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A thermal model for accretion, sintering and differentiation of asteroid 21 Lutetia

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Abstract

The early thermal evolution and differentiation of the asteroid 21 Lutetia has been studied using new data obtained by the Rosetta flyby in 2011. We have used the thermal evolution model by [1], which includes accretion (based on the accretion model by [2]), sintering due to hot pressing[3], associated changes of the material properties (such as density and thermal conductivity), melting, and the convective heat transport and differentiation by porous flow. Our work provides constraints on the macroporosity, the internal structure and the formation time of Lutetia.

1. Introduction

The Rosetta flyby at the asteroid 21 Lutetia on 10 July 2010 revealed the unexpected high bulk density of 3400 kg m^{-3} from the mass measurements and a global shape model (the dimensions are (121±1)×(101±1)×(75±13) km). This high density indicates a non-chondritic bulk composition enriched in heavy elements like iron. It is suggested that Lutetia formed from enstatitic material[4] at a distance of 1.4 AU and then moved outward to its present semi-major axis at 2.435 AU[4]. According to [5], the OSIRIS images provide evidence of a complex geology and an ancient surface which, together with the high bulk density, suggests partial differentiation of the asteroid and infer that Lutetia may be a primordial planetesimal.

2. Model and Methodology

To account for the location of formation and the outward migration of Lutetia, we have modified the thermal evolution and differentiation model by [1] with a radiation boundary condition and a ambient temperature in the protoplanetary nebula, which depends on the time t since the formation of the calcium-aluminum rich inclusions (CAIs) and on the distance $d(t)$ to the proto-sun. The temperature distribution is an approximation on the results by [6, Fig. 1 (a)]. The initial material properties (such as intrinsic density, mass fractions of the components iron and silicates, abundances of the radiogenic heat sources ^{26}Al and ^{60}Fe) are calculated assuming enstatitic nature of the primordial material. The body is assumed to accrete asymptotically at the time t_0 relative to the CAI formation within t_{accr} = 0-1 Ma at ≈1.4 AU and to migrate to 2.4 AU within 0.2 Ma due to the migration of Jupiter[4,7]. The initial radius 1 km and the theoretical final radius D=60 km (both corresponding to entirely compacted material) have been used. The latter is the radius of the smallest sphere Lutetia fits into. The above radius and the initial initial porosity 0.4 of the accreting material result in the potential radius R≈71 km at the end of accretion if no compaction takes place. The heat transport by melt segregation is modeled assuming melt flow in porous media and by supplementing the energy balance equation with additional advection terms. The advection terms for iron and silicate melts are calculated using the Darcy flow equation. This approach is valid for melt fractions large enough such that the melt forms an interconnected network but lower than the rheological critical melt fraction (≈50%).

In the following, we have varied the intrinsic density (and hence the macroporosity for the observed bulk density of 3400 kg m^{-3}), the onset time of accretion and the accretion duration to study the compaction, partial differentiation and resulting internal structure of Lutetia. The final bulk density arising from our models have been compared to the observed bulk density in order to constrain the macroporosity, the onset time of accretion and accretion duration and the internal structure.

3. Results

Figure 1 shows the average density at the end of the evolution as a function of accretion onset time and accretion duration assuming an intrinsic density 3579 kg m^{-3}, i.e. an initial bulk density of 2147 kg m^{-3} with an initial porosity of 40%. The observed average density of 3400 kg m^{-3} (corresponding to a macroporosity of 0.05) lies on the line connecting the parameters $(t_0,t_{accr})=(1.5,0)$ Ma and $(t_0,t_{accr})=(0.5,1)$ Ma. Core formation occurs in bodies for which the parameters (t_0,t_{accr}) lie below the line connecting $(t_0,t_{accr})=(1.7,0)$ and $(t_0,t_{accr})=(0.7,1)$ *Ma*. All bodies on the line corresponding to 3400 kg m^{-3} have a similar structure. With a final radius of 61 km, the relative core radii vary between 0.13 and 0.15 and the mantle thicknesses between 0.12 and 0.13. On top of the silicate mantle is a partially differentiated layer whose composition deviates only slightly from the primordial composition. The outer layer is undifferentiated but compacted for the most part except the upper few radius percent. With an intrinsic density less than 3542 kg m^{-3} (corresponding to a present-day macroporosity of less than 0.04) the compaction is not efficient enough to obtain the observed present-day density. For an intrinsic density of more than 3617 kg m^{-3} (corresponding to a macroporosity of more than 0.06), a core differentiates only for larger bulk densities than the observed value.

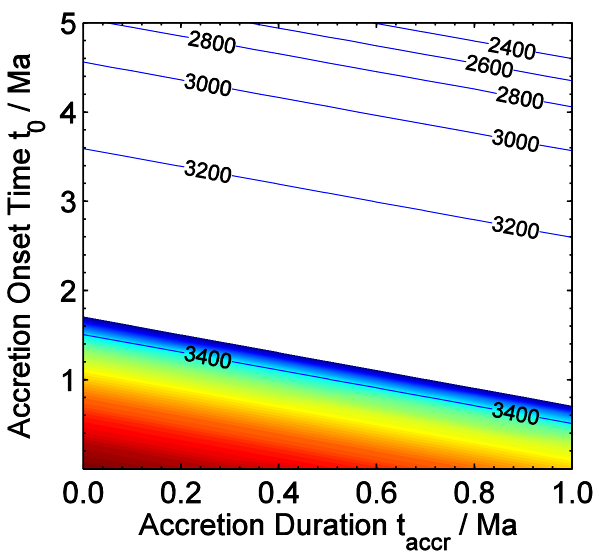

Figure 1: Bulk density of a Lutetia-like body as a function of the accretion onset time t_0 and the accretion duration t_{accr} assuming an intrinsic density of 3579 kg m^{-3}. The colored region marks the bodies that formed a core with increasing core size from blue to red. The contour lines correspond to the present bulk density.

4. Summary and Conclusions

Our results imply that the most probable macroporosities for a Lutetia-like body with the bulk density of 3400 kg m^{-3} are $\varphi_m \geq 0.04$. Depending on the adopted value of φ_m, the formation times range from the formation contemporarily with the formation of the CAIs for $\varphi_m = 0.04$ to 7 Ma after the formation of the CAIs for $\varphi_m = 0.25$. It is suggested that the upper bound for φ_m is about 0.13[8] which implies the latest formation time about 3.1 Ma after the CAIs. If Lutetia is differentiated and has an iron rich core, the macroporosity ranges between 0.04 and 0.06 and the formation time is between 0 Ma and 1.8 Ma after the CAIs. In that case, the size of the core is at most 25 km and the thickness of the mantle amounts to approximately the same value. In all simulations the extent of the partially molten zone and the degree of melting did not suffice for the silicate melt to penetrate the surface due to porous flow. This is consistent with the lack of basalt at the surface of Lutetia.

Acknowledgements

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