Asteroid (21) Lutetia as a remnant of Earth's precursor planetesimals

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ABSTRACT

Isotopic and chemical compositions of meteorites, coupled with dynamical simulations, suggest that the main belt of asteroids between Mars and Jupiter contains objects formed in situ as well as a population of interlopers. These interlopers are predicted to include the building blocks of the terrestrial planets as well as objects that formed beyond Neptune (Bottke et al. 2006, Levison et al. 2009, Walsh et al. 2011). Here we report that the main belt asteroid (21) Lutetia – encountered by the Rosetta spacecraft in July 2010 – has spectral (from 0.3 to 25 μm) and physical (albedo, density) properties quantitatively similar to the class of meteorites known as enstatite chondrites. The chemical and isotopic compositions of these chondrites indicate that they were an important component of the formation of Earth and other terrestrial planets. This meteoritic association implies that Lutetia is a member of a small population of planetesimals that formed in the terrestrial planet region and that has been scattered in the main belt by emerging protoplanets (Bottke et al. 2006) and/or by the migration of Jupiter (Walsh et al. 2011) early in its history. Lutetia, along with a few other main-belt asteroids, may contains part of the long-sought precursor material (or closely related materials) from which the terrestrial planets accreted.

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Whereas its orbital elements (a = 2.435 AU, e = 0.16, i = 3.07°) undoubtedly qualify (21) Lutetia as a main belt asteroid (from the inner belt), its classification, and therefore its composition have long been a matter of debate (Chapman et al., 1975; Barucci et al., 2005, 2008; Mueller et al., 2006; Shepard et al., 2008; Lazzarin et al., 2009; Vernazza et al., 2009; Ockert-Bell et al., 2010; see Supplementary Information). The most recent classification (Xc; De-Meo et al., 2009), based on a spectroscopic survey of ∼370 asteroids, has established that objects akin to Lutetia are very rare in the main belt; only three objects have been found, which is <1% of the population.

To clarify the mineralogical composition of (21) Lutetia, we used spectroscopic data from (i) the OSIRIS camera onboard Rosetta in the ultraviolet, (ii) the NTT (New Technology Telescope; La Silla Observatory, Chile) in the visible, (iii) the IRTF (Infrared Telescope Facility; Mauna Kea, Hawaii) in the near-infrared, and (iv) the Spitzer space telescope in the mid-infrared (Barucci et al.,

2008). We performed a detailed comparison of Lutetia's spectrum with laboratory measurements of meteorites catalogued in the RE-LAB and ASTER databases[1] and with new mid-infrared laboratory measurements of meteorites obtained at the University of New Mexico.

To search for plausible meteoritic analogs in the 0.3–2.5 μm range, we compared the spectral reflectance of Lutetia with those of selected meteorites. The selection was based on their reflectance at 0.55 μm, limited to the 0.10–0.28 range, in order to be compatible with the geometric albedo of Lutetia (p_V = 0.19 ± 0.01) that was determined from Rosetta/OSIRIS images (Sierks et al., in press). We further excluded meteorite spectra with absorption bands deeper than ∼3% since Lutetia is featureless in this spectral range. Finally, the difference between the Lutetia and meteorite spectra was minimized using the minimum least squares method. To search for plausible meteoritic analogs in the 8–25 μm range, we used the location of the following diagnostic features: (i) residual reststrahlen features, which occur as reflectance peaks, (ii) absorption bands due to overtone/combination tone bands, which occur as

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[1] http://www.planetary.brown.edu/relab/, http://speclib.jpl.nasa.gov/.

reflectance troughs, and (iii) the Christiansen feature, which also occurs as a trough in reflectance (Salisbury et al., 1991).

Over the full 0.3–25 μm range, we found only one meteorite class that has spectral reflectance properties compatible with Lutetia (Fig. 1), namely enstatite chondrites (ECs). Recent studies over a shorter wavelength range (0.4–2.5 μm) have suggested the same meteoritic analog (Vernazza et al., 2009; Ockert-Bell et al., 2010). CO and CV meteorites, which have also been proposed as Lutetia's meteoritic analog based on mid-infrared spectroscopy (Barucci et al., 2008), provide a less satisfactory fit to Lutetia's spectrum over the full range (see Appendix A). Interestingly, only KBr-diluted enstatite chondrite meteorites (Izawa et al., 2010; see Appendix A) display mid-infrared spectral features similar to those of 21 Lutetia (see Fig. 1). This may indicate that scattering from its regolith is a mixture of transmission and reflectance. The most probable explanation for the similarity between the Lutetia and the KBr-diluted spectra is that surface scattering is dominated by the fine-grained component of a loosely consolidated regolith, both properties cooperating to enhance the transmission of incident light. Indeed, the spectral properties of KBr-diluted materials mimic very well the spectral properties of fine-grained samples of similar composition (grain size <5 μm, see Appendix A). Although there are certainly larger particles in Lutetia's regolith, most of the scattering (volumetrically) is likely to come from these small particles. This is further consistent with the very low thermal inertia ($\leqslant$30 J K^{-1} m^{-2} s$^{-1/2}$; Carvano et al., 2008; Lamy et al., 2010a,b) of Lutetia, which indicates that its regolith is dominated by very fine-grained material (Delbo and Tanga, 2009).

The link between Lutetia and enstatite chondrite meteorites has profound consequences for the origin of Lutetia and implies that its current location is incompatible with its formation location. These meteorites – which represent a reduced, volatile-poor, anhydrous end-member of early Solar System materials (Rubin, 1997; Scott,

Fig. 1. Spectral comparison of (21) Lutetia and enstatite chondrite meteorites. Top panel (a): comparison from the ultraviolet to the near-infrared of (21) Lutetia and the enstatite chondrite meteorite (grain size <25 μm) KLE 98300 (EH3). Both have similar spectral characteristics, showing no absorption bands in this spectral range. A notable spectral feature shared by (21) Lutetia and the EH3 enstatite chondrite is the absence of a pronounced decrease in the ultraviolet (below 0.4 μm) that is commonly observed in most meteorites and minerals spectra. Bottom panel (b): comparison between KBr-diluted enstatite chondrite emissivity spectra with the mid-infrared spectrum of (21) Lutetia. The spectral emission features are strikingly similar, dominated by silicate fundamental vibrations. *Note*: an excess emission is found in the Spitzer space telescope data, between 13.2 and 15 μm. This feature known as the '14 μm teardrop' depends in a complicated way upon both source position in the slit and extraction aperture and is therefore difficult to correct. Extreme caution must be exercised in interpreting features in this spectral range highlighted by a light gray box. See http://ssc.spitzer.caltech.edu/irs/features/ for additional details.

2007) – are important because they are thought to have formed in the inner region of the solar nebula, near the proto-Sun (Wasson, 1988) and to have substantially contributed to the accretion of the terrestrial planets. For instance, the scarcity of evidence for FeO in Mercury's spectrum (Vilas, 1985) and the inferred high metal/silicate ratio led to the suggestion that Mercury was formed from materials related to enstatite chondrites (Wasson, 1988), although this is a matter of some debate. The rare gas abundances of the Venusian atmosphere (Donahue and Pollack, 1983) resemble those measured in components of EH chondrites (Crabb and Anders, 1981), suggesting likewise that many of the building blocks of Venus were enstatite chondrites (Wasson, 1988). All elements investigated so far in ECs (oxygen, nitrogen, ruthenium, chromium, titanium) have the same stable isotopic composition as Earth samples (apart from silicon and tungsten but internal processes such as the formation of a core can explain the difference, Trinquier et al., 2007), strongly suggesting that the Earth also accreted largely from enstatite chondrite-like materials (Clayton, 1993; Mohapatra and Murty, 2003; Burbine and O'Brien, 2004; Righter et al., 2006; Rubin and Choi, 2009; Javoy et al., 2010). In sum, EC may have a role as the building blocks of the three inner planets: Mercury, Venus and Earth.

The question naturally arises as to how Lutetia escaped accretion into one of the terrestrial planets and ultimately reached the main belt. The dynamical mechanism is likely to be similar to the one explaining the origin of iron meteorites as remnants of differentiated planetesimals formed in the terrestrial planet region (Bottke et al., 2006). Extended dynamical simulations reveal that, at the time when terrestrial accretion was ongoing, a small fraction (<2%) of the planetesimals residing in the 0.5–1.5 AU region were scattered out by emerging protoplanets (Bottke et al., 2006) and/or by the migration of Jupiter (Walsh et al., 2011) and achieved main-belt orbits, thus becoming dynamically indistinguishable from the rest of the main-belt population. According to this scenario, planetesimals of the size of Lutetia ($D \sim 100$ km) that formed in the 0.5–1.5 AU region experienced significantly more heating by short-lived nuclides than asteroids formed in the main belt. A direct consequence is that most of these planetesimals are likely to be differentiated in accordance with iron meteorites having formed in this region. Lutetia has a bulk density of 3.4 ± 0.3 g/cm^3 (Sierks et al., in press), one of the highest densities measured so far for an asteroid, comparable to the density of M-type asteroids 216 Kleopatra (Descamps et al., 2011) and 22 Kalliope (Descamps et al., 2008). Whether this implies that Lutetia is differentiated and possesses a metallic core cannot, however, be tested via a simple comparison of its bulk density with that of enstatite chondrites (average 3.46 ± 0.16 g/cm^3, Consolmagno et al., 2008; Macke et al., 2010) because such a comparison ignores the effects of Lutetia's possible macroporosity. Also, the idea of a metallic core versus distributed iron alloy within Lutetia cannot be directly tested with the available data. Two scenarios are then possible: (1) either Lutetia has negligible macroporosity ($\lesssim$2%) and consequently it is undifferentiated or alternatively, (2) Lutetia's macroporosity is greater than ~2% in which case Lutetia is differentiated and possesses an iron alloy core or distributed iron alloy (see Appendix A). Note that Lutetia's density is marginally compatible with a CO/CV meteoritic association (see Appendix A), therefore providing additional support to the conclusion derived from the spectral analysis.

The scenario of Lutetia being a main-belt interloper that formed in the terrestrial planet region and that has been scattered into the main belt early in its history by emerging protoplanets is also consistent with the paucity of objects akin to Lutetia in the unusual Xc spectral class (DeMeo et al., 2009). Indeed, numerical simulations (Bottke et al., 2006) have shown that most planetesimals having diameters of 20–100 km originating from the 0.5–1.5 AU zone disrupt after a few Myr. Very few survive intact and the largest
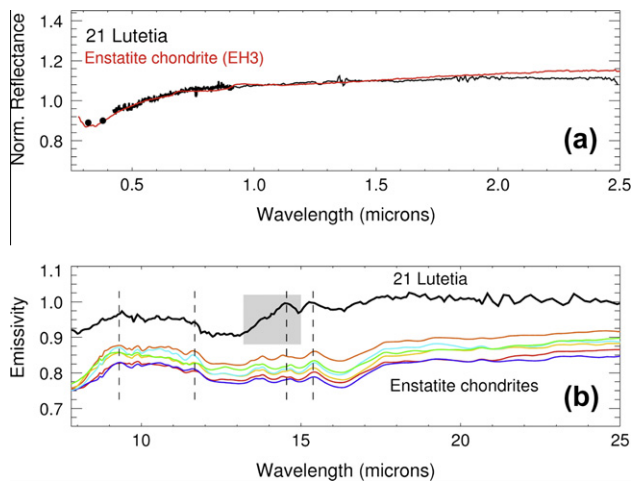
ones with $D \approx 100$ km (like Lutetia) stand the best chance to reach the main-belt. Lutetia, along with a few other main-belt asteroids, appears to be a rare survivor that escaped planetary accretion, and therefore contains the precursor material from which the terrestrial planets accreted.

Our results have important implications for asteroid and meteorite studies. To the crucial question of determining what known chondritic materials could possibly be the building blocks of Earth, current investigations show that, whereas enstatite chondrites are certainly part of them, they cannot account by themselves for all characteristics of Earth's bulk chemical and isotopic compositions (Burbine and O'Brien, 2004). It therefore appears that samples of the remaining building blocks of Earth are currently missing in our meteorite collections. Incidentally, this may also be the case for other bodies as, for instance, a substantial fraction of E-type asteroids that seem to be composed of materials that are not presently sampled by meteorites (Clark et al., 2004). Hence, by studying the surface composition of main belt interlopers not yet represented in our meteorite collection via extensive (multi-wavelength) spectroscopic surveys, we may infer the composition of the primordial Earth. These objects should be top priority targets of sample return missions.

Acknowledgments

Appendix A

A.1. The debate on the nature of Lutetia

Drummond et al. (2010) and Belskaya et al. (2010) have made an excellent summary of the work that has been performed by the community over the last ~35 years in order to understand Lutetia's surface composition and nature. We therefore refer the reader to those papers.

Very briefly, Lutetia was first classified as an M-type (metallic) based on spectral and albedo properties (McCord and Chapman,

1975; Chapman et al., 1975; Zellner and Gradie, 1976). As a matter of fact, the M-Class was originally defined by Lutetia and two other asteroids. Chapman and Salisbury (1973) were the first to suggest that what we now call M-types might be associated with enstatite chondrites (ECs) and Rivkin et al. (2000) suggested a hydrated EC as a plausible composition for Lutetia. More recent interpretations of Lutetia's spectrum have argued that Lutetia shows certain visible and mid-infrared spectral characteristics that resemble CO and CV types (Lazzarin et al., 2004, 2009, 2010; Barucci et al., 2005, 2008; Birlan et al., 2006; Perna et al., 2010) while VNIR ground-based spectroscopy has reinforced an association with ECs (Vernazza et al., 2009; Ockert-Bell et al., 2010). Recently, Lutetia was reclassified in the X-complex of asteroids (the original M-class actually belong to the new X-complex) characterized by their lack of strong spectral features, and their flat to red near-infrared slopes, and more precisely in the Xc subclass which contains very few members (3 out of 371 observed objects by DeMeo et al., 2009), so less than 1% of the population (DeMeo et al., 2009).

A.2. Comparison between the spectral properties of Lutetia and its likely meteoritic analogs (CO, CV, CK and enstatite chondrites) over the 0.3-25 μm range

A.2.1. UV, visible and near infrared spectral range (0.3–2.5 μm)

Because CO, CV and CK chondrites are olivine-rich meteorites (Hutchison, 2004), they possess a 1-μm absorption band in their near-infrared spectrum (see Fig. A1). For example, the CV3 meteorite Allende is made of more than 80% olivine (by vol%, Bland et al., 2004). These meteorites, however, contain an abundant matrix (30–75% in vol%, Hutchison, 2004) that is relatively featureless in the near infrared. The presence of the latter explains why the 1-μm absorption features in the CO, CV and CK spectra are subtler than in ordinary chondrite spectra (ordinary chondrites contain 10–15% matrix, Hutchison, 2004).

On the other hand, enstatite chondrites are made of minerals that are featureless (Fig. 1 and Fig. A2) in the visible and near infrared. They mainly contain (nearly) FeO-free enstatite, Si-bearing metal, and a variety of sulfides (Weisberg et al., 1995). The mineralogy of the E-chondrites shown in Fig. 1 is given in Izawa et al. (2010).

As shown in Fig. 1 and Fig. A1, Lutetia is featureless in the visible and near infrared, similar to enstatite chondrites. To highlight the compatibility between Lutetia and enstatite chondrites and the incompatibility between Lutetia and CO/CV/CK chondrites, we display (i) Lutetia's spectrum versus the mean spectrum of CO and CV chondrite meteorites (Fig. A1) and (ii) the depth of the 1-μm band in meteorite spectra (CO, CV, CK, enstatite chondrites) and in Lutetia's spectrum versus the reflectance value at 0.55 μm (proxy for the albedo) in Fig. A3. We also add K-type asteroids on the latter plot. These asteroids have been associated with CO/CV/CK meteorites by various authors (Burbine et al., 2001; Mothé-Diniz et al., 2008; Clark et al., 2009). Note: most enstatite chondrites show a very shallow absorption band around 0.9 μm, which is due to terrestrial weathering. Indeed, all the enstatite chondrite meteorites in our sample are affected by such weathering, although at different degrees (see Izawa et al., 2010). In Fig. 1 of the manuscript, we show the spectrum of the least weathered enstatite chondrite, as deduced from its very shallow 3-μm band; see Fig. A4.

The spectral similarity between K-type asteroids and CK, CO, and CV meteorites demonstrates that space weathering effects do not strongly affect the spectral properties of the latter meteorites. In particular, it appears very unlikely that these effects could erase the 1-μm feature on certain K-type asteroids to transform their appearance into that of Lutetia. It is also interesting to note the positive correlation between the 1-μm band depth on CO/CV/CK meteorites and their reflectance value at 0.55 μm. In order for these meteorites to match Lutetia's albedo, they need to have a
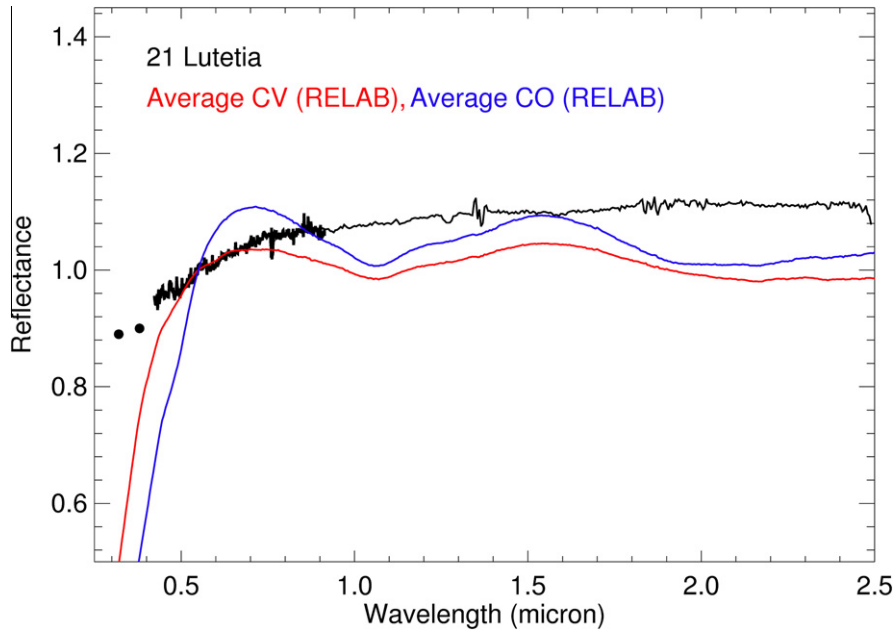
Fig. A1. Comparison between the UV, Visible to Near-infrared spectrum of (21) Lutetia and the mean spectrum of CO and CV chondrite meteorites from RELAB. The meteorites display obvious 1- and 2-μm absorption features that are not seen in Lutetia's spectrum. There is a further inconsistency between the UV spectrum of these meteorites and Lutetia's spectrum.
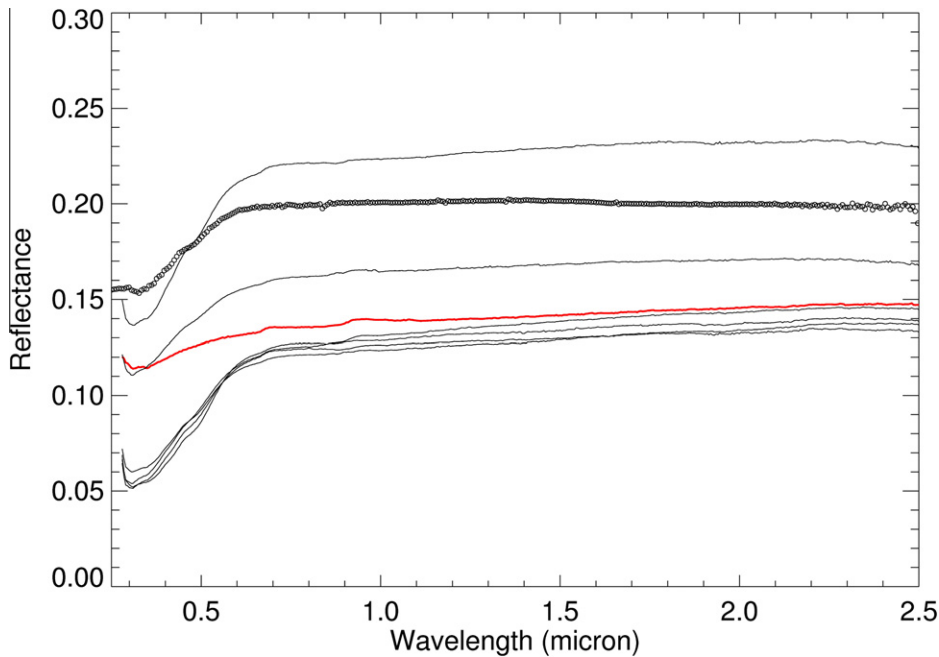

Fig. A2. Reflectance spectra (0.3-2.5 μm) of enstatite chondrites (grain size < 25 μm). The samples include: ALH84206 (EH3), ALHA81021 (EL6), EET96135 (EH4/5), EET96341 (EL4/5), KLE98300 (EH3), LEW88180 (EH5), QUE93372 (EH5), and Eagle (EL6). All measurements have been carried at RELAB (Brown University, US) besided the spectrum plotted with unfilled circles (the latter has been obtained for the EL6 Eagle meteorite at the Observatory of Catania, Italy). In red, we highlight the RELAB spectrum shown in Figure 1 of the manuscript. The latter meteorite (KLE 98300) that shows the smallest UV drop with respect to the other spectra is the least affected by terrestrial weathering (attested by the smallest water absorption feature in the 3-micron region, see Supplementary figure 4).

very deep 1-μm band, which is at odds with Lutetia's featureless spectrum. Reciprocally, in order to match Lutetia's absence of spectral absorption, the meteorites need to be very dark which is at odds with Lutetia's relatively high albedo (these arguments have already been put forward by Drummond et al. (2010)). The correlation seen for CO/CV/CK meteorites can be well explained by a variation of the proportion of the matrix (more matrix will darken the spectrum and make the 1-μm band shallower).

We would like to stress here that we found a single additional class of meteorites for which we obtained a good spectral match and that is aubrites. This is not a surprise since these meteorites have similar compositions to those of ECs. Indeed, the spectra of aubrites such as Peña Blanca Spring, Mayo Belwa and Bishopville strongly resemble the spectrum of Lutetia. Yet, the fundamental problem with an aubrite–Lutetia association is that these meteorites are much brighter (reflectance at 0.55 μm is around 0.5) than
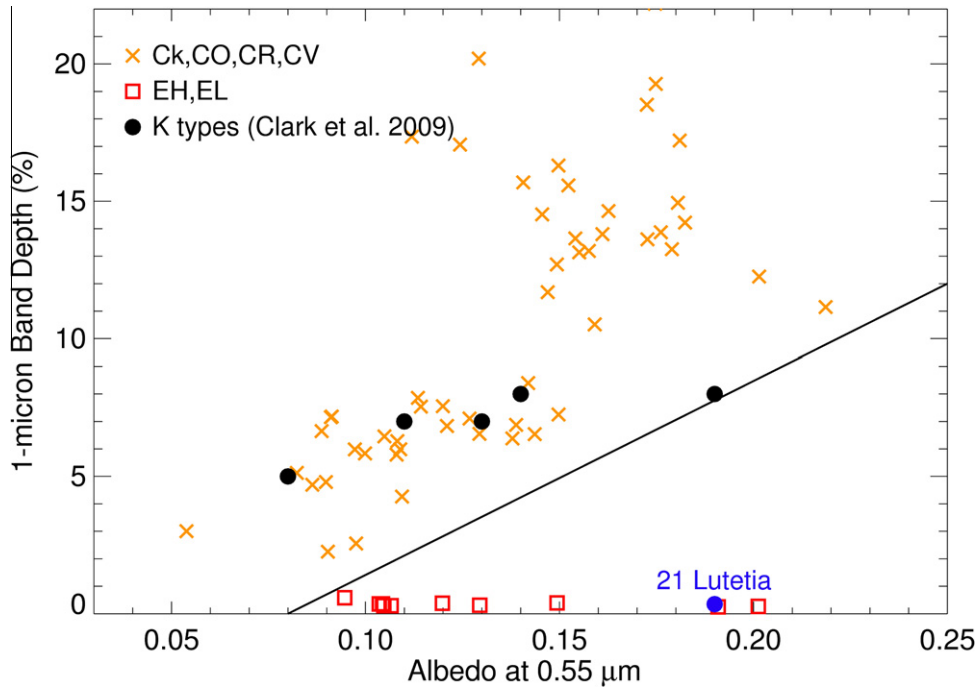
Fig. A3. Band depth of absorptions in the 0.7–1.5 μm region versus brightness (albedo of asteroids or hemispheric albedo of meteorites) for Lutetia, K type asteroids (from Clark et al. 2009), enstatite chondrites and CO, CV, CK, and CR chondrites. The hemispheric albedo of meteorites has been calculated using the relationship between the hemispheric albedo and the bi-directional reflectance from RELAB at phase angle 30 degrees (Shkuratov & Grynko 2005). The enstatite chondrite that matches Lutetia's albedo is ALHA81021 (EL6).
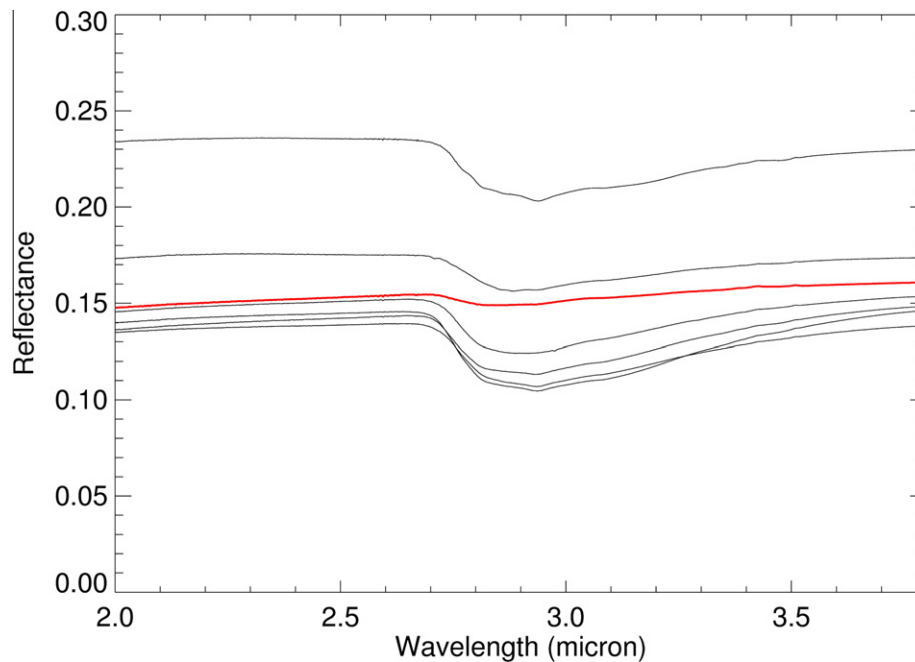

Fig. A4. Reflectance spectra (2-3.8 μm) of the same enstatite chondrites (grain size < 25 μm) shown in Supplementary Figure 2 apart from the Eagle meteorite. In red, we highlight the RELAB spectrum shown in Figure ure1 of the manuscript. This spectrum shows the shallowest 3-micron absorption, suggesting that this meteorite is the least affected by terrestrial weathering.

Lutetia (more than a factor of 2). It is therefore very unlikely that aubrites originate from this asteroid.

Finally, most minerals (e.g., olivine) show a strong UV drop in their spectra, especially between 0.3 and 0.4 μm (Cloutis et al., 2008). In this context, the OSIRIS data (UV colors) appears to be particularly helpful for discriminating between different

meteoritic analogs for Lutetia, the asteroid showing a very small UV drop. In the UV, CO/CV/CK show a strong UV drop (see their mean spectrum in Fig. A1) while the least weathered enstatite chondrite follows the same trend as Lutetia : namely a very small UV drop below 0.4 μm that is commonly observed in most meteorites and minerals spectra. Note here that terrestrial weathering is
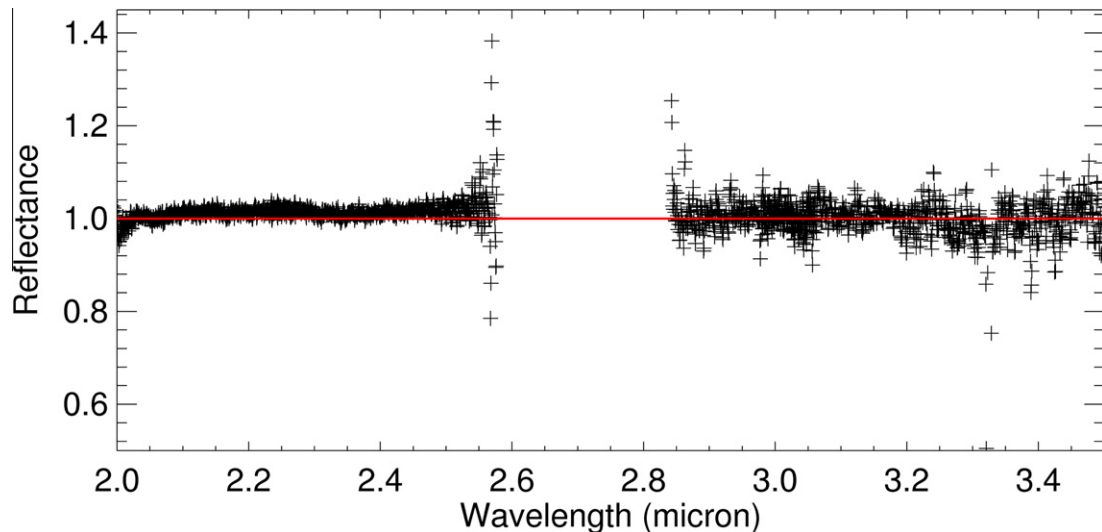
Fig. A5. Reflectance spectrum (2-3.5 μm) of Lutetia (black symbols) obtained with the NASA IRTF on March 1, 2010. In red, we display a straight line to highlight the absence of 3-micron band for O-H stretching in Lutetia's spectrum, which implies that the asteroid surface is dry.

well known for affecting the spectral properties of meteorites and minerals, especially in the UV region (Gooding, 1982). The typical effect is to significantly increase the UV drop. In this context, a spectral comparison in this range should focus on the least weathered meteorites.

All in all, the albedo and spectral properties (over the 0.3–2.5 μm range) of CO/CV/CK meteorites are not compatible with the albedo and reflectance spectrum of Lutetia while those of enstatite chondrites are compatible with Lutetia's.

A.2.2. Mid-infrared spectral range (8–25 μm)

Most major mineral groups found in meteorites and silicate glasses (e.g., maskelynite) that lack useful diagnostic features at visible to near-IR wavelengths do produce diagnostic mid-infrared features. There is therefore a strong interest in exploring the spectral properties of asteroids that are featureless in the VNIR range at those longer wavelengths. However, it has recently been shown that, in the case of asteroids and even if the main surface minerals are well known from the VNIR range, spectral deconvolution using existing mid-infrared spectral libraries does not indicate their presence nor constrain their relative abundance (Vernazza et al., 2010). This implies that the current approach in terms of sample preparation, referred to here as the classical sample preparation method (i.e. loose powder) may not reproduce well the actual properties of asteroid regolith. Otherwise, the laboratory and asteroid spectra would match.

Interestingly, Izawa et al. (2010) showed that changing the sample preparation results in a strong spectral modification for a given sample: by diluting an enstatite chondrite powder (<30 μm) into an infrared-transparent KBr powder (scattering from KBr-diluted samples mimics that from fine-grained, loosely-packed surfaces, which is particularly useful in the case of asteroid surfaces), Izawa et al. (2010) produced mid-IR reflectance spectra very different from those of pure EC powders of equivalent grain size. Their new approach highlights the fact that, depending upon the regolith structure (grain size and porosity that can be inferred from the thermal inertia), the resulting mid-infrared spectrum will not be the same. Therefore, in order to correctly interpret remote sensing data in the mid-infrared, it appears fundamental to acquire mid-infrared data for all meteorites using both the new approach of Izawa et al. as well as the classical approach.

In the asteroidal context, the mid-infrared spectral properties of asteroids having a low thermal inertia ($\leqslant 30\,\mathrm{J\,K^{-1}\,m^{-2}\,s^{-1/2}}$; e.g. MBAs) should be best reproduced by emissivity spectra of KBr-diluted meteorites and/or minerals while the mid-infrared spectral properties of asteroids having a high thermal inertia ($>100\,\mathrm{J\,K^{-1}\,m^{-2}\,s^{-1/2}}$; e.g. NEAs) should be best reproduced by emissivity spectra of non KBr-diluted meteorites and/or minerals.

- Mid-infrared laboratory measurements of meteorites obtained at the University of New Mexico.

Meteorites reflectance IR spectra were collected from 2.0 to 25.0 μm for several meteorites (OCs, ECs, CO, CV, CM, CI) using a Nicolet Nexus 670 FTIR with KBr beamsplitter and deuterated triglycine sulfate (DTGS) detector fitted with a Pike AutoDIFF attachment, at the University of New Mexico. Reflectance spectra were collected both from meteorite powders (referred as the classical sample preparation method) and meteorite powders mixed with spectroscopic-grade KBr (i.e. KBr-diluted meteorite powders).

Specifically, from each chondrite powder, three aliquots for reflectance IR analysis were prepared by mechanically mixing 2 mg meteorite powder with 43 mg of powdered spectroscopic-grade KBr. KBr is transparent in the mid-IR, and is routinely used in transmission IR studies because suspending a sample in an IR-transparent salt mitigates the effects of preferred mineral orientation and eliminates potential detector saturation. Despite the benefits of KBr, it was necessary to take precautions to ensure that it did not take up water. Samples (three aliquots of each) were scanned under a dry air purge and exposure to lab air during sample preparation was minimized; in no case were samples mixed with KBr left exposed to lab air for more than 2 min. The ground KBr was dried in a dessicator for at least 24 h prior to mixing with meteorite samples. Each allotment of KBr was checked for water and other contaminants prior to use, by collecting a reflectance IR spectrum of a ~45 mg sample under the same experimental conditions as for meteorite data collection. Relative humidity and temperature within the purge chamber were monitored continuously. Temperature in the sample chamber was 20–25 °C. Relative humidity was allowed to stabilize at 0% for 2 h before scanning; this purge time was the rate-limiting step in this analysis. Desiccant (Drierite) was placed inside the purge cover to further reduce contamination by atmospheric H_2O. Spectra were collected in the
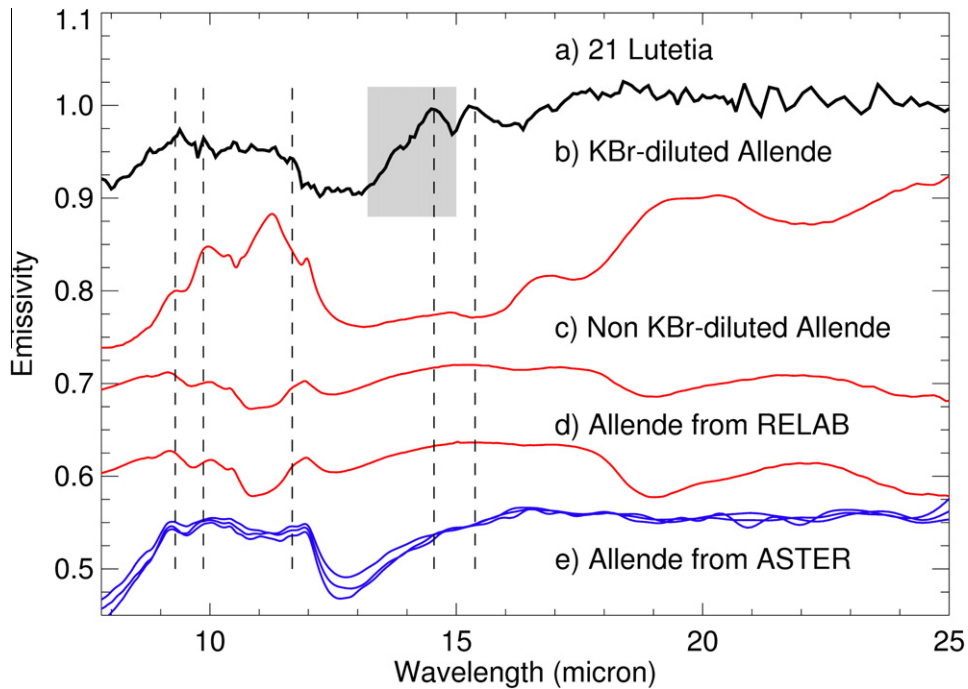
Fig. A6. Comparison between KBr-diluted and non KBr-diluted emissivity spectra [from the University of New Mexico (b, c), RELAB (d) and ASTER (e)] of Allende (CV3) with the mid-infrared spectrum of (21) Lutetia (6). The meteorite spectra are inverted from biconical reflectance. Spectral emission features of (21) Lutetia are very different from any of the Allende spectra. Note: an excess emission is found in the Spitzer space telescope data, between 13.2 and 15 microns. This feature known as the '14 micron teardrop' depends in a complicated way upon both source position in the slit and extraction aperture and is therefore difficult to correct. Extreme caution must be exercised in interpreting features in this spectral range highlighted by a light gray box.
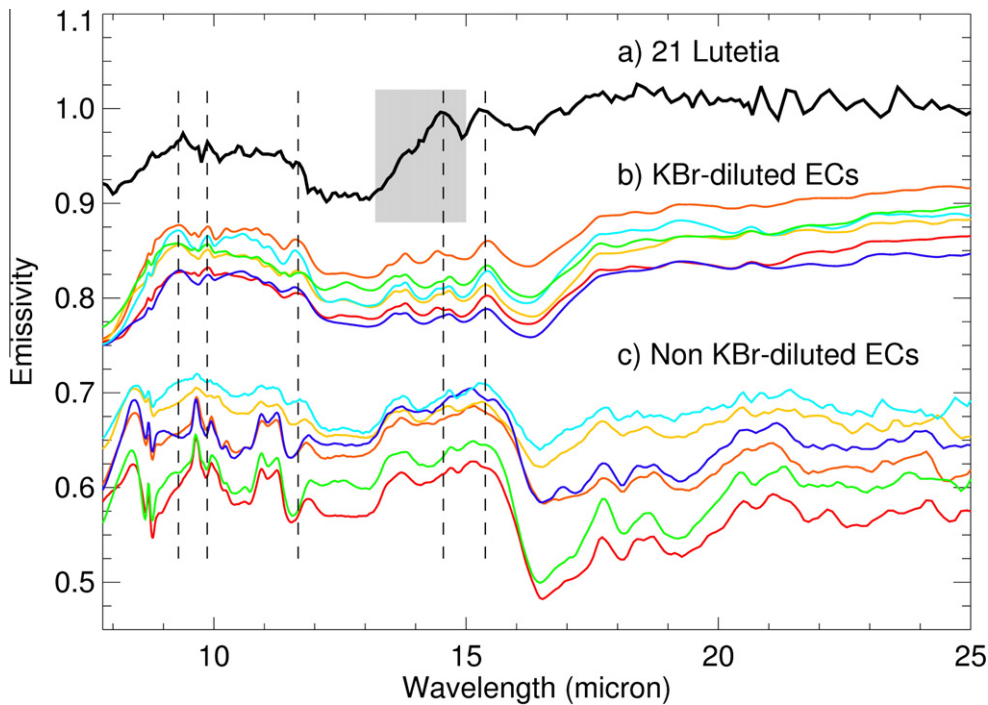
Fig. A7. Comparison between KBr-diluted and non KBr-diluted enstatite chondrite (EC) emissivity spectra (11) with the mid-infrared spectrum of (21) Lutetia (6). The meteorite spectra are inverted from biconical reflectance. Spectral emission features of (21) Lutetia are strikingly similar to those of KBr-diluted ECs, dominated by silicate fundamental vibrations.

thermal (mid) IR from 2.0 to 25.0 μm (4500–400 cm^{-1}), with spectral resolution 4 cm^{-1}.

- Mid-Infrared spectral properties of Lutetia, enstatite chondrites and CO/CV chondrites.

Fig. A8. Relative core size of (21) Lutetia, (4) Vesta, and the terrestrial planets as a function of their radius. For Lutetia, we considered an iron-nickel core and a mantle composed of either carbonaceous chondrites (CO, CV, CK) or enstatite chondrites (EH, EL) with no porosity. For the meteorites, we adopted bulk densities from Consolmagno et al. (2008), CO: 3.03 g/cm^3, CVr: 3.12 g/cm^3, CVo: 2.79 g/cm^3, CK: 2.85 g/cm^3, and EH/EL: 3.45 g/cm^3.
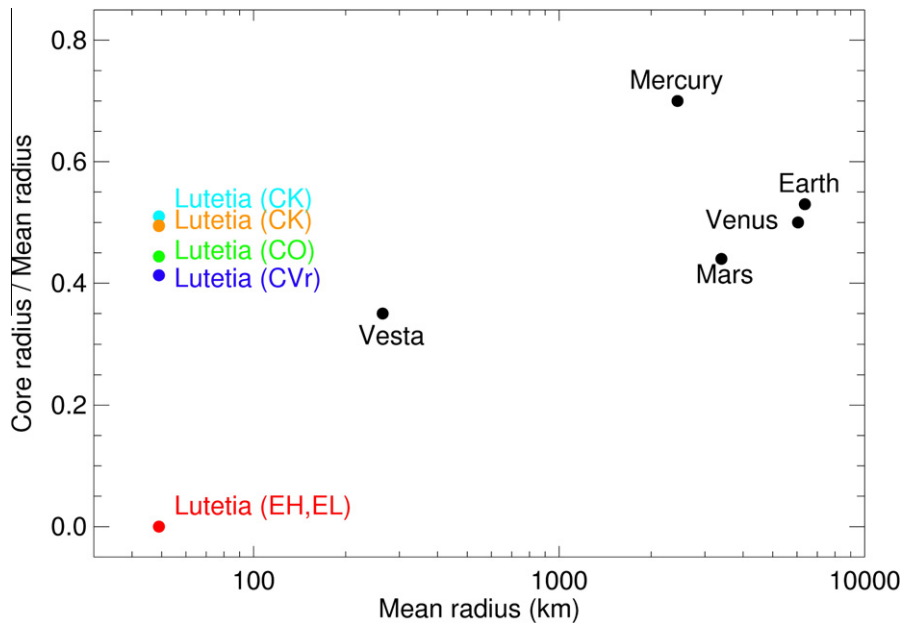
Comparison with the spectra of enstatite chondrite and carbonaceous chondrite meteorites (Fig. A6 and Fig. A7; for both we show the spectra for the KBr-diluted and non-KBr diluted meteorites) reveals that the closest spectral matches to 21 Lutetia are found among the enstatite chondrites. Like the laboratory spectra of KBr-diluted enstatite chondrites, the spectrum of 21 Lutetia exhibits a Christiansen feature (emissivity maximum) just longward of 9 μm (~9.3 μm), a transparency feature starting at ~11.7 μm, a local maximum at 15.4 μm, a local minimum in the 15.4–17.5 μm region, and a featureless, flat spectrum in the 17.5–25 μm region.

On the contrary, none of the features in the Allende spectra match those in Lutetia's (highlighted by the dotted lines), apart from the first one, which is the principle Christiansen feature. Allende spectra (1) have a transparency feature that starts at longer wavelengths with respect to Lutetia, (2) do not show a local maximum at 15.4 μm, (3) do not show a local minimum in the 15.4–17.5 μm region. In addition, the Allende spectra from both RELAB and the non KBr diluted version show additional features (e.g., a local minimum in the 18–21 μm region) that are not seen in Lutetia's spectrum; while the KBr-diluted spectrum is completely incompatible with Lutetia's spectrum.

Here we would like to stress that Lutetia's spectrum displays many features in the mid-IR that hint at the presence of silicates on its surface. Opaques such as iron or troilite are mostly featureless in this range. Most silicates, especially those containing iron or other transition metals, display clear features in the near infrared. The absence of absorption features in Lutetia's spectrum at shorter wavelengths implies that the silicates are most likely iron free. This is exactly the case for the silicates present in enstatite chondrites.

A.3. Caveats for an enstatite chondrite–Lutetia association from the literature (Belskaya et al., 2010): Water on Lutetia and Polarimetry of Lutetia

Belskaya et al. (2010) in their review mention that an enstatite chondrite–Lutetia association has difficulties in explaining (1) the observed features in Lutetia's visible spectra which are interpreted as being indicative of aqueous alteration material (Lazzarin et al., 2009), (2) the presence of a 3 μm feature in Lutetia's spectrum associated with hydrated minerals (Rivkin et al., 2000) and (3) the particular polarization properties of Lutetia.

(1) Observations of Lutetia in the visible (signal to noise ratio of ~200) with the NTT show no absorption features in this spectral region that could suggest hydrated minerals on the asteroid surface. Similar results have been obtained onboard Rosetta (Coradini et al., 2010). Note that the features (Lazzarin et al., 2009), even if valid, are by no means indicative of aqueous alteration, their positions and widths being different from those observed in hydrated silicates.

(2) New observations of Lutetia in the 3-μm region with the NASA IRTF (Birlan et al., 2010, Fig. A5) show that there is no 3-μm absorption feature in this spectral region at a 0.5% level. Similar results have been obtained onboard Rosetta (Coradini et al., 2010). These observations imply that most of Lutetia's surface must be dry. We have currently no explanation for the Rivkin et al. (2000) observation of a 15% deep 3-μm band in Lutetia' spectrum. If real, the water-rich area must be very localized, as the most recent observations have covered a large portion of Lutetia's surface. In this context, the water-rich area could be due to the impact of a water-rich object. It is commonly assumed that the impactor completely vaporizes during the impact but the color change observed on Phobos around the crater Stickney (e.g., Thomas et al., 2010) could question this. Also, the water could be adsorbed water that is readily exchangeable; hence the observation that it was present at one time but absent at another. We note that a water band is routinely observed in the spectrum of objects that are near dry such as the Moon (Clark, 2009; Pieters et al., 2009; Sunshine et al., 2009) and may be related to adsorption processes. The presence of water on the surface of nominally dry object is a mystery and will certainly get the attention of the community during the forthcoming years.

(3) The polarization properties of Lutetia are effectively quite different from most of the main belt asteroids. However, they are strikingly similar to those of the planet Mercury

and of the Moon. For Lutetia the depth of the polarization minimum is −1.3% and the inversion angle is 25 degrees (Belskaya et al., 2010). For both Mercury and Lunar fines the depth of the polarization minimum is −1.4% and the inversion angle is 25° (Dollfus and Auriere, 1974). The similarity in polarization properties of Mercury, Lunar fines, and Lutetia, is consistent with the presence of very fine-grained silicates on their surfaces, as suggested by our mid-IR spectroscopic measurements.

A.4. Density and internal structure of Lutetia

• The flyby by the Rosetta spacecraft on 10 July 2010 at a closest approach distance of 3170 km offered a unique opportunity to determine its bulk density and, in turn, to probe its internal structure. This requires measuring its volume and mass. OSIRIS, the imaging system onboard Rosetta resolved approximately 60% of the surface of Lutetia from which a partial shape model was constructed by stereo-photoclinometry. The unseen hemisphere was modeled by combining inversion of a set of 50 photometric light curves and limb profiles from adaptive optics (AO) images (Carry et al., 2010). The resulting global shape model has a volume of $5.0 \pm 0.3 \times 105 \ km^3$ and a volume-equivalent diameter of 98 ± 2 km. The volume error is well constrained due to: (i) the mid-latitude (30°N) flyby viewing direction (i.e., neither along the rotation axis nor in the equatorial plane) imposing that all potential mass configurations along this direction are strongly constrained by the dynamical requirement of principal-axis rotation, and (ii) the existence of AO images from viewing directions other than the flyby one. As a matter of fact, the latest pre-flyby shape solution matches the shape model of the flyby-visible part within 5% and the two independently determined volumes are identical (Lamy et al., 2010a,b). The Rosetta Radio Science Investigation determined a mass (Sierks et al., in press) of $1.70 \pm 0.0085 \times 1018$ kg thus yielding a density of $3.4 \pm 0.3 \ g/cm^3$, the uncertainty being dominated by that affecting the volume.

• As discussed in the main text, we cannot firmly constrain the internal structure of Lutetia because we do not know its macroporosity. However, we can estimate the size of Lutetia's core (if any) for a range of plausible macroporosity values, assuming an enstatite chondrite composition for its mantle.

To do so, we calculated the size of a putative iron-nickel core assuming a macroporosity for its enstatite chondrite mantle in the range 5–15%, consistent with the values currently observed or predicted for silicate and metal-rich asteroids (e.g., S-type asteroids – see Consolmagno et al., 2008) with masses less than 10^{20} kg. We found a relative core size (ratio core to object effective diameters) comparable to those of (4) Vesta and Mars, namely between 0.3 and 0.45. A 30% macroporosity value would lead to a relative core size of ∼0.58 and a 50% macroporosity value to a relative core size of ∼0.66. Conversely, the absence of a metallic core – that is no differentiation – implies essentially no macroporosity (≲2%), an unlikely situation. Note that it is also possible that Lutetia does not have an actual core, but instead contains metal that has separated partially and is distributed in silicate material (as observed in the enstatite chondrites and other meteorite types). This alternative structure would likewise explain its large bulk density.

Overall, the most likely scenario is that Lutetia is differentiated (or partially differentiated) consistent with an origin in the terrestrial region. Indeed, the same mechanism explaining the origin of iron meteorites as remnants of differentiated planetesimals formed in the terrestrial planet region, namely heating by the decay of short-lived nuclides (Bottke et al., 2006), applies to Lutetia, as well to other planetesimals and is particularly effective on large,

100 km sized objects which are therefore likely to be differentiated or partially differentiated.

• We now demonstrate that Lutetia's density is only marginally compatible with a CO/CV/CK meteoritic association.

The CO, CV and CK chondrites, the so-called high-density carbonaceous chondrites, have slightly different bulk densities (∼3.03 for CO, ∼2.79 for oxidized CV, ∼3.12 for reduced CV and ∼2.85 for CK, see Consolmagno et al., 2008) averaging to $2.92 \pm 0.20 \ g/cm^3$. Considering the extreme values allowed by the respective uncertainties, a carbonaceous composition of Lutetia is formally possible under the assumption of zero macroporosity. This is highly unlikely since no well-studied asteroids are known not to have a significant macroporosity of at least 6% (e.g. 433 Eros, Wilkison, 2002) and the nominal values of the respective densities impose that Lutetia is differentiated and possesses a large core.

To estimate the minimum size of such a core, we consider the extreme case of the total absence of macroporosity (macroporosity >0% would imply an even larger core size). This leads to a relative core size of 0.45, comparable to that of Mars (see Fig. A8). Such a relative core size for a $D \sim 100$ km object like Lutetia, implies a site of formation (Bottke et al., 2006) as close to the Sun as Mars or even closer (we recall here that small bodies dissipate internal heat faster than larger ones and thus are less likely to be affected by differentiation). This location is, however, not compatible with the presence of aqueous alteration in the carbonaceous chondrites (Zolensky et al., 1993; Lee et al., 1996; Krot et al., 2004 and references therein, Greenwood and Franchi, 2004), the snow line being located around ∼3 AU. Independently, high-precision measurements of stable Sr isotopes prove that CV and CO chondrites cannot be the primary building blocks for Earth and Mars (Moynier et al., 2010).

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