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Possible evidence for partial differentiation of asteroid Lutetia from Rosetta

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ABSTRACT

The petrologic diversity of meteorites demonstrates that planetesimals ranged from unmelted, variably metamorphosed aggregates to fully molten, differentiated bodies. However, partially differentiated bodies have not been unambiguously identified in the asteroid belt. New constraints on the density, composition, and morphology of 21 Lutetia from the Rosetta spacecraft indicate that the asteroid's high bulk density exceeds that of most known chondritic meteorite groups, yet its surface properties resemble those of some carbonaceous and enstatite chondrite groups. This indicates that Lutetia likely experienced early compaction processes like metamorphic sintering. It may have also partially differentiated, forming a metallic core overlain by a primitive chondritic crust.

1. Introduction

Chondritic meteorites are aggregates of primitive materials formed in the solar nebula. However, it has long been known that nearly all chondrites experienced varying degrees of postaccretional aqueous alteration and thermal metamorphism on their parent planetesimals (Anders, 1964). These processes led to textural, chemical and mineralogical changes that form the basis of a petrologic classification scale (types 1–7) that reflects increasing degrees of thermal equilibration (types 3–7) (Huss et al., 2006) and aqueous alteration (types 1–2) (Brearley, 2006). The heat sources that drove these processes were most likely short-lived radionuclides (Hevey and Sanders, 2006; Huss et al., 2006) and, to some extent, meteoroid impacts (Davison et al., 2010; Keil et al., 1997; Rubin, 2004). Thermal modeling of asteroid metamorphism from radionuclide decay has motivated the onion shell model in which the planetesimal's interior forms a radially layered structure with a highly metamorphosed deep interior overlain by progressively less heated outer layers. However, despite the ubiquitous meteoritic evidence for thermal metamorphism, it has been difficult to identify evidence for this process on extant asteroids. A key difficulty is the lack of detailed in situ observations of bodies that are sufficiently large to retain their large-scale structures intact from the early solar system.

A second longstanding problem in asteroid science is that the great majority of known meteorite parent bodies melted and formed metallic cores, but very few differentiated asteroids have been identified in the asteroid belt (Burbine et al., 2002). Three possible explanations for this discrepancy are that the meteorite suite is not representative of the present-day asteroid belt (Burbine et al., 2002), that few differentiated asteroids have survived to the present day (Bottke et al., 2006), or that some asteroid spectral classes typically associated with chondritic bodies also contain differentiated members (Gaffey et al., 1993a). A fourth possibility is that partially differentiated asteroids, with metallic cores and partially or totally melted mantles

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overlain by unmelted chondritic crusts, formed in the early solar system (Carporzen et al., 2011; Elkins-Tanton et al., 2011; Sahijpal and Gupta, 2011; Weiss et al., 2010) and are extant but undiscovered in the asteroid belt. However, the latter scenario is at odds with the traditional view that chondrites, whose aggregational textures require that they never melted, formed on smaller and/or younger bodies that never differentiated.

Large-scale melting of rocky asteroids is thought to have been driven by heating from short-lived radionuclides on bodies larger than $\sim$10–30 km in radius that accreted within $\sim$1.5–2 million years (Ma) after the formation of calcium aluminum inclusions (CAIs) (Elkins-Tanton et al., 2011; Hevey and Sanders, 2006; Sahijpal et al., 2007; Sahijpal and Gupta, 2011). With triaxial ellipsoid dimensions of $\sim 126 \times 103 \times 95$ km^3 (Sierks et al., in press), 21 Lutetia is the first asteroid unambiguously in the size regime capable of large-scale melting and metallic core formation to be visited by a spacecraft. The next two largest asteroids previously encountered, 253 Mathilde and 243 Ida, have mean radii of 26.5 and 15.7 km, respectively (Davis, 1999; Thomas et al., 1996; Veverka et al., 1997). Asteroids with radii greater than $\sim$20–30 km have collisional lifetimes (e.g., mean time between impacts capable of breaking an asteroid into fragments whose largest piece has a mass less than half of the parent asteroid) greater than the age of the solar system (Bottke et al., 2005; Marchi et al., 2006). Therefore, Lutetia is also the first asteroid visited by a spacecraft that is of sufficient size to have potentially retained most of its original large scale structure against impact disruption. This means that Lutetia may have retained a mostly intact record of any early metamorphic and melting processes. Whether Lutetia actually melted, was just thermally metamorphosed, or remained unheated would have depended predominantly on when it began to accrete and on its initial composition. Here we use recent Rosetta observations, ground-based astronomical measurements, and meteorite data to demonstrate that Lutetia experienced at least large scale thermal metamorphism and possibly even partial differentiation and core formation.

2. Composition of Lutetia's surface

The composition and nature of Lutetia have long been perplexing (Barucci and Fulchignoni, 2009). Ground-based visible-near-infrared reflectance spectra and new infrared spectra from VIRTIS onboard Rosetta (Coradini et al., in press) are flat and nearly featureless [spectral class Xc (Demeo et al., 2009)], compatible with some carbonaceous chondrites (Belskaya et al., 2010; Birlan et al., 2006) and enstatite chondrites (Ockert-Bell et al., 2010) but distinct from all other meteorite groups with the possible exception of iron meteorites (Cloutis et al., 2010). Some Lutetia spectra (Birlan et al., 2006) show a weak $\sim$1 μm absorption feature like that observed for some carbonaceous chondrites (Clark et al., 2009; Gaffey, 1976) and enstatite chondrites (Gaffey, 1976), although this feature is not present in many other spectra including that of VIRTIS (Coradini et al., in press).

The mean visible geometric albedo measured by the OSIRIS camera onboard Rosetta is 0.19 ± 0.01. This is consistent with bidirectional reflectance measurements of enstatite chondrites (Ockert-Bell et al., 2010). Although it has been suggested that Lutetia's visual geometric albedo is too high to be consistent with carbonaceous chondrites (Vernazza et al., 2009), the reflectance of CK, CO, CR, and CV chondrites are actually known to range from 0.5 to 0.22 (Chapman and Salisbury, 1973; Clark et al., 2009; Gaffey, 1976). Because laboratory experiments have typically either measured the bidirectional reflectance at phase angles larger than 5–10° [e.g., Clark et al. (2002)] or else the directional-hemispherical reflectance [e.g., Clark et al. (2009)], such experiments should place lower limits on the inferred geometric albedo (which is defined at zero phase angle) due to the opposition effect. Using the phase function for Lutetia determined by OSIRIS observations (Sierks et al., in press), the asteroid's mean albedo is in fact only 0.13 at a phase angle of 5° and much lower at higher phase angles (Coradini et al., in press). Therefore, as pointed out by Drummond et al. (2010), Lutetia's geometric albedo is in agreement with high-albedo (CO, CK, and probably CV and CR) carbonaceous chondrites as well as enstatite chondrites (Fig. 1).

Lutetia's polarization properties differ from those of all other measured asteroids but are distinctively similar to CV and CO chondrites and different from other chondrite groups as well as all known achondrites (Belskaya et al., 2010). Moreover, Spitzer Space Telescope 8–38 μm emissivity spectra of Lutetia show a clear Christiansen peak at 9.3 μm that is typical of CO and CV carbonaceous chondrites (Barucci et al., 2008) and differs from that of enstatite and ordinary chondrites and stony achondrites (whose Christiansen peaks are known to range from 8.3–8.9 μm) (Izawa et al., 2010; Salisbury et al., 1991). The lack of a deep 3 μm absorption for much of Lutetia's surface (Barucci and Fulchignoni, 2009; Coradini et al., in press) does not favor a connection with hydrated carbonaceous chondrites (CI, CM, CR, CH, and CB) [although the other face of Lutetia that was not visible to Rosetta may show this hydration feature (Rivkin et al., 2011)]. Finally, two measurements of the OC radar albedo of Lutetia obtained values of 0.19 ± 0.07 (Magri et al., 1997) and 0.24 ± 0.07 (Shepard et al., 2010) (1σ uncertainties), implying bulk regolith densities of 1900–2900 and 2300–3300 kg m^{-3}, respectively [using equation (8) from Shepard et al., 2010)]. Assuming 40–50% regolith total porosity, the radar measurements of Magri et al. (1997) and

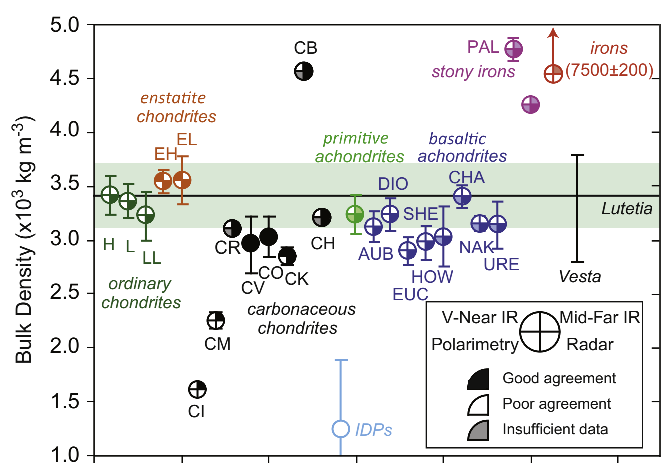

Fig. 1. Measured mean bulk densities and surface observational properties of various meteorite groups as compared to those of asteroid 21 Lutetia (Pätzold et al., in press; Sierks et al., in press). Vertical position of each circular symbol gives bulk density, while quadrants in each symbol denote agreement with four different compositional constraints on the surface of Lutetia: top-left=visible to near infrared reflectance spectra (0.5–3.0 μm) (best studied constraint), top-right=mid-far infrared reflectance spectra (>3 μm), bottom-left=visible polarimetry, and bottom-right=OC radar-albedo (second best studied constraint). IDPs=interplanetary dust particles (unmelted chondritic), AUB=aubrites, DIO=diogenites, EUC=eucrites, HOW=howardites, SHE=shergottites, CHA=chassignites, NAK=nakhlites, URE=ureilites, PAL=pallasites, MES=mesosiderites. Meteorite classes (ordinary chondrites, basaltic achondrites, etc.) are arranged along vertical axis approximately by petrologic similarity. The density of Vesta is shown for comparison (mean value given by black line and uncertainty range shown in green). Data and references for the density and surface composition measurements are presented in Tables 2 and 4, respectively. Error bars give measured one standard deviation variance of meteorites within each group when known (for exceptions and details, see Table 2). The bulk densities shown here should not be compared to the lower grain densities used to estimate the regolith composition from radar albedo measurements (see Section 2).