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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.

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; DeMeo 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 RELAB 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/.

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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, 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.

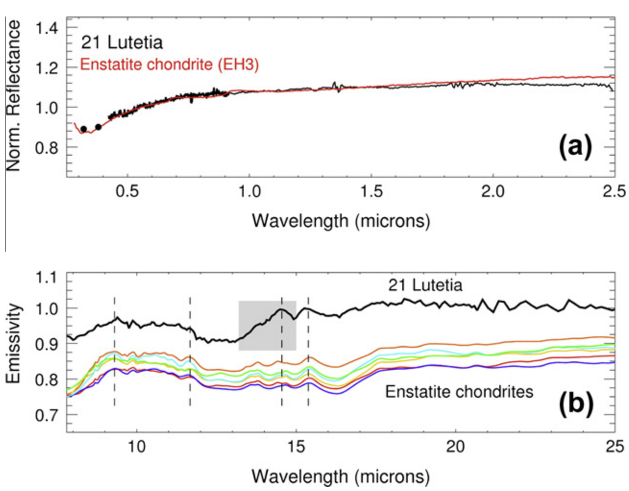

Fig. 1. Spectral comparison of (21) Lutetia and enstatite chondrite meteorites. Top panel (a): comparison from the ultraviolet to the near-infrared of (21) Lutetia and the enstatite chondrite meteorite (grain size <25 μm) KLE 98300 (EH3). Both have similar spectral characteristics, showing no absorption 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.

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 $\sim$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