilicates. These
243 distinct behaviors may also be related to the fact that the petrographic constituents
244 (Chondrules, matrix, metal, CAI) are not distributed in the same way between those
245 various meteorite groups and are not of the same size (Krot et al., 2006). Post-accretion
246 thermal history may also have played a role in shaping the reflectance spectra of these
247 samples.

248 Because the energy of the absorption is spread among the whole band, band
249 areas or integrated band depths are criteria often used in spectroscopy. In figure 4, we
250 present the integrated 3- μm band depth (between 2.6 and 3.8 μm) as a function of the
251 water content, and a behavior similar to the 2.90 μm band depth is seen. After testing
252 several metrics, the sum of the 2.75 and 2.80 μm band depths was found to correlate
253 best with water content (Figure 5). Still, the quality of the correlation is modest. Such a
254 combination of band depth was already tested in previous studies (Garenne et al., 2016;
255 Beck et al., 2018), with the idea to define a criteria that would be specific to CM
256 chondrites phyllosilicate, that tend to have band maxima in the 2.75-2.80 μm range, at
257 shorter wavelength than adsorbed water (2.85 μm) or water ice (3.1 μm). The fact that
258 this criterion shows the best correlation with water content when considering
259 carbonaceous chondrites in general appears somehow fortuitous given the difference in
260 3- μm band shape between CM, CR, CV and CO. The difference in band shape implies
261 different mineral host of -OH groups, which a priori should have different molar
262 absorption coefficient at a given wavelength. To explain this improved correlation, one
263 may then invoke that molar absorption coefficient are about the same at 2.75 and 2.80
264 μm for all these samples, which could in principle be tested but not simply (this may
265 need transmission measurement of samples of well controlled thicknesses). The other
266 possibility is that because CO and CV chondrites are brighter than CM chondrites, for a
267 given water content, band depth are smaller for CM chondrites than CO and CV, as found
268 in our simulations (part 3.2 and figure 1). By using a wavelength which in the case of CV
269 and CO chondrite is on the wing of the absorption band, this effect is somehow
270 compensated.

271 Still overall, the correlation in Figure 5 is not great which may be due to errors on
272 the measurements of water content. This error can be estimated by comparing the water
273 content measured with TGA to that measured by mass spectrometry, and should be of
274 the order of 2 wt.% H₂O. This is not enough to explain the spread observed in figure 5,
275 which is rather attributed to a true spectral diversity, in relation with grain sizes,
276 mineralogy, which themselves are related to the often-complex accretion and
277 metamorphic history of these samples. Still, this trend enables us to remotely infer
278 water content for samples expected to be “similar” to carbonaceous chondrites, though
279 with large error. Errors on the retrieved amount of water content were estimated by
280 calculating confidence bands to the linear regression of the whole dataset presented in
281 figure 5. This resulted in typical errors of +/- 4 wt.% for a 90 percent confidence.

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284 3.4 Temperature, grain size and observation geometry effects

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286 Some limitations apply to the “hygrometer” proposed above, which was
287 defined using powders (typical grain size 50-150 μm , Garenne et al., 2016) measured
288 under standard observation geometry, under vacuum and 80C.

3.4.1 Effect of temperature

Temperature has an effect on the 0.4-2.5 μm reflectance spectra of ordinary chondrites (Hinrich and Lucey, 2002), and corrections need to be applied to determine remotely the composition of S-type asteroids (Dunn et al. 2013, Burbine et al. 2002). Less is known in the case of carbonaceous chondrites, and the change of the 3- μm band of carbonaceous chondrites when exposed to low-temperature has not been studied to our knowledge. While molecular water in the form of ice or hydrated minerals has a 3- μm band that will change with temperature because of slight re-organization in the crystal structures, metal-OH in phyllosilicates are not expected to show a strong variation of their absorption when exposed at main-belt asteroid temperature as was observed for the Ceres simulants measured under Ceres-like temperature (Galliano et al., 2020).

3.4.2 Powder vs rock

Because of collisions occurring on their surfaces, a layer of fine powder, analogue to the lunar regolith is likely to cover large main-belt asteroids. Typical grain size determined for lunar soils is of 0.1 mm (Carrier, 1973). On the contrary small near-earth asteroids, and to some extent possibly small main-belt asteroids, appear to be rubble-piles, and therefore may have a surface covered by rocks rather than by fine particulate materials, as observed for asteroid Bennu (DellaGiustina et al., 2019). This difference in texture is reflected in the difference in thermal inertia between small and large asteroids (Delbo et al., 2015). In order to investigate the difference between the hydration signatures of powder and rocks, fragments of the CM fall Aguas Zarcas were measured before and after grinding (Fig. 6). Results showed systematic differences between rock and powder including, a change of slope from blue to red, more pronounced 0.7 and 0.9 μm feature in the case of the powder, and a deeper 3- μm band for powders than for rocks. Because the measurements were not obtained under vacuum, the exact shape of the 3- μm band cannot be compared to the rest of the dataset. Still, when considering absorption depth at 2.75 μm (where adsorbed water contribution should be more limited) the band depth is typically 35 to 60 % larger in the case of powder than rocks. This analysis suggests that applying the calibration defined in figure 5 to an asteroid covered by rocks rather than regolith will result in an underestimation of the water content. Note also that differences in the spectral signatures of CM powders and thin section were also observed by Hanna et al. (2020).

3.4.3 Observation geometry

Reflectance spectra of meteorites are often measured in the laboratory under “standard” geometry, i.e. with a phase angle of 30° and a usually low-incidence angle. Ground-based observations of main-belt asteroids are obtained at phases ranging from 0 to 30° and are integrated over a whole hemisphere. As a consequence, the phase angle is usually different between laboratory data and ground-based observations but incidence and emergence as well. Meteorite powders and rocks do not behave as lambertian surfaces (Gradie et al., 1980, Capaccioni et al., 1986, Beck et al., 2012, Potin et al., 2019), which can have an impact on band depth. Typically, if we exclude extreme observation geometries (incidence and emergence above 50°) the variation of the 2.75- μm band depth of a powdered CM chondrites was found to be of the order of 20% within

338 the range of geometry studied by [Potin et al. \(2019\)](#). While it may be worth modeling the
339 effect of observation geometry on the band depth for an asteroid with topography, it
340 may not impact the remote estimate of water content too significantly.

344 4. Application to **C-complex** MBAs

345 4.1 The amount of water

346
347 The new combined band depth parameter we defined was applied to space-based
348 observations of **C-complex** main-belt asteroids from [Usui et al. \(2018\)](#) and to orbit-based
349 observation of Ceres ([DeSanctis et al., 2015](#); [Marchi et al., 2018](#)) (Table 2). The shape of
350 the 3- μ m band varies among the studied objects (see Table 1). For most C-complex the
351 band shape resembles that of CM chondrites (sharp-type, [Usui et al., 2018](#); [Potin et al.,](#)
352 [2020](#)) but for a few asteroids the band shape is different. Two objects (Ceres, Hygiea)
353 have a small absorption at 3.06 μ m interpreted by ammonium ions in phyllosilicates
354 ([King et al., 1992](#)), and a few asteroids have a broader feature with a maxima at 3.1 μ m
355 that has been interpreted by a thin layer of water-ice ([Rivkin and Emery, 2010](#); [Campins](#)
356 [et al., 2010](#)), goethite ([Beck et al., 2011](#)), or ammonium-salts ([Poch et al., 2020](#)). Given
357 the fact that our criteria uses a lower wavelength (2.75-2.80 μ m) than where ammonium
358 ion or thin layer of water-ice absorb, it should not be too much perturbed by the
359 presence of these compounds, and will enable to retrieve the amount of “water” present
360 in a same form as in carbonaceous chondrites. Water ice will not be accounted for with
361 our criteria.

362 The band depth at 2.75 and 2.80 microns were calculated (with a continuum at
363 2.6 μ m), summed and converted into water content using the regression line in [figure 5](#).
364 The values found are between 0 and 10.3 wt. % for the studied dataset. Water contents
365 for some of the asteroids investigated with Akari ([Usui et al., 2018](#)) were also
366 determined by [Rivkin et al. \(2003\)](#). The values derived in the present work are slightly
367 lower than those found in [Rivkin et al. \(2003\)](#) with the exception of 2-Pallas for which
368 the estimate in the present work is higher than their value. Note that within the limit of
369 the calibration errors presented earlier the estimates from this work and those of [Rivkin](#)
370 [et al. \(2003\)](#) agree.

371 In [figure 7](#), the water content derived for **C-complex** is plotted against the asteroid
372 diameter. This graph does not reveal obvious relations between the derived amount of
373 water and the size of the asteroid. Comparison of the derived water content also reveals
374 that at present there are no large asteroids that are a match to the water-rich CI
375 chondrite Orgueil. This is somewhat paradoxical since, among meteorites, **CI chondrites**
376 **have the chemical composition that is closest to the solar photosphere, suggesting that**
377 **CI-precursor like material should have been the dominant dust within the solar**
378 **protoplanetary disk. Two propositions can explain this paradox: whether CI-precursor**
379 **like material did not accrete onto small bodies, or the small bodies that accreted CI-**
380 **precursor like material only rarely experienced aqueous alteration.**

381 This graph also confirms the observations previously noted by [Rivkin et al. \(2003\)](#)
382 and [Hiroi et al. \(1996\)](#) that **C-complex** asteroids appear less hydrated than the most
383 hydrated carbonaceous chondrites. As studied by several authors, aqueous alteration
384 has been found to be variable among carbonaceous chondrites, and the definition of an
385 extent of aqueous alteration has been debated ([Rubin et al., 2007](#), [Alexander et al., 2013](#),
386 [Howard et al., 2009](#), [Beck et al., 2014](#)). Generally, the total amount of OH/H₂O present in

387 carbonaceous chondrites appear to vary in the order CI > CM > CV-CO-CR. Some
388 exceptions to this trend have been found. Some CO or CR can show unusually large
389 amount of water (the CR1 GRO95577 or the CO MIL 07687). Also, an important fraction
390 of CM chondrites has been classified as thermally metamorphosed, and contain lower
391 amount of water than “normal” CM (Nakamura et al., 2005, Alexander et al., 2012,
392 Garenne et al., 2014, Quirico et al., 2018).

393 When comparing the water content derived from B&C objects observed by Usui et
394 al. (2018), it is found that their water content are more similar to those derived for CO-
395 CV-CR, and lower than non-metamorphosed CM. However, the position of the maxima of
396 absorption is **generally at shorter wavelengths** than that measured for CO-CV-CR
397 (Eschrig et al., 2020).

398

399 4.2 The hydration-dehydration trend

400

401 There are three hypotheses that have been formulated to explain the distribution
402 of water observed for **C-complex**: space weathering, thermal metamorphism, and the
403 presence of un lithified IDP-related objects.

404

405 Space weathering can be described as the ensemble of processes acting at the
406 surface of an airless body (Pieters and Noble, 2016). These processes include irradiation
407 by the solar wind and galactic cosmic rays, as well as impacts by micrometeorites. Space
408 weathering has been shown to significantly modify the optical properties of ordinary
409 chondrites and S-type asteroids (Chapman, 2004). A number of recent studies have
410 investigated the impact of both processes on carbonaceous chondrites-like surfaces by
411 ion or laser irradiation to simulate solar wind effects and micrometeorite impacts
412 respectively (Matsuoka et al., 2020; Lantz et al., 2017). Both processes were found to
413 induce a progressive but moderate bluing of the spectra as well as a progressive
414 decrease in the 3- μ m band, with increasing irradiation dose or laser intensity. In order
415 to search for these signatures of space weathering on large **C-complex** asteroids, the
416 intensity of hydration is plotted against the spectral slope (R2.45.R0.55) in figure 8.
417 This graph reveals however an increase of slope with decreasing hydration, which is the
418 opposite of the trend observed in space weathering experiments. This observation does
419 not mean that space weathering is not active on **C-complex**. Indeed, the difference
420 between CM chondrites and the most altered **C-complex** asteroids observed in figure 8
421 could be explained by space weathering. However, the observed trend suggests that the
422 variability among **C-complex** main-belt asteroids is not due to different intensities of
423 space weathering but rather to variable compositions.

424 Thermal metamorphism has been proposed as a mechanism to explain the
425 general depletion of **C-complex** asteroids in water when compared to CM chondrites
426 (Hiroi et al., 1996). Thermal metamorphism may have occurred at the surface of small
427 bodies as a consequence of radioactive decay in the first tens of millions of years of the
428 Solar System, or as impact-induced heating over a longer period of time. The
429 identification of heated CM chondrites supports the idea that the surface of C-types may
430 have been thermally dehydrated. This view is supported by observations of the NEA
431 Ryugu by the Hayabusa-2 spacecraft (Kitazato et al., 2019). In the case of MBAs, several
432 challenges to this hypothesis have been discussed in Vernazza et al. (2015). They
433 include observation in the 10- μ m region, the overall low-density of **C-complex** and the
434 proportion of heated CM among CM chondrites. The favored hypothesis in Vernazza et
435 al. (2015), discussed also in Rivkin et al. (2019), is rather that the non-hydrated C-

436 complex are primitive bodies that rather deliver samples to Earth in the form of
437 interplanetary dust particles. Because heated CMs tend to have noticeable water content
438 and 3- μm band depths, the presence of water-poor C-complex would tend to favor the
439 hypothesis of Vernazza et al. (2015).

440 The reader should also keep in mind that present-day delivery of carbonaceous
441 chondrites is unlikely to be samples directly ejected from the large C-complex asteroids
442 discussed here. The

443 A last possibility, that has not been formulated previously, is that the amount of
444 terrestrial water present in carbonaceous chondrites is underestimated, and
445 subsequently that the amount of asteroidal water in carbonaceous chondrites is
446 overestimated. Recent analysis of Vacher et al. (2020) may support this hypothesis.
447 Indeed, the amount of hydrogen derived for CM samples exposed to 120°C and vacuum
448 for 48h were significantly lower than those estimated by Alexander et al. (2012). This is
449 of particular interest for Orgueil, the sample that shows the largest change in the shape
450 of the 3- μm band when exposed to vacuum and moderate heating (Beck et al., 2014;
451 Potin et al., 2020). The spectral slope of powders from the fresh fall Aguas Zarcas were
452 not found to be significantly bluer than other CM chondrites (1.32;1.38;1.57). This means
453 that if terrestrial oxidation occurs and modifies mineralogy and water content of CM
454 chondrites powders, this may be a quasi-immediate effect. Samples from Bennu and
455 Ryugu will certainly be beneficial in understanding possible issues with contamination
456 by terrestrial water, if they can remain unexposed to terrestrial water before reflectance
457 spectra measurements and water abundance estimates.

458 459 4.3 The Ceres case

460
461 Ceres is the largest main-belt asteroid and is now considered as a past ocean
462 world. As observed from orbit and by the Dawn mission, Ceres is covered by dark
463 hydrated material (Lebofsky et al., 1981; DeSanctis et al., 2015). The 3- μm region of
464 Ceres is distinct from most C-complex asteroids, since signatures of ammonia have been
465 observed, suggesting an outer Solar System signature (DeSanctis et al., 2015) and a
466 connection to comets (Poch et al., 2020). Only a few asteroids share this peculiar
467 signature (Takir et al., 2013; Rivkin et al., 2019).

468 In addition to a detailed mapping of the surface of Ceres in the Vis and IR, the
469 Dawn mission also remotely determined the amount of hydrogen present in the top first
470 meter of Ceres (Prettyman et al., 2016). These measurements revealed the presence of
471 “permafrost” in the high latitude regions of Ceres and a typical hydrogen content of 1.9
472 wt.% (± 0.2) in equatorial regions (Prettyman et al. 2016, Marchi et al., 2018).

473 By applying the calibration of water content presented here, it is possible to
474 estimate how much water is present at the surface of Ceres, and therefore how much
475 hydrogen detected by GRaND is related to -OH in phyllosilicates. Using typical
476 reflectance spectra of Ceres in the 3- μm region (Marchi et al., 2018) the water content
477 derived for Ceres equatorial region is 5.2 wt. % (± 4), which converts into a [H wt.%] of
478 0.58 wt. % (± 0.44). This means that at least 1.32 wt. % (± 0.44) of hydrogen in the
479 equatorial regions of Ceres is present in other forms than hydrated minerals, the
480 candidates being NH_4^+ and H-bearing organics as observed by the VIR instrument
481 (DeSanctis et al., 2015). In order to estimate how much hydrogen may be present in the
482 form of NH_4^+ , we used the experimental reproduction of Ceres spectra presented in
483 Galiano et al., (2020). The best match to Ceres average spectra was obtained with a
484 mixture using 28 wt. % of NH_4^+ -montmorillonite. Within NH_4^+ -montmorillonite,

485 hydrogen present in NH_4^+ is estimated to be around 0.3 wt. % (Pironon et al., 2003),
486 which converts into an estimated abundance of hydrogen contained in ammonium ions
487 of around 0.1 wt. % of the equatorial material of Ceres. The hydrogen content remaining
488 for organic compounds is therefore 1.22 wt.% (± 0.44). If the organic compounds are
489 similar to CM chondrite **insoluble organic matter** (IOM) with an H/C close to 0.65 this
490 converts into a carbon content of 22.5 wt. % (± 8.1). This is slightly higher but in
491 reasonable agreement with one of the models proposed for Ceres surface composition
492 (20.2 wt. %, Marchi et al., 2019). Such very high values have also been proposed by
493 Kaplan et al., 2018 but for the organic hotspots. If the organic carbon is present in the
494 form of less refractory organics, similar to the soluble organic compounds encountered
495 in meteorites then its H/C may be much higher and the carbon content on the surface of
496 Ceres lower (for instance, with H/C = 1.55 for methanol extract in Schmitt-Kopplin et al.,
497 2010, the carbon content would be around 9.4 wt. % (± 3.4).

499 It is important to stress that these estimates of organic content at the surface of
500 Ceres (as well as the ones of Marchi et al., 2018) rely on several hypothesis, one of the
501 strongest being that the surface of Ceres is vertically homogeneous within the depth
502 probed by both infrared and neutron. This hypothesis is reasonable since it is probable
503 that similarly to the Moon surface, gardening induces some level of mixing in the top
504 meter at geological timescales. Under the hypothesis that Ceres' organics are similar to
505 meteorite IOM or **soluble organic matter** (SOM), the amount of carbon obtained here is
506 much higher than the C-content of bulk carbonaceous **chondrites (at. C/Si about 0.8), but**
507 **in the range of values found for IDPs (at. C/Si around 2) or similar to values derived for**
508 **comet 67P (at. C/Si=5.5)** (Bardyn et al., 2017, Herique et al., 2018). In addition to the
509 identification of ammonium ion on both Ceres and comets (Poch et al., 2020; Altwegg et
510 al. 2020), the richness in carbon strengthens the connection between Ceres and
511 cometary materials.

512 513 4.4 Total amount of water in the B&C reservoir

514
515 The volume average for the studied asteroids is 5.0 wt.% (4.5 wt. %, excluding
516 Ceres). Under the hypothesis that this value is representative of the bulk material
517 constituting the C-type population of asteroids, we can use the mass of this population
518 by DeMeo and Carry (2013) to estimate the amount of water they represent (this
519 calculation neglects the possible presence of ice in their interior). This is certainly a
520 strong **assumption** but at the moment there is little evidence for internal heterogeneity
521 for **C-complex** (at least for Ch-Cgh). First a Vis-NIR survey of Vernazza et al. (2016)
522 revealed that Cgh-Ch asteroids of different sizes show very little spectral diversity with
523 the exception of a change of slope that can be attributed to a change of grain size. Second
524 in the case of (41) **Daphne, one of the few C-complex asteroids with constrain on the**
525 **internal structure**, observation of its shape and determination of its density do not
526 support differentiation (Carry et al., 2019).

527 The **assumption** that the $[\text{H}_2\text{O}]$ value derived is representative of the object as a
528 whole implies that exogeneous process do not modify the water content. If we make the
529 hypothesis that the **C-complex** richest in $[\text{H}_2\text{O}]$ is a space-weathered version of the most
530 altered CM, this means that we underestimate water content of **C-complex** by 20-30 %.
531 Also, impact may produce dehydration of surface material, but at least in the case of
532 Ceres the 2.7 μm band depth shows limited variability across the surface, and the
533 variability does not seem to be related to cratering (Ammannito et al., 2017). Also note

534 that when making the estimate of total amount of water in the C-type reservoir, we
535 neglect the present of water-ice in their interior. **Water-ice is suspected to be a major**
536 **constituent of Ceres interior, and may also be present in the interior of C-type asteroids**
537 **in general. However, it is difficult at the moment to estimate how much water ice (and**
538 **possibly also other type of ices) is present within C-type.**

539 With the above-mentioned limitations in mind, the value obtained for the amount of
540 water in the **C-complex** reservoir is of 7.1×10^{19} kg, i.e. 3/4 of the mass of Enceladus. As
541 a whole, the **C-complex** reservoir only represents 0.5 % of the total amount of water
542 present on Earth (Marty, 2012). Note that the fact that this amount of water derived is
543 much lower than that found on Earth does not preclude the fact that **C-complex**
544 asteroids may have been a major source of volatiles in the inner Solar System
545 (Alexander et al., 2012). Main-belt C-complex asteroids are thought to be implanted
546 from a more distant source region (beyond Jupiter), as a consequence of the dynamical
547 evolution of the Solar System (Raymond and Izodoro, 2017; Walsh et al., 2012). In other
548 words, the initial mass of the **C-complex** reservoir was probably several orders of
549 magnitude higher than what can be weighted today in the main-belt.

550

551 5. Conclusions

552

553 In this work we discuss an approach to quantify the equivalent water abundance
554 at the surface of main-belt asteroids from space-based observations of the 3- μ m
555 absorption band in comparison to laboratory measurements on carbonaceous
556 chondrites obtained under a controlled atmosphere. From this work, the following
557 conclusions can be drawn.

558 - When using band depths above 2.9 μ m (i.e. outside of the atmospheric vapor
559 absorption), there is no unique relation between band depth and water content that is
560 valid for all classes of carbonaceous chondrites studied here (CI, CM, CO, CV, CR).

561 - A metric is defined that appears to work for all classes of carbonaceous
562 chondrites studied, using a combination of band depths at 2.75 and 2.80 μ m. A
563 significant error on the estimate exists (typically 4 wt. %), that is inherent to the
564 complexity of radiative transfer in a complex media like carbonaceous chondrites.

565 - This metric is used to infer the water content on large B & C types, which were
566 investigated in the 3- μ m region by Usui et al. (2018) using the Akari space telescope. In
567 the case of asteroids which were also studied in Rivkin et al. (2003) using ground-based
568 observations, the derived values are in agreement within the error. The derived values
569 for water content range between 0 and 11.5 wt. % (+/- 4 wt.%, 90 % confidence). The
570 average value for the 20 objects investigated is 5.0 wt % (4.5 wt. % if Ceres is excluded).
571 If this value is taken as a representative of the whole population, the **C-complex** "water"
572 reservoir is of 7.1×10^{19} kg, which is about the mass of Enceladus or 0.05 Earth oceans.

573 - The water content calculated for the most hydrated asteroids are lower than
574 those of the most hydrated meteorites including Orgueil. This difference may be
575 attributed to space weathering or to an underestimated contribution of terrestrial water
576 to the carbonaceous chondrites water budget.

577 - An anticorrelation is found between the water content and the vis-NIR slope for
578 B & C type MBA. This is opposite to the expected space weathering trends and appears
579 to reflect a continuous mixing between two styles of materials.

580 - Applying this water quantification tool to Ceres enables the estimation of the
581 amount of hydrogen present in the form of organics, within the equatorial region. At

582 least 1.22 wt. % of hydrogen is expected to be present in the form of organics. This
583 richness in organics strengthens the connection between Ceres and cometary materials.
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598 REFERENCES:

- 599 Alexander, C.M.O. 'D, Bowden, R., Fogel, M.L., Howard, K.T., Herd, C.D.K., Nittler, L.R.,
600 2012. The provenances of asteroids, and their contributions to the volatile
601 inventories of the terrestrial planets. *Science* 337, 721.
- 602 Alexander, C.M.O. 'D, Howard, K.T., Bowden, R., Fogel, M.L., 2013. The classification of CM
603 and CR chondrites using bulk H, C and N abundances and isotopic compositions.
604 *Geochimica et Cosmochimica Acta* 123, 244–260.
- 605 Altwegg, K., Balsiger, H., Hänni, N., Rubin, M., Schuhmann, M., Schroeder, I., Sémon, T.,
606 Wampfler, S., Berthelier, J.-J., Briois, C., Combi, M., Gombosi, T.I., Cottin, H., De
607 Keyser, J., Dhooghe, F., Fiethe, B., Fuselier, S.A., 2020. Evidence of ammonium salts
608 in comet 67P as explanation for the nitrogen depletion in cometary comae. *Nature*
609 *Astronomy* 4, 533.
- 610 Ammannito, E., DeSanctis, M.C., Ciarniello, M., Frigeri, A., Carrozzo, F.G., Combe, J.-P.,
611 Ehlmann, B.L., Marchi, S., McSween, H.Y., Raponi, A., Toplis, M.J., Tosi, F., Castillo-
612 Rogez, J.C., Capaccioni, F., Capria, M.T., Fonte, S., Giardino, M., Jaumann, R.,
613 Longobardo, A., Joy, S.P., Magni, G., McCord, T.B., McFadden, L.A., Palomba, E.,
614 Pieters, C.M., Polanskey, C.A., Rayman, M.D., Raymond, C.A., Schenk, P.M., Zambon,
615 F., Russell, C.T., 2016. Distribution of phyllosilicates on the surface of Ceres. *Science*
616 353, aaf4279.
- 617 Bardyn, A., Baklouti, D., Cottin, H., Fray, N., Briois, C., Paquette, J., Stenzel, O., Engrand, C.,
618 Fischer, H., Hornung, K., Isnard, R., Langevin, Y., Lehto, H., Le Roy, L., Ligier, N.,
619 Merouane, S., Modica, P., Orthous-Daunay, F.-R., Rynö, J., Schulz, R., Silén, J.,
620 Thirkell, L., Varmuza, K., Zaprudin, B., Kissel, J., Hilchenbach, M., 2017. Carbon-rich
621 dust in comet 67P/Churyumov-Gerasimenko measured by COSIMA/Rosetta.
622 *Monthly Notices of the Royal Astronomical Society* 469, S712.
- 623 Bates, H.C., King, A.J., Donaldson Hanna, K.L., Bowles, N.E., Russell, S.S., 2020. Linking
624 mineralogy and spectroscopy of highly aqueously altered CM and CI carbonaceous
625 chondrites in preparation for primitive asteroid sample return. *Meteoritics and*
626 *Planetary Science* 55, 77.
- 627 Battandier, M., Bonal, L., Quirico, E., Beck, P., Engrand, C., Duprat, J., 2016.
628 Characterization of the Organic Matter and Hydration State of a Series of Antarctic
629 Micrometeorites, in: *Lunar and Planetary Science Conference*. p. 1475.
- 630 Beck, P., Garenne, A., Quirico, E., Bonal, L., Montes-Hernandez, G., Moynier, F., Schmitt, B.,
631 2014a. Transmission infrared spectra (2-25 μ m) of carbonaceous chondrites (CI,
632 CM, CV-CK, CR, C2 ungrouped): Mineralogy, water, and asteroidal processes. *Icarus*
633 229, 263–277. <https://doi.org/10.1016/j.icarus.2013.10.019>

- 634 Beck, P., Maturilli, A., Garenne, A., Vernazza, P., Helbert, J., Quirico, E., Schmitt, B., 2018.
635 What is controlling the reflectance spectra (0.35-150 μm) of hydrated (and
636 dehydrated) carbonaceous chondrites? *Icarus*, Volume 313, p. 124-138. 313, 124-
637 138. <https://doi.org/10.1016/j.icarus.2018.05.010>
- 638 Beck, P., Pommerol, A., Thomas, N., Schmitt, B., Moynier, F., Barrat, J.-A., 2012.
639 Photometry of meteorites. *Icarus* 218, 364-377.
- 640 Beck, P., Quirico, E., Garenne, A., Yin, Q.-Z., Bonal, L., Schmitt, B., Montes-Hernandez, G.,
641 Montagnac, G., Chiriac, R., Toche, F., 2014b. The secondary history of Sutter's Mill
642 CM carbonaceous chondrite based on water abundance and the structure of its
643 organic matter from two clasts. *Meteoritics & Planetary Science* 49, 2064-2073.
644 <https://doi.org/10.1111/maps.12273>
- 645 Beck, P., Quirico, E., Montes-Hernandez, G., Bonal, L., Bollard, J., Orthous-Daunay, F.-R.,
646 Howard, K.T., Schmitt, B., Brissaud, O., Deschamps, F., Wunder, B., Guillot, S., 2010.
647 Hydrous mineralogy of CM and CI chondrites from infrared spectroscopy and their
648 relationship with low albedo asteroids. *Geochimica et Cosmochimica Acta* 74,
649 4881-4892.
- 650 **Beck, P., Quirico, E., Sevestre, D., Montes-Hernandez, G., Pommerol, A., Schmitt, B., 2011.**
651 **Goethite as an alternative origin of the 3.1 μm band on dark asteroids.**
652 ***Astronomy & Astrophysics* 526, A85.** [https://doi.org/10.1051/0004-](https://doi.org/10.1051/0004-6361/201015851)
653 [6361/201015851](https://doi.org/10.1051/0004-6361/201015851)
- 654 Beran, A., Koeberl, C., 1997. Water in Tektites and Impact Glasses by FTIR Spectrometry.
655 *Meteoritics and Planetary Science* 32, 211.
- 656 Bischoff, A., Scott, E.R.D., Metzler, K., Goodrich, C.A., 2006. Nature and Origins of
657 Meteoritic Breccias, in: *Meteorites and the Early Solar System II*. p. 679.
- 658 Bonal, L., Beck, P., Nakamura, T., Enokido, Y., Gattacceca, J., Eschrig, J., 2019. A Complex
659 Interplay of Heat and Aqueous Alteration Experienced by the Paris CM Chondrite,
660 in: 82nd Annual Meeting of The Meteoritical Society. p. 6298.
- 661 Bonal, L., Gattacceca, J., Garenne, A., Eschrig, J., Rochette, P., Krämer Ruggiu, L., 2020.
662 Water and heat: New constraints on the evolution of the CV chondrite parent body.
663 *Geochimica et Cosmochimica Acta* 276, 363.
- 664 Burbine, T.H., McCoy, T.J., Meibom, A., Gladman, B., Keil, K., Cellino, A., Paolicchi, P.,
665 Binzel, R.P., 2002. Meteoritic Parent Bodies: Their Number and Identification, in:
666 Bottke, W.F. (Ed.), *Asteroids III*. pp. 653-667.
- 667 **Campins, H., Hargrove, K., Pinilla-Alonso, N., Howell, E.S., Kelley, M.S., Licandro, J., Mothé-**
668 **Diniz, T., Fernández, Y., Ziffer, J., 2010. Water ice and organics on the surface of the**
669 **asteroid 24 Themis. *Nature* 464, 1320-1321.**
- 670 **Carrier, W.D., 1973. Lunar Soil Grain Size Distribution. *Moon*.**
- 671 Capaccioni, F., Cerroni, P., Barucci, M.A., Fulchignoni, M., 1990. Phase curves of
672 meteorites and terrestrial rocks - Laboratory measurements and applications to
673 asteroids. *Icarus* 83, 325-348.
- 674 Carry, B., 2012. Density of asteroids. *Planetary and Space Science* 73, 98-118.
- 675 Carry, B., Vachier, F., Berthier, J., Marsset, M., Vernazza, P., Grice, J., Merline, W.J.,
676 Lagadec, E., Fienga, A., Conrad, A., Podlowska-Gaca, E., Santana-Ros, T., Viikinkoski,
677 M., Hanuš, J., Dumas, C., Drummond, J.D., Tamblyn, P.M., Chapman, C.R., Behrend, R.,
678 Bernasconi, L., Bartczak, P., Benkhaldoun, Z., Birlan, M., Castillo-Rogez, J., Cipriani,
679 F., Colas, F., Drouard, A., Āurech, J., Enke, B.L., Fauvaud, S., Ferrais, M., Fetick, R.,
680 Fusco, T., Gillon, M., Jehin, E., Jorda, L., Kaasalainen, M., Keppler, M., Kryszczyńska,
681 A., Lamy, P., Marchis, F., Marciniak, A., Michalowski, T., Michel, P., Pajuelo, M.,
682 Tanga, P., Vigan, A., Warner, B., Witasse, O., Yang, B., Zurlo, A., 2019. Homogeneous

683 internal structure of CM-like asteroid (41) Daphne. *Astronomy and Astrophysics*
684 623, A132.

685 **Chapman, C.R., 2004. Space Weathering of Asteroid Surfaces. *Annual Review of Earth***
686 **and Planetary Sciences.**

687 **Dellagiustina, D.N., Emery, J.P., Golish, D.R., Rozitis, B., Bennett, C.A., Burke, K.N., Ballouz,**
688 **R.-L., Becker, K.J., Christensen, P.R., Drouet D'Aubigny, C.Y., Hamilton, V.E., Reuter,**
689 **D.C., Rizk, B., Simon, A.A., Asphaug, E., Bandfield, J.L., Barnouin, O.S., Barucci, M.A.,**
690 **Bierhaus, E.B., Binzel, R.P., Bottke, W.F., Bowles, N.E., Campins, H., Clark, B.C., Clark,**
691 **B.E., Connolly, H.C., Daly, M.G., Leon, J.D., Delbo', M., Deshapriya, J.D.P., Elder, C.M.,**
692 **Fornasier, S., Hergenrother, C.W., Howell, E.S., Jawin, E.R., Kaplan, H.H., Kareta, T.R.,**
693 **Le Corre, L., Li, J.-Y., Licandro, J., Lim, L.F., Michel, P., Molaro, J., Nolan, M.C., Pajola,**
694 **M., Popescu, M., Garcia, J.L.R., Ryan, A., Schwartz, S.R., Shultz, N., Siegler, M.A.,**
695 **Smith, P.H., Tatsumi, E., Thomas, C.A., Walsh, K.J., Wolner, C.W.V., Zou, X.-D.,**
696 **Lauretta, D.S., Team, O.-R., 2019. Properties of rubble-pile asteroid (101955)**
697 **Bennu from OSIRIS-REx imaging and thermal analysis. *Nature Astronomy.***

698 De Sanctis, M.C., Ammannito, E., Capria, M.T., Tosi, F., Capaccioni, F., Zambon, F., Carraro,
699 F., Fonte, S., Frigeri, A., Jaumann, R., Magni, G., Marchi, S., McCord, T.B., McFadden,
700 L.A., McSween, H.Y., Mittlefehldt, D.W., Nathues, A., Palomba, E., Pieters, C.M.,
701 Raymond, C.A., Russell, C.T., Toplis, M.J., Turrini, D., 2012. Spectroscopic
702 Characterization of Mineralogy and Its Diversity Across Vesta. *Science* 336, 697.

703 De Sanctis, M.C., Ammannito, E., Raponi, A., Marchi, S., McCord, T.B., McSween, H.Y.,
704 Capaccioni, F., Capria, M.T., Carrozzo, F.G., Ciarniello, M., Longobardo, A., Tosi, F.,
705 Fonte, S., Formisano, M., Frigeri, A., Giardino, M., Magni, G., Palomba, E., Turrini, D.,
706 Zambon, F., Combe, J.-P., Feldman, W., Jaumann, R., McFadden, L.A., Pieters, C.M.,
707 Prettyman, T., Toplis, M., Raymond, C.A., Russell, C.T., 2015. Ammoniated
708 phyllosilicates with a likely outer Solar System origin on (1) Ceres. *Nature* 528,
709 241–244.

710 DeMeo, F.E., Carry, B., 2014. Solar System evolution from compositional mapping of the
711 asteroid belt. *Nature* 505, 629–634.

712 DeMeo, F.E., Carry, B., 2013. The taxonomic distribution of asteroids from multi-filter all-
713 sky photometric surveys. *Icarus* 226, 723–741.
714 <https://doi.org/10.1016/j.icarus.2013.06.027>

715 Drouard, A., Gattacceca, J., Hutzler, A., Rochette, P., Braucher, R., Boursier, D., Gounelle, M.,
716 Morbidelli, A., Debaille, V., Van Ginneken, M., Valenzuela, M., Quesnel, Y., Martinez,
717 R., 2019. The meteorite flux of the past 2 m.y. recorded in the Atacama Desert.
718 *Geology* 47, 673.

719 Dunn, T.L., Burbine, T.H., Bottke, W.F., Clark, J.P., 2013. Mineralogies and source regions
720 of near-Earth asteroids. *Icarus* 222, 273.

721 Fornasier, S., Lazzarin, M., Barbieri, C., Barucci, M.A., 1999. Spectroscopic comparison of
722 aqueous altered asteroids with CM2 carbonaceous chondrite meteorites.
723 *Astronomy and Astrophysics Supplement Series* 135, 65–73.

724 Galliano, A., Diri, F., Palomba, E., Longobardo, A., Schmitt, B., Beck, P., 2020. Spectral
725 investigation of Ceres analogue mixtures: in-depth analysis of crater central peak
726 material (ccp) on Ceres. *Icarus*.

727 Garenne, A., Beck, P., Montes-Hernandez, G., Chiriac, R., Toche, F., Quirico, E., Bonal, L.,
728 Schmitt, B., 2014. The abundance and stability of “water” in type 1 and 2
729 carbonaceous chondrites (CI, CM and CR). *Geochimica Et Cosmochimica Acta* 137,
730 93–112. <https://doi.org/10.1016/j.gca.2014.03.034>

731 Gilmour, C.M., Herd, C.D.K., Beck, P., 2019. Water abundance in the Tagish Lake
732 meteorite from TGA and IR spectroscopy: Evaluation of aqueous alteration.
733 *Meteoritics and Planetary Science* 54, 1951–1972.

734 Gradie, J.C., Veverka, J., Buratti, B.J., 1980. The Effects of Photometric Geometry on
735 Spectral Reflectance, in: *Lunar and Planetary Science Conference*. p. 357.

736 **Hanna, R.D., Hamilton, V.E., Haberle, C.W., King, A.J., Abreu, N.M., Friedrich, J.M., 2020.**
737 **Distinguishing relative aqueous alteration and heating among CM chondrites with**
738 **IR spectroscopy. *Icarus*.**

739 Hapke, B., 2012. Theory of reflectance and emittance spectroscopy.

740 Herique, A., Agnus, B., Asphaug, E., Barucci, A., Beck, P., Bellerose, J., Biele, J., Bonal, L.,
741 Bousquet, P., Bruzzone, L., Buck, C., Carnelli, I., Cheng, A., Ciarletti, V., Delbo, M., Du,
742 J., Du, X., Eyraud, C., Fa, W., Gil Fernandez, J., Gassot, O., Granados-Alfaro, R., Green,
743 S.F., Grieger, B., Grundmann, J.T., Grygorczuk, J., Hahnel, R., Heggy, E., Ho, T.-M.,
744 Karatekin, O., Kasaba, Y., Kobayashi, T., Kofman, W., Krause, C., Kumamoto, A.,
745 Küppers, M., Laabs, M., Lange, C., Lasue, J., Levasseur-Regourd, A.C., Mallet, A.,
746 Michel, P., Mottola, S., Murdoch, N., Mütze, M., Oberst, J., Orosei, R., Plettemeier, D.,
747 Rochat, S., RodriguezSuquet, R., Rogez, Y., Schaffer, P., Snodgrass, C., Souyris, J.-C.,
748 Tokarz, M., Ulamec, S., Wahlund, J.-E., Zine, S., 2018. Direct observations of asteroid
749 interior and regolith structure: Science measurement requirements. *Advances in*
750 *Space Research*, Volume 62, Issue 8, p. 2141-2162. 62, 2141–2162.
751 <https://doi.org/10.1016/j.asr.2017.10.020>

752 Hinrichs, J.L., Lucey, P.G., 2002a. Temperature-Dependent Near-Infrared Spectral
753 Properties of Minerals, Meteorites, and Lunar Soil. *Icarus* 155, 169–180.

754 Hinrichs, J.L., Lucey, P.G., 2002b. Temperature-Dependent Near-Infrared Spectral
755 Properties of Minerals, Meteorites, and Lunar Soil. *Icarus* 155, 169–180.

756 Hiroi, T., Zolensky, M.E., Pieters, C.M., Lipschutz, M.E., 1996. Thermal metamorphism of
757 the C, G, B, and F asteroids seen from the 0.7 micron, 3 micron and UV absorption
758 strengths in comparison with carbonaceous chondrites. *Meteoritics and Planetary*
759 *Science* 31, 321–327.

760 Howard, K.T., Benedix, G.K., Bland, P.A., Cressey, G., 2011. Modal mineralogy of CM
761 chondrites by X-ray diffraction (PSD-XRD): Part 2. Degree, nature and settings of
762 aqueous alteration. *Geochimica et Cosmochimica Acta* 75, 2735–2751.

763 Howard, K.T., Benedix, G.K., Bland, P.A., Cressey, G., 2010. Modal mineralogy of CV3
764 chondrites by X-ray diffraction (PSD-XRD). *Geochimica et Cosmochimica Acta* 74,
765 5084–5097.

766 Howard, K.T., Benedix, G.K., Bland, P.A., Cressey, G., 2009. Modal mineralogy of CM2
767 chondrites by X-ray diffraction (PSD-XRD). Part 1: Total phyllosilicate abundance
768 and the degree of aqueous alteration. *Geochimica et Cosmochimica Acta* 73, 4576–
769 4589.

770 Kaplan, H.H., Milliken, R.E., Alexander, C.M.O., Herd, C.D.K., 2019. Reflectance
771 spectroscopy of insoluble organic matter (IOM) and carbonaceous meteorites.
772 *Meteoritics and Planetary Science* 54, 1051.

773 **King, A.J., Schofield, P.F., Russell, S.S., 2017. Type 1 aqueous alteration in CM**
774 **carbonaceous chondrites: Implications for the evolution of water-rich asteroids.**
775 ***Meteoritics and Planetary Science*.**

776 **King, A.J., Solomon, J.R., Schofield, P.F., Russell, S.S., 2015. Characterising the CI and CI-**
777 **like carbonaceous chondrites using thermogravimetric analysis and infrared**
778 **spectroscopy. *Earth, Planets, and Space*.**

779 King, T.V.V., Clark, R.N., Calvin, W.M., Sherman, D.M., Brown, R.H., 1992. Evidence for
780 ammonium-bearing minerals on Ceres. *Science* 255, 1551–1553.

781 Kitazato, K., Milliken, R.E., Iwata, T., Abe, M., Ohtake, M., Matsuura, S., Arai, T., Nakauchi,
782 Y., Nakamura, T., Matsuoka, M., Senshu, H., Hirata, N., Hiroi, T., Pilorget, C.,
783 Brunetto, R., Poulet, F., Riu, L., Bibring, J.-P., Takir, D., Domingue, D.L., Vilas, F.,
784 Barucci, M.A., Perna, D., Palomba, E., Galiano, A., Tsumura, K., Osawa, T., Komatsu,
785 M., Nakato, A., Arai, T., Takato, N., Matsunaga, T., Takagi, Y., Matsumoto, K.,
786 Kouyama, T., Yokota, Y., Tatsumi, E., Sakatani, N., Yamamoto, Y., Okada, T., Sugita, S.,
787 Honda, R., Morota, T., Kameda, S., Sawada, H., Honda, C., Yamada, M., Suzuki, H.,
788 Yoshioka, K., Hayakawa, M., Ogawa, K., Cho, Y., Shirai, K., Shimaki, Y., Hirata, N.,
789 Yamaguchi, A., Ogawa, N., Terui, F., Yamaguchi, T., Takei, Y., Saiki, T., Nakazawa, S.,
790 Tanaka, S., Yoshikawa, M., Watanabe, S., Tsuda, Y., 2019. The surface composition
791 of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy. *Science*.

792 Krot, A.N., Keil, K., Scott, E.R.D., Goodrich, C.A., Weisberg, M., n.d. Classification of
793 meteorites, in: *Treatise on Geochemistry*. Elsevier.

794 Lantz, C., Brunetto, R., Barucci, M.A., Fornasier, S., Baklouti, D., Bourçois, J., Godard, M.,
795 2017. Ion irradiation of carbonaceous chondrites: A new view of space weathering
796 on primitive asteroids. *Icarus* 285, 43–57.

797 Lebofsky, L.A., Feierberg, M.A., Tokunaga, A.T., Larson, H.P., Johnson, J.R., 1981. The 1.7-
798 to 4.2-micron spectrum of asteroid 1 Ceres - Evidence for structural water in clay
799 minerals. *Icarus* 48, 453–459.

800 Lee, M.R., Lindgren, P., King, A.J., Greenwood, R.C., Franchi, I.A., Sparkes, R., 2016.
801 Elephant Moraine 96029, a very mildly aqueously altered and heated CM
802 carbonaceous chondrite: Implications for the drivers of parent body processing.
803 *Geochimica et Cosmochimica Acta* 187, 237.

804 Marchi, S., Raponi, A., Prettyman, T.H., De Sanctis, M.C., Castillo-Rogez, J., Raymond, C.A.,
805 Ammannito, E., Bowling, T., Ciarniello, M., Kaplan, H., Palomba, E., Russell, C.T.,
806 Vinogradoff, V., Yamashita, N., 2019. An aqueously altered carbon-rich Ceres.
807 *Nature Astronomy* 3, 140.

808 Marty, B., 2012. The origins and concentrations of water, carbon, nitrogen and noble
809 gases on Earth. *Earth and Planetary Science Letters* 313, 56.

810 Masiero, J.R., Mainzer, A.K., Grav, T., Bauer, J.M., Cutri, R.M., Dailey, J., Eisenhardt, P.R.M.,
811 McMillan, R.S., Spahr, T.B., Skrutskie, M.F., Tholen, D., Walker, R.G., Wright, E.L.,
812 DeBaun, E., Elsbury, D., Gautier, T., Gomillion, S., Wilkins, A., 2011. Main Belt
813 Asteroids with WISE/NEOWISE. I. Preliminary Albedos and Diameters. *The*
814 *Astrophysical Journal* 741, 68.

815 Matsuoka, M., Nakamura, T., Hiroi, T., Okumura, S., Sasaki, S., 2020. Space Weathering
816 Simulation with Low-energy Laser Irradiation of Murchison CM Chondrite for
817 Reproducing Micrometeoroid Bombardments on C-complex Asteroids. *The*
818 *Astrophysical Journal* 890, L23.

819 Milliken, R.E., Mustard, J.F., 2005. Quantifying absolute water content of minerals using
820 near-infrared reflectance spectroscopy. *Journal of Geophysical Research (Planets)*
821 110.

822 Miyamoto, M., Zolensky, M.E., 1994. Infrared Diffuse Reflectance Spectra of
823 Carbonaceous Chondrites: Amount of Hydrous Minerals. *Meteoritics* 29, 849.

824 Morbidelli, A., Gladman, B., 1998. Orbital and temporal distributions of meteorites
825 originating in the asteroid belt. *Meteoritics and Planetary Science* 33, 999.

826 Nakamura, T., 2005. Post-hydration thermal metamorphism of carbonaceous chondrites.
827 *Journal of Mineralogical and Petrological Sciences* 100, 260–272.

828 Nakamura, T., Noguchi, T., Tanaka, M., Zolensky, M.E., Kimura, M., Tsuchiyama, A.,
829 Nakato, A., Ogami, T., Ishida, H., Uesugi, M., Yada, T., Shirai, K., Fujimura, A., Okazaki,
830 R., Sandford, S.A., Ishibashi, Y., Abe, M., Okada, T., Ueno, M., Mukai, T., Yoshikawa,
831 M., Kawaguchi, J., 2011. Itokawa Dust Particles: A Direct Link Between S-Type
832 Asteroids and Ordinary Chondrites. *Science* 333, 1113-.

833 Osawa, T., Kagi, H., Nakamura, T., Noguchi, T., 2005. Infrared spectroscopic taxonomy for
834 carbonaceous chondrites from speciation of hydrous components. *Meteoritics and*
835 *Planetary Science*.

836 Pieters, C.M., Noble, S.K., 2016. Space weathering on airless bodies. *Journal of*
837 *Geophysical Research (Planets)* 121, 1865.

838 Pironon, J., Pelletier, M., de Donato, P., Mosser-Ruck, R., 2003. Characterization of
839 smectite and illite by FTIR spectroscopy of interlayer NH₄⁺cations. *Clay Minerals*
840 38, 201.

841 Poch, O., Istiqomah, I., Quirico, E., Beck, P., B., Schmitt, B., Theulé, P., Faure, A., Hily-Blant,
842 P., Rousseau, B., Potin, S., Brissaud, O., Flandinet, L., Bonal, L., Raponi, A., Ciarniello,
843 M., Filacchione, G., Pommerol, A., Thomas, N., Kapel, D., Mennella, V., Moroz, L.,
844 Vinogradoff, V., Arnold, G., Bockelee-Morvan, Capaccioni, F., De Sanctis, M.C., Erard,
845 S., Leyrat, C., Longobardo, A., Palomba, E., Tosi, F., 2020. First detection of
846 ammonium salts on a cometary nucleus, revealing a new reservoir of nitrogen.
847 *Science*.

848 Pommerol, A., Schmitt, B., 2008. Strength of the H₂O near-infrared absorption bands in
849 hydrated minerals: Effects of particle size and correlation with albedo. *Journal of*
850 *Geophysical Research (Planets)* 113.

851 Potin, S., Beck, P., Schmitt, B., Moynier, F., 2019. Some things special about NEAs:
852 Geometric and environmental effects on the optical signatures of hydration. *Icarus*
853 333, 415.

854 Potin, S., Beck, P., Usui, F., Bonal, L., Vernazza, P., Schmitt, B., 2020a. Style and intensity of
855 hydration among C-complex asteroids: A comparison to desiccated carbonaceous
856 chondrites. *Icarus* 348, 113826.

857 Potin, S., Brissaud, O., Beck, P., Schmitt, B., Magnard, Y., Correia, J.-J., Rabou, P., Jocu, L.,
858 2018. SHADOWS: a spectro-gonio radiometer for bidirectional reflectance studies
859 of dark meteorites and terrestrial analogs: design, calibrations, and performances
860 on challenging surfaces. *Applied Optics*, vol. 57, issue 28, p. 8279-8279.
861 <https://doi.org/10.1364/AO.57.008279>

862 Potin, S., Manigand, S., Beck, P., Wolters, C., Schmitt, B., 2020b. A model of the 3- μ m
863 hydration band with Exponentially Modified Gaussian (EMG) profiles: Application
864 to hydrated chondrites and asteroids. *Icarus* 343, 113686.

865 Prettyman, T.H., Yamashita, N., Toplis, M.J., McSween, H.Y., Schörghofer, N., Marchi, S.,
866 Feldman, W.C., Castillo-Rogez, J., Forni, O., Lawrence, D.J., Ammannito, E., Ehlmann,
867 B.L., Sizemore, H.G., Joy, S.P., Polanskey, C.A., Rayman, M.D., Raymond, C.A., Russell,
868 C.T., 2017. Extensive water ice within Ceres' aqueously altered regolith: Evidence
869 from nuclear spectroscopy. *Science* 355, 55.

870 Quirico, E., Bonal, L., Beck, P., Alexander, C.M.O., Yabuta, H., Nakamura, T., Nakato, A.,
871 Flandinet, L., Montagnac, G., Schmitt-Kopplin, P., Herd, C.D.K., 2018. Prevalence and
872 nature of heating processes in CM and C2-ungrouped chondrites as revealed by
873 insoluble organic matter. *Geochimica et Cosmochimica Acta*, Volume 241, p. 17-37.
874 241, 17-37. <https://doi.org/10.1016/j.gca.2018.08.029>

875 Raymond, S.N., Izidoro, A., 2017. The empty primordial asteroid belt. *Science Advances*
876 3, e1701138.

877 Rivkin, A.S., Davies, J.K., Johnson, J.R., Ellison, S.L., Trilling, D.E., Brown, R.H., Lebofsky,
878 L.A., 2003. Hydrogen concentrations on C-class asteroids derived from remote
879 sensing. *Meteoritics and Planetary Science* 38, 1383–1398.

880 Rivkin, A.S., Howell, E.S., Emery, J.P., 2019. Infrared Spectroscopy of Large, Low-Albedo
881 Asteroids: Are Ceres and Themis Archetypes or Outliers? *Journal of Geophysical*
882 *Research (Planets)* 124, 1393.

883 Rivkin, A.S., Campins, H., Emery, J.P., Howell, E.S., Licandro, J., Takir, D., Vilas, F., DeMeo,
884 F.E., Bottke, W.F., 2015. *Astronomical Observations of Volatiles on Asteroids*, in:
885 Michel, P. (Ed.), *Asteroids IV*. pp. 65–87.

886 Rivkin, A.S., Emery, J.P., 2010. *Detection of ice and organics on an asteroidal surface.*
887 *Nature* 464, 1322–1323.

888 Rubin, A.E., Trigo-Rodríguez, J.M., Huber, H., Wasson, J.T., 2007. Progressive aqueous
889 alteration of CM carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 71,
890 2361–2382.

891 Sato, K., Miyamoto, M., Zolensky, M.E., 1997. Absorption bands near 3 μ m in diffuse
892 reflectance spectra of carbonaceous chondrites: Comparison with asteroids.
893 *Meteoritics and Planetary Science* 32.

894 Takir, D., Emery, J.P., McSween, H.Y., Hibbitts, C.A., Clark, R.N., Pearson, N., Wang, A.,
895 2013. Nature and degree of aqueous alteration in CM and CI carbonaceous
896 chondrites. *Meteoritics and Planetary Science* 48, 1618–1637.

897 Takir, D., Stockstill-Cahill, K.R., Hibbitts, C.A., Nakauchi, Y., 2019. 3- μ m reflectance
898 spectroscopy of carbonaceous chondrites under asteroid-like conditions. *Icarus*
899 333, 243.

900 Usui, F., Hasegawa, S., Ootsubo, T., Onaka, T., 2019. AKARI/IRC near-infrared asteroid
901 spectroscopic survey: AcuA-spec. *Publications of the Astronomical Society of Japan*
902 71.

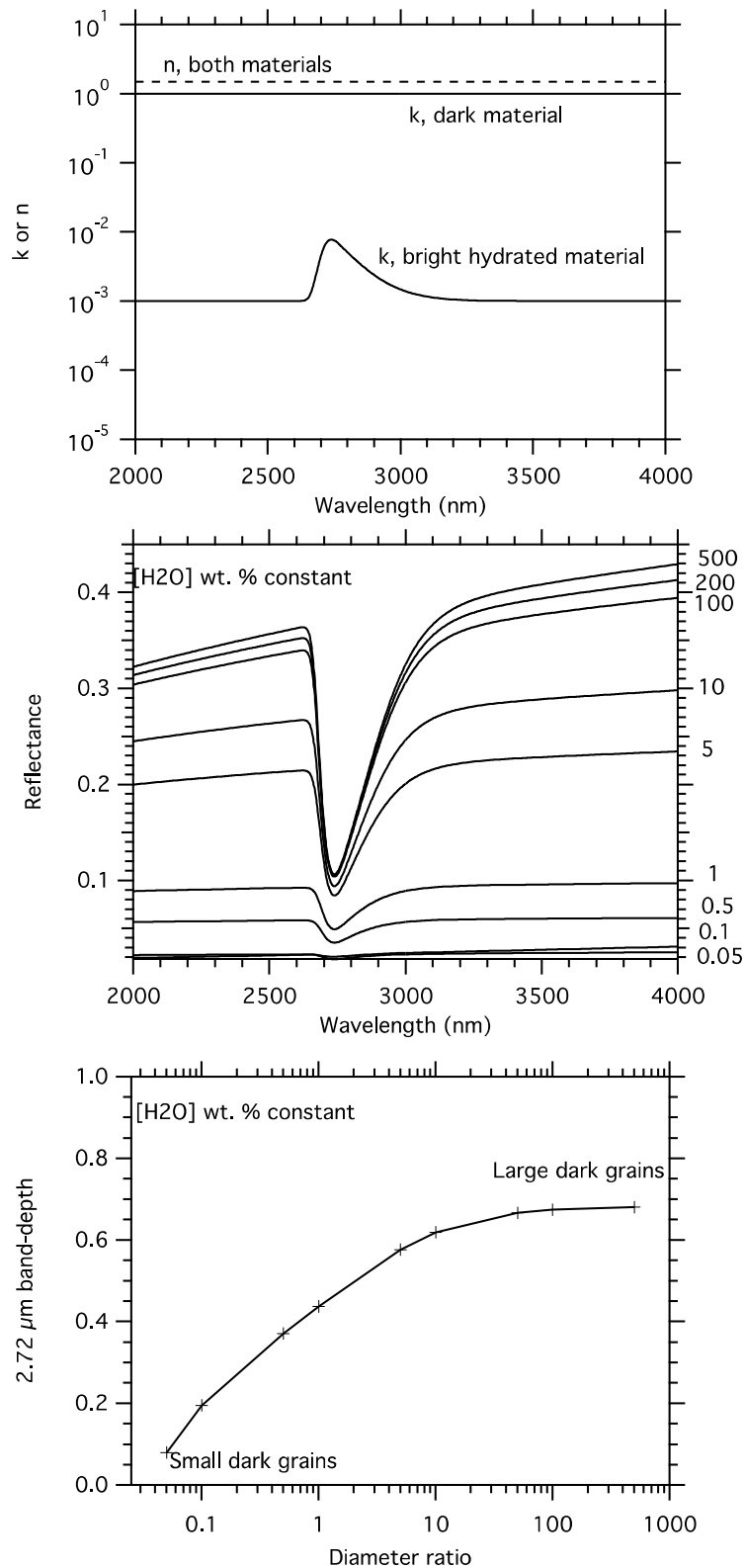
903 Vacher, L.G., Piani, L., Rigaudier, T., Thomassin, D., Florin, G., Piralla, M., Marrocchi, Y.,
904 2020. Hydrogen in chondrites: Influence of parent body alteration and
905 atmospheric contamination on primordial components. *Geochimica et*
906 *Cosmochimica Acta* 281, 53.

907 Vernazza, P., Beck, P., 2017. *Composition of Solar System small bodies*, in: *Planetesimals*.
908 Cambridge Univ. Press.

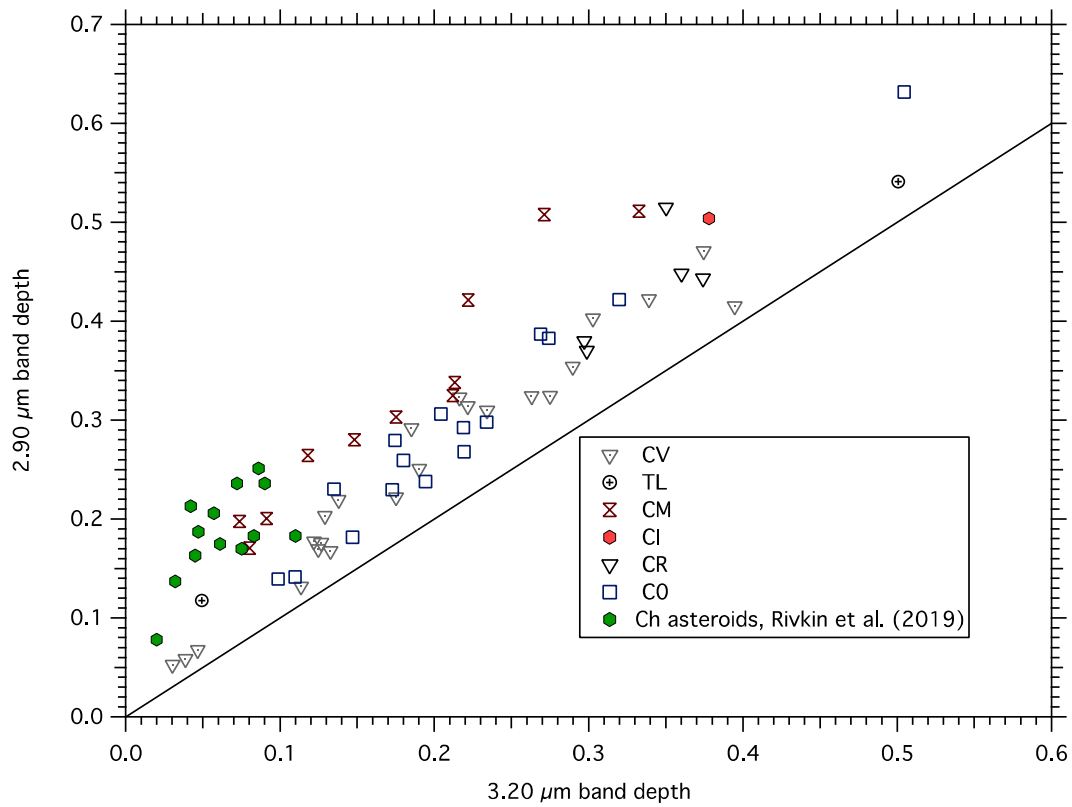
909 Vernazza, P., Marsset, M., Beck, P., Binzel, R.P., Birlan, M., Brunetto, R., Demeo, F.E.,
910 Djouadi, Z., Dumas, C., Merouane, S., Mousis, O., Zanda, B., 2015. Interplanetary
911 Dust Particles as Samples of Icy Asteroids. *The Astrophysical Journal* 806.

912 Walsh, K.J., Morbidelli, A., Raymond, S.N., O'Brien, D.P., Mandell, A.M., 2012. Populating
913 the asteroid belt from two parent source regions due to the migration of giant
914 planets—"The Grand Tack". *Meteoritics and Planetary Science* 47, 1941–1947.

915

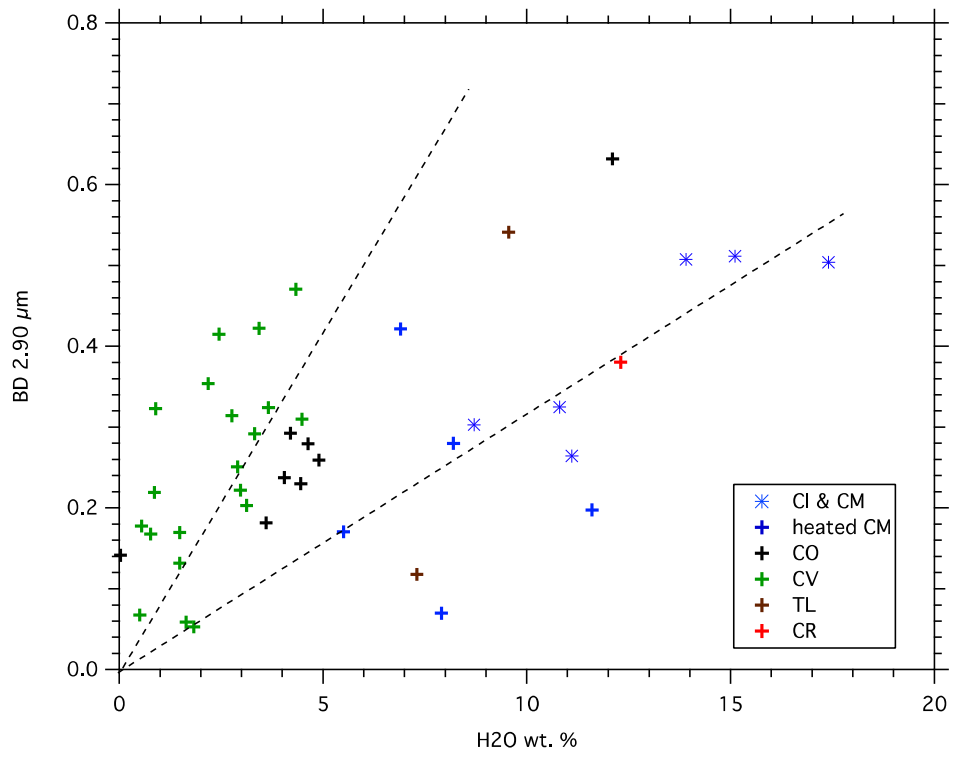


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 917 **FIGURE 1: Mixing model of hydrated material with a dark component, using synthetic**
 918 **optical constants. Top) Optical constants used for these calculations. Middle) Modeled**
 919 **reflectance for changes in the grain size ratio. Bottom) 2.72 μm band depth calculated**
 920 **for the various mixtures.** Note that the water content of the mixture is constant but the
 921 relative grain size of the two constituents is changed.
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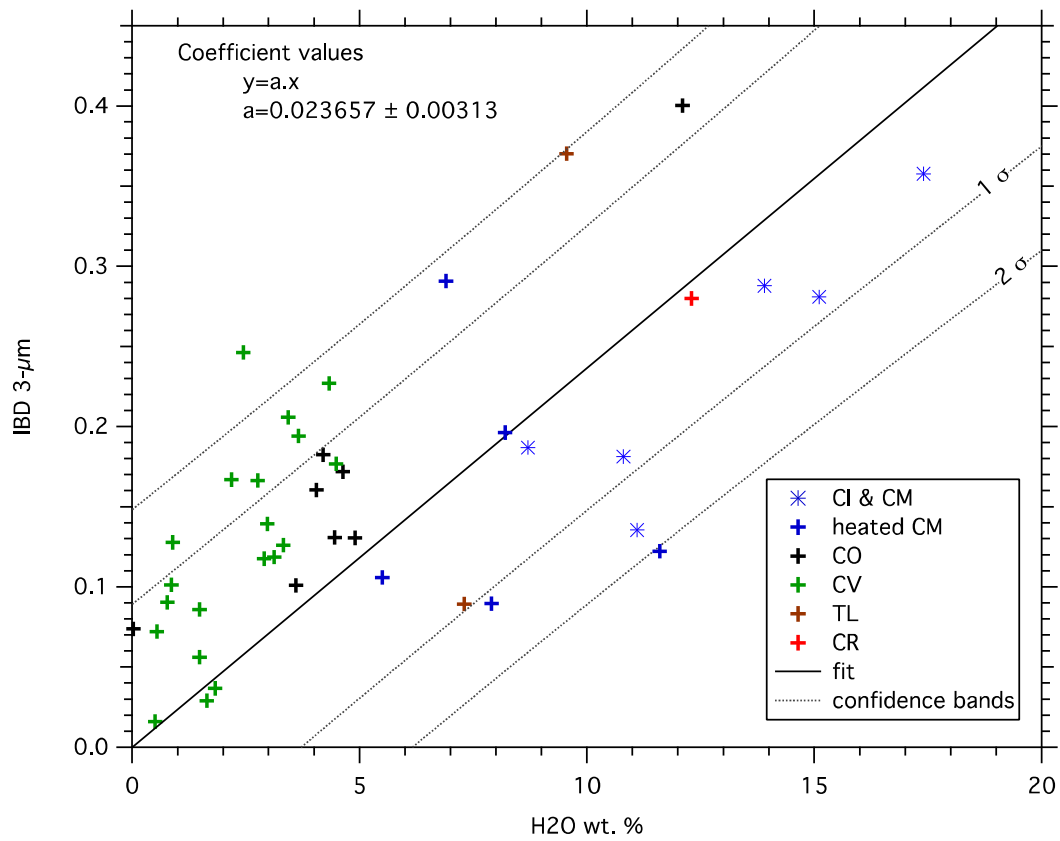
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FIGURE 2: Band depth at 2.90 μm against band depth at 3.20 μm of meteorite powders of different classes measured under simulated asteroidal conditions. The black line is $y=x$. The two Tagish Lake measurements correspond to two different lithologies.



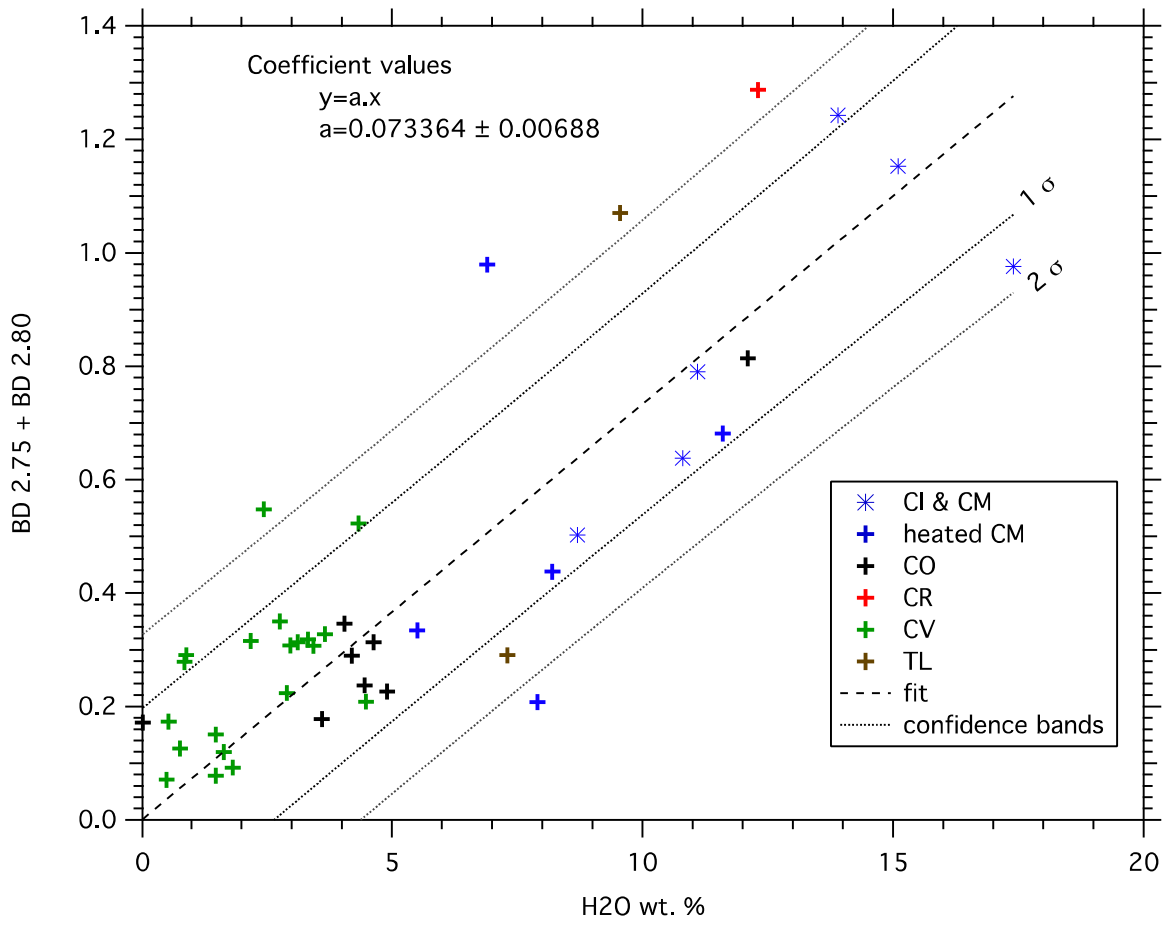
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FIGURE 3: The 2.90 μm band depth as a function of water content (TGA analysis) for different classes of carbonaceous chondrites. Two distinct trends appear for CI & CM and CO-CV. A unique quantification scheme for carbonaceous chondrites is not possible.



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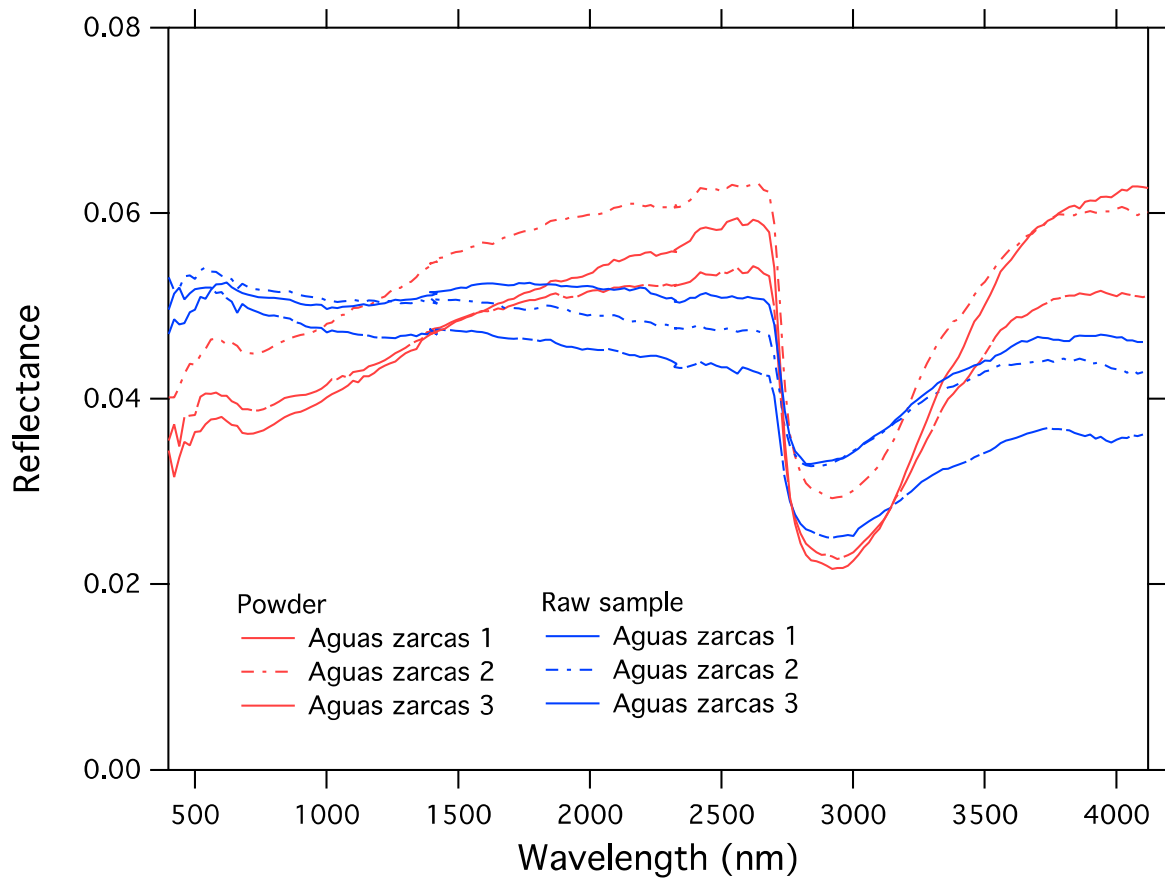
FIGURE 4: The integrated 3- μm band depth as a function of water contents (TGA analysis) for different classes of carbonaceous chondrites. Two distinct trends appear for CI & CM and CO-CV. A unique quantification scheme for carbonaceous chondrites is not possible.



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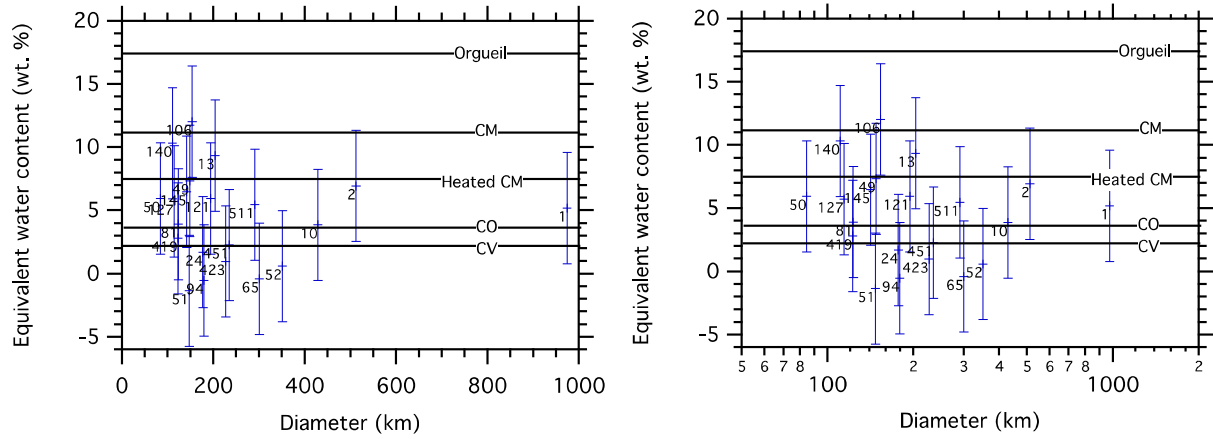
FIGURE 5: Spectral criterion used for the remote quantification of water compared to the water content (measured by TGA) of different classes of carbonaceous chondrites. **W**

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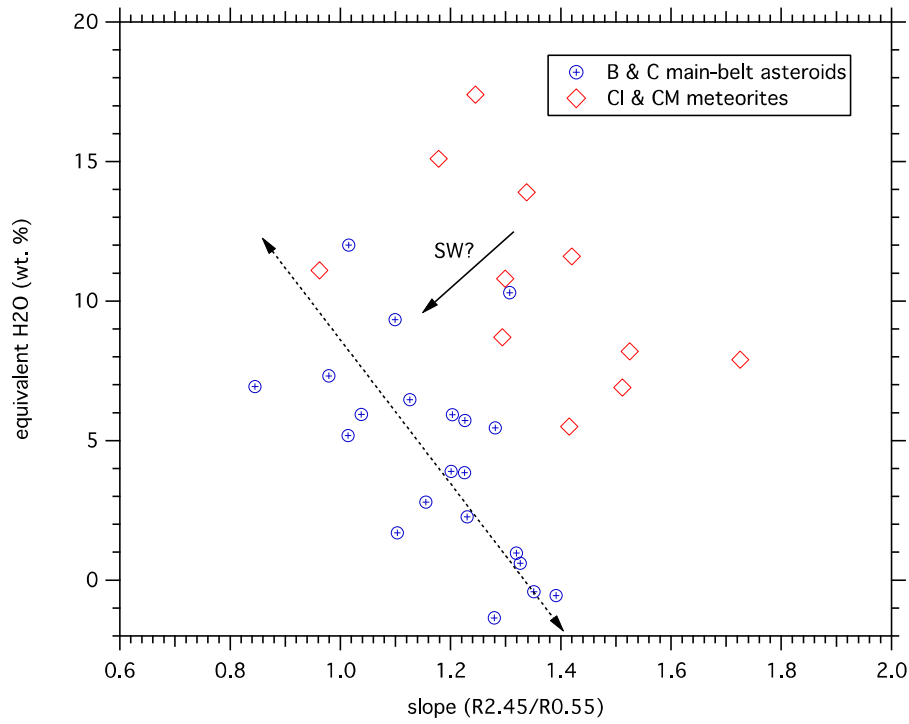
FIGURE 6: The effect of texture (rock vs powder) on the reflectance spectra of CM chondrites. Note that these spectra were not measured under vacuum. **The three different samples correspond to three different lithologies from a large piece of the meteorite.**



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FIGURE 7: Equivalent water content estimated for large **C-complex** asteroids. The water content were estimated from reflectance spectra obtained from AKARI (Usui et al., 2018) with the exception of Ceres (Marchi et al., 2018). **The horizontal lines are averaged for a given group, but note that there is important variability within each group (Table 1).**

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FIGURE 8: Vis-IR spectral slope as a function of equivalent water content C-complex main-belt asteroids and CI & CM meteorites. SW=Solar Wind.

976 Table 1: List of samples that were used in this study and the corresponding band depth
 977 at selected wavelength. The H2O estimated from TGA are taken from Garenne et al.
 978 (2014) and Bonal et al. (2020). Note that they correspond to the 200-770° mass loss as
 979 used in Garenne et al. for CI and CM and to the 200-900°C mass loss for CO, CV and CR
 980 (Bonal et al., 2020). *The star symbol denotes samples that were measured under
 981 vacuum at 25°C, unlike others that were measured under vacuum at 80-100°C. **The
 982 mass loss for Tagish Lake lithologies is from Gilmour et al. (2019)(200-700°C, average of
 983 two aliquotes). Paris lithologies were studied in Bonal et a. (2019) and Tagish Lake
 984 lithologies are described in Gilmour et a. (2020).
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Group	Name	H2O from TGA (wt. %)	Band depth wavelength					
			2750	2800	2750+2800	2900	3200	
CI	Orgueil	17.4	0.491	0.485	0.976	0.504	0.378	
CM	ALH 83100	13.9	0.612	0.631	1.242	0.508	0.271	
CM heated	ALH 84033	6.9	0.493	0.486	0.979	0.421	0.222	
	DOM							
CM	08003	15.1	0.571	0.582	1.153	0.511	0.333	
CM heated	EET 96029	8.2	0.255	0.182	0.438	0.28	0.148	
CM heated	MAC 88100	11.6	0.297	0.385	0.682	0.198	0.074	
CM	MET 01070	11.1	0.361	0.429	0.79	0.264	0.118	
CM heated	MIL 07700	5.5	0.182	0.152	0.334	0.17	0.08	
CM	Murchison	10.8	0.361	0.277	0.638	0.325	0.212	
CM	QUE 97990	8.7	0.308	0.195	0.503	0.303	0.175	
CM heated	WIS 91600	7.9	0.105	0.103	0.208	0.07	-0.004	
CM	Paris B1-4B	*	0.372	0.243	0.615	0.338	0.213	
CM	Paris B2-3D	*	0.051	0.038	0.089	0.032	-0.003	
	Paros B2-							
CM	3B	*	0.182	0.122	0.303	0.201	0.091	
CO	ALH 77003	3.6	0.113	0.064	0.178	0.182	0.147	
	DOM							
CO	08006	4.5	0.219	0.127	0.346	0.238	0.194	
CO	MIL 05024	4.4	0.161	0.077	0.238	0.23	0.135	
CO	MIL 07193	4.6	0.21	0.103	0.314	0.279	0.174	
CO	ALH 83108	*	0.138	0.045	0.182	0.23	0.173	
CO	EET 092126	*	0.155	0.045	0.2	0.298	0.234	
CO	MET 00737	*	0.179	0.052	0.231	0.306	0.204	
CO	MIL 05104	*	4.2	0.193	0.097	0.29	0.293	0.219
CO	MIL 07687	*	12.1	0.539	0.275	0.814	0.632	0.504

CO	MIL 07709	*		0.267	0.091	0.358	0.387	0.269
CO	MIL 07709	*	<0.1	0.112	0.059	0.172	0.142	0.11
CO	Moss	*		0.067	0.023	0.09	0.139	0.099
CO	Kainsaz	*		0.282	0.11	0.392	0.383	0.274
CO	LAP 031117	*		0.278	0.119	0.397	0.422	0.32
CO	QUE 97416	*		0.164	0.064	0.228	0.268	0.219
CO	ALH 85003		4.9	0.168	0.059	0.227	0.259	0.18
CR	EET 92042			0.335	0.189	0.524	0.38	0.297
CR	GRA 95229			0.377	0.2	0.577	0.443	0.374
CR	GRO 95577		12.3	0.615	0.673	1.288	0.515	0.35
CR	LAP 04720			0.307	0.157	0.464	0.37	0.299
CR	MIL 090657			0.369	0.221	0.59	0.448	0.36
CV	ALH 81033			0.093	0.023	0.115	0.176	0.127
CV	ALH 85006			0.265	0.122	0.387	0.403	0.303
CV	Allende		0.8	0.102	0.024	0.126	0.168	0.133
CV	Axtell		2.4	0.339	0.209	0.548	0.415	0.395
CV	Efremovka			0.224	0.088	0.311	0.324	0.263
CV	GRA 06101		0.5	0.113	0.06	0.173	0.178	0.122
CV	GRO 95652		3.7	0.225	0.103	0.328	0.324	0.275
CV	Grosnaja		2.9	0.157	0.067	0.224	0.251	0.19
CV	Kaba		4.5	0.168	0.041	0.209	0.31	0.234
CV	LAP 02206		0.5	0.037	0.034	0.071	0.068	0.047
CV	LAR 06317		3.4	0.242	0.066	0.307	0.422	0.339
CV	MCY 05219		1.5	0.061	0.017	0.078	0.132	0.114
CV	MET 00761		2.2	0.226	0.089	0.316	0.354	0.29
CV	MIL 07002		0.9	0.212	0.078	0.291	0.323	0.216
CV	MIL 07277		1.5	0.11	0.04	0.151	0.17	0.125
CV	MIL 07671		0.9	0.174	0.105	0.279	0.219	0.138
CV	MIL 091010		3.3	0.222	0.096	0.318	0.292	0.185
CV	Mokoia		1.8	0.051	0.042	0.092	0.053	0.03
CV	QUE 94688		4.3	0.358	0.165	0.523	0.471	0.374
CV	RBT 04302		2.8	0.234	0.116	0.35	0.314	0.222
CV	Leoville		3.0	0.212	0.096	0.308	0.222	0.175
CV	Vigarano		3.1	0.189	0.125	0.314	0.203	0.129
CV	MET 01074		1.6	0.065	0.055	0.12	0.059	0.039
Tagish Lake	TL 11h	**	9.6	0.538	0.533	1.070	0.541	0.500
Tagish Lake	TL4	**	7.3	0.143	0.147	0.290	0.118	0.049

#	Name	D	p_v	Tax.	Tax.	3- μ m shape	BD Combo	H ₂ O	slope	Ref
		km		(B&D)	(Bus)			wt. %		
1	Ceres	974	0.087	C	C	Ceres-like	0.39	5.18	1.01	1
2	Pallas	512	0.150	B	-	sharp	0.75	6.94	0.85	2
10	Hygiea	429	0.066	C	-	Ceres-like	0.15	3.86	1.23	2
13	Egeria	203	0.086	Ch	-	sharp	0.67	9.34	1.10	2
24	Themis	177	0.084	C	C	rounded	0.53	1.70	1.10	2
49	Pales	148	0.061	Ch	-	sharp	0.85	7.32	0.98	2
50	Virginia	84	0.050	Ch	C	sharp	0.43	5.94	1.04	2
51	Nemausa	147	0.094	Cgh	-	sharp	0.79	0.00	1.28	2
52	Europa	350	0.043	C	-	Europa-like	-0.37	0.60	1.33	2
65	Cybele	301	0.044	Xk	C	rounded	-0.18	0.00	1.35	2
81	Terpsichore	123	0.048	C	-	sharp	0.32	3.90	1.20	2
94	Aurora	179	0.053	C	-	-	-0.10	0.00	1.39	2
								12.0		
106	Dione	153	0.084	Cgh	Cgh	sharp	0.80	1	1.02	2
121	Hermione	194	0.058	Ch	-	sharp	0.48	5.93	1.20	2
127	Johanna	114	0.065	Ch	Ch	sharp	0.46	5.73	1.23	2
								10.3		
140	Siwa	111	0.067	Xc	Cb	-	-0.05	1	1.31	2
145	Adeona	141	0.050	Ch	Ch	sharp	0.40	6.47	1.13	2
419	Aurelia	122	0.051	C	Cb	-	0.12	2.79	1.16	2
423	Diotima	227	0.049	C	-	sharp?	0.23	0.97	1.32	2
451	Patientia	235	0.071	C	Cb	Europa-like	-0.16	2.26	1.23	2
511	Davida	291	0.070	C	X	sharp	0.44	5.46	1.28	2

989 Table 2: List of asteroids used in this study. Albedo and band shape were compiled in
990 Usui et al., 2019. 1=DeSanctis et al., 2015; 2=Usui et al., 2018. B&D=Bus -DeMeo
991 taxonomy, B : Bus taxonomy