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# Origins of colors variability among C-cluster main-belt asteroids asteroids

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13 Abstract: The Sloan Digital Sky Survey provides colors for more than 100 000 moving 14 objects, among which around 10 000 have albedos determined. Here we combined colors and albedo in order to perform a cluster analysis on the small bodies population, and 15 identify a C-cluster, a group of asteroid related to C-type as defined in earlier work. 16 Members of this C-cluster are in fair agreement with the color boundaries of B and C-type 17 18 defined in DeMeo and Carry (2013). We then compare colors of C-cluster asteroids to those of carbonaceous chondrites powders, while taking into account the effect of phase angle. 19 20 We show that only CM chondrites have colors in the range of C-cluster asteroids, CO, CR 21 and CV chondrites being significantly redder. Also, CM chondrites powders are on average slightly redder than the average C-cluster. The colors of C-cluster members are further 22 investigated by looking at color variations as a function of asteroid diameter. We observe 23 that the visible slope becomes bluer with decreasing asteroids diameter, and a transition 24 seems to be present around 20 km. We discuss the origin of this variation and, if not related 25 26 to a bias in the dataset - analysis, we conclude that it is related to the surface texture of the 27 objects, smaller objects being covered by rocks, while larger objects are covered by a 28 particulate surface. The blueing is interpreted by an increased contribution of the first 29 reflection in the case of rock-dominated surfaces, which can scatter light in a Rayleigh-like 30 manner. We do not have unambiguous evidence of space weathering within the C-cluster 31 based on this analysis, however the generally bluer nature of C-cluster objects compared to 32 CM chondrites could be to some extent related to space weathering.

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49 1. Introduction

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51 The present-day Solar System can be classified as a debris disk. It hosts a large 52 population of objects referred as small bodies, that are the leftovers of planet formation, 53 and offer an opportunity to access the mineralogy and composition of the materials that were incorporated in terrestrial planets and giant planetary cores. An important reservoir 54 55 of small bodies is located between Mars and Jupiter, main-belt asteroids (MBAs). Among 56 MBAs, a major fraction belongs to the so-called C-complex (DeMeo et al., 2009), being 57 identified by a low-albedo and the lack of strong anhydrous silicate absorption features in their visible and near-infrared spectra. They have been historically linked to carbonaceous 58 59 chondrites, a particular type of meteorites belonging to a distinct chemical reservoir when 60 compared to the other types of chondrites (Tringuier et al. 2007, Warren et al. 2011).

61 The construction of classification schemes for small bodies has enabled to assess their compositional diversity, and to map their geographical distribution across the Solar 62 63 System (Gradie and Tedesco, 1982; DeMeo and Carry, 2014). The classification schemes are multiple and evolving with time, as the number and type of observations increase, and new 64 classification methods emerge. At the same time, debris of asteroids are naturally delivered 65 to Earth in large amounts, meteorites, which provide an opportunity to anchor and 66 67 understand the spectral diversity of small bodies in term of composition. Because only a few compounds have absorptions in the visible and near infrared spectral range, the 68 meteorite approach is key: as an example we would not know that the silicate feature 69 70 observed on S-type asteroids is related to the presence of chondrules, and the spectra of S-71 type could be matched by an olivine- and pyroxene-rich rock, the mantle of a terrestrial 72 planet for example.

73 The meteorite approach has also several limitations. First, the Earth atmosphere 74 filters out most of the fine-grained material, and the extra-terrestrial material collections is 75 immensely biased toward rocky material. Second, laboratory measurements on meteorite 76 are not done in the same geometrical conditions as small bodies observations. They are 77 typically measured at 30° phase angle while main-belt asteroids observation have phase 78 angle ranging from 0 to 30°. In addition, ground-based observations are integrated over a 79 hemisphere, and reflectance is not controlled by phase angle only but also incidence and 80 emergence (Potin et al., 2019). Approaches have been developed to account for these 81 effects in observation of Near-Earth Asteroids (Binzel et al., 2015). Last but not least, 82 airless bodies are exposed to a number of specific processes that may alter the physical and 83 chemical properties of their surfaces and these processes need to be emulated in the 84 laboratory to understand how they impact the meteorite/asteroid spectral connection.

85 A first process that occurs on asteroid surfaces is macroscopic impacts. The heat 86 deposited by hypervelocity collisions can lead to a transient increase of temperature and 87 more prolonged heating in the case of burial below ejecta blankets. In addition to macroscopic impact, micrometeorites impacts can also alter the surface composition by 88 89 leading to the deposition of small but optically modifying layers of vapor condensate, or the 90 production of agglutinates (Hapke, 2001). Last, the exposure to irradiation by the solar 91 wind and galactic cosmic rays can also change the optical properties of silicate-rich 92 surfaces. A review on the understanding of the processes that may alter the optical 93 properties of airless bodies, space weathering, can be found in Pieters and Noble (2016).

94 Space weathering is now largely accepted as the process that explains the
95 differences between S-type asteroid spectra and reflectance spectra of ordinary chondrites.
96 Space weathering on S-type is likely the results of faster changes due to solar wind

97 exposure, and slower modification related to micrometeorites impacts (Vernazza et al., 98 2009). In the case of C-types asteroids, important progresses have been made recently on 99 simulating the effects in the laboratory (Lantz et al. 2017, Brunetto et al. 2020, Matsuoka et 100 al. 2020, Thompson, et al., 2020), in the framework of sample-return missions to near-Earth asteroids. The effects appear to be less pronounced than in the case of ordinary 101 chondrites, with generally a bluing of dark sample with increasing irradiation dose, 102 103 whether in the case of solar wind simulation or micrometeorite impact simulations (Lantz 104 et al. 2017; Brunetto et al. 2020; Matsuoka et al. 2020; Thompson, et al., 2020). Hints of 105 space-weathering have been provided by the Small Carry-on Impactor experiment on 106 board Hayabusa2, which revealed a small shift of the 2.7 µm metal-OH absorption in 107 subsurface material compared to typical surface spectra (Kitazato et al., 2021). Still, 108 unambiguous evidence of space weathering effects on C-type asteroids in the visible range 109 are absent at present, and while lunar-style space-weathering products have been 110 identified in ordinary chondrite regolith breccias (Noble et al., 2010) they have not been 111 observed so far in carbonaceous chondrite regolith breccias, to the best of our knowledge.

112 In the present work, we investigate the variability of colors of C-type main-belt 113 asteroids based on the Sloan Digital Sky Survey dataset (SDSS) with the intent to compare to laboratory spectra of carbonaceous chondrites, discuss the C-type carbonaceous 114 chondrites relations, and search for evidences of space-weathering. The data processing of 115 116 the SDSS dataset is in essence identical to that presented in DeMeo and Carry (2013). Ccomplex asteroid are then extracted from a cluster analysis combining colors and albedo. 117 118 This work builds on a recently developed approach to assess the impact of observation 119 geometry on meteorites spectra (Beck et al., 2021). We show that C-type asteroids are 120 overall bluer than carbonaceous chondrites, which may suggest that space-weathering is generally affecting the surface of C-type main-belt asteroids. However, we find that large C-121 122 type asteroids (D>20 km) are redder than small C-type asteroids (D<20 km). This 123 difference could be related to a sampling artifact of the SDSS dataset, biased toward smaller 124 objects. If not, we suggest that this overall blue nature of smaller C-type is related to the 125 presence of coarser-grained material.

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2. Method

2.1 Colors and albedo

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130 This work uses data from the 4th release of the Sloan Digital Sky Survey (SDSS). The 131 data processing was done following the procedure developed in DeMeo and Carry (2013). 132 Chiefly, SDSS offers a color filter survey of about 400 000 Solar System moving objects. The 133 colors used for this work are g' (0.4686 µm), r' (0.6166 µm), i' (0.7480 µm) and z' (0.8932 134 μm) while the u' band was excluded for the reason described in DeMeo and Carry (2013). 135 We used color specific magnitude thresholds as defined in DeMeo and Carry (2013) to exclude the faintest objects from the catalogue. Objects with too high photometric 136 uncertainties were also excluded from the dataset. For each object, relative reflectance 137 138 (normalized to the g' filter) is calculated using:

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 $Rf = 10^{0.4*\{(M_f - M_g) - (M_{f,\odot} - M_{g,\odot})\}}$ 

143 Where  $M_f$  and  $M_{f,\odot}$  are the magnitudes in a filter for the object and for the Sun 144 respectively. Solar colors are taken from Holmberg et al. (2006) following DeMeo and Carry 145 (2013). Albedos and diameters used in this study were taken from the WISE catalog 146 (Masiero et al., 2011).

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2.2 Cluster analysis

151 Cluster analysis was performed using a routine available within the IDL environment. 152 Three components were used for the cluster analysis. The first two are the g'r'i' spectral 153 slope (referred to as *gri* slope in the rest of the manuscript, %/100 nm) and *z-i* magnitude difference. These two parameters were shown to display a large spread in DeMeo and 154 155 Carry (2013) analysis and were used to map the compositional structure of the asteroid population. The *gri* slope corresponds to the visible slope of each object while *z*-*i* is an 156 157 indication of the presence of an Fe-related absorption band.

158 Because historically C-type asteroids have been identified as being dark objects, 159 albedo was added as a third component to the cluster analysis. Before running the 160 algorithm, the average of each 3 parameters were calculated and subtracted. Then the standard deviation was calculated and each of the 3 parameters was divided by its 161 standard deviation. From there, cluster analysis was performed with equal weights given to 162 each of the three parameters. Data with the following parameters were filtered out gri 163 164 slope > 30 or < -10 %/100 nm, *z*-*i* > 0.25 or < -0.75, and albedo > 0.5. This enables a better definition of the clusters by minimizing the impact of strong outliers in the analysis. An 165 arbitrary number of clusters was used in the analysis (n = 9). This number was chosen 166 167 since it enables to have a cluster definition reminiscent of the *gri* slope and *z*-*i* boundaries 168 from DeMeo and Carry (2013). It appeared that the position of the "C-type" clusters was 169 not impacted by the number of cluster chosen as long as n > 5.

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2.3 Laboratory data and phase angle effects

173 Laboratory spectra were taken from the RELAB database, which provides today the 174 most extensive suite of reflectance spectra of extra-terrestrial materials. The Tagish Lake 175 spectra were measured at IPAG on the same lithologies described in Gilmour et al. (2019).

176 One of the difficulties of comparing laboratory spectra of meteorite to asteroid 177 observation is the impact of observation geometry, in particular in the case of spectral 178 slope. This work builds on the recent study of Beck et al. (2021a) that investigated the 179 effect of observation geometry on reflectance spectra of a series of about 70 different 180 meteorites. This showed that for dark objects reflectance and slope could be significantly 181 impacted, but that these effects can be accounted for. Building on that work, for each 182 reflectance spectra used here and measured at  $g = 30^\circ$ , the same spectra could be 183 calculated for  $g = 0^{\circ}$  (Beck et al., 2021).

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3. Definition of the C-type cluster

The work presented here strongly depends on how asteroids are attributed as 187 188 members of the C-type cluster, which deserves some discussion. Once run, the cluster 189 analysis shows the presence of a large cluster of objects with *gri* slope and *z*-*i* within the range of the "C-box" defined in DeMeo and Carry (2013) (Figure 1) and overlapping with 190 191 the B and X-boxes. This cluster will be defined as the C-cluster. The cluster analysis did not 192 reveal the presence of a B-cluster, showing that B-class asteroids do not represent a 193 distinct population of objects. Rather, it appears that the transition from C- to B-type object 194 is a continuous process when considering SDSS colors only. On Figure 1 (top left) the gri 195 slope vs *z-i* array is displayed with a threshold applied on albedo values. This reveals that most of members of the C-cluster correspond to a dark population of objects. While B- and 196 197 C- type cannot be distinguished in our cluster analysis, it enables to separate a C-type from 198 a D-type related cluster (cyan and upper violet clusters in Figure 1 (bottom right) and 199 figure 2.

200 The clusters identified are presented in Figure 2, and were grouped according to their 201 expected link to taxonomic endmember. Their proper element distribution is also shown in 202 Figure 3. While difficulties may exist in distinguishing C-type from X-type or D-type objects 203 using colors only, the cluster analysis was efficient in separating a cluster overlapping with 204 C and D-type in term of colors but with a significantly higher albedos (Cluster 0) that are 205 more related to S, K or X-complex asteroids based on the proper element distribution. 206 Discussion and investigation of the different cluster identified will be the subject of further 207 work, and we will focus here on the C-cluster.

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#### 4. Comparison of C-cluster asteroid colors to carbonaceous chondrites colors

213 In Figure 4, a comparison is made between colors of C-cluster members and colors 214 calculated for carbonaceous chondrites spectra (in the gri slope vs z-i space), under 215 standard geometry  $g=30^{\circ}$  or after applying a correction to  $g=0^{\circ}$  (described in section 2). 216 The effect of the phase angle correction is to generally decrease the gri slope of studied 217 samples (Figure 4) while *z*-*i* does not change significantly. The comparison is made with 218 CV-CR-CO (Figure 4 top), CM and heated CM (Figure 4 middle) and Tagish Lake (Figure 4 219 bottom). Several observations can be made from this diagram. First, carbonaceous 220 chondrites belonging to CV, CR and CO groups (about half of carbonaceous chondrites falls) 221 are significantly redder that C-complex asteroids. This clearly shows that a significant 222 fraction of carbonaceous chondrites does not match the colors of C-type asteroids. Such a 223 conclusion has been reached previously based on spectroscopy (therefore mostly for the 224 largest objects) and based on albedo considerations (Bell 1988, Burbine et al. 2001, 2002; 225 Clark et al. 2009, Eschrig et al., 2021). Because terrestrial weathering is known to affect 226 colors and spectra of meteorites, we investigated the difference between falls and finds in 227 this diagram. In the case of CM chondrites, the meteorite falls studied (Mighei, Murray and 228 Murchison) span almost the range of value for all the CM studied (falls and finds). It 229 appears then than terrestrial weathering does not impact significantly the colors of CM falls 230 (or that it affects both falls and finds). In the case of CR, CV and CO chondrites, which can contain a significant amount of metal and sulfides, there is a clear difference between falls 231 232 and finds. The gri-slope value for falls is between 3 and 12 %/100 nm, while the gri-slope 233 value for finds is between 1 and 41 %/100 nm (Figure 4). Such a difference could be attributed to the terrestrial formation of Fe<sup>3+</sup>-rich oxides at the expense of Fe-metal. When 234 comparing the gri-slope and z-i of CR, CV and CO falls against the boundaries defined by 235 236 DeMeo and Carry (2013), it appears that the *gri* slope values of these meteorites powders 237 are higher than the average C-cluster, and more in agreement with the X- and K-type 238 boundaries.

239 In the case of the ungrouped carbonaceous chondrite Tagish Lake, colors of powdered 240 samples clearly fall outside of the C-type cluster defined here, and falls within the X and D 241 boxes defined in DeMeo and Carry (2013) (Fig. 4). This is somehow in agreement with the proposition that Tagish Lake is a fragment of a D-type asteroid, and as discussed in Beck et
al. (2021a), more likely a fragment of the interior of a D-type.

244 Among the suite of carbonaceous chondrites studied here, only CM chondrites appear 245 to correspond to the range of values of C-cluster asteroids. Among those, samples that have 246 been described as heated CM chondrites (Nakamura et al., 2005, Alexander et al., 2012, 247 Quirico et al. 2018) tend to show a more pronounced gri slope than non-heated CM 248 chondrites (Fig. 4 middle), while their *z-i* value remains similar. In addition, on average CM 249 chondrites appear to show redder slopes than C-cluster members. This is confirmed by 250 analyzing the distribution of *gri* slope values of CM chondrites and comparison to C-cluster 251 members (Fig. 5). 252

5. Discussion

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5.1 The B-type / C-type continuum

256 B-types asteroids spectra in the Vis-Nir are defined as "Linear, featureless spectrum 257 over the interval from 0.44 to 0.92 µm, with negative (blue) to flat slope" (Bus and Binzel, 258 2002). The B-type was identified as a spectral endmember in the DeMeo et al. (2009) 259 taxonomy, where the B-type spectrum resembles C-type, but to which a blue slope has been added. Famous objects classified as B-type includes 2-Pallas, 3200-Phaeton or 335-Roberta. 260 261 B-type asteroids tend to have spectra showing a broad  $1-\mu m$  feature and sometimes  $3-\mu m$ band indicative of hydrous minerals (Yang and Jewitt, 2010), but not always (Takir et al., 262 263 2020). The broad 1-μm feature has been interpreted as magnetite (Yang and Jewitt, 2010).

In the color-based classification scheme of DeMeo and Carry (2013), B-type asteroids represent 11.10 % of the mass of the main-belt, and 3.55 wt.% when Pallas is removed. When the cluster analysis was applied to the dataset studied here, there was no cluster identified with negative *gri* slope value and low-albedo, which would correspond to B-type asteroids. Rather, this analysis suggests that there is a continuum of objects between B- and C- type rather than two distinct categories. This is in agreement with the somehow arbitrary definition of the B-type, as being objects bluer than the Sun.

271 In order to assess the potential "separability" of a C-cluster from a B-cluster, we need 272 to address whether the slope variability found within the C-cluster is true, or related to 273 observational uncertainty and biases. First, the slope variability found is significant, and 274 can hardly be explained by observation uncertainty or phase angle effects. While in some 275 special cases phase angle can change the spectral slope from red to blue (lost et al., 276 2017a,b), measurements performed on carbonaceous chondrites showed that phase angle 277 can decrease or increase slope, but not change its sign for the phase angle range of interest 278 (typically 0-30°, Beck et al., 2021a).

279 Second, error on color magnitudes may transpose into error on the slope 280 determination. We investigated this effect by using average error on color for members of the C-type cluster (g=0.0218, r=0.0171, i=0.0181) and propagating this error on *gri* slope 281 determination using a Monte-Carlo approach. This analysis enables to estimate the 282 uncertainty on *gri* slope for the C-cluster to be +/- 0.934 %/100 nm (1 sigma). This analysis 283 284 suggests that some of the spread in gri slope observed (Figure 1 and 5) is due to 285 uncertainty on color magnitudes, but that the overall variability within the cluster is real 286 and that identification of a B-type cluster may have been possible.

The presence of a continuum of objects with varying slopes can be explained whether by the presence of a continuum of composition between a B and C endmembers, or by a process that continuously modifies the C signature onto a B signature or vice-versa.

291292 5.2 Size dependence of the *gri* slope

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294 In order to identify the origin of the slope variability among the C-cluster, the 295 relation between the gri slope was studied as a function of asteroid diameter (Fig. 5). This analysis revealed than when considering objects smaller or larger than 20 km in diameter. 296 297 there is a difference in the distribution of *gri* slope. The average *gri* slope of large objects 298 is higher by about 1 % / 100 nm when compared to smaller objects. This is a small 299 difference but that appears significant. On Figure 5 is also shown the *gri* slope distribution 300 for CM and heated CM chondrites powders, which appears more similar to the larger C-301 types (>20 km) than the smaller ones.

In order to further investigate the variability of colors with size, the *z*-*i* and *gri* slope were plotted as a function of diameter, and running median and average were calculated over 50 elements (Figure 6). This shows that both *z*-*i* and *gri* slope decrease with decreasing diameter. In the case of *gri* slope two regions seem to be present with a slope change around 20 km diameter objects. In line with the observations discussed here,

Vernazza et al. (2016) observed a spectral evolution with asteroid diameter in a spectral
survey of about 70 Ch/Cgh objects (sub-type of the C-complex). The smaller object
analyzed in Vernazza et al. (2016) tend to be bluer than larger ones, as well as to present
fainter phyllosilicate absorption bands.

311 Because the SDSS dataset (and the asteroid belt) contains much less large asteroid 312 than small asteroids, one needs to verify that the difference in *gri* slope observed is not due 313 to a number-related bias. Considering large (>20 km) vs small (<20 km) objects, the 314 average values of *gri* slope seems so be statistically different if the error on the mean 315 (standard deviation divided by the square root of the number) is considered (2.27 %/100 316 nm ± 0.10, n=470; 1.43 %/100 nm ± 0.03, n=6272). Nevertheless, it cannot be strictly ruled 317 out that some bias exists in the dataset or analysis that would produce the *qri* slope vs 318 diameter trend. We tested phase angle as a possible source of bias, but the range of phase 319 angle are similar between large and small objects, and no correlation was found between 320 phase angle and gri slope. Because large and small objects are on average of different 321 magnitude, the difference may be caused by a magnitude dependent bias. But at the 322 moment we do not have evidence for such a bias.

To summarize 5.1 and 5.2, there is a continuous variability of slope within the Ccluster, and smaller members seem to be slightly bluer than larger members. We will suppose that this variation is true, and discuss in the following sections several possible causes for this variability.

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5.3 Space weathering

330 In the case of S-type asteroids, space-weathering effects appear widespread with the exception of small near-earth asteroids whose surface might be refreshed by physical 331 effects (Binzel et al., 2004). In the case of C-type asteroids, considerable efforts have been 332 333 undertaken in the last years to understand the consequences of high-energy irradiation as 334 well as micrometeorites impact from a laboratory perspective. In the case of ordinary chondrites, containing large crystal (>50  $\mu$ m) of translucent silicates (olivine & pyroxene), 335 the production of small nano-phase iron particles whether by vapor deposition or *in situ* 336 337 transformation within the grains lead to an increase of spectral slope, and a decrease of 338 visible reflectance and absorption band contrast (Hapke, 2001). The lack of strong silicate 339 feature on fresh carbonaceous chondrites spectra implies that the spectral effects of space

weathering will be different from ordinary chondrites. Another option to investigate spaceweathering effects is to observe the spectral variability of asteroid families as a function of dynamical age (Vernazza et al., 2009) or to observe spectral signature of freshly exposed material from asteroids surfaces (by impact of mass wasting processes). In the case of Stype, these two approaches have been used and suggest that the spectral effects observed in the laboratory reproduce well those observed on asteroid surfaces (Chapman, 1996).

346 Laboratory investigations of space-weathering effects on carbonaceous chondrites 347 have shown behavior quite distinct from S-type, with bluing or reddening of the samples 348 upon ion irradiation (Lantz et al., 2017), and bluing in the case of simulated micrometeorite impacts using pulsed laser (Matsuoka et al., 2020). Spectra from these studies were 349 350 digitized and used to calculate the impact of space weathering on the z-i vs gri slope 351 diagram (Fig. 7). Within this array, simulated micrometeorite impact produces a diagonal 352 vector pointing toward lower *z-i* and lower *gri* slope. In the case of ion irradiation studies 353 on Mighei (CM) and Tagish Lake (UCC: ungrouped carbonaceous chondrite) (Lantz et al., 354 2017), the effect is to induce a bluing without impacting the *z*-*i* value. Note that in the case 355 of these two samples, there were no absorption around 0.9 µm in the starting material, and 356 the lack of impact on the *z*-*i* value can be attributed to the absence of feature in the initial 357 sample (a feature that is not present cannot disappear).

Observations of C-type asteroids by the Hayabusa2 (HY2) spacecraft is providing 358 359 important clues on space-weathering of C-type Near Earth Objects (NEOs). The Small Carry-on Impactor (SCI) experiment onboard HY2 seems to show that space weathering 360 effects are not as pronounced as for C-type asteroids, as suggested by space weathering of 361 dark carbonaceous chondrite (Lantz et al., 2017). It is not known at the time of the writing 362 363 what the exact value is for the inferred vector for space weathering in the *z*-*i* vs *gri* slope 364 space as observed remotely for C-type. In the case of CO and CV chondrites, space-365 weathering tends to redden the spectra, which further excludes a connection between C-366 type and these groups of carbonaceous chondrites.

A conclusion that can be drawn from laboratory studies of space weathering effects is that the difference in *gri* slope between carbonaceous chondrites powders (CM, 3.8 %/100 nm on average) and C-type asteroids (1.3 %/100 nm on average) (Figure 4 middle) can be explained by space weathering because it is known to induce a shift of *gri* slope by 2 to 4 %/100 nm (Figure 7).

372 One observation that is not easily attributable to space weathering is the difference in 373 gri slope between large and small asteroids. One might expect that being of collisional 374 origin and therefore with a younger surface, small asteroids may be somehow less affected by space weathering than larger objects. This is contrary to the observation of Figure 4 and 375 376 5. A possibility is that larger objects may be shielded from some of the solar wind particles, 377 if a remnant of a magnetic field is present. This has been proposed for 4-Vesta (Vernazza, et 378 al., 2006), may be applicable to Ceres (Neuman et al., 2015), but is difficult to imagine for C-379 type asteroids in the 20-200 km diameter range. Their density is around 1.4 (Carry, 2012) and their shape does not suggest hydrostatic equilibrium which would be expected from 380 differentiation of a metallic core. Recent study of the C-type Daphne appears to reveal a 381 fairly homogeneous structure (Carry et al., 2019). As discussed in the following, other 382 383 effects may explain the difference in spectral slope between large and small C-type as well 384 as the overall slope variability.

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- 386 5.4 Rayleigh-like scattering particles
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388 The presence of particles smaller than the wavelength can lead to blue spectra as 389 shown experimentally (Clark et al., 2008; Poch et al., 2016; Sultana et al., 2020), and the 390 presence of such "hyperfine" particles has been proposed to explain the blue areas of the 391 C-type Ceres (Schroder et al., 2021). The size of the individual constituents of the matrix 392 of carbonaceous chondrites is µm to sub-µm as well as the size of the individual 393 constituents of Inter-planetary Dust Particles (IDPs) or cometary dust. Therefore, if the 394 hypothesis that the "non-hydrated" C-types are made of IDP-related material is correct 395 (Vernazza et al., 2015), this would imply that the surface material of many C-types is 396 constituted of dust with sub-um building blocks. If hyperfine particles are more abundant 397 in the case of the smaller C-type asteroids, this could explain the color difference when 398 compared to larger objects. However, because of the recurrent collisions (micro and 399 macro) occurring on their surfaces, we may expect some degree of compaction of 400 asteroidal surfaces. If initially constituted by hyperfine particles, compaction may 401 suppress a Rayleigh-like behavior and a process is needed to be active in restoring the porosity. This could be sublimation of dust-rich ice that would produce upon sublimation 402 403 a fluffy residue where Rayleigh-like scattering may occur (Poch et al., 2016; Schroder et 404 al., 2021, Sultana et al., 2020).

However, this scenario would suggest that the smaller and bluer objects have a
surface finer-grained or/and with higher porosity, and therefore a lower thermal inertia.
As discussed below this is at odd with observations of thermal inertia for asteroids of
difference sizes.

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5.5 Grain size effect and Rayleigh-like scattering by grain surfaces

413 Grain size are known to have a significant impact on reflectance spectra of 414 carbonaceous chondrites, and more generally texture (powder, pellet, chip) can affect 415 spectral slope and the depth of absorption features (Ross et al., 1969; Johnson and Fanale, 416 1973, Cloutis et al., 2018). In order to assess the impact of sample texture, we used 417 reflectance spectra obtained on small fragments of fresh CM chondrites, which were 418 subsequently ground into powders. These data obtained on the Aguas Zarcas CM fall are 419 presented in Beck et al. (2021b), and revealed that CM fragments are much bluer than 420 powders, and show fainter absorption features. The reason for this reddening after 421 grinding may be due to the comminution of red-sloped phases that may become more 422 visible when finely mixed with other minerals (Ross et al., 1969). In other words when 423 grinding a sample, the mixture becomes intimate (proportional in single-scattering albedo 424 space to the surface area of grains) while in the case of chips the mixture is more 425 geographical (proportional to the surface area of the various phases).

Another possibility is than when grinding the sample, and increasing the specific surface area, the interaction with Earth's atmosphere is magnified, producing some oxidation of the sample. This may explain some observation related to the D/H isotopic composition of CM chondrites (Vacher et al., 2020) if hydroxides or oxy-hydroxides are produced by this process. However, observation of a similar slope change for ordinary chondrites that are likely less reactive than carbonaceous chondrites may disqualify this explanation.

433 Clark et al. (2008) suggested that the blue slope measured for some natural rock 434 samples could be explained by Rayleigh-like scattering. This is our favored hypothesis to 435 explain the blue slope of meteorite rocks or large grained powder (>1 mm) when compared 436 to finer powder. In the case of absorbing compact material, the intensity of the reflected

light will be strongly controlled by the first external reflection, at the rock surface. If 437 438 asperities smaller than the wavelengths are present at the surface of the rock, they may scatter light in a Rayleigh-like manner and produce the increase of reflectivity with 439 440 decreasing wavelength observed. If the same rock is ground to finer powder, multiple scattering may start to contribute more to the measured reflectance, which will be less 441 442 sensitive to the first external reflection, and then surface asperities. This is consistent with 443 emission observations of the silicate features from Marchis et al. (2012) that revealed more 444 contrasted emissivity signatures for the larger objects.

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446 When the spectra of raw and powdered carbonaceous chondrites are plotted in the *z-i* vs *gri* slope diagram (Fig. 7), a shift of typically 2  $\%/\mu$ m is found for the *gri* slope. This 447 change is of the order of the difference in box-averaged *gri* slope between small and large 448 449 C-type (Figure 5). The hypothesis of a variation of grain size with diameter was favored by 450 Vernazza et al. (2016) to explain the spectral variability of Cgh/Ch objects. It is also supported by variation of thermal inertia with asteroid diameter as reported in Delbo et al. 451 452 (2007). Thermal inertia is obtained through infrared observations of asteroids, and is 453 directly related to heat capacity and thermal conductivity of surface material. Powder surfaces tend to have a low thermal inertia, while large block tend to have a high thermal 454 inertia. The fact that larger objects are covered by material with low thermal inertia, 455 456 contrary to smaller objects, points to the presence of finer-grained material at the surface 457 of large asteroids.

458 Radar measurements of the SC/OC ratio of planetary bodies enables to probe a 459 combination of grain size and roughness at a scale of the order of the radar wavelength, 460 therefore several cm. Radar observations of small asteroids are dominated by NEA, while 461 radar observations of large objects are dominated by MBAs. These observations reveal a 462 clear decrease in the SC/OC ratio of small C-type (i.e. NEAs, 0.285 +/- 0.120) compared to 463 large C-type (i.e. MBAs, 0.098 +/- 0.058, all objects observed being larger than 20 km 464 diameter) (Benner et al., 2008). The scarcity of radar observation of C-type objects (total of 465 42 objects in Benner et al., 2008) does not permit to pinpoint a particular diameter for the transition. Still the very low SC/OC ratio of large C-type has been interpreted by the 466 467 presence of a fine-grained regolith (not rough or not scattering at the scale of the radar wavelength), while the SC/OC ratio of small objects points toward a rougher or lager 468 469 grained surface, in line with the conclusion we derive in our manuscript from optical 470 observations.

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6. What is the favored process to explain colors within the C-cluster?

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474 Based on the discussion above we have identified three processes that can explain 475 the difference in colors of C-cluster asteroids and carbonaceous chondrites. They are spaceweathering, the absence of a regolith on C-type MBAs, and the presence of a porous 476 sublimation lag. All these three processes can explain the C-cluster asteroid vs 477 carbonaceous chondrites difference, but at the moment only one of them can also explain 478 479 the difference in slope between large and small C-type MBAs: grain-size effect. As discussed 480 above, a surface covered by rocky fragments rather than regolith is likely to present a blue 481 slope, as observed in the case of C-type NEOs. The present analysis suggests that small C-482 type MBAs host on their surface a significant fraction of rocks rather than a fine-grained

483 material, in agreement with thermal inertia measurements (Delbo et al., 2007).

The transition from redder to bluer C-type MBAs may be related to the transition from primordial objects to fragments, i.e. small family members. Based on the "wavy" nature of the size frequency distribution of MBAs, it has been proposed that D<100 km asteroids represent objects produced by the collisional fragmentation of larger objects (Bottke et al., 2015). Most of the small asteroids from the C-cluster defined here belong to dynamical families and were therefore produced by collisions (Fig. 3, Nesvorny et al., 2015; Delbo et al., 2017).

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But being a collisional fragment does not imply that the surface should be devoid of 493 494 fine-grained material. Many asteroid families are ancient (>100 My), and even small objects 495 may have had time to develop a fine-grained regolith. Even if an asteroid is a rubble-pile, 496 exogenous processes will still act and may lead to the production of surface fines. However, 497 because of the low escape velocity for the smallest asteroids, the preservation of fine-498 grained material produced by impact will be more difficult. Different style and thickness of 499 regolith are expected to be present on small bodies depending on their size, as modeled by 500 Housen et al. (1979). We propose here that the progressive bluing for smaller objects is 501 related to the presence of more rocky regolith. The "rockier" nature of smaller asteroids 502 may be related to the fact that fine-grained material escape during impacts, or other 503 physical process that may enrich the surface in larger grains material, like the "Brasil-Nut" 504 effect (see review by Murdoch et al. 2015 on physical processes that may occur on micro-505 gravity environment).

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507 This does not mean that space-weathering does not impact on the colors of C-cluster. 508 While the maxima of the distributions are similar (Figure 5), on average large C-cluster 509 asteroids (D>20 km) have a slightly bluer spectral slope than average CM chondrites 510 powders from our study (2.3 vs  $3.6 \ \%/100 \ \text{nm}$ ). This difference could be explained by the 511 presence of a fraction of rocky material at the surface of large C-types as well. However 512 thermal inertia observation of large C-type suggest that their surface is covered by a fine 513 regolith rather than rocks, and D > 50 km C-type objects can be expected to be primordial 514 rather than collisional in origin (Marchis, et al., 2012; Delbo et al., 2017). In that case, the 515 effects of space-weathering may be invoked to explain this difference and both irradiation 516 and micrometeorite provide efficient ways to turn bluer the surface of large C-types when 517 compared to carbonaceous chondrites. These effects are in any case modest when 518 compared to those observed for S-complex objects.

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### 7. Conclusions

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In this article, we have presented an analysis of colors of dark asteroids from the SDSSdataset with a focus on "C-type". We found that:

- A cluster analysis based on *gri* slope, *z-i* and albedo enables to identify a cluster that can be assigned to "C-type" with boundaries in the *z-i* vs *gri* slope space close to the ones defined by DeMeo and Carry (2013). The analysis does not identify a B-type cluster, but rather enlightens the presence of a continuum of objects with varying visible slopes.

- CM chondrites are the closest match to the C-cluster identified. Other types of
carbonaceous chondrites studied here are not (CO-CV-CR and Tagish Lake). Carbonaceous
chondrites of CO, CR and CV groups have colors more similar to X-, K- and L-type as defined
in DeMeo and Carry (2013).

- There appears to be a size dependency of the colors of C-cluster members, which merits further investigation and confirmation by other datasets. The smaller objects (D<20 km) appear bluer than larger objects. The preferred explanation is that smaller C-cluster
asteroids have surfaces covered by rocks, or large grained material (>1 mm) rather than a
fine-grained regolith. This suggest that a size-sorting mechanism may act under microgravity environment. Possible mechanisms include escape of finer material during impact
of the "Brazil-nut" effect.

- CM chondrites powders are slightly redder than large C-cluster asteroids that are
expected to be covered by regolith. This difference may be attributed to high-energy
irradiation based on available laboratory data.

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Figure 1: *z-i* vs *gri* slope diagram for the asteroid subset extracted from the SDSS database (see text for details). Top left: All objects with albedo <0.07. Top right: All objects color-coded with albedo value. Bottom right: All clusters identified. Bottom left: objects from the cluster defined as C-type. The boxes correspond to the limits defined by DeMeo and Carry (2013). Gri slope is in %/100 nm.



Figure 2: Cluster extracted from the analysis discussed in the text, grouped according to their supposed link to taxonomic types. The distribution of albedo in each cluster is presented in the lower right graph. The total number of members is also given for each cluster or group of clusters. Gri slope is in %/100 nm.



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Figure 3: Proper elements (sin(inclinaison) and semi-major axis ) for individual cluster or
cluster groups. Only objects with known proper elements in the ADR4 catalogue are shown,
which explains the absence of high-inclination objects in the plots as well as objects with
semi-major axis above 3.6.





Figure 4: The C-cluster compared to colors of carbonaceous chondrites (meteorite spectra from the RELAB database, except for Tagish Lake measured at IPAG). The boxes correspond to the limits defined by DeMeo and Carry (2013). HCM=heated CM. Gri slope is in %/100 nm. A) CV, CR, CO chondrites falls and find B) CR, CO, CV and CM chondrites falls only C) CM and heated CM falls and finds D) Tagish Lake (ungrouped carbonaceous chondrite fall).

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- 717 gri slope (%/100 nm)
   718 Figure 5: Slope distribution for C-cluster asteroids and CM & heated CM chondrites. The
- distribution is shown for objects of different sizes. Gri slope is in %/100 nm. The horizontal
  bar represents the average error on the gri slope.
- 721



722 Diameter (km)
723 Fig. 6: z-i and gri slope of C-cluster members shown as a function of asteroid diameter. A 50
724 elements running average and median were calculated and are shown on this graph. Gri
725 slope is in %/100 nm.



729Figure 7: Top) The C-cluster asteroids in the *z-i* vs *gri* slope space and the vector730associated to grain size and space weathering simulations. Bottom) *z-i* vs *gri* slope731diagram from the running average (see Fig. 6). The data are color coded according732to asteroid diameter. This reveals an increasing bluing with decreasing diameter,733together with a decrease of *z-i*. This trend is in line with a rock vs powder effect. Gri734slope is in %/100 nm.