ASTEROID SHAPE AS A CONSTRAINT ON EARLY MELTING AND DIFFERENTIATION.
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Introduction: The origin of differentiated meteorites such as the iron meteorites and several groups of achondrites has been a long-standing mystery in the study of small bodies in the solar system. The iron meteorites alone originate from up to 55 distinct, differentiated asteroidal parent bodies [1]. In contrast, telescopic observations of main-belt asteroids have found only a handful of objects that exhibit the expected spectral features and densities of differentiated bodies [e.g. 2, 3].

One possible explanation for this apparent deficit of differentiated asteroids is that some bodies with undifferentiated crusts may have undergone partial differentiation, resulting in bodies that exhibit chondritic surface properties while hosting differentiated interior material.

In support of this hypothesis, paleomagnetic evidence from the Allende carbonaceous (CV) chondrite has pointed to the possibility of a past magnetic dynamo, and therefore metallic core, in the CV parent body [4]. The recent flyby of asteroid 21 Lutetia by the Rosetta spacecraft provided possible evidence for the partial differentiation of that body. Although the surface spectra of 21 Lutetia are most consistent with enstatite chondrites or carbonaceous chondrites of the CV or CO groups, its high density (~ 3400 kg m^{-3}) suggests that the interior of the asteroid consists of denser material than chondrites or that it has anomalously low macroporosity [5].

In addition to the above lines of evidence, the global shapes of asteroids, in particular the extent of their deviation from an hydrostatic shape, may provide further constraints on possible early melting and differentiation. During its early history, a highly molten asteroid may have adjusted to a hydrostatic shape due to self gravity whereas an essentially unheated asteroid would have been unable to overcome the strength of its constituent material to achieve a relaxed shape.

Thermal evolution models of planetesimals show that bodies that accrete within the first ~1.5 Myr of the solar system retain sufficient abundances of short-lived radioisotopes to induce large scale melting. Bodies as small as 20 km in diameter may achieve > 50% melting if accretion occurred sufficiently early. The cooling timescale of partially melted planetesimals may range from several Myr for 20 km objects to over 50 Myr for objects more than 300 km in diameter [6, 7]. If the timescale of viscous relaxation of these partially melted asteroids due to their self gravity is shorter than their cooling timescales, then they are expected to take on hydrostatic shapes.

An early study on the relaxation of asteroid shapes based on simple analytic scalings concluded that, for silicate compositions equilibrated to temperatures in the modern asteroid belt, large-scale topography (spherical harmonic degree ~30 or lower) would take longer than 4.5 Gyr to relax due to self-gravity [8]. However, silicate asteroids uniformly heated to near their liquidus temperature may relax to a hydrostatic geometry in less than 0.1 Myr.

In order to better understand the relationship between the early thermal evolution of asteroids and their shape, we aim to model numerically the gravitational relaxation of asteroids given a range of initial shapes, sizes, and rheological profiles. We present here preliminary model results for asteroids with simple initial shapes.

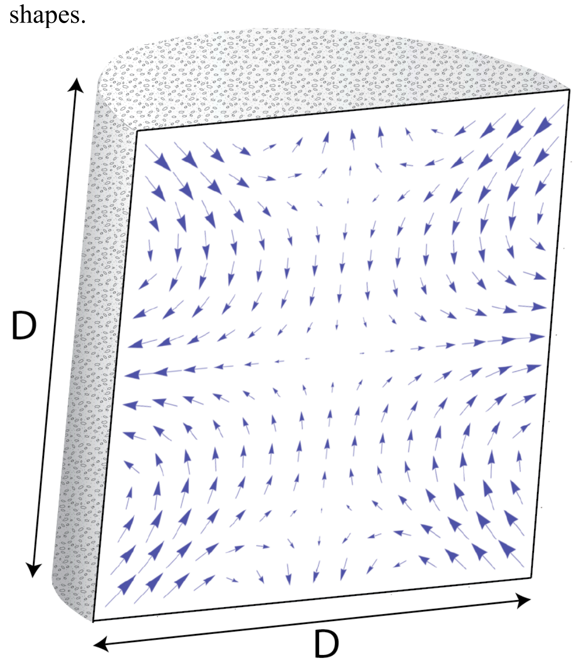

Fig. 1. The geometry of the asteroids modeled in this work. D ranges from 50 to 500 km. Vector field shows the flow velocities in a case of uniform viscosity throughout the body. Actual magnitude of the velocity varies with the assumed viscosity and the size of the body.

Methods: Using the deal.II finite element library [9] we first explicitly calculate the gravity field inside the model asteroid by solving Gauss' Law for gravity. We then solve for the corresponding viscous flow field assuming non-inertial (Stokes) flow. We focus here on one particular initial asteroid shape: a cylinder with diameter equal to its height (Figure 1). We model asteroids with diameters from 50 to 500 km and a density of 2500 kg m^{-3}. We impose (1) uniform viscosity over the entire volume and (2) a low viscosity interior with a 5-10 km thick, high viscosity crust. Development of more sophisticated models incorporating a broader range of time-dependent viscosity and progressive volume change is ongoing.

Results: The timescale of readjustment to a hydrostatic shape depends strongly on the size of the asteroid and its viscosity (Figure 2). For an asteroid with uniform viscosity (η), assuming Newtonian flow, analytic arguments suggest the following relationship:

$$t_{relax} \propto \frac{\eta}{\sigma_s} \propto \frac{\eta}{\rho^2 D^2}$$

where t_{relax} is the relaxation timescale, σ_s is a characteristic internal shear stress, and ρ and D are the density and dimensions of the body, respectively.

Our model asteroids with uniform viscosity recover the expected analytic relation. Asteroids with uniform viscosity below ~10^{20} Pa·s are able to undergo gravitational relaxation on timescales of less than 10 Myr for objects larger than 50 km and less than 1 Myr for ones larger than 150 km. Such timescales are likely to be shorter than the bodies' respective cooling timescales assuming very early accretion and therefore the maximum degree of radiogenic heating [6].

The effect of a high viscosity crust on the relaxation timescale can be dramatic in the case of smaller bodies (Figure 2, Red Curves). In contrast, the addition of a crust to larger bodies has limited affect on its readjustment. The assumed interior viscosity (10^{20} Pa·s) is a generous upper bound for the viscosity of silicate melts [8, 10]. However, the viscosity for the unmelted crust is poorly constrained, and the assumed value (10^{22} Pa·s) is one that is similar to the Earth's crust [11]. A chondritic crust may be more viscous due to its lower temperature or less viscous due to its low degree of compaction and consolidation.

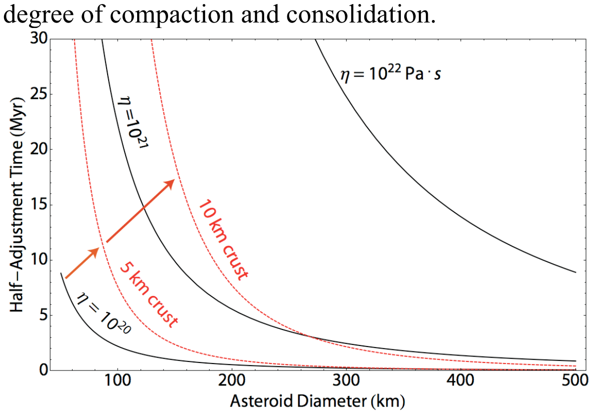

Fig. 2. Time interval required for the strongest surface topography (the rim of the cylinder) to relax to 1/2 of its original elevation. Black curves denote cases of uniform viscosity while the red curves describes body with a high-viscosity crust (η = 10^{22} Pa·s) and a weaker interior (η = 10^{20} Pa·s).

Discussion: These preliminary results from our finite element models can be applied to observed asteroids. Due to its size (~100 km diameter) and high density, 21 Lutetia has likely survived catastrophic disruption by impacts since the beginning of the solar system. The largest known impact, which generated a 55 km diameter crater, likely fractured, but did not shatter the body [12]. We therefore regard the shape of 21 Lutetia as nearly primordial, sustaining only regional resculpting due to impacts during its history.

Our models results show that the non-spherical shape of 21 Lutetia is consistent with partial melting under a crust greater than 5 km in (Figure 1). However, more extensive melting, which may generate crusts as thin as < 1 km [6, 13], is unlikely to have occurred on 21 Lutetia. Improved calculations using realistic shape models of 21 Lutetia coupled with thermal evolution models will provide tighter constraints on the maximum degree of melting sustained by the body, which in turn may constrain the timing of its formation. Future models may also be applied to other differentiated or possibly differentiated bodies such as 4 Vesta and 22 Massalia.

Conclusions: Large scale melting of asteroids in the early solar system had a pronounced effect on the shape of the asteroids. Observations of the shapes of asteroids that have escaped catastrophic impact disruption can yield constraints about their early thermal history. Thorough melting (i.e., no preserved crust) of bodies as small as 50 km in diameter would allow relaxation to a hydrostatic shape. However, the presence of a crust of < 10 km thickness can dramatically increase the relaxation time for small asteroids. In the case of 21 Lutetia, the observed, non-hydrostatic shape is consistent with interior melting that preserved a crust > 5 km in thickness.

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