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# 1 Low-phase spectral reflectance and equivalent “geometric 2 albedo” of meteorites powders

3

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10

11 **Abstract:** Generally, the reflectance of a particulate surface depends on the phase angle  
12 at which it is observed. This is true for laboratory measurements on powders of natural  
13 materials as well as remote observations of Solar System surfaces. Here, we measured  
14 the dependences of reflectance spectra with phase angles, of a suite of 72 meteorites in  
15 the 400-2600 nm range. The 10-30° phase angle range is investigated in order to study  
16 the contribution of Shadow Hiding Opposition Effect (SHOE) to the phase behavior. The  
17 behavior is then extrapolated to phase angle of 0° using a polynomial fit, in order to  
18 provide grounds for comparison across meteorite groups (enabling to remove the  
19 contribution of shadows to reflectance) as well as to provide “equivalent albedo” values  
20 that should be comparable to geometric albedo values derived for small bodies. We find  
21 a general behavior of increasing strength of the SHOE with lower reflectance values  
22 (whether between samples or for a given samples with absorption features). This trend  
23 provides a first order way to correct any reflectance spectra of meteorite powders  
24 measured under standard conditions ( $g=30^\circ$ ) from the contribution of shadows. The  
25  $g=0^\circ$  calculated reflectance and equivalent albedos are then compared to typical values  
26 of albedos for main-belt asteroids. This reveals that among carbonaceous chondrites  
27 only Tagish Lake group, CI, and CM chondrites have equivalent albedo compatible with  
28 C- and D-type asteroids. On the other hand equivalent albedo derived with CO, CR and  
29 CK chondrites are compatible with L- and K-type asteroids. The equivalent albedo  
30 derived for ordinary chondrites is related to petrographic types, with low-grade  
31 petrographic type (type 3.6 and less) being generally darker than higher petrographic

32 types. This work provides a framework for further understanding of the asteroids  
33 meteorite linkage in particular when combining with colors and spectroscopy.

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## 38 **1. Introduction**

39

40 Solar System small bodies are a make-up of heterogeneous objects in term of size,  
41 orbit and colors. Observations available are much more numerous and detailed for the  
42 largest members, while for the smallest - and faintest - objects, orbit is generally the only  
43 available information. Still, there are 10 000s of objects for which, size, colors and  
44 albedo have been determined in addition to orbit (Izevic et al., 2001, Mainzer et al.,  
45 2011, Usui et al., 2019). Albedo is then one of the properties that is known for the largest  
46 number of small bodies and, combined with colors, could in principle be used to help  
47 mapping the composition distribution of small bodies across the solar system. However,  
48 the interpretation of albedo in term of composition is degenerate; the brightness of a  
49 material can be related to chemistry (the presence of Fe-related absorption features, the  
50 presence of opaque phases, metals, oxides, organics,...) as well as to physical properties  
51 such as grain size. Still, albedo has been used as a zero order connection between  
52 asteroid classes to meteorites groups by qualitatively comparing albedos to reflectance  
53 levels measured on meteorites: the dark asteroid families are often named C-complex,  
54 where C refers to “carbonaceous”, by analogy to the dark carbonaceous chondrites. This  
55 has so far remained a qualitative comparison since reflectance levels cannot be  
56 compared to albedos: they are not the same physical quantity by definition, which  
57 forfeits a direct comparison.

58 There are multiple types and definitions of albedo. In the case of large asteroid  
59 surveys, the geometric albedo in the visible,  $p_v$ , is determined on the basis of mid-  
60 infrared observations coupled with a thermal model and visible observations (Lebofsky  
61 et al., 1986). The geometric albedo is defined as the brightness ratio between the  
62 reflected sunlight (averaged spectrally over the visible range) to that of a perfectly  
63 lambertian disk with the same cross-section, everything being observed at a phase angle  
64 of  $g=0^\circ$ . This quantity is therefore different from laboratory measurements obtained on

65 meteorite samples, which typically provide biconical or bidirectional reflectance spectra  
66 in a phase angle range around  $30^\circ$ . While the definition of  $p_v$  is at zero phase angle, note  
67 that asteroid observations are essentially conducted at low phase angles but only rarely  
68 obtained at exactly  $g=0^\circ$ . They are extrapolated to  $g=0^\circ$  using measurements (or  
69 guesses) of the phase coefficient (the dependence of brightness on phase angle). This  
70 approach is complicated by the fact that the opposition effect, the strong increase of  
71 reflectance towards  $0^\circ$  phase, shows variability in both its magnitude and shape  
72 depending on the composition and physical properties of the surface material.

73 Here, we present an attempt to provide laboratory measurements that can in  
74 principle be used to compare with the geometric albedo of a smooth-surfaced asteroid,  
75 covered by particulate meteorite-like material. Previous investigations have looked at  
76 some aspects of this topic on extra-terrestrial samples ([Gradie et al., 1980](#); [Gradie and](#)  
77 [Veveřka, 1986](#); [Capaccioni et al., 1990](#)), but the originality of our approach is to focus on  
78 the low phase angle range and to sample a large diversity of samples. For that we  
79 present multispectral measurements on a suite of 72 meteorite samples belonging to 10  
80 different classes, with a special emphasis on carbonaceous chondrites. For each sample,  
81 multispectral measurements were obtained in the 400-2500 nm spectral range, at phase  
82 angles of  $10^\circ$ ,  $20^\circ$  and  $30^\circ$ . This enables to extrapolate the reflectance spectra at  $0^\circ$  phase  
83 angle for each sample, and to calculate the reflectance at  $0^\circ$  phase angle averaged over  
84 the Solar spectrum, two quantities that can be seen as equivalent to  $p_v$  and  $p$ . We then  
85 compare these values to albedo values derived for various asteroids classes, and discuss  
86 the connection between meteorite classes and asteroid families.

87

88

## 89 **2. Samples & Method**

90

### 91 **2.1 Samples**

92 A suite of 72 meteorite samples was analyzed for this study. We particularly  
93 focused on carbonaceous chondrites, which have been related in the past to C-type  
94 asteroids. Samples from the CI, CM, CR, CO and CV groups were analyzed together with  
95 ungrouped C2 chondrites. Many of these samples were provided through the Antarctic  
96 meteorite research program. Meteorites were grinded in an agate mortar, in order to  
97 obtain a particulate sample. Previous samples prepared with the same protocol resulted

98 in typical grain size in the range 30-200  $\mu\text{m}$  (Beck et al., 2012). A list of samples used in  
99 this study and their reflectance values is provided in [supplementary materials](#).

100

## 101 2.2 Bidirectional reflectance measurements

102

103 The reflectance measurements were obtained with the SHADOWS spectro-gonio  
104 radiometer (Potin et al., 2018). For each sample, we measured the reflectance between  
105 400 nm and 2500 nm, every 100 nm at a spectral resolution of around 4 nm in the 360-  
106 670 nm range, 8 nm in the 680-1420 nm range and 16 nm in the 1430-2640 nm range  
107 (Figure 1). This wavelength range was measured in order to cover a significant fraction  
108 (88%) of the solar energy spectral distribution.

109 The SHADOWS instrument enables to measure bi-directional reflectance over a  
110 range of incidence and emergence angles, down to phase angles of  $5^\circ$ . For this work  
111 spectra of each sample were measured at 10, 20 and  $30^\circ$  phase angle for nadir incidence  
112 ( $0^\circ$ ). The instrument was used in standard mode with a spot size of 5.2 mm (much larger  
113 than the grain size) and the typical sample mass used was around 50 mg. Spectra were  
114 obtained under ambient conditions and calibrated using Spectralon<sup>TM</sup> and Infragold<sup>TM</sup>.  
115 The system used a 20mm diameter diaphragm placed in front of the optics of both  
116 detectors to increase the bidirectionality (i.e. the angular resolution) of the observation  
117 to  $\pm 0.8^\circ$  (therefore the angular resolution of the system is of  $3^\circ$ , constrained by  
118 incidence).

119 For each sample, the reflectance values obtained are extrapolated to zero phase  
120 angle using a second order polynomial fit of the measurements at 10, 20 and  $30^\circ$ . This is  
121 possible in the 400-1000 nm range measured by a silicon detector with a high signal to  
122 noise ratio (SNR). This is not possible in the near-IR range where the SNR of the InSb  
123 detector was not sufficient to enable a reliable extrapolation to zero-phase. The  
124 significance of the 3-points polynomial approach is investigated in the case of four  
125 samples (1 CO, 1 CV, 1 CR, and one ordinary chondrite) by measuring the phase-curve  
126 every two degrees from  $g=8$  to  $g=40^\circ$  (Fig. 2) and comparing the interpolated values to  
127  $g=0^\circ$  using either the 3-point approach or the full dataset (second-order polynomial fit  
128 of the 17 data points). This test reveals that using 3 points or 17 points does not change  
129 the zero-phase interpolated value by more than a few percent ( $<0.005$  in absolute  
130 reflectance) (Fig. 2).

131           Astronomical observations of small bodies, and derivation of zero-phase  
132 magnitude from phase curves are generally performed by using an exponential fit to the  
133 magnitude vs. phase angle relation. We chose not to use the same analytical formalism  
134 because these observations are not directly analogous to our laboratory measurements.  
135 Indeed the phase curves of small bodies are a combination of photometric behavior of  
136 the surface, and the fraction of the object that is illuminated when seen from the  
137 observer. As a consequence, the polynomial approach was used since it provided a  
138 simple and satisfactory fits to the 17 points curves.

139

140

### 141 **3. Calculation of « albedo » and zero phase reflectance.**

#### 142 3.1 Method

143           At present, the SHADOWS instrument does not allow to perform measurement at  
144 zero phase angle. Therefore, for each wavelength the reflectance at zero phase angle is  
145 obtained by extrapolating the reflectance at 10°, 20°, 30° to a phase of 0° using a second  
146 order polynomial. At low phase angle ( $g < 30^\circ$ ), two contributions result in an increase of  
147 reflectance with decreasing phase angle ([Hapke, 2012](#)). First, the shadow-hiding  
148 opposition effect (SHOE) that typically occurs below 30° is related to the fact that at  
149 lower phase, there are less shadows at grain scale, and then the surface is brighter. It is a  
150 geometrical effect although its magnitude may depend on the scattering properties of  
151 the grains. A second contribution is the coherent back-scattering opposition effect  
152 (CBOE), which is related to additive or destructive interactions of photons and occurs  
153 for phase angles typically below 2° for many particulate samples and for the lunar  
154 surface ([Hapke, 2012](#)).

155           In the case of small bodies observations, the geometric albedo that was computed  
156 is based on thermal modeling of mid-IR thermal emission observations as well as on the  
157 values of the visible absolute magnitude (H) and phase slope parameter (G). The latter is  
158 measured from telescopic observations that are only rarely obtained at very low phase  
159 angle ([Harris, 1989](#)) and therefore may not take into account the CBOE. This is why we  
160 prefer in this work not to use zero-phase angle measurements directly but rather to use  
161 an interpolation approach.

162           Two quantities are calculated that could in principle be used for comparison with  
163 small bodies observations. The first one is the 550 nm reflectance at zero-phase angle,

164 which is calculated by averaging the 500 and 600 nm zero-phase reflectances, that are  
165 estimated using the polynomial interpolation. This quantity can in principle be  
166 compared to the visible geometric albedo  $p_v$  and may be called *calculated zero-phase*  
167 *reflectance* or *equivalent visible geometric albedo*.

168

169 A second quantity that is calculated is the solar-spectrum averaged zero-phase  
170 reflectance. For each sample and each phase angle, the spectral integral of a black body  
171 spectrum at 5500°C multiplied by the reflectance spectrum of the sample is divided by  
172 the spectral integral of the same blackbody multiplied by the spectrum of a lambertian  
173 surface (reflectance of 1).

174

$$175 \quad A_{Lab}^g = \frac{\int_{\lambda=400}^{2500} R_{\lambda} \times BB_{\lambda} d\lambda}{\int_{\lambda=400}^{2500} BB_{\lambda} d\lambda} \quad (\text{eq. 1})$$

176

177 This calculated quantity represents the ratio between the solar radiation  
178 reflected by the sample surface at a given phase angle to that reflected by a lambertian  
179 surface. This quantity was calculated for  $g=10, 20$  and  $30^{\circ}$  and then interpolated to  $g=0^{\circ}$   
180 using a second order polynomial fit, in order to estimate the fraction of solar radiation  
181 reflected by the surface at zero-phase angle. This quantity is somehow analogous to the  
182 geometric albedo  $p$  and may be called *equivalent geometric albedo*.

183

### 184 3.2 Cautions and underlying hypothesis

185

186 When comparing calculated zero-phase reflectance and equivalent geometric  
187 albedo from our work to asteroid observations, there are some strong underlying  
188 hypotheses that the reader needs to keep in mind:

189

190 - Photometric properties are hypothesized to be dependent on phase angle only,  
191 while in reality incidence and emergence angles also have an independent role (see for  
192 instance Beck et al., 2012 or Potin et al., 2019), an observation also noted at larger  
193 phase angles and having led to the weighting of measurements made at high incidence  
194 angles in the photometric inversion procedures (e.g., Souchon et al., 2011).

195

196 - The contribution from the CBOE is not taken into account. The zero-phase  
197 reflectance derived here cannot be used to compare with observations obtained at very-  
198 low phase angles ( $<2^\circ$ ). For low-albedo samples (i.e. carbonaceous chondrites) the CBOE  
199 might be moderate (Skhuratov and Helfenstein, 2001) but detailed investigations of  
200 CBOE on carbonaceous chondrites are not available at present.

201

202 - The impact of large-scale shadows is not taken into account when comparing  
203 disk-integrated observation to laboratory measurements. The effects of large-scale  
204 shadows are expected to be modest at low phase making this hypothesis reasonable  
205 (Hapke et al., 2012).

206

207 - A particulate material with a wide range of particle sizes is covering asteroids  
208 surfaces. The measurements in this work were obtained on fine powders and the  
209 behavior of a surface covered by large particles ( $>1\text{ cm}$ ) could differ from that of a  
210 surface covered by smaller ones (especially for weakly absorbing materials). Grain  
211 shape as well as the style of topography at all scales may also play a role (e.g., Shepard  
212 and Campbell, 1998; Helfenstein and Shepard, 1999; Cord et al., 2003; Skhuratov et al.,  
213 2005; Souchon et al., 2011).

214

215 - We did not carry out any measurement on pure Fe-metal, so this work does not  
216 apply to metal dominated surfaces.

217

218

#### 219 **4. The scattering behavior of meteorites at low phase angle**

220

##### 221 4.1 A back-scattering behavior at low phase angle

222

223 All 72 meteorite samples analyzed in this study reveal a similar behavior of  
224 increasing reflectance at low phase angle. We quantify the relative magnitude of the  
225 opposition effect as the ratio between the extrapolated reflectance at zero phase angle  
226 and the reflectance in standard geometry ( $i=0^\circ$ ,  $e=30^\circ$ ). Note that this definition is close  
227 but slightly different from that in Beck et al. (2012) ( $i=3^\circ$ ,  $e=30^\circ$ ). In figure 3, the  
228 relative intensity of the opposition effect is shown as a function of the reflectance at



229 standard geometry for the six wavelengths measured below 1  $\mu\text{m}$  (zero-phase angle  
 230 reflectance could not be extrapolated for the near-IR range due to the lower SNR). This  
 231 graph reveals a general behavior among all samples and wavelengths, namely that the  
 232 relative magnitude of the opposition effect is greater for darker surfaces. The values  
 233 found in this work are in fair agreement with previous results we obtained on 6 samples  
 234 (Beck et al., 2012, Fig. 3,5).

235 For asteroid observations this translates into the fact that darker asteroids  
 236 should present higher phase coefficient values, which is indeed the case (Belskaya and  
 237 Shevchenko, 2000; Longobardo et al., 2014, 2016). This increased back-scattering  
 238 behavior for low-reflectance surfaces can be explained by the shadow-hiding opposition  
 239 effect (SHOE). Indeed darker materials have a steeper phase slope due to a combination  
 240 of surface texture and radiative transfer effects. When grain sizes are of the order of the  
 241 surface roughness length scale, multiple scattering dilutes the effect of shadowing for  
 242 transparent materials (i.e. bright surfaces). In the case of more opaque materials, the  
 243 effect of shadowing is more pronounced compared to the reduced multiple scattering  
 244 contribution (Skhuratov et al., 2005).

245  
 246 Several analytical functions were tested in order to model the distribution  
 247 observed in figure 3. Among those investigated, the function that resulted in the best  
 248 quality of fit is a log-normal distribution, that is expressed as:

249  
 250 
$$\frac{R_{\lambda,g=0^\circ}}{R_{\lambda,g=30^\circ}} = C_1 + C_2 \exp\left(-\left[\frac{\ln\left(\frac{R_{\lambda,g=30^\circ}}{C_3}\right)}{C_4}\right]^2\right) \quad (\text{eq. 2})$$

251  
 252 with  $C_1=5.48 \pm 1.14$ ,  $C_2=-4.40 \pm 1.14$ ,  $C_3=0.388 \pm 0.019$ ,  $C_4=6.08 \pm 0.95$

253  
 254 This law should in principle enable to calculate a low phase reflectance from a  
 255 reflectance value measured under standard conditions. Note that this law does not take  
 256 into account the CBOE, and should not be used to compare laboratory data to  
 257 observations at very low-phase angle ( $g < 2^\circ$ ) where the CBOE starts to play a significant  
 258 role. Note also that this law was obtained for powders and should not be applied to bulk  
 259 samples (i.e. not powdered) until it is proven valid for such samples as well (which is  
 260 most likely not the case). law also only applies to reflectance lower than 0.5 which is the

261 range investigated here (this is fortuitous, only related to the arbitrary choice of a  
262 mathematical description of this dataset, which is not a bijection in the range of value  
263 investigated here). Conversely, this law may enable to convert asteroid albedo values  
264 into reflectance under standard laboratory conditions, for comparison with laboratory  
265 data measured under “standard” conditions.

266

#### 267 4.2 The low-phase relative blueing

268

269 The behavior observed in figure 3 could also be modeled by a law  $f(x)=x/(a+x)$ ,  
270 but with a slightly lower quality of the fit. This means somehow that the shadow-hiding  
271 opposition effect studied here is close to being an additive contribution:

272

$$273 R_{\lambda,g=0^\circ} \approx C + R_{\lambda,g=30^\circ} \text{ with } C \text{ a constant value}$$

274

275 This means that in relative intensity the effect will appear stronger for darker  
276 samples. Another consequence is that when working in relative reflectance, which is a  
277 common way to analyze ground-based observations, phase angle can have an effect on  
278 the calculated spectral slope. To illustrate this point, the spectra obtained for 4  
279 meteorite samples at different phase angles are normalized at 500 nm and displayed in  
280 figure 1. These graphs reveal that a red sample will appear bluer at low phase angle if  
281 the slope is calculated after spectral normalization, and particularly in the case of dark  
282 meteorites (see the CV chondrite LAP 02206 in figure 1). Such a behavior is also  
283 revealed when the visible slope is calculated for each meteorite in absolute and relative  
284 reflectance, at  $g=0$  and  $g=30^\circ$  (Figure 4). This is due to the fact that the SHOE behaves  
285 almost like an additive contribution, because it is only due to external reflections on the  
286 grains, therefore without absorption. This also means that at low-phase a spectrally flat  
287 sample will not become blue, but that a sample with a spectral slope will have a  
288 decreasing spectral slope at decreasing phase angle, if the slope is calculated in  
289 normalized reflectance. The redder the spectra, the more pronounced the low-phase  
290 blueing (Figure 4). Note that, at least in the case of S-type asteroids, these effects appear  
291 minor when compared to the magnitude of space weathering effects (Vernazza et al.,  
292 2009).

293

#### 294 4.3 The opposition effect as a function of meteorites groups in carbonaceous chondrites

295

296 In figure 5, the same data as figure 3 are shown but each meteorite group is color  
297 coded, in order to investigate differences in magnitudes of SHOE among the various  
298 groups investigated. Within that plot, meteorites groups with particular high opposition  
299 effect will appear above the average trend (the global fit presented in Figure 3) while  
300 meteorites groups with relatively low opposition effect will appear below. This graph  
301 reveals that among carbonaceous chondrites, some CV chondrites appear to have an  
302 unusually pronounced SHOE. On the other hand heavily aqueously altered meteorites  
303 (C2, CI and CM) appear to have a relatively less pronounced SHOE, and meteorites from  
304 the CO and CR groups appear to be in between.

305 The existence of these group behaviors may be related to different mineralogy  
306 (optical properties of grains), grain sizes and grain shapes. It is certainly difficult to  
307 disentangle which property is responsible for these contrasted behaviors. The first  
308 observation that should be made is that meteorites groups that experienced the  
309 strongest aqueous alteration tend to lie below the global fit. Aqueous alteration has  
310 mineralogical consequences, since it induces the hydrolysis of primary phases and the  
311 production of phyllosilicates and secondary opaques. Aqueous alteration has also  
312 physical consequences, for instance to increase porosity (Britt and Consolmagno, 2000)  
313 or decrease strength of the samples (personal experience of the authors with grinding  
314 such samples).

315 The presence of a significant amount of metal may produce a peculiar behavior,  
316 but metal abundance varies in the order  $CM-C2-CI < CV < CO < CR$  (Krot et al., 2006).  
317 Also note that the only metal rich meteorites studied here (mesosiderite) tend to show a  
318 rather low SHOE. The presence of an elevated amount of CAI in CV could provide a lead  
319 to explain the unusually strong opposition effect observed, but CAI are abundant in CO  
320 as well.

321

322

#### 323 **5. Low-phase reflectance and equivalent geometric albedos among meteorite** 324 **families**

325

326

## 327 5.1 Comparison to RELAB data

328

329         Several parameters may in principle impact the reflectance value measured for a  
330 given sample. These include grain size, sample heterogeneity (meteorites are often  
331 breccia), as well as measurement uncertainty. Also, because the final goal of this work is  
332 to provide a way to compare laboratory data to observations, it is important to assess  
333 how laboratory measurements may differ between different laboratories. In order to  
334 investigate interlaboratory variability, we chose to compare to data from the RELAB  
335 facility since it provides at the moment the most extensive suite of measurements on  
336 extra-terrestrial materials. In figure 6 we present the range of reflectance values at 550  
337 nm for different classes of meteorites using the IPAG setup (SHADOWS, this study and  
338 Eschrig et al., submitted) and data obtained on meteorite powders with the RELAB setup  
339 (Brown University). This graph shows a good agreement for all classes of meteorite  
340 studied here. The only difference found is for type 3 ordinary chondrites (OC), which  
341 appear to show a globally lower reflectance in the dataset measured with SHADOWS,  
342 but this difference may be related to the different definition of the petrographic types  
343 used at IPAG (based on Raman studies, Bonal et al. 2018).

344

345

## 346 5.2 Equivalent albedo values

347

### 348 5.2.1 Carbonaceous chondrites

349

350         The equivalent albedo values derived for our suite of meteorites vary  
351 significantly from family to family (Fig. 7). In the case of carbonaceous chondrites, the  
352 average equivalent albedo decreases in the order CK > CR > CV > CO > CM > CI > TL. A  
353 first explanation for this variation could be the different amount of carbonaceous  
354 compounds in those meteorite samples. In figure 7, the average equivalent albedo per  
355 meteorite class is plotted against the average carbon content. The carbon content was  
356 calculated using data in Alexander et al. (2012, 2013) as well as Jarosewich (1990) and  
357 Pearson et al. (2006). As can be seen in Fig. 7 a rough correlation exists between carbon  
358 content and equivalent albedo but correlation does not imply causality. Indeed, the  
359 carbon content in carbonaceous chondrites is a proxy for the amount of matrix and this

360 correlation might also be explained by the fact that meteorites rich in carbon also tend  
361 to have an elevated amount of dark matrix, which is enriched in iron-rich opaque  
362 minerals.

363

#### 364 5.2.2 The impact of thermal processing on carbonaceous chondrites

365

366 A significant fraction of CM chondrites has experienced a post-aqueous alteration  
367 heating process (Nakamura et al., 2005). The measurements obtained here on heated  
368 CM chondrites enable to assess the impact of thermal processing on equivalent albedo of  
369 primitive carbonaceous chondrites. Results show that on average heated CM chondrites  
370 are not darker than more primitive CM chondrites, but they show more variability in  
371 equivalent albedo values (see supplementary table). This variability was explained in  
372 Beck et al. (2018) by the fact that upon heating CM chondrites first become darker due  
373 to modifications of organic compounds, and then become brighter upon more intense  
374 thermal processing, as a consequence of the recrystallization of the matrix.

375

376

#### 377 5.2.3 Ordinary chondrites

378

379 Our dataset contains mostly ordinary chondrites of low petrographic types since  
380 we focus here on “primitive meteorite samples”. It is therefore important to remark that  
381 this dataset is not representative of the average of the whole range of metamorphic  
382 grades of ordinary chondrites.

383 We find that primitive ordinary chondrites of petrologic type 3, with an average  $p$   
384 of  $0.154 \pm 0.024$  (1 sigma,  $n=6$ ), appear darker than petrologic types  $> 4$ . This  
385 difference can be explained by the fact that small opaque phases that are present in low  
386 petrographic grade meteorites tend to coalesce during the metamorphic process, and  
387 becomes less efficient in darkening the sample. Low-metamorphic grade ordinary  
388 chondrites have a higher equivalent albedo than CI and CM chondrites, but their  
389 equivalent albedo values are in the range of CO, CV and CR chondrites.

390

#### 391 5.2.4 HED meteorites

392

393 Values derived for HED meteorites vary typically in the 0.2-0.5 range (see  
394 supplementary [table](#)). Within this suite the howardite sample has the lowest albedo  
395 when compared to eucrite and diogenite but the dataset is too small to address whether  
396 this is a general behavior.

397

398 5.3 p vs pv

399

400 When asteroid albedo values are determined, an assumption often made is that  
401  $p/p_v=1$  ([Lebofsky et al., 1986](#)). In [Figure 8](#), we present the values of the ratio of  
402 equivalent albedos to equivalent visible albedos, which can be considered as analogous  
403 to  $p/p_v$ . The values found range from 0.85 to 1.25 with an average of 1.04. The values  
404 are mostly above 1 except for HED meteorites and type 4-5 ordinary chondrite. The  
405 specificity of these meteorites is the presence of a strong absorption band around 850  
406 nm that absorbs a significant fraction of the solar energy. On the other hand, most  
407 samples studied have a red slope, which may explain the overall values above 1.

408

## 409 **6. Comparison to small bodies**

410

411 In [figure 9](#) we present a comparison of equivalent albedo values derived for our  
412 series of meteorites, to the asteroid family modal distribution albedos as obtained by  
413 [DeMeo and Carry \(2013\)](#). The [DeMeo and Carry \(2013\)](#) data were obtained by mapping  
414 [DeMeo et al. \(2009\)](#) spectral endmembers on multi-filter sky surveys, enabling to study  
415 objects down to diameters as low as 5 km and providing the most detailed taxonomy of  
416 main-belt objects. The values used for comparison are the modes of the albedo value  
417 distribution for each taxonomic group (Table 4 in [DeMeo and Carry, 2013](#)).

418

### 419 6.1 “Carbonaceous” asteroids vs carbonaceous chondrites

420

421 While the denomination “C”-type asteroid initially stands for carbonaceous, a first  
422 important observation is that only a fraction of carbonaceous chondrites appears  
423 compatible with C-type asteroids. The CO, CV, CR and CK chondrites have albedos  
424 significantly higher than CM chondrites and are too bright to be related to C-type. These

425 meteorites classes represent about 50% of the carbonaceous chondrite falls and their  
426 possible parent bodies will be discussed in sections 6.3-6.4 and 6.5.

427         Among C-type asteroids, a significant fraction ( $\frac{1}{3}$  to  $\frac{1}{2}$ ) is hydrated and shares  
428 very strong spectral similarities with CM chondrites (Vernazza et al., 2015, 2016;  
429 Vernazza and Beck, 2017). The average albedo value derived for CM chondrite  
430 (including heated samples) is  $0.066 \pm 0.019$  which is in good agreement with C-complex  
431 asteroid ( $0.054 \pm 0.023$ , DeMeo and Carry, 2013; Fig. 9). This good agreement reinforces  
432 the connection between hydrated C-complex asteroids (Ch, Cgh) and CM chondrites.

433         The rest of the C-complex that do not show evidences of hydration remains  
434 puzzling and there are at present two competing hypothesis. The first one is that they  
435 represent thermally metamorphosed CM chondrites (Hiroi et al., 1993). From an albedo  
436 perspective this hypothesis remains valid since heated CM chondrites have albedo  
437 values consistent with C-type asteroids (Table 1) except for those that have been the  
438 most extensively thermally processed (Beck et al., 2018). However, this hypothesis is  
439 challenged by the fact that heated CM chondrites do show evidence of hydration at 3- $\mu$ m  
440 (Garenne et al., 2016; Beck et al., 2018) and they often show olivine feature in their mid-  
441 infrared spectra (Beck et al., 2014) unlike “non-hydrated” C-type (Vernazza et al., 2015).  
442 An alternative interpretation is that these objects may represent loosely consolidated  
443 material related to Interplanetary Dust Particles (Vernazza et al., 2015).

444

445 6.2 S-type: the scarcity of low-metamorphic grade objects

446

447

448         The albedo values calculated for type 3 ordinary chondrites are much lower than  
449 those obtained for the LL4-5 chondrites, as well as values found for type 4 and above  
450 ordinary chondrites measured under low phase angles (Capaccioni et al., 1990). Type 3  
451 ordinary chondrites escaped the thermal metamorphism event experienced by most  
452 ordinary chondrites (Bonal et al., 2016). The thermal metamorphism process is  
453 explained by the build-up of heat within the parent body due to decay of short and long-  
454 lived radionuclides, and type 3 ordinary chondrites are thus expected to have been at  
455 some point the surficial lithology of their parent bodies.

456

457 The albedo values of S-type ( $0.247 \pm 0.084$ , [DeMeo and Carry, 2013](#)) is  
458 significantly higher than values obtained for type 3 ordinary chondrites ([Fig. 9](#)). This  
459 difference cannot be attributed to space weathering that tends to darken asteroid  
460 surfaces with time ([Pieters and Noble, 2016](#)). This observation suggests that the surface  
461 of S-type asteroids is not covered by material analogue to type 3 chondrites, but rather  
462 by more thermally processed material analogous to type 4 or above. Such an  
463 observations is in agreement with a fast accretion of S-type parent bodies, followed by  
464 fragmentation and surface brecciation ([Vernazza et al., 2014](#)).

465

### 466 6.3 K -and L-types

467

468 L-type asteroids are a peculiar class of objects with an absorption band above 2-  
469  $\mu\text{m}$ , which has been explained by the presence of FeO bearing spinel ([Burbine et al.,](#)  
470 [1991](#)) in excess of what is observed in carbonaceous chondrites ([Sunshine et al., 2008](#)).  
471 This led to the idea that they could represent a reservoir of early solar system material  
472 not sampled by meteorites, enriched in refractory inclusions ([Sunshine et al., 2008](#)).  
473 Another peculiarity of L-type asteroids is the presence of unusual polarimetric curves  
474 ([Devogèle et al., 2018; Cellino et al., 2005](#)) with an inversion angle much larger than  
475 other asteroid taxonomic types (i.e.  $> 25^\circ$ ).

476 K-type asteroids are characterized by the presence of a red-slope and a moderate  
477 1- $\mu\text{m}$  silicate band (olivine). K-type asteroids are distributed among the entire main-  
478 belt according to multi-color surveys but a large number of K-type objects are found  
479 among the EOS family ([Mothes-Diniz et al., 2008; DeMeo and Carry, 2013](#)).

480 K-type objects can be distinguished from the L-type by the presence of a weaker  
481 2  $\mu\text{m}$  band and a stronger 1- $\mu\text{m}$  band. The average albedos derived for K- and L-type by  
482 DeMeo and Carry (2013) are similar (so it is difficult to distinguish between the two  
483 types in multicolor surveys). Among the meteorites studied, only CO, CK and CV groups  
484 appear consistent with a connection to L and K-types based on their low-phase  
485 reflectance ([Fig. 9](#)); L- and K-type are thus very likely related to carbonaceous  
486 chondrites but not all types of carbonaceous chondrites.

487 Since albedo does not discriminate between CO, CK and CV, to further investigate  
488 the nature of L- and K-types, it is necessary to turn to spectroscopy. Spectroscopic  
489 surveys of the EOS family have revealed the presence of a strong 1- $\mu\text{m}$  band but only



490 weak 2- $\mu\text{m}$  features (Mothes-Diniz et al., 2008). These spectral characteristics are  
491 typically found in laboratory spectra of CK meteorites, while spectra obtained for CO and  
492 CV tend to show a lot a variability from featureless spectra, to spectra containing both a  
493 1- and a 2- $\mu\text{m}$  band. Therefore, some CO and CV chondrites have affinities with L-type  
494 asteroids but not all meteorites of these groups.

495

#### 496 6.4 D-type vs Tagish Lake group

497

498 The Tagish Lake meteorite was the first identified as having a reflectance  
499 spectrum similar to D-type asteroids (Hiroi et al., 2011). Since then, a few other  
500 meteorites have been recognized as having spectra similar to Tagish Lake and D-types.  
501 From an albedo perspective, the connection between D-type and Tagish Lake appears  
502 reinforced (Fig. 9) given the similarities found in “albedo” values. The spectra similarity  
503 and the albedo similarity are therefore making a strong case for a meteorite-parent body  
504 relation, but there are some major difficulties in this connection. A first one is the  
505 difference in mid-IR emissivity spectra that was noticed by Vernazza et al. (2011), which  
506 suggests a very fine-grained surface (not lithified) similar to comets. The second one is  
507 the lack of a strong 3- $\mu\text{m}$  band on the only D-type object visited by a spacecraft, comet  
508 67P/CG (Cappaccioni et al., 2015; Quirico et al., 2016), while all Tagish Lake samples  
509 show the presence of abundant hydrated minerals, leading to a well-defined 3- $\mu\text{m}$  band  
510 (Gilmour et al., 2019). Therefore Tagish Lake has strong affinities to D-type asteroids  
511 when looking at the VNIR, but its mineralogy appears to be different from D-type surface  
512 when looking at the 3- an 10- $\mu\text{m}$  regions.

513 An explanation to reconcile these observations is that Tagish Lake arises from the  
514 interior of a D-type object where sufficient heat enabled to transform primary phases  
515 into phyllosilicates but without strongly altering its VNIR properties (and then its  
516 spectrum and low-phase reflectance). *If the D-type population accreted late,  $^{26}\text{Al}$  decay  
517 was insufficient to induce a total differentiation of 100 km sized objects (Neveu and  
518 Vernazza, 2019), and while a muddy interior may have existed, their surface may have  
519 remained pristine. The remaining difficulty is to explain how aqueous alteration may  
520 have produced abundant phyllosilicates, without changing the VNIR spectra. One  
521 possibility is that the peculiar spectrum of Tagish Lake is related to the abundant  
522 macromolecular organics, (Herd et al., 2011) and that they were not modified during*

523 aqueous alteration. Experiments on soluble organics mixed with phyllosilicates under  
524 hydrothermal conditions reveal that they experience important transformations  
525 (Vinogradoff et al., 2018; Vinogradoff et al., 2020). In the case of more refractory  
526 organics (IOM, insoluble organic matter), the impact of hydrothermal alteration is less  
527 understood, in particular due to difficulties in generating a valuable laboratory  
528 analogue. An approach to investigate the impact of aqueous alteration on the D-type  
529 signature that can be pursued, is to look at the VNIR signature of different lithologies of  
530 Tagish Lake, that experienced different level of aqueous alteration. Such an approach  
531 was started in Gilmour et al. (2019), and showed that all lithologies investigated have a  
532 D-type signature, while they experienced different levels of aqueous alteration.

533

534

## 535 7. Summary and conclusions

536

537 The results and conclusions can be summarized as follows:

538

539 An approach is proposed using low-phase angle measurements of meteorites to  
540 provide observable quantities analogous to geometric albedo for meteorites powders.  
541 This is done under a number of hypotheses listed in 3.2.

542

543 There appears to be a general trend in the low-g behavior of meteorite powders.  
544 The increase of reflectance due to the shadow-hiding opposition effect (SHOE) is an  
545 almost additive contribution. A relation is derived to obtain the zero-phase angle  
546 reflectance from standard geometry observations (Fig. 3). Note that this relation (eq. 2)  
547 does not take into account the coherent back-scattering opposition effect.

548

549 Albedo values derived for Tagish-Lake lithologies and “Tagish-Lake group”  
550 meteorites are in agreement with D-type asteroids. We propose that they represent  
551 samples from the interior of a D-type or a piece of D-type asteroid that experienced  
552 heating and hydrothermal alteration.

553

554 Albedos values derived for CM chondrites are in good agreement with values  
555 found for C-type asteroids. Heated CM chondrites tend to show more variability in

556 albedo with both brighter and darker samples when compared to “standard” CM  
557 chondrites. This reinforces the relation between CM chondrites and hydrated C-complex  
558 asteroids.

559

560           Carbonaceous chondrites from the CO, CV, CR and CK groups are brighter than  
561 those from the CI, CM and Tagish Lake groups. The derived albedo values are higher  
562 than for C-type asteroids, while in the range of K and L-type. This confirms that a  
563 significant fraction of carbonaceous chondrites does not originate from C-type.  
564 Combined with spectroscopic observations, this also reinforces the relation between K-  
565 type (mostly EOS family) and CK meteorites. This dataset further delves into the  
566 mystery of the parent bodies of CO-CV-CR meteorites for which there are no well-  
567 identified parent bodies that match the spectra and albedo of these meteorites.

568

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## Figure captions

Figure 1: Multispectral observations of powdered meteorites (LL4, CO, CR, CV) at phase angles ranging from 8 to 40° (incidence=0°). Spectra are shown in reflectance factor (left graphs) or in relative reflectance normalized at 500 nm (right graphs). The black line is the extrapolated reflectance at  $g=0^\circ$  using a polynomial fit of the data (see Fig. 2).

Figure 2: Examples of fits of the phase curve for the extrapolation of the reflectance at  $g=0^\circ$  using a 2<sup>nd</sup> order polynomial. The graphs show the reflectance at 500 nm as a function of phase angle for the same samples as in figure 1 and compare the extrapolated value at  $g=0^\circ$  using a 3-point interpolation (all 72 samples from this study) against a 17-points interpolation (tested only for these 4 samples). The difference between the two extrapolated values at  $g=0^\circ$  is less than 0.005.

Figure 3: « Relative magnitude » of the opposition effect as a function of the reflectance at standard geometry. This magnitude is defined as the ratio between the extrapolated reflectance at  $g=0^\circ$  and the reflectance in standard geometry.

Figure 4: The effect of phase angle ( $g=0$  or  $g=30^\circ$ ) on the 400-900 nm visible spectral slope (in  $\mu\text{m}^{-1}$ ) whether calculated in reflectance or in relative reflectance. In the case of reflectance, a slight redening is present for low-phase angle. When slope are calculated for relative reflectance spectra, a significant blueing is observed at low phase angle for the spectra with initially red slopes.

Figure 5: « Relative magnitude » of the opposition effect as a function of the reflectance measured under standard geometry. This graph shows the same data as figure 3, but color- and symbol-coded according to meteorite groups. The data from [Beck et al. \(2012\)](#) is also shown (circles) with the same color code.

Figure 6: Comparison of the reflectance at 550 nm for meteorite powders of carbonaceous chondrites measured at IPAG and at RELAB for different meteorite groups. **This graph shows that while some variability is present for each meteorite group, the range of value is in agreement for measurements obtained in two different laboratories.**

Figure 7 : Relation between meteorite equivalent albedo and average carbon content for different meteorite groups. Carbon contents are from [Alexander et al. \(2012\)](#), [Jarosewich \(1990\)](#) and [Pearson et al. \(2006\)](#)

Figure 8: Ratio between equivalent geometric albedos and equivalent visible geometric albedos for different meteorites belonging to different classes.

Figure 9: Comparison of the reflectance at 550 nm from this work for different meteorites groups, the calculated equivalent geometric albedo, and geometric albedos of asteroids for different taxonomical families ([DeMeo and Carry, 2013](#)). Top: linear scale. Bottom: logarithmic scale.



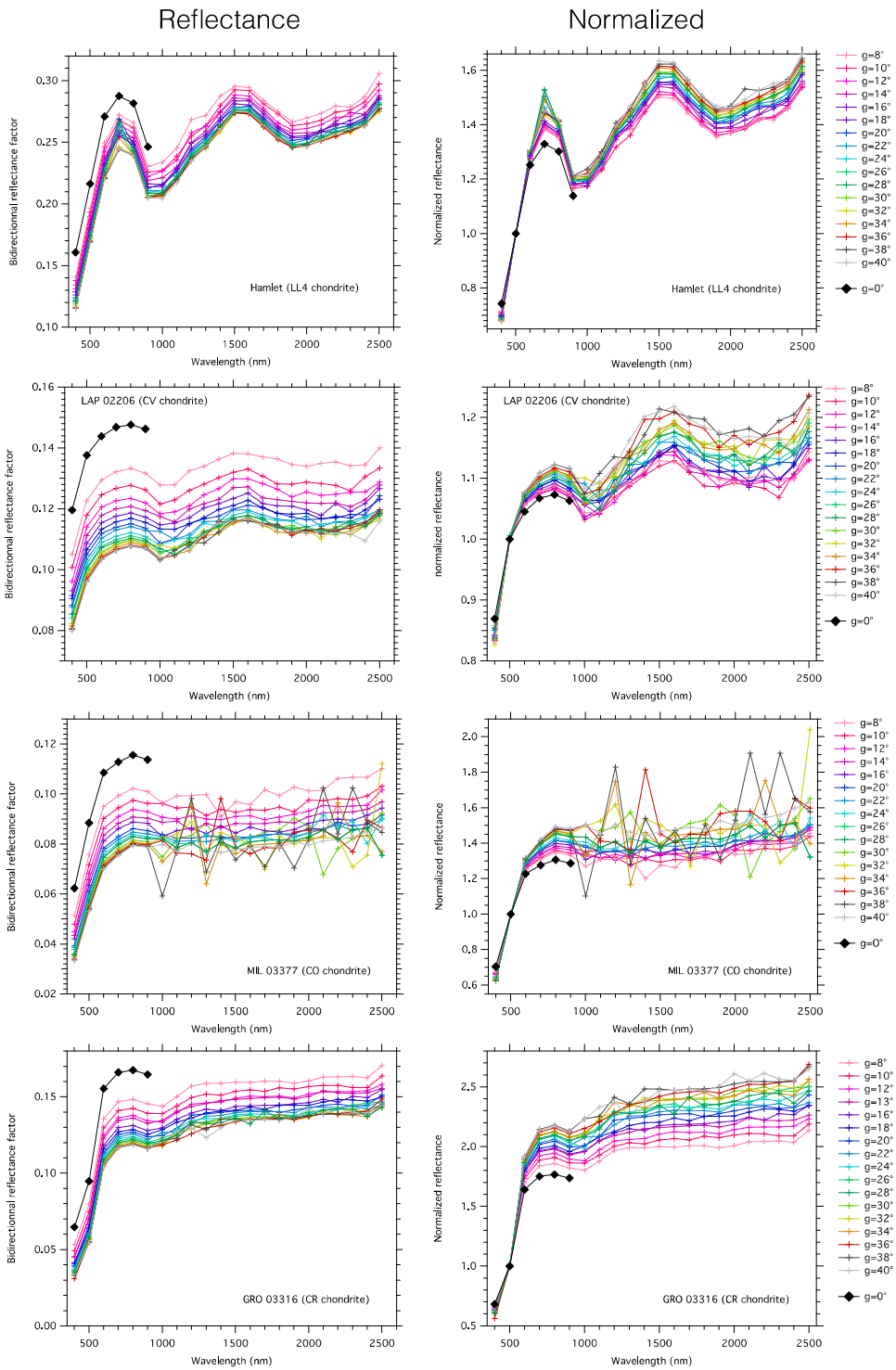


FIGURE 1

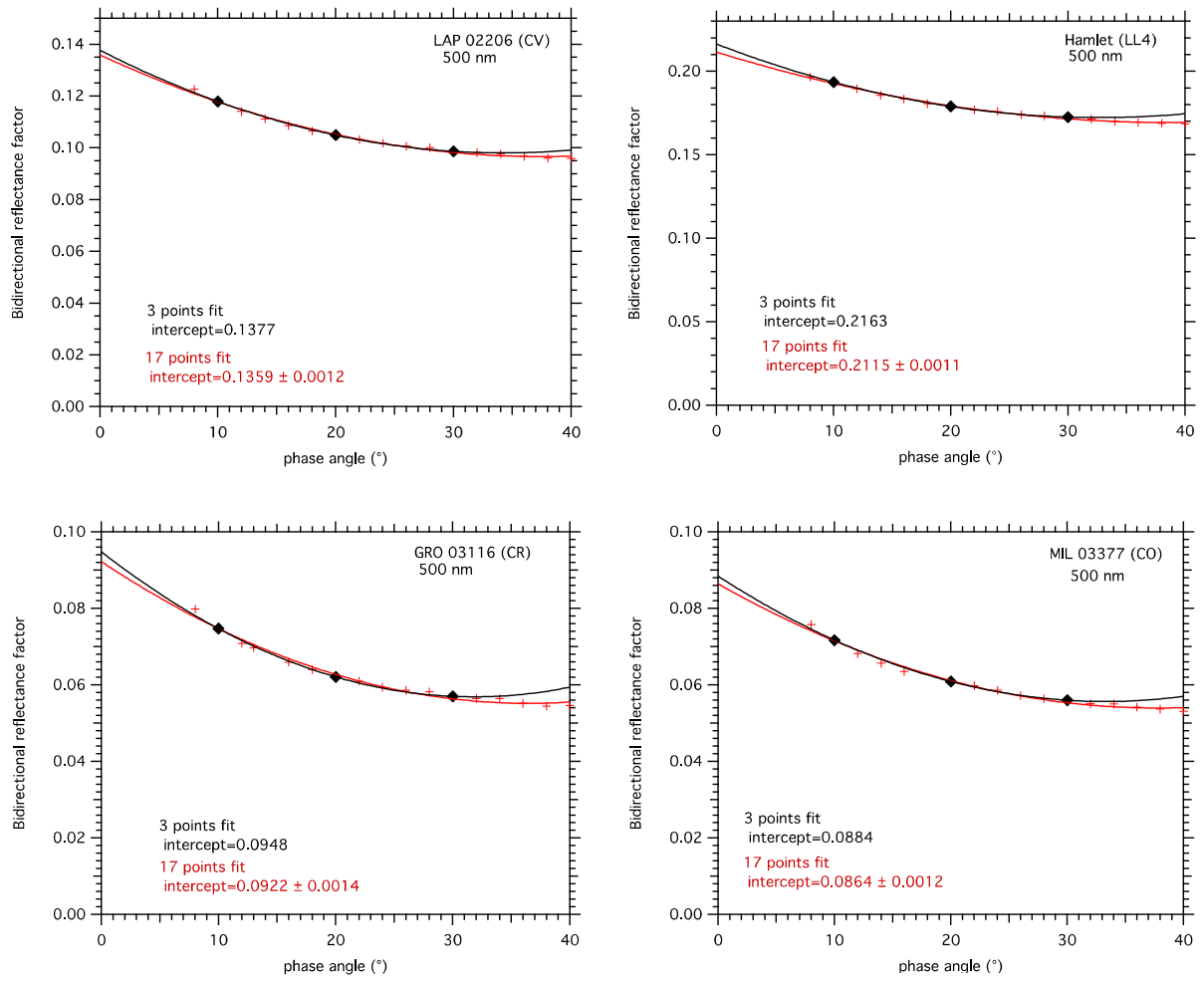


FIGURE 2

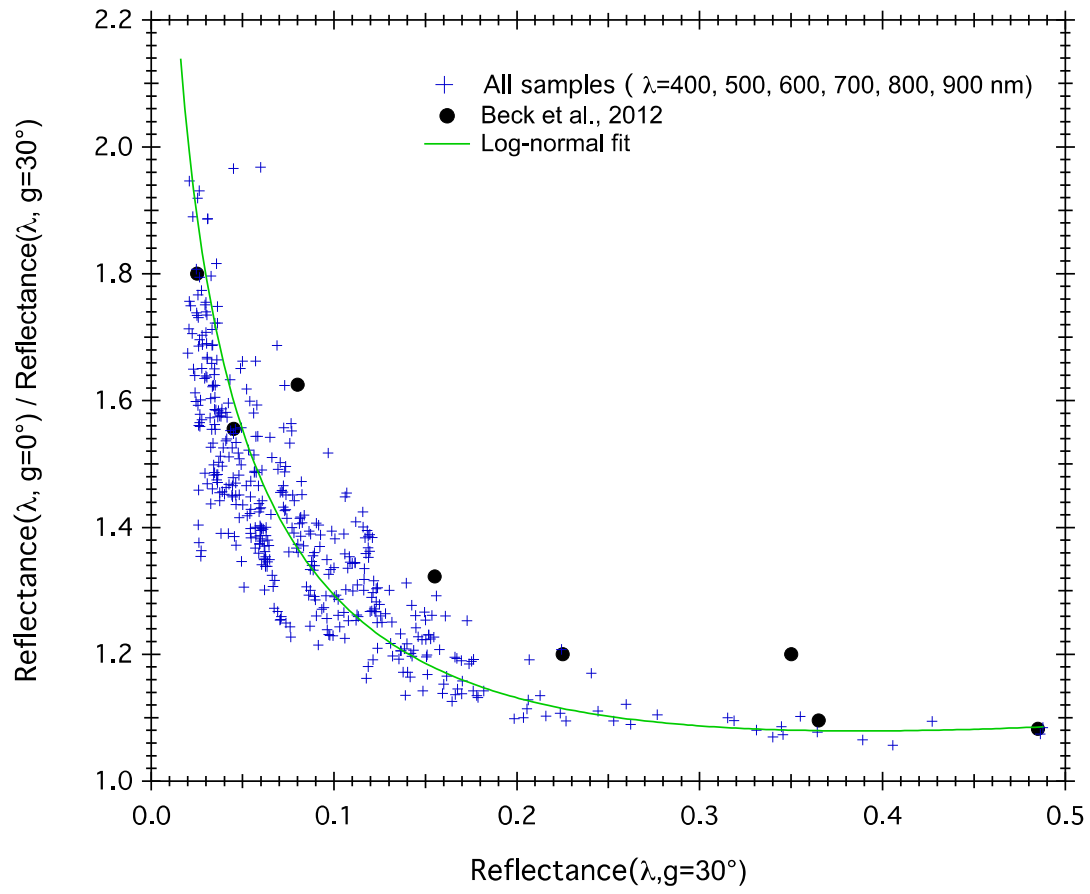
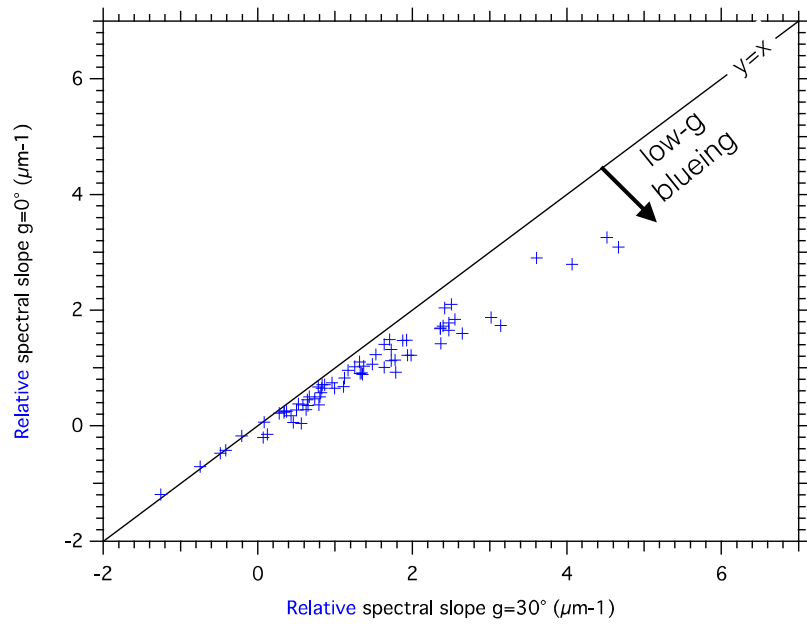
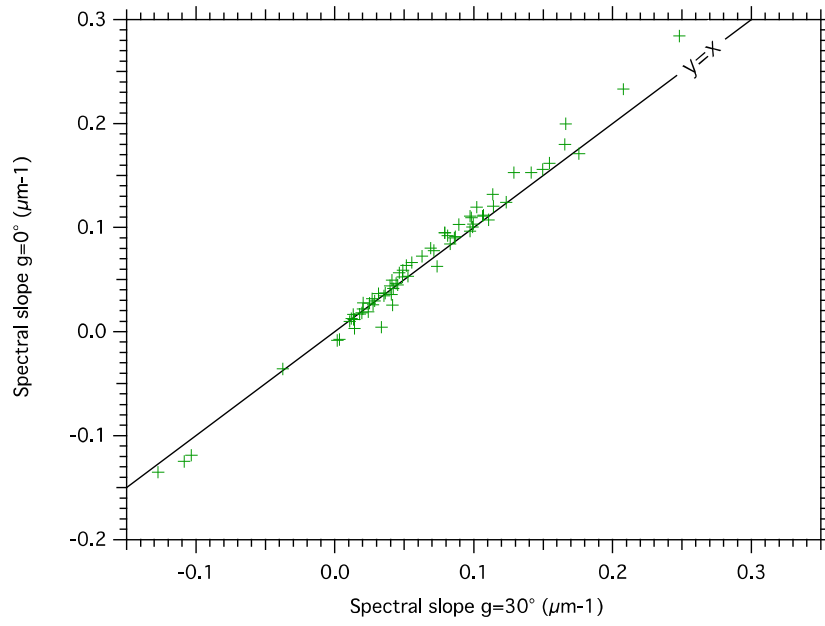


FIGURE 3



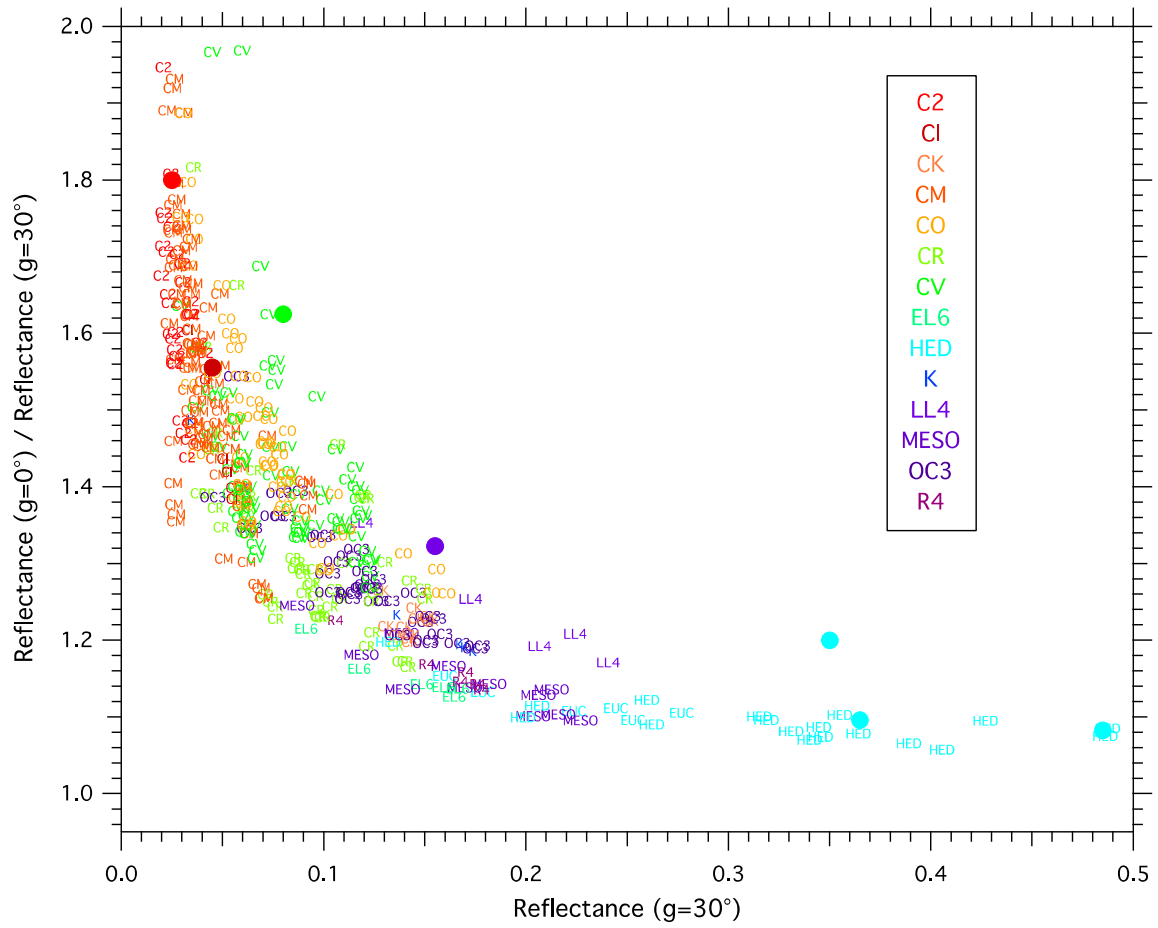


FIGURE 5

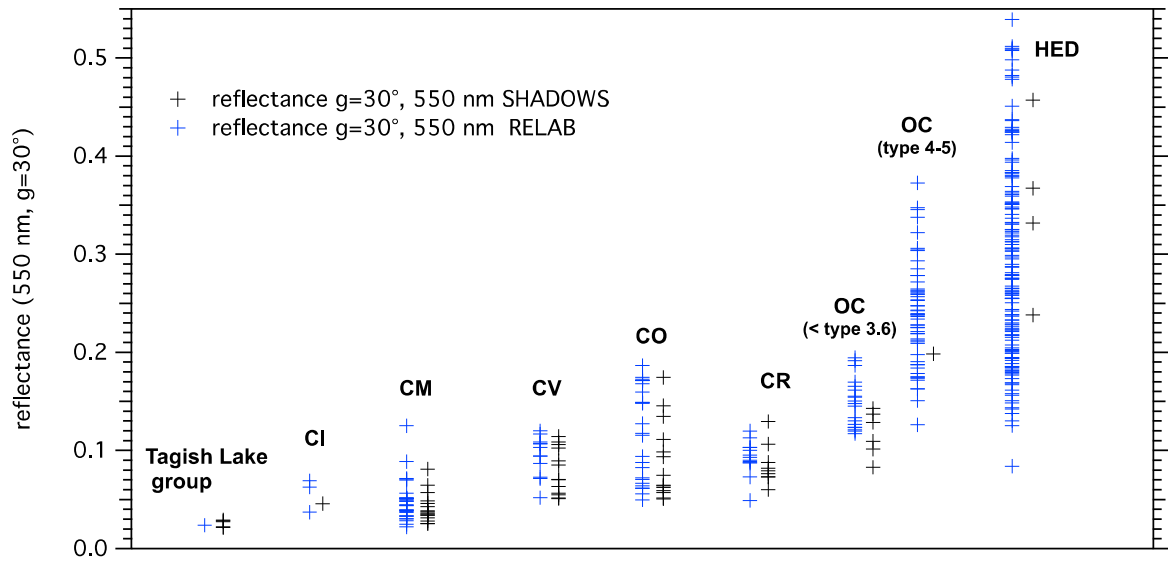


FIGURE 6

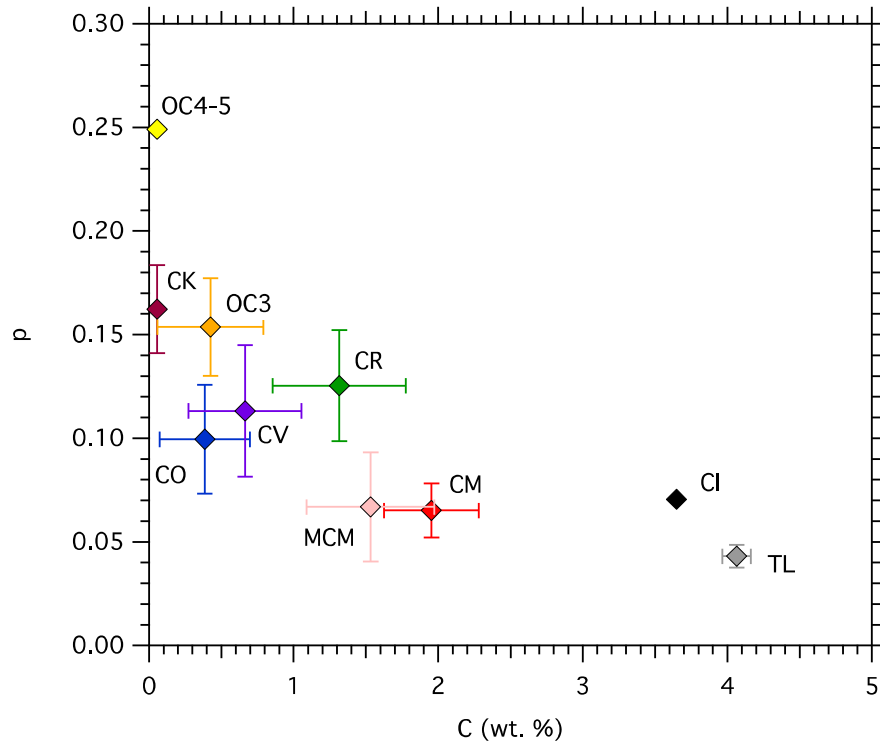


FIGURE 7

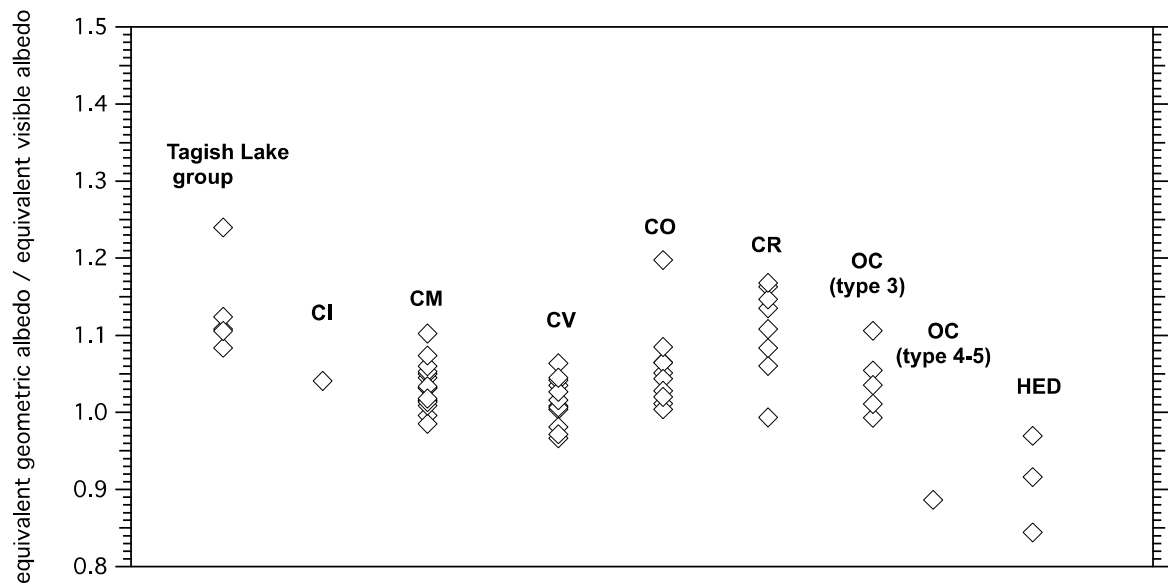


FIGURE 8



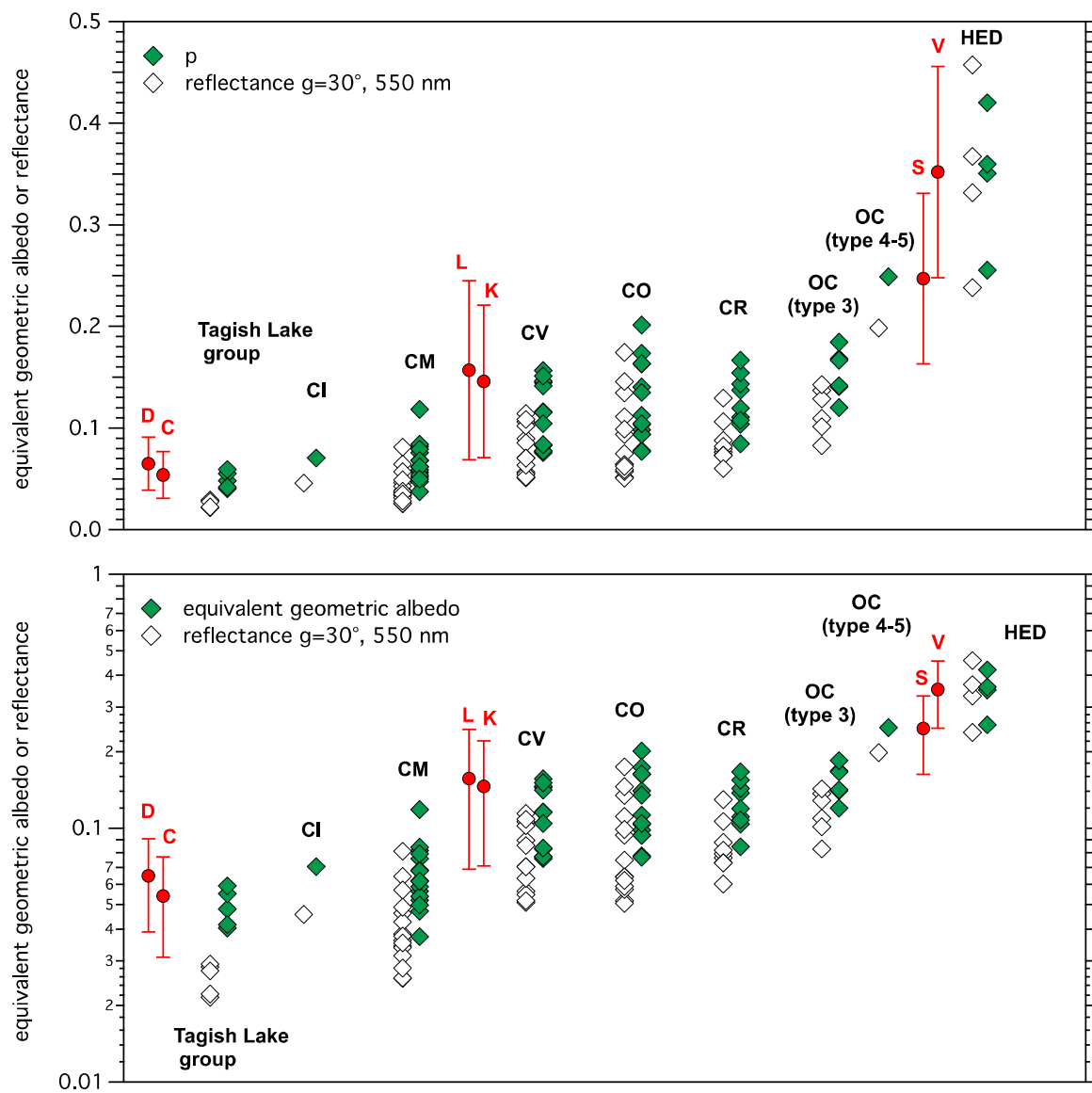


FIGURE 9

