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The thermo-chemical evolution of Asteroid 21 Lutetia

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ABSTRACT

In the present study, we model the thermo-chemical evolution of Asteroid 21 Lutetia using new data obtained by the Rosetta flyby in July 2010. We investigate the dependence of the evolution on the accretion onset time and duration for both instantaneous accretion and continuous accretion scenarios, assuming late runaway material accumulation. The thermo-chemical evolution model considers accretion, sintering (hot pressing), melting and differentiation by porous flow. The evolution scenarios arising from assumptions on the macroporosity φ_m are examined to derive implications on the compaction of an initially highly porous material, (partial) differentiation and the internal structure. The calculated final structures are compared with the observational data to derive bounds on the present-day macroporosity of Lutetia. Varying the macroporosity φ_m, we calculate the initial material properties such as intrinsic density, composition, and radiogenic heat source abundance, assuming an enstatitic origin of Lutetia's primordial material. We obtain a number of possible compaction and differentiation scenarios consistent with the properties of the present-day Lutetia. The most probable macroporosity for a Lutetia-like body with the observed bulk density of 3400 kg m^{-3} is $\varphi_m \geqslant 0.04$. Small changes can be expected if an error of ±300 kg m^{-3} in the bulk density is considered. Depending on the adopted value of φ_m, Lutetia may have formed contemporaneously with the calcium–aluminium-rich inclusions (CAIs) ($\varphi_m = 0.04$) or up to 8 Ma later ($\varphi_m = 0.25$). We find a differentiated interior, i.e., an iron-rich core and silicate mantle, only for a rather narrow interval between $0.04 \leqslant \varphi_m < 0.06$ with the formation times between 0 Ma and 1.8 Ma after the CAIs. Regardless of melting and partial differentiation, no melt extrusion through the porous layer is likely, which is consistent with the lack of basalt at the surface of Lutetia. For $\varphi_m \geqslant 0.6$, an iron–silicate differentiation is not possible, but the interior is compacted due to sintering below a porous outer layer.

1. Introduction

The Rosetta flyby in July 2010 of the Asteroid 21 Lutetia provided important new insights into early stages of our Solar System. Images taken with the OSIRIS imaging system on-board Rosetta with a resolution of up to 60 m per pixel covered approximately 60% of the surface, mostly in the northern hemisphere. Using these images, a partial shape model has been constructed by using stereo-photoclinometry (Jorda et al., 2010). The remaining surface areas were modelled using photometric light curves and limb profiles from adaptive optics (Carry et al., 2010), yielding a combined global shape model with a volume of $(5.0 \pm 0.3) \times 10^5$ km^3 and axes of 121 ± 1 by 101 ± 1 by 75 ± 13 km (Sierks et al., 2011). The mass measurement produced by tracking Rosetta's radio signals back to Earth yielded a value of $(1.70 \pm 0.0085) \times 10^{18}$ kg, which is lighter than the pre-flyby estimate of 2.57×10^{18} kg. By combining the mass with the volume of the global shape model, a bulk density of 3400 ± 300 kg m^{-3} has been obtained (Pätzold et al., 2011), where the uncertainty of 300 kg m^{-3} results mainly from the volume measurement error. This density is one of the highest densities obtained so far for an asteroid. Bearing in mind a possible macroporosity (average porosity of a body) with a maximum of 0.25 (Weiss et al., 2012 infer a stringent upper limit of 0.52 and a more realistic upper limit of 0.25), the intrinsic density of Lutetia exceeds that of a typical stony meteorite (e.g., Lutetia could have a higher density than Asteroid Vesta). This high density implies a metal-rich rock composition and even a differentiated interior with a silicate mantle and an iron-rich core is possible (see estimates in Weiss et al. (2012) for the possible evidence for a differentiated interior).

Lutetia has an irregular elongated shape. Its surface is geologically heterogeneous and displays geological units of various ages, including numerous craters with radii of up to 22 km that are intersected by a network of groves and scarps (possible fractures). A large amount of surface material appears to have been ablated by impacts with smaller objects. The asteroid is covered by a

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layer of dusty, lunar-like regolith, as the presence and morphology of landslides, the cratering record and the low thermal inertia suggest. The regolith thickness is estimated to be up to 3 km (Sierks et al., 2011). Below this surface layer, it is suggested – both from thermal evolution models of planetesimals (see e.g., Henke et al., 2012; Neumann et al., 2012) and the high bulk density – that Lutetia's interior underwent compaction and is not porous.

The composition of this asteroid has been puzzling astronomers for some time and is still under debate. Usually classified as an M-type asteroid, the asteroid is one of the few M-type asteroids lacking evidence of sufficient metal on the surface. The low-frequency flat spectrum (similar to carbonaceous chondrites and C-type asteroids) is not typical for metallic meteorites. Furthermore, certain characteristics exhibited by Lutetia are rather more common with C-type asteroids: a low radar albedo (strongly metallic asteroids have high radar albedo, e.g., 16 Psyche), a thick regolith, the evidence for aqueous alteration (hydrated minerals), and abundant silicates that indicate a non-metallic surface. Detailed studies of the spectrum at a wide range of wavelengths are now available, which allows us to draw conclusions about the composition. The lack of space weathering, aqueous processes, and olivine on the surface suggest, due to the high bulk density, that Lutetia is either composed of the enstatite chondrite material or is related to the chondritic classes CB, CH, or CR (Coradini et al., 2011). According to Vernazza et al. (2011), only enstatite chondrites exhibit spectral reflectance properties that are compatible with those of Lutetia over the range of 0.3–25 μm, and similar results have been obtained for a shorter wavelength range of 0.4–2.5 μm (Vernazza et al., 2009). This suggests that the properties of enstatite chondrites provide the best match of the spectrum over the full range of colours. The regolith consists, presumably for the most part, of impact debris from the extensive cratering process, so it would be assembled mostly of material originating from the impacting bodies in addition to the shattered material from Lutetia itself. Due to the high gravity, a significant portion of the impacting bodies' debris would fall back onto the asteroid after striking the surface. One can expect that the regolith is enriched in the material originating from such impactors, which, assuming carbonaceous chondritic composition of the objects (comets or small asteroids) that collided with Lutetia in the past, would explain the spectral features indicating the surface presence of carbonaceous chondrites.

Based on the iron content, Sears et al. (1982) initially defined two enstatite groups, EH and EL. Consolmagno et al. (2007, 2008) reported the average intrinsic densities for EH as 3700 ± 30 kg m^{-3} and for EL as 3610 ± 70 kg m^{-3} based on the measurements performed on nine enstatite chondrites. More recent measurements (Macke et al., 2009) yield average intrinsic densities grouped mostly between 3450 and 3750 kg m^{-3}, with 3610 ± 140 kg m^{-3} for EH and 3650 ± 240 kg m^{-3} for EL (thus suggesting a minimum value of 3410 kg m^{-3} and a maximum value of 3890 kg m^{-3}; note, though, the outlier EL Khairpur, with a considerably higher intrinsic density 4170 kg m^{-3} reported by Macke et al. (2009)). The measurements of the porosity and magnetic susceptibility performed by the same group of authors indicate that there is a considerable overlap between EL and EH and no apparent difference in iron content. Macke et al. (2009) reported porosities between 0.003 and 0.126, whereby the porosities of the most samples were between 0.003 and 0.064. By coupling those porosities with the extremes of the upper intrinsic densities via the equation $\rho_b = (1-\phi)\rho_i$ (with bulk density ρ_b, intrinsic density ρ_i and porosity ϕ), we arrive at the minimal possible average bulk density of 2980 kg m^{-3} and the maximal possible bulk density of 3880 kg m^{-3}. The average bulk density 3400 ± 300 kg m^{-3} reported for Lutetia lies well between the two extreme values.

For a body that formed during the first few million years after the formation of the Solar System, the short-lived isotopes ^{26}Al and ^{60}Fe are believed to be the viable heat sources. The initial ratio $[^{26}\mathrm{Al}/^{27}\mathrm{Al}]_0 = 5 \times 10^{-5}$ at the formation of the calcium–aluminium-rich inclusions (CAIs) has been inferred for the H-chondrites. It is referred to as the "canonical" ratio and used by most researchers for H-chondritic bodies. The values of $[^{60}\mathrm{Fe}/^{56}\mathrm{Fe}]_0$ inferred in various publications range between 10^{-8} and 10^{-6} (e. g., Tachibana and Huss, 2003; Mostefaoui et al., 2005). The initial ratios in other groups of ordinary chondritic meteorites appear to deviate from the upper values. Analyses of the oxygen and magnesium isotopic compositions of aluminium-rich chondrules from unequilibrated enstatite chondrites by Guan et al. (2006) resulted in the initial ratio of $[^{26}\mathrm{Al}/^{27}\mathrm{Al}]_0 = (6.8 \pm 2.4) \times 10^{-6}$. In a further publication, in situ measurements of ^{60}Fe–^{60}Ni and ^{53}Mn–^{53}Cr isotopic systems in unequilibrated enstatite chondrites were carried out by Guan et al. (2007). They inferred a large variation in the initial ratios (2×10^{-7}–2×10^{-6}) and considered high ratios the result of Fe–Ni redistribution during later alteration processes. According to their findings, the most probable range is between 2×10^{-7} and 7×10^{-7}. It is not certain whether the values from Guan et al. (2006, 2007) reflect the abundance of the respective nuclides in the early Solar System in the region where the enstatite parent bodies accreted or the abundances at the respective formation time (which would then not be equal to the formation time of the CAIs) of the parent bodies of the enstatitic meteorites. In the latter case, the ratio $[^{26}\mathrm{Al}/^{27}\mathrm{Al}]_0 = (6.8 \pm 2.4) \times 10^{-6}$ would be a leftover of the canonical ratio 5×10^{-5}. The pros and cons of both interpretations are discussed in e.g. Gounelle and Russell (2004), Rudraswami and Goswami (2007), Bateman et al. (1996), and Nichols et al. (1999).

According to numerical simulations of Cremonese et al. (2011), even the impact that formed the largest crater, Massilia (diameter ≈45 km), did not shatter Lutetia, but it still caused serious fracturing. Hence, Lutetia most likely did not re-accrete from the chunks and dust produced by impacts but survived intact from its accretion from the protoplanetary nebula. The interiors seem to have considerable strength (not a rubble-pile structure, such as with many smaller asteroids), according to the impact crater morphology and the existence of linear fractures. These observations suggest that Lutetia is more like a primordial planetesimal or a planet-precursor than an asteroid (and not a fragment of a parent asteroid). Thus, Lutetia differs from some smaller bodies such as Itokawa and Mathilde, which are rubble piles formed from reaccretion of planetesimal debris.

The accretion of small bodies is controlled by collision and adhesion of micrometre-sized grains until a size of approximately 1 km is reached, at which point the bodies become dominated by gravitational interactions (Weidenschilling, 1988; Kaula, 1998). The subsequent growth of 1–10 km-sized planetesimals to bodies with radii of up to 500 km can be described using the term "runaway growth" (growth of the largest body within a swarm of self-interacting planetesimals). This phenomenon applies to only a few bodies in the swarm, which serve as embryos for the accretion of planets. Kortenkamp et al. (2000) described late runaway accretion in terms of radial growth by the relation

$$\frac{dR_p(t)}{dt} \propto R_p(t)^{\beta} \quad (1)$$

where $R_p(t)$ is the radius at the time t and $\beta = 2$. Diverse accretion durations have been discussed in the literature: several million years for bodies with a final size of 500 km (Weidenschilling, 1988), 10^4 years for bodies with a radius of 100 km (Kaula, 1998), and 10^5–10^6 years for embryos in the terrestrial planet region (Wetherill and Stewart, 1989). The runaway accretion stage is followed by the oligarchic growth stage, which is dominated by the largest bodies of the swarm. Those bodies continue to slowly