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AS SAMPLES OF ICY ASTEROIDS*

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INTERPLANETARY DUST PARTICLES AS SAMPLES OF ICY ASTEROIDS

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ABSTRACT

Meteorites have long been considered as reflections of the compositional diversity of main belt asteroids and consequently they have been used to decipher their origin, formation, and evolution. However, while some meteorites are known to sample the surfaces of metallic, rocky and hydrated asteroids (about one-third of the mass of the belt), the low-density icy asteroids (C-, P-, and D-types), representing the rest of the main belt, appear to be unsampled in our meteorite collections. Here we provide conclusive evidence that the surface compositions of these icy bodies are compatible with those of the most common extraterrestrial materials (by mass), namely anhydrous interplanetary dust particles (IDPs). Given that these particles are quite different from known meteorites, it follows that the composition of the asteroid belt consists largely of more friable material not well represented by the cohesive meteorites in our collections. In the light of our current understanding of the early dynamical evolution of the solar system, meteorites likely sample bodies formed in the inner region of the solar system (0.5–4 AU) whereas chondritic porous IDPs sample bodies that formed in the outer region (>5 AU).

Key words: comets: general – interplanetary medium – meteorites, meteors, meteoroids – methods: data analysis – minor planets, asteroids: general – zodiacal dust

1. INTRODUCTION

Observations of more than 100,000 main belt asteroids (MBAs) in visible wavelengths show that ~60% of the mass of the asteroid belt belongs to the so-called C-complex, which comprises six subclasses (B, C, Cb, Cg, Cgh, Ch; DeMeo et al. 2009; DeMeo & Carry 2013). While one-third of all C-complex asteroids (Ch- and Cgh-types; Rivkin 2012) possess a well-established meteoritic analog (CM chondrites; see Figure 4; e.g., Cloutis et al. 2011), the bodies in the remaining subclasses (B-, C-, Cb- and Cg-type), including Ceres, appear unsampled by our meteorite collections, similar to P- and D-type asteroids (see A.1 and A.2). Importantly, whereas metamorphosed CI/CM chondrites have been proposed in the past as analogs of B-, C-, Cb- and Cg-type surfaces (Hiroi et al. 1993), such a possibility is presently untenable for the majority of these asteroids for three reasons, namely the paucity of these meteorites among falls (~0.2% of meteorite falls) compared to the abundance of B-, C-, Cb- and Cg-types, the difference in density between these meteorites and these asteroids, and the difference in spectral properties (in the mid-infrared) between the two groups (see A.1 for discussion). Overall, it appears that the surface material of ~66% of the MBAs masses (B-, C-, Cb-, and Cg-types—BCG-types in the following—represent ~53% and P- and D-types represent ~13% of the main belt's mass; DeMeo & Carry 2013) are absent from our meteorite collections.

A plausible explanation to this paradox could be the “comet-like” nature of these objects (see A.3). Indeed, the few existing density measurements ($\sim 0.8 < \rho < \sim 1.5 \text{ g cm}^{-3}$ for $D < 200 \text{ km}$ bodies; Carry 2012; Marchis et al. 2012) indicate that these

bodies cannot be made of silicates only, and must comprise a significant fraction of ice(s). This “comet-like” nature applies also to the dwarf planet Ceres as plumes of water vapour have unambiguously been detected at this object (Küppers et al. 2014; Ceres' mass ~35% of the main belt mass). It is thus not a surprise that several so-called main-belt comets were discovered among BCG-, P- and D-type objects (e.g., Hsieh & Jewitt 2006; Jewitt 2012; Hui & Jewitt 2015). Additional support to the “comet-like” nature of these objects is provided by spectroscopy in the 3 μm region, which indicates that water ice may not only be present in the interior of these bodies but also on their surfaces, as in the case of the Themis family (Campins et al. 2010; Rivkin & Emery 2010; Licandro et al. 2011; Hargrove et al. 2012, 2015; Takir & Emery 2012).

Because a large fraction of MBAs appears unsampled by our meteorite collections (at least their surface material), it seems logical, as a next step, to test a link between these asteroids and the other significant source of extraterrestrial materials, namely interplanetary dust particles (IDPs). IDPs differ from meteorites in being smaller (<2 mm), more plentiful (they contribute most of the extraterrestrial material that comes to the present-day Earth) and different in texture and composition (Bradley 2005). In particular, some classes of IDPs appear to be the most primitive material in the solar system and at present provide our best source of information on the nature and evolution of the particles in the preplanetary solar nebula (Bradley 1999, pp. 485–503). While both comets and asteroids are proposed as the most important contributors to the influx of IDPs, the relative contributions of these two populations to the IDP influx as well as the nature of the parent bodies of the three main classes of

IDPs (chondritic porous pyroxene-rich or olivine-rich IDPs, and phyllosilicate-rich IDPs; Bradley 2005) remain elusive. Presently, existing spectral datasets open the possibility that hydrous IDPs originate from C-complex asteroids (Bradley et al. 1996) and that anhydrous chondritic porous (pyroxene-rich and/or olivine-rich) IDPs originate from P- and D-type asteroids (although this proposed link relies on the visible range alone; Bradley et al. 1996) and/or comets (Sandford & Walker 1985; Campins & Ryan 1989; Sandford & Bradley 1989; Wooden 2002, 2008; Brunetto et al. 2011; Schulz et al. 2015). Modeling work based on observations of solar system dust bands suggests that either asteroids (e.g., Dermott et al. 2002 and references therein) or comets (e.g., Nesvorný et al. 2010) are the dominant source of zodiacal dust and thus of IDPs, leaving both possibilities open for further investigation.

The structure of this paper is as follows. In Section 2, we compare the spectral properties of BCG-, P- and D-type asteroids on the one hand, and those of comets on the other hand, with those of IDPs over a very large wavelength range (0.4–13 μm). In Section 3, we present the implications of our spectral analysis regarding the origin of IDPs. Finally, we list in Section 4 the remaining issues regarding both the origin of IDPs and the asteroid–comet-IDP link that require critical new data.

2. RESULTS

To explore the composition of the enigmatic icy asteroids (BCG-, P- and D-type asteroids) in more detail as well as a possible link with IDPs, we first compared their spectra in both the visible and mid-infrared ranges with those of IDPs (as of today, analog data in the 0.8–2.5 μm range unfortunately does not exist for IDPs). Spectra in these two wavelength ranges were available from previously published studies (see the figure captions for the complete list of references). In both ranges, it appears that the spectral properties of BCG-, P- and D-type asteroids are compatible with those of chondritic porous (anhydrous) IDPs (Figure 1). The mid-infrared spectral range, which is known to be significantly more powerful for the determination of the composition of silicate assemblages than the 0.4–0.8 μm range alone (Vernazza et al. 2011, 2012, 2013), further allows us to pinpoint the likely parent bodies of the two classes of chondritic porous IDPs: BCG-type asteroids have spectral properties compatible with pyroxene-rich IDPs, while P-types, D-types and comets have spectral properties compatible with a mixture of pyroxene-rich and olivine-rich IDPs (Figure 1). Note that P-types and some comets (see Figures 6 and 8 as well as A.7) seem to fill the gap that separates the pyroxene-rich BCG-types from the more olivine-rich D-types as well as most comets.

As a next step, we verified that the proposed link between BCG-, P- and D-type asteroids and chondritic porous IDPs is still valid in the near-infrared spectral range (0.8–2.5 μm) for which IDP spectra are currently missing. To test this link, we applied a radiative transfer model based on the Mie and Hapke theory (see A.7 for a detailed description of the model) to a subset of asteroid spectra representative of the spectral diversity seen among BCG-, P- and D-type asteroids (DeMeo et al. 2009; we actually applied the model to both the 0.45–2.45 μm and 8–13 μm ranges in order to cover the entire existing spectral range). The near-infrared asteroid spectra were collected with the SpeX instrument on the NASA Infrared

Telescope Facility (IRTF) on Mauna Kea, Hawaii (see A.4 and A.5).

As end-member, we used all the major and most minor minerals found in chondritic porous IDPs (Bradley 2005; crystalline olivine and pyroxene, silicate glasses, amorphous carbon, sulfides such as pyrothite and FeNi metal). To reproduce the spectral slope of P- and D-type asteroids we used the space-weathering model of Brunetto et al. (2006). Our results confirm that the spectral properties of BCG, P- and D-type asteroids are compatible in both investigated spectral ranges with their surfaces being covered by fine-grained silicates (grain size in the ~ 0.2 – $1 \mu\text{m}$ range as observed in IDPs) that have chondritic porous IDP-like compositions (see Figures 2 and 8).

3. IMPLICATIONS

If we follow the reasonable assumption proposed in the literature that hydrous IDPs originate from water-rich (or ice-rich) asteroids (e.g., Sandford & Bradley 1989; Dermott et al. 2002, pp. 423–442; Bradley 2005), then our study implies that asteroids (both their surfaces and their interiors) are fully representative of the compositional diversity of IDPs (surfaces of BCG-type asteroids = pyroxene-rich IDPs; surface of P- and D-type asteroids = mixture of pyroxene-rich and olivine-rich IDPs; interior of large BCG-, P- and D-types = hydrous IDPs? —see conclusion) whereas most comets (>65%; see A.6, A.7, Figures 6–8) are compatible with olivine-rich IDPs only. MBAs consequently appear as the most likely parent bodies of a large fraction of IDPs (and thus of most sporadic meteors). In addition, the relatively low maximum temperatures experienced during atmospheric entry by pyroxene-rich and hydrous IDPs, which implies that they originally had relatively circular, prograde orbits (asteroid-like), support an asteroidal origin for these particles (Sandford & Bradley 1989). However, it should be noted that comets still are likely to be a major source of olivine-rich IDPs.

Overall, our results imply that IDPs sample a larger fraction of MBAs (in terms of mass) than meteorites (Figure 3). In particular, whereas meteorites have been known for a long time to be representative of the surfaces of metallic, rocky and hydrated asteroids ($\sim 34\%$ of the mass of the belt), it now appears that only IDPs are representative of the surfaces of icy asteroids ($\sim 66\%$ of the mass of the belt). Note that a compositional overlap (and thus an overlap in the asteroid sampling) likely exists between the two classes of extraterrestrial material (e.g., between CI/CM meteorites and hydrous IDPs).

Finally, combined with existing density measurements (Carr 2012; Marchis et al. 2012), our results provide additional evidence to the “comet-like” nature of BCG-type asteroids. In particular, they support the possibility that not only P- and D-type asteroids (Levison et al. 2009) but also a large fraction of the C-complex asteroids (namely BCG-type asteroids) are implanted bodies from the outer solar system, as proposed in the Grand Tack model (Walsh et al. 2011). A formation location closer to the Sun for BCG-type asteroids (pyroxene-rich) with respect to D-type asteroids (olivine-rich) as proposed in the Grand Tack model would suggest, following our results, that the abundance of olivine relative to pyroxene was higher in the outer part of the disk than in the inner part, in perfect agreement with the trend observed in young disks around other stars (Bouwman et al. 2008; Sargent et al. 2009).

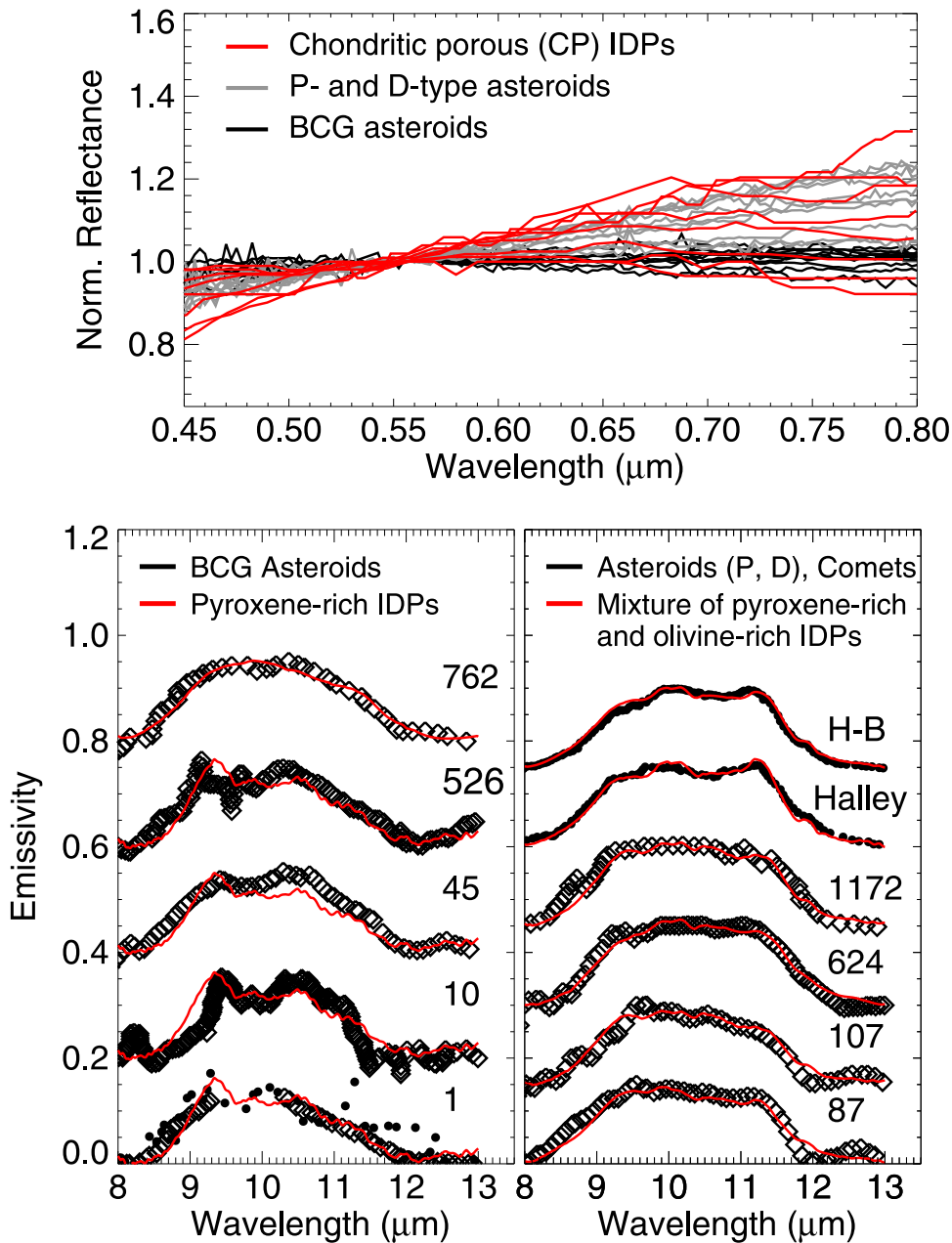


Figure 1. Interplanetary dust particles as analogues of BCG-, P-, and D-type asteroids. (Top): comparison in the visible range between the spectral properties of B-, C-, Cb-, Cg-, P-, and D-type asteroids and those of chondritic porous IDPs (from Bradley et al. 1996). The asteroid spectra were retrieved from SMASS (Bus & Binzel 2002). All spectra were normalized to unity at $0.55 \mu\text{m}$. This panel mainly illustrates Bradley et al.'s (1996) findings, where they opened the possibility that C-, P-, and D-type asteroids may have IDP-like surfaces based on the spectral properties of IDPs in the visible range. (Bottom): the continuum for all spectra has been removed and the contrast has been adjusted to the same intensity in order to allow a uniform mineralogical analysis of the silicate band. (Left): BCG-type asteroids (Cohen et al. 1998; Barucci et al. 2002; Takahashi et al. 2011; Licandro et al. 2012; Marchis et al. 2012) have spectral properties that are compatible with those of pyroxene-rich IDPs only. For (1), (10), (45), and (526), their spectra are well matched by the pyroxene-rich IDP L2036AE3 (Merouane & Djouadi 2014) whereas (762) is well match by a linear combination of a pyroxene-rich IDP and a GEMS-rich IDP (Bradley 1999, pp. 485–503). (Right): P-type (87, 107; Marchis et al. 2012) and D-type (624, 1172; Emery et al. 2006) asteroids and comets (here: Hale-Bopp and Halley; Campins & Ryan 1989; Hanner et al. 1997; Harker et al. 2011) have spectral properties in the mid-infrared range that are compatible with those of chondritic porous IDPs enriched in olivine. The best fit (red spectrum) is a linear combination of olivine-rich and pyroxene-rich IDPs (Merouane & Djouadi 2014). Note that P-types seem to fill the gap that separates the pyroxene-rich BCG-types from the more olivine-rich D-types as well as most comets (see Figure 8).

On the basis of both our current understanding of the early dynamical evolution of the solar system (Grand Tack model; Walsh et al. 2011) as well as previously established asteroid–meteorite links (Burbine 2014, pp. 365–415), our results suggest that meteorites likely sample bodies formed in the inner region of the solar system (0.5–4 AU) whereas IDPs sample

bodies (both asteroids and comets) formed in the outer region (>5 AU). Our work thus opens the possibility that our IDP collections sample a large diversity of small bodies that formed in the outer solar system, thus ultimately enabling a better comprehension of the various processes that occurred in this region of the solar system during the earliest epochs.

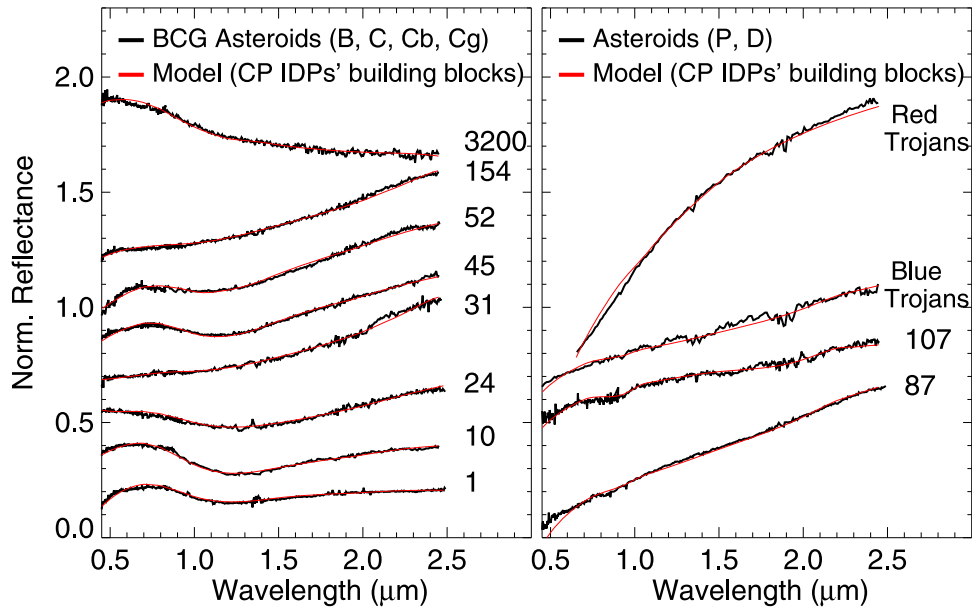


Figure 2. IDP-like surface composition for BCG-, P- and D-type asteroids. All spectra were normalized to unity at $0.55 \mu\text{m}$ and vertically shifted for clarity. Since IDP spectra have not been collected so far in the near-infrared range, we used a radiative transfer model (see A.6) to verify that the spectral properties in the $0.7\text{--}2.5 \mu\text{m}$ range of BCG-types (left) and those of P- and D-types (right) are compatible with those of chondritic porous (CP) IDPs (Bradley 2005). It appears that our model is able to reproduce well the spectra of BCG-, P-, and D-types assuming a CP IDP-like composition (olivine, enstatite, amorphous silicates, sulfides, and amorphous carbon being the dominant phases) and IDP-like grain sizes (grain size in the $0.2\text{--}1 \mu\text{m}$ range). We obtain a similar result in the mid-infrared range with this model (see A.6 and Figure 8). The average spectra of blue and red Jupiter Trojans (right) are from Emery et al. (2011).

4. CONCLUSION AND UNRESOLVED ISSUES REGARDING THE ORIGIN OF IDPS

Long considered to reflect their compositional diversity, meteorites have been used to decipher the origin, formation, and evolution of MBAs. However, finding a plausible meteoritic analog for low-density icy asteroids (i.e., for $\sim 2/3$ of the mass of the asteroid belt) has been an unsuccessful quest for decades. It has thus been gradually accepted in the community that these objects, although they comprise most of the mass of the asteroid belt, are unsampled in our meteorite collections. Strangely, the interesting findings by Bradley et al. (1996) that opened the possibility that BCG-, P- and D-type asteroids could be linked to IDPs have never really found an echo in the community of asteroid spectroscopists. The same can be said regarding predictions by Dermott et al. (2002) based on observations of solar system dust bands that were advocating an asteroidal origin for most IDPs.

Here we show that BCG-, P- and D-type asteroids are in fact well sampled in our collections, namely as IDPs, thus confirming earlier suggestions/predictions (e.g., Bradley et al. 1996; Dermott et al. 2002 and references therein). To reach this conclusion, we rely on spectral data covering a large wavelength range ($0.4\text{--}13 \mu\text{m}$) thus significantly extending the coverage by Bradley et al. (1996). Our extended wavelength coverage further allows us to pinpoint the parent bodies of two important families of IDPs: BCG-type asteroids with pyroxene-rich IDPs, and P- and D-type asteroids with a mixture of pyroxene-rich and olivine-rich IDPs. Comets, on the other hand, appear mostly compatible with olivine-rich IDPs and to a lesser extent with a mixture of pyroxene-rich and olivine-rich IDPs. Overall, our results imply that IDPs sample a larger fraction of MBAs than meteorites. Reciprocally, they suggest that asteroids are the likely parent bodies of a large fraction of IDPs (as suggested earlier by Dermott et al. 2002),

hence of a large fraction of sporadic meteors. Considering that current models of the early dynamical evolution of the solar system (Walsh et al. 2011) predict that icy asteroids are implanted bodies from the outer solar system, our findings thus imply that IDPs may also sample the building blocks of icy bodies in the outer solar system including giant planet satellites and TNOs and not only those of comets as previously suggested. Our work thus opens the possibility that our IDP collections sample a large diversity of bodies that formed in the outer solar system, ultimately enabling a better comprehension of the various processes that occurred over an extensive range of radial distances in the outer solar system ($>5 \text{ AU}$) during the earliest epochs, hence nicely complementing the information we have for the inner solar system via the study of meteorites.

There are, however, several issues (listed below as questions) remaining that require critical new data and/or new modeling efforts.

1. Which objects are the parent bodies of hydrous IDPs? Could slightly hydrated IDPs be associated with hydrated P- and D-type asteroids (whose spectra exhibit a $3 \mu\text{m}$ absorption band; Takir & Emery 2012)? or is the Tagish Lake meteorite a better analog for these objects? Also, since the mineralogy of hydrous IDPs is roughly similar but not identical to that of CI/CM chondrites (Bradley 1999 and references therein), it is a priori excluded that hydrous IDPs originate from Ch and Cgh-types. Instead, do hydrous IDPs originate from the interior of BCG-, P- and D-type asteroids where aqueous alteration has certainly occurred?
2. Asteroid families likely are a main source of meteorites (Vernazza et al. 2008, 2014). Is this also the case for IDPs? That is, which objects contribute the most to the IDP flux and why?

APPENDIX

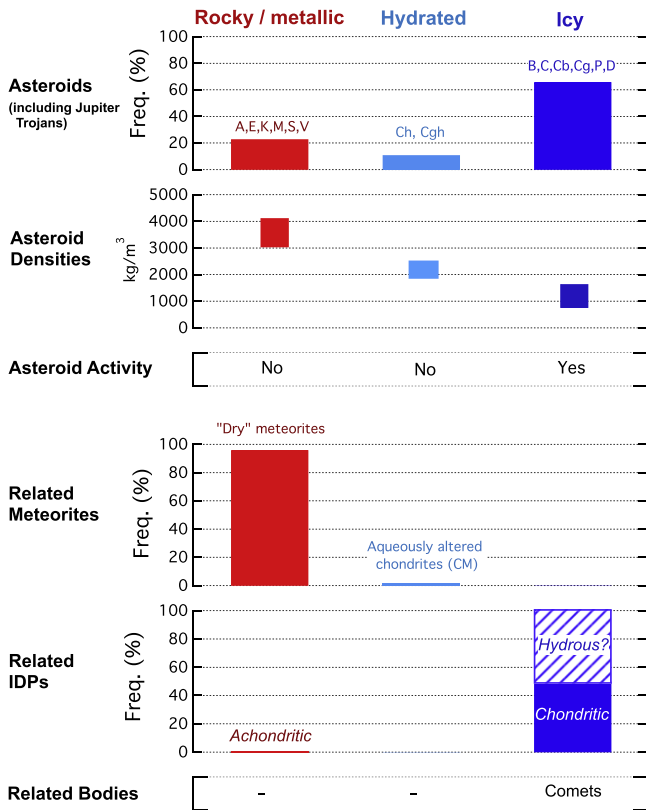


Figure 3. Illustration of the interrelations between different groups of solar system small bodies (asteroids, comets) and the two groups of extraterrestrial materials (meteorites, IDPs). The column on the right illustrates the main results of this paper. In the left column, dry meteorites include all meteorites besides the heavily hydrated CI and CM meteorites. For the left and middle panels, the following asteroid meteorite associations have been proposed: A-type with olivine-rich achondrites (pallasites, brachinites), E-types with enstatite chondrites and aubrites, K-types with CO, CK, CV, CR, M-types with iron meteorites, S-types with OCs, V-types with HEDs, and Ch-, Cgh-types with CMs (Burbine 2014 and references therein). In the second row, we report the density of $D \sim 100\text{--}200$ km sized asteroids (we use the same size range for the three different populations in order to avoid a size-related bias). $D \sim 100\text{--}200$ km sized asteroids are considered as “primordial” undisrupted bodies (e.g., Morbidelli et al. 2009) and their density therefore provides key constraints on their primordial internal composition. The density ranges are particularly robust for the middle and right columns as they are “provided” by binary asteroids, which are abundant among both hydrated and icy asteroids (Carry 2012; Marchis et al. 2012). In the third row, we highlight the asteroid classes for which activity has been detected. On this diagram, “Chondritic” corresponds to two of the main IDP classes (chondritic porous pyroxene-rich and chondritic porous olivine-rich), while “Hydrous” designates phyllosilicate-rich IDPs. Future work will help establishing whether the latter are linked to the interior of BCG-, P- and D-type asteroids or not (this is why we added a question mark).

Finally, the acquisition of near-infrared spectra ($0.8\text{--}4\ \mu\text{m}$) for all classes of IDPs will help refine the associations proposed in this work.

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A.1. Metamorphosed CMs as Improbable Analogues of BCG-type Surfaces

Metamorphosed CM chondrites, which represent $\sim 0.2\%$ of the falls, have been proposed in the past as analogues of BCG-type (B-, C-, Cb- and Cg-type) surfaces (Hiroi et al. 1993) but such a possibility is presently untenable for three reasons.

1. First, metamorphosed CM chondrites only represent $\sim 10\%$ of all CM chondrites whereas BCG-types are twice as abundant as CM-like bodies (Ch and Cgh-types) (Rivkin 2012), implying that BCG-types would be ~ 20 times less abundant than Ch and Cgh-types among meteorite falls. Whereas it is well known that atmospheric entry biases our meteorite collections by preferentially selecting the denser and more compact objects (which explains, for example, why ordinary chondrites are largely over-represented in our collections with respect to carbonaceous chondrites, such as CI and CM chondrites) it has been shown recently by Vernazza et al. (2014) that for materials having similar densities and tensile strength meteorite falls are representative of the compositional diversity of the asteroid belt within a factor of ~ 4 . This implies that metamorphosed CM chondrites should be at least as abundant as typical CMs in our collections; but they are not.
2. Second, the high-precision density measurements collected so far for a few BCG-types indicate that these are significantly lower than those of Ch and Cgh-types (BCG-types (45) Eugenia, (90) Antiope, (253) Mathilde and (762) Pulcova have densities in the $0.8\text{--}1.5\ \text{g cm}^{-3}$ range whereas Ch- and Cgh-types (41) Daphne, (121) Hermione and (130) Elektra have densities in the $1.9\text{--}2.4\ \text{g cm}^{-3}$ range; Carry 2012; Marchis et al. 2012). Yet, the opposite trend would be expected for bodies that were heated throughout so that their near surface reached temperatures of the order of $\sim 500\ ^\circ\text{C}$. Instead, it appears that BCG-types have densities in the same range as P- and D-type asteroids (low densities which suggest that these bodies contain a high fraction of ice). What’s more, water ice has been observed at the surface of some BCG-type asteroids (Campins et al. 2010; Rivkin & Emery 2010; Takir & Emery 2012), which is incompatible with the presence of heated CM material at the surface.
3. Third, the mid-infrared spectral properties of heated CM chondrites (Figure 5) are at odds with those of BCG-type asteroids (which also applies to CI and CM chondrites).

In summary, there are no meteorites in our collections whose spectra match well those of BCG-type asteroids over both the $0.4\text{--}2.5$ and $8\text{--}13\ \mu\text{m}$ ranges.

A.2. P- and D-type Surface Material Absent from Our Meteorite Collections

In the case of P-type asteroids, it has recently been demonstrated that most of these objects cannot be linked to the Tagish Lake meteorite (Tagish Lake has been regularly associated with P-type asteroids on the basis of similar spectral properties in the $0.4\text{--}2.5\ \mu\text{m}$ range), on the basis of a spectral mismatch in the mid-infrared (Vernazza et al. 2013). D-type

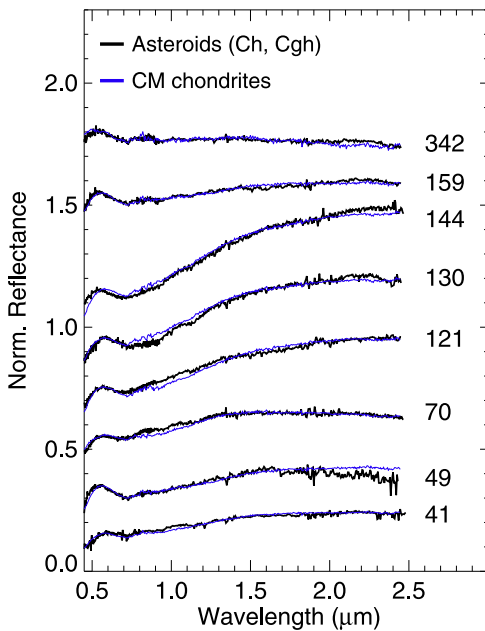


Figure 4. Surface composition of Ch- and Cgh-type asteroids. Ch- and Cgh-type asteroids (black) have spectral properties that appear perfectly compatible with those of CM chondrites (e.g., Cloutis et al. 2011) implying that they are the likely parent bodies of this meteorite class. The blue line is a best-fit consisting of a linear combination of CM chondrite spectra (taken from the RELAB database: <http://www.planetary.brown.edu/relab/>).

asteroids, on the other hand, possess a visible and near-infrared spectrum that is redder than any meteorite spectrum, implying that these objects (at least their surfaces) are unsampled by our collections. These objects are therefore very similar to BCG-type asteroids both because they are absent from our meteorite collections and because they share similar—very low—densities ($<1.5 \text{ g cm}^{-3}$, Marchis et al. 2012).

A.3. The “Comet-like” Nature of Low-density Asteroids

As described in the main text, there are now many elements (activity, low density, water ice present at the surface; e.g., Hsieh & Jewitt 2006; Campins et al. 2010; Rivkin & Emery 2010; Licandro et al. 2011; Carry 2012; Hargrove et al. 2012, 2015; Jewitt 2012; Marchis et al. 2012; Takir & Emery 2012; Küppers et al. 2014; Hui & Jewitt 2015) that suggest that icy bodies are abundant in the asteroid belt. Being icy but also dust-rich, these bodies thus appear similar to comets and other icy small bodies of the solar system, which shows that there is a continuum between asteroids and comets (Gounelle 2011). However, one should be cautious about terminologies and their meanings and this is why we use the expression “comet-like.” Indeed, whereas ices must be present in those asteroids, we currently ignore their compositions. Water ice is certainly present but how about other volatile species? More than 20 volatile species have now been detected in comets (e.g., Mumma & Charnley 2011) and future research, possibly via space missions, should aim at characterizing the volatile content of icy asteroids to further test the link between icy asteroids and comets. Finally, whereas the volatile content of icy asteroids is currently unknown, we show here that the dust phase (i.e., IDPs) in these bodies is very similar to the one that has been incorporated into comets (i.e., IDP-like and not meteorite-like) thus reinforcing the “comet-like” nature of icy asteroids.

A.4. Observation and Data Reduction

New data presented here are near-infrared asteroid spectral measurements for C-complex asteroids from 0.7 to 2.5 μm obtained using SpeX, the low- to medium-resolution near-IR spectrograph and imager, on the 3 m NASA IRTF located on Mauna Kea, HI. Observing runs were conducted remotely primarily from the Observatory of Paris-Meudon, France. The spectrograph SpeX, combined with a 0.8×15 arcsec slit was used in the low-resolution prism mode for acquisition of the spectra in the 0.7–2.5 μm wavelength range. In order to monitor the high luminosity and variability of the sky in the near-IR, the telescope was moved along the slit during the acquisition of the data so as to obtain a sequence of spectra located at two different positions (A and B) on the array. These paired observations provided near-simultaneous sky and detector bias measurements.

Objects and standard stars were observed near the meridian to minimize their differences in airmass and match their parallactic angle to the fixed N/S alignment of the slit. Our primary solar analog standard stars were 16 Cyg B and Hyades 64. Additional solar analog stars with comparable spectral characteristics were utilized around the sky. Two to three sets of eight spectra per set were taken for each object, each with exposures typically being 120 s. Finally, reduction was performed using a combination of routines within the IRAF and IDL.

A.5. Representativeness of Our Dataset

Spectroscopic observations of asteroids in both the visible (Bus & Binzel 2002) and near-infrared ranges (DeMeo et al. 2009) indicate that most ($>99\%$) asteroids do not possess unique spectral properties. Instead, it appears that “clones,” namely asteroids with identical spectral properties (e.g., Vernazza et al. 2014), are a common feature of the asteroid population (and likely of solar system small bodies in general). These asteroid “clones” have been labeled with a letter (A, B, C, etc.), commonly known as the taxonomic class (Bus & Binzel 2002, DeMeo et al. 2009).

In the present case, we have therefore used asteroid spectra belonging to the C-complex that are representative of the spectral diversity observed in this group, in order to decipher their composition.

A.6. Pyroxene-rich and Phyllosilicate-rich IDPs as Improbable Analogues of Cometary Dust

In Figures 6 and 7, we compare the spectra of the different classes of IDPs with those of comets (including both long-period and short-period comets). It appears that more than 50% of the comets have spectral properties compatible with olivine-rich IDPs mixed with a minor fraction of pyroxene-rich IDPs (Figure 6). The remaining comets but one (Austin) are best fitted if a pyroxene-rich IDP at the $\sim 30\%$ – 50% level is included in the mixture. This is for example the case for comet Linear. Overall, the composition of cometary dust overlaps well with the one inferred for P- and D-type asteroids, although some comets ($\sim 1/3$) appear to be more olivine-rich than D-types (e.g., Hale-Bopp, Halley). In our sample, there is one clear exception (in terms of composition), namely comet Austin for which a pyroxene-rich IDP provides the best fit. However, one needs to remain cautious about this comet’s spectrum because of its very low signal-to-noise ratio. There

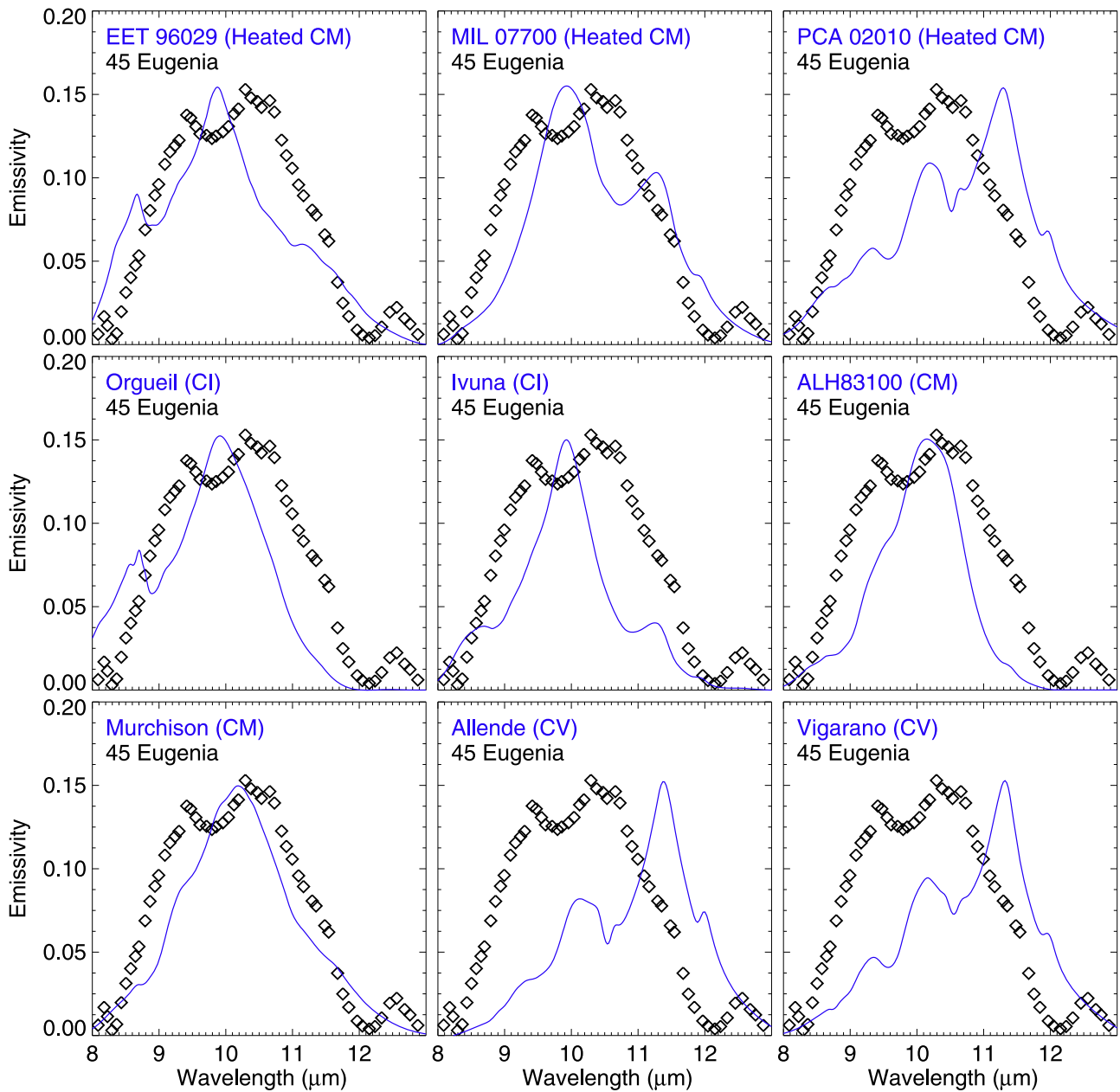


Figure 5. CI, CM, CV and heated CM chondrites as poor analogues of BCG-type asteroid surface. Here, we compare the mid-infrared spectrum of (45) Eugenia (Marchis et al. 2012; Eugenia has so far the highest signal-to-noise ratio for an object belonging to the BCG complex), with the emissivity spectra of several CI, CM and heated CM chondrites (Beck et al. 2014) in order to demonstrate that these meteorites cannot be linked to asteroids such as Eugenia. The continuum for all spectra has been removed and the contrast has been adjusted to the same intensity in order to allow a uniform mineralogical analysis of the silicate band.

are a few other comet spectra in the literature that are not displayed here. In all cases but one (comet Wilson, Hanner et al. 1994), a clear olivine feature at $11.3 \mu\text{m}$ is observed preferentially linking these comets to IDPs enriched in olivine.

Finally, we use Figure 7 to show how poorly both pyroxene-rich and phyllosilicate-rich IDPs fit cometary spectra, implying that these IDPs cannot originate from comets.

A.7. Modeling of the Spectra with a Radiative Transfer Code

A.7.1. The Model

We applied a radiative transfer model in both the $0.4\text{--}2.5$ and $8\text{--}13 \mu\text{m}$ ranges to analyze the mineralogies of BCG-type

asteroids, as well as the composition of P- and D-types and comets (for comets we used the $8\text{--}13 \mu\text{m}$ range only). In the visible and near-infrared spectral range, the single-scattering albedo was calculated using the Mie theory (Bohren & Huffman 1983) for grains with sizes small or comparable to the wavelength, and from optic-geometric equations for larger grains. The single-scattering albedo was then injected in Hapke’s equation of the bidirectional reflectance (Hapke 1993). In the mid-infrared range, the emissivity was approximated by the absorption efficiency factor (Q_{abs}) calculated for a distribution of hollow spheres with small sizes ($<1 \mu\text{m}$) compared to the wavelength (Min et al. 2003).

We used the optical constants (n and k) of common end-member minerals retrieved from the Jena database (<http://>

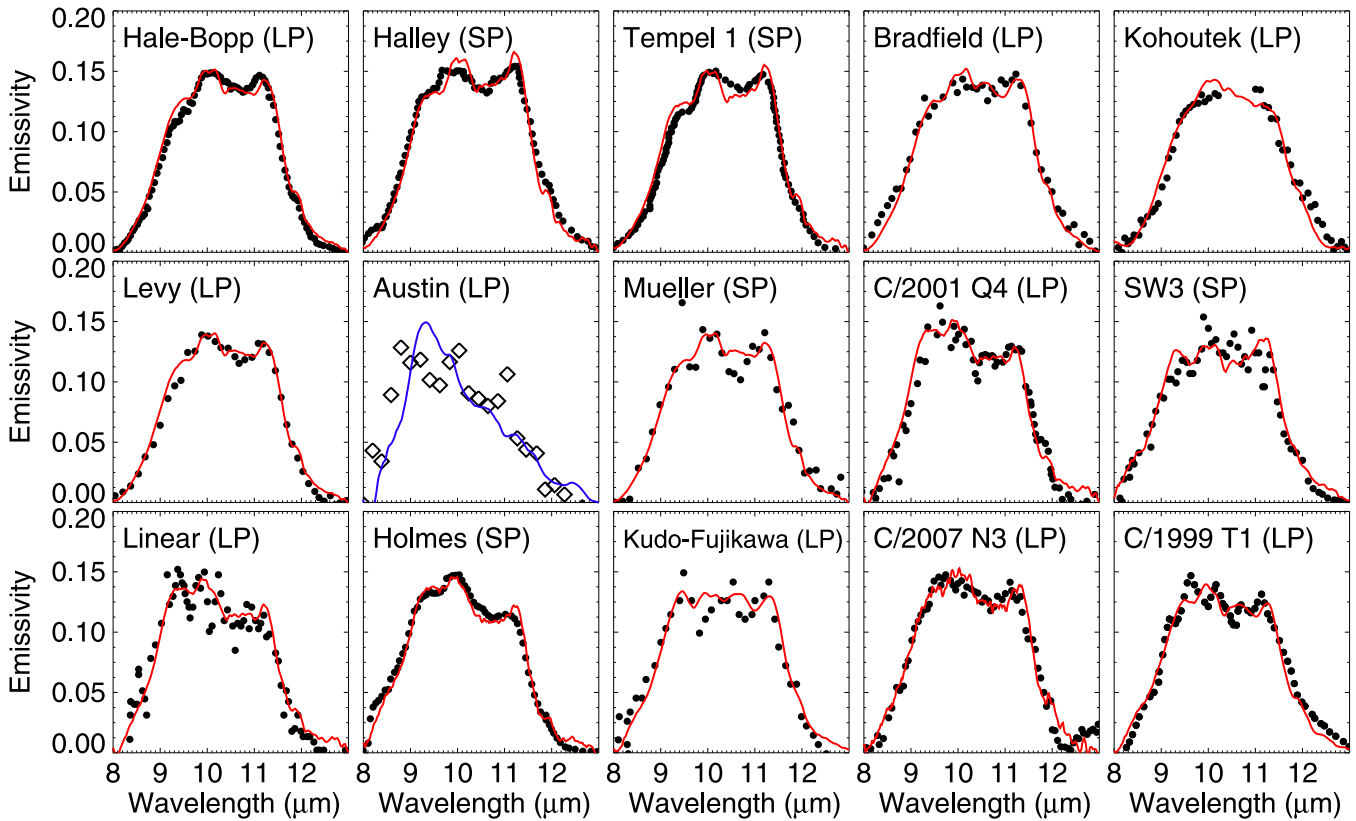


Figure 6. Composition of cometary dust. Here we compare the mid-infrared spectra of 15 long period (LP) and short-period (SP) comets (Campins & Ryan 1989; Hanner et al. 1994, 1997; Hayward et al. 2000; Lynch et al. 2002; Sitko et al. 2004; Wooden et al. 2004; Lisse et al. 2006; Harker et al. 2011; Woodward et al. 2011) with either their most likely IDP analogue or mixtures of IDP spectra (Merouane & Djouadi 2014). All comets’ spectral fits but one (Austin is best-fitted by a pyroxene-rich IDP) require an important fraction (>40%) of olivine-rich IDPs. Note that some comets required an important fraction (~50%) of pyroxene-rich IDPs (Linear, Kohoutek, C/2001 Q4, and Holmes), in the same way as do P-type asteroids and to a lesser extent D-type asteroids. Kohoutek, as an exception, required an important fraction of a GEMS-rich IDP (Bradley 1999). The continuum for all spectra has been removed and the contrast has been adjusted to the same intensity in order to allow a uniform mineralogical analysis of the silicate band.

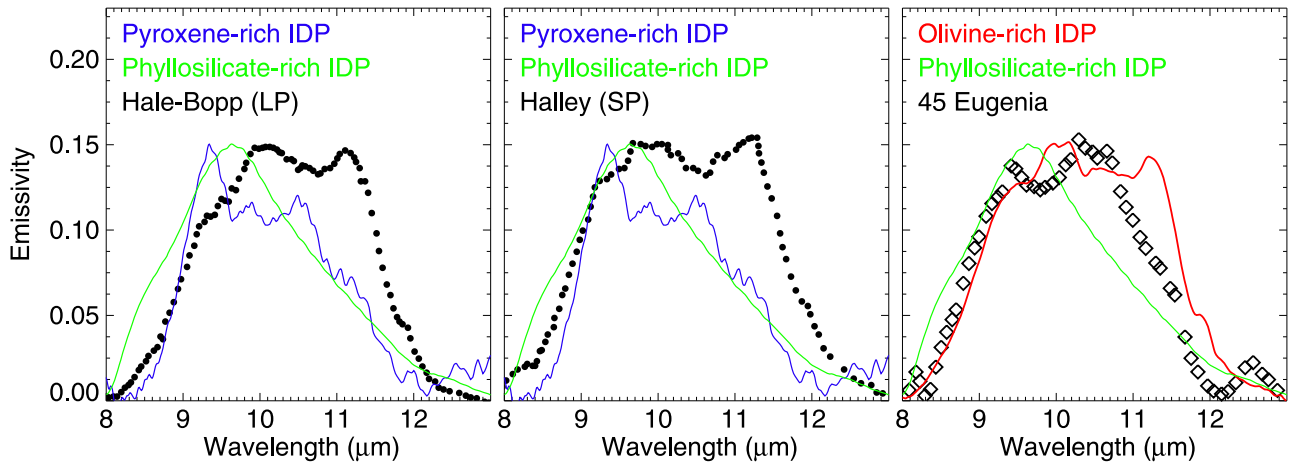


Figure 7. Impossible IDP analogues for both comets and BCG-type asteroids. Here we compare the mid-infrared spectra of two comets (Hale–Bopp, Halley) and of one C-type asteroid (45 Eugenia) with IDPs (Merouane & Djouadi 2014) to highlight impossible associations between given IDP classes (olivine-rich, pyroxene-rich, phyllosilicate-rich) and objects’ classes (comets, asteroids). In particular, it appears that both pyroxene-rich and phyllosilicate-rich IDPs cannot originate from comets whereas olivine-rich IDPs cannot originate from BCG-type asteroids. The continuum for all spectra has been removed and the contrast has been adjusted to the same intensity in order to allow a uniform mineralogical analysis of the silicate band.

www.astro.uni-jena.de/Laboratory/Database/databases.html found in anhydrous chondritic porous IDPs (Bradley 2005). Chondritic porous IDPs are heterogeneous aggregates of predominantly submicrometer-sized crystalline mineral grains (olivine, pyroxenes, iron-rich sulfides, and FeNi metal),

polycrystalline aggregates (olivine-like and enstatite-like), silicate glasses (GEMS), and carbonaceous material (Bradley 2005). Enstatite and forsterite with <5% mol. Fe are the most common crystalline silicates, although crystals with up to 30% mol. Fe are also observed. Sulfides are the second most

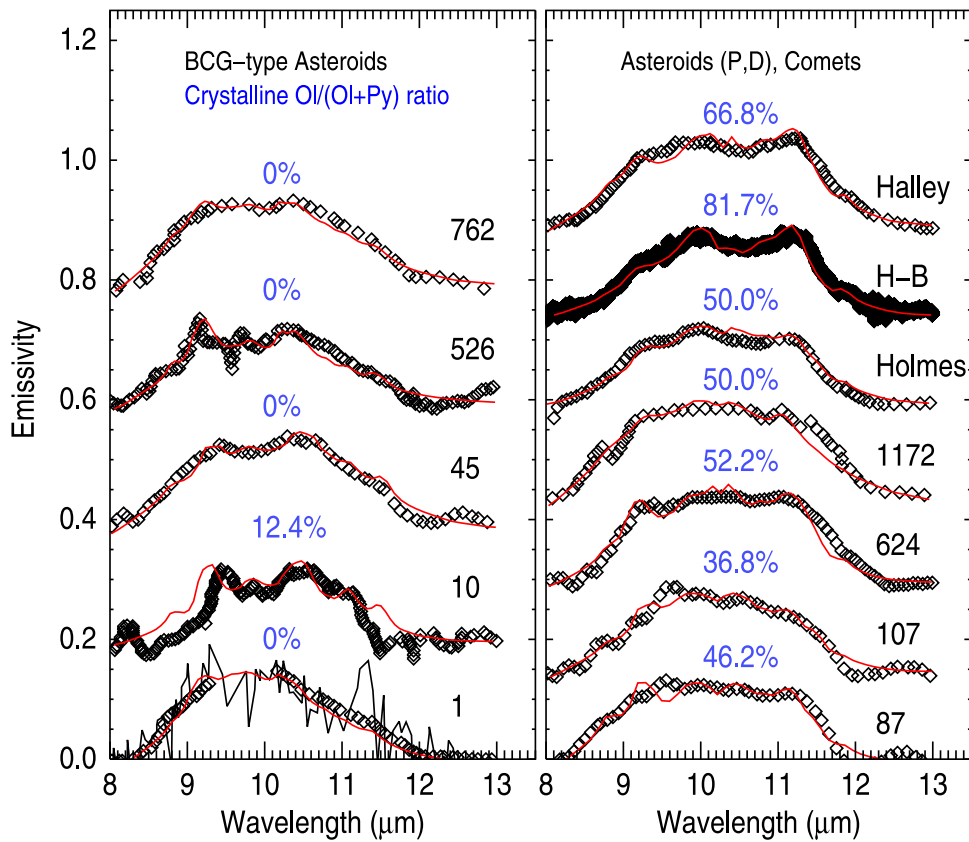


Figure 8. Composition of BCG, P- and D-type asteroids and comets constrained using a Rayleigh scattering model. The best fits were obtained using four end-members only (olivine, enstatite, olivine-like glass, pyroxene-like glass). The relative abundance of crystalline olivine to crystalline silicates (olivine+pyroxene) is directly indicated on the plot. (Left): BCG-type asteroids (Cohen et al. 1998; Barucci et al. 2002; Takahashi et al. 2011; Licandro et al. 2012; Marchis et al. 2012) have a crystalline ol/(ol+px) ratio in the 0–0.15 range. Most objects require no olivine. (Right): P-type asteroids (87) and (107; Marchis et al. 2012) have a crystalline ol/ol(px) ratio in the 0.3–0.5 range whereas the remaining objects (D-types and comets; Campins & Ryan 1989; Hanner et al. 1997; Emery et al. 2006; Harker et al. 2011) possess a crystalline ol/ol(opx) $> \sim 0.5$.

abundant class of minerals in chondritic porous IDPs, the most common sulfide being pyrrhotite with grain sizes in the range ~ 10 nm– $5 \mu\text{m}$.

The free parameters of our model are the relative abundance of the components (whose sum must be equal to 1), the mineral chemistries of the various components (variation of the Mg-number) and the grain size distribution (between 0.2 and $1 \mu\text{m}$). Finally, an IDL routine was used to find the minimum rms residual between the measured spectrum and the computed spectrum.

A.7.2. Results

A.7.2.1. 0.4–2.5 μm Range

In the 0.4–2.5 μm range, silicate glasses and sulfides were necessary end-members for reproducing the spectral properties of BCG-type asteroids (in particular for reproducing the broad band whose center varies from ~ 1 to $\sim 1.3 \mu\text{m}$). Since both enstatite and forsterite possess a neutral, flat spectrum in this wavelength range (due to the small grain size), they were not necessary components to achieve good fits of BCG-types. Amorphous carbon helped improving the fits of BCG-type spectra in the visible part of the spectrum. For P- and D-types, the use of a space-weathering model (Brunetto et al. 2006) was necessary for reproducing their high spectral slopes.

Overall, it appears that the spectra of BCG-, P- and D-type asteroids are well reproduced by our model if we assume end-members and grain sizes similar to those observed in chondritic porous IDPs. The main issue in this wavelength range is the lack of absorption feature in both enstatite and forsterite spectra which prevents us from a detailed compositional analysis. In the case of surfaces covered by small grains (smaller than $1 \mu\text{m}$), the mid-infrared spectral range is known to be significantly more powerful for the determination of the composition of silicate assemblages than the 0.4–2.5 μm range alone. We therefore used, as a next step, available spectra of BCG-type, P- and D-type asteroids and comets in the 8–13 μm range to constrain their surface composition in more detail.

A.7.2.2. 8–13 μm Range

In the mid-infrared, crystalline silicates (both olivine and pyroxene) were essential ingredients for reproducing the spectral properties—in particular the peaks—of BCG-type and P/D-type asteroids (as well as those of comets). Our spectral analysis thus implies that both olivine and pyroxene (both in amorphous and crystalline phase) are present at the surfaces of BCG-type asteroids as well as those of P- and D-types and comets (Figure 8). In terms of relative abundance, we found that BCG-type asteroids are more pyroxene-rich than P-types, which are themselves more pyroxene-rich than D-types and comets (the latter being conversely more

olivine-rich). This finding is supported by a direct comparison of IDP spectra with both asteroid and comet spectra (Figures 1, 8).

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