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Modeling KBOs Charon, Orcus and Salacia by means of a new equation of state for porous icy bodies

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Abstract

We use a one-dimensional adaptive-grid thermal evolution code to model intermediate sized Kuiper belt objects Charon, Orcus and Salacia and compare their measured bulk densities with those resulting from evolutionary calculations at the end of 4.6 Gyr. Our model assumes an initial homogeneous composition of mixed ice and rock, and follows the multiphase flow of water through the porous rocky medium, consequent differentiation and aqueous chemical alterations in the rock. Heating sources include long-lived radionuclides, serpentinization reactions, release of gravitational potential energy due to compaction, and crystallization of amorphous ice. The density profile is calculated by assuming hydrostatic equilibrium to be maintained through changes in composition, pressure and temperature. To this purpose, we construct an equation of state suitable for porous icy bodies with radii of a few hundred km, based on the best available empirical studies of ice and rock compaction, and on comparisons with rock porosities in Earth analog and Solar System silicates. We show that the observed bulk densities can be reproduced by assuming the same set of initial and physical parameters, including the same rock/ice mass ratio for all three bodies. We conclude that the mass of the object uniquely determines the evolution of porosity, and thus explains the observed differences in bulk density. The final structure of all three objects is differentiated, with an inner rocky core, and outer ice-enriched mantle. The degree of differentiation, too, is determined by the object's mass.

1. Introduction

This work [1] is an extension of a predecessor model presented by Malamud and Prialnik [2], which calculates the evolution of relatively small icy objects, having a radius of approximately 200-250 km. Here we consider the addition of physical processes that apply to much larger icy objects, with a radius of up to 600 km. In such intermediate sized icy objects the internal core pressure by self-gravity can be up to an order of magnitude larger. Therefore, we consider how these larger icy bodies react to the change in porosity as water migrates out from the core to colder regions. Maintaining hydrostatic equilibrium while various processes occur (phase changes, chemical reactions, differentiation) requires more than the parameterized EOS (Birch-Murnaghan) used in the predecessor model, which is why we devise an empirically based EOS that explicitly accounts for changes in porosity, temperature and composition. This EOS is then tested on three mid-sized KBOs, Salacia, Orcus and Charon, which can be considered a coherent sample. According to Kenyon and Bromley [3], their formation timescale is approximately 30–45 Myr, which rules out heating by short lived radionuclides (SLRs). In accretionary scenarios for growth of KBOs [4], objects are considered to form in regions that have similar physical characteristics. Thus their composition is estimated to have about the same rock/ice mass ratio. Therefore, it is reasonable to adopt the same initial composition, and the same abundance of SLRs. The main goal is to explain the present state of different objects in the Kuiper belt, starting from identical initial conditions, and using a unique set of model assumptions and parameters. We then compare the outcomes of their evolutionary computations, to measurements obtained from observations. Assuming that these selected objects were formed under similar initial conditions, we demonstrate that the differences among them (more specifically, their different bulk densities) could be explained by a single free parameter, their total mass. Note that other intermediate sized icy objects in the solar system, also have reliable bulk density measurements, but unlike the three objects mentioned above, their evolutions may also heavily depend on initial variability in the abundance of SLRs, as well as upon their orbital, tidal and collisional histories [5], affecting the final bulk density. Collisional events are also likely to have affected several other intermediate sized KBOs [6], which are therefore not considered in this sample.

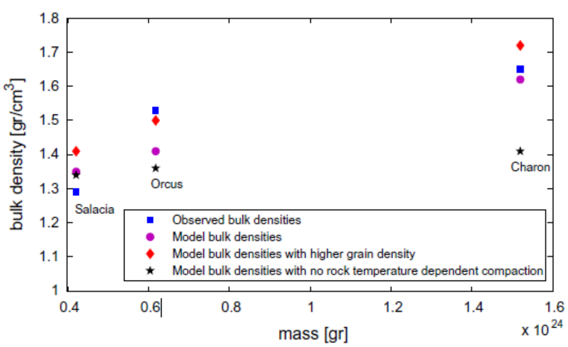
1.1 Equation of state

The EOS is we have constructed is based on the two-layer model suggested by Yasui and Arakawa [7]. The compaction curves are obtained from various empirical studies.

2. Main results

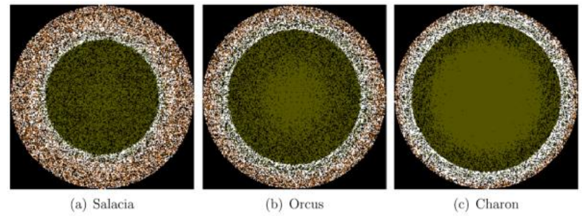
Our model and newly developed EOS can account for differentiated structures with bulk densities that are in good agreement with observed ones (Figure 1).

Figure 1: Model vs. observed bulk densities.



From the detailed evolution runs of Salacia, Orcus and Charon, we identify correlations between the object's mass and other physical quantities. Thus, a more massive object reaches higher temperatures, which result in a more differentiated structure. The rocky core is bigger and more compacted, while the ice-enriched mantle is smaller and has a lower rock fraction (Figure 2).

Figure 2: Final structure and composition of models, Color interpretation: *black* (pores); *white* (crystalline ice); *pink* (amorphous ice); *brown* (anhydrous rock); *olive* (aqueously altered rock)



At the surface, amorphous ice can survive, but with increasing mass, its survival depth is diminished. We also find that while overall, radioactive heating is an order of magnitude more important than heating by serpentinization, in the early evolution stage their roles are reversed. Gravitational energy released due to differentiation & compaction has a marginal contribution. Finally, we investigate the effect of grain density, adopting typical values for Earth analog rocks and for meteorites, concluding that for both selections, the final model bulk densities are still in agreement with the observation (Figure 1).

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