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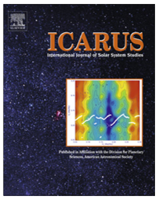

Modeling Kuiper belt objects Charon, Orcus and Salacia by means of a new equation of state for porous icy bodies

Uri Malamud *, Dina Prialnik

Department of Geophysical, Atmospheric and Planetary Sciences, Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel

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ABSTRACT

We use a one-dimensional adaptive-grid thermal evolution code to model 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

Very little is known about the inner composition, structure or processes that take place during the differentiation of medium and large icy objects of the Solar System. However it is clear that the thermal evolution is very strongly coupled to the structural evolution of an object. For example, if water ice is able to melt, liquid water chemically interacts with the rock. This interaction has multiple effects: (a) it changes the specific density of the rock; (b) it changes the rock's thermal properties, such as heat capacity and thermal conductivity; (c) it changes the composition, both because water is lost through rock hydration and because the release of latent heat causes more melting and accelerates water–rock differentiation; (d) it affects compaction (loss of porosity) by self gravity, since compaction of porous water ice is much easier to achieve than compaction of porous rock; and so on.

Realistic models of such objects thus face the challenge of coupling compositional, structural and thermodynamical effects. In the present paper we develop a complex thermo-physical model, suitable for computing the long-term evolution of mid-sized icy objects. The model includes heating by long-lived radionuclides, serpentinization reactions, release of gravitational energy due to self compaction, and crystallization of amorphous ice. We apply the model to three Kuiper belt objects (KBOs) – Charon, Orcus and Salacia – which are large enough to maintain hydrostatic equilibrium, but not so large as to permit rock melting, even partially. We follow their evolution for the age of the Solar System, paying special attention to the progress of rock–water differentiation and to changes in porosity. We then compare the final (present-day) bulk densities with those derived from observations. Our goal is to find whether the same model can explain different bulk densities of KBOs, assuming the same initial conditions and parameters. We discuss our choice of objects in the next section, Section 2.

The solution of the hydrostatic equation that yields the density (and porosity) profile, requires an equation of state (EOS), where the pressure $P(\rho, T, X_d)$ is a function of the local density ρ, temperature T and mass fraction of rock X_d. In Section 3, we develop such an equation of state for a porous mixture of water ice and rock, based on the best available empirical studies of ice and rock compaction, and comparisons with rock porosities in Earth analog and Solar System silicates. The details of our model are provided in Section 4. The model is largely based on an earlier model,

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* Corresponding author.
E-mail addresses: urimalam@post.tau.ac.il (U. Malamud), dina@planet.tau.ac.il (D. Prialnik).

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presented by Malamud and Prialnik (2013). The results are given in Section 5, and discussed in Section 6. We conclude with some final remarks in Section 7.

2. The choice of sample objects

In order to calculate the density profile, our model assumes hydrostatic equilibrium. So any object with a radius smaller than about 200 km is excluded (Lineweaver and Norman, 2010). Our model of Charon suggests that during its evolution, Charon's core temperatures are nearing the point of partial melting of the rock. Since internal temperatures are generally increasing with increasing mass, partial melting is likely to occur in objects larger than Charon. As we have already mentioned, rock melting is not treated in this study, therefore objects larger than Charon are excluded as well. In the outer Solar System there are 13 objects with radii in the interval 200–600 km, which have measured bulk densities, if we consider only reliable densities deduced from flyby missions or from binary systems. Out of these, seven are satellites of the gaseous giant planets: Mimas, Miranda, Enceladus, Tethys, Dione, Ariel and Umbriel (listed according to size in ascending order). We exclude satellites from our sample because their present-day bulk densities depend upon their orbital, tidal and collisional histories (Schubert et al., 2010), which are unique for each individual object. Volatile loss, for instance, whether tidally driven (Fagents, 2003; Spencer et al., 2009) or impact related (Nimmo and Korycansky, 2012), may lead to preferential loss of mass and affect the bulk rock/ice mass ratio, and thus the bulk density. Other factors may indirectly affect the bulk density of satellites. The initial rock/ice mass ratio is not likely to be identical in satellites of different planets (Lunine, 2006), or even satellites of the same planet (Dwyer et al., 2013). Furthermore, the time scale of formation of these satellites is of the order of several million years, but differs for various satellites (Barr and Canup, 2008). Different formation time means that the initial fraction of short-lived radionuclides varies, which in turn implies different initial rates of radioactive heating. Consequently, differentiation of water and rock, if it occurs, will increase or decrease along with the fraction of initial short-lived radionuclides. This will affect the bulk density, because compaction is linked to composition.

Selecting a sample of KBOs, reduces some of these concerns. According to Kenyon and Bromley (2012), the formation timescale for KBOs with a maximal radius between 200 and 600 km, and a semi-major axis in the range 33–40 AU, is approximately 30–45 Myr. Accretion timescales of a few Myrs are only possible at much closer heliocentric distances. We can therefore safely ignore heating by short-lived radionuclides in large KBOs. In accretionary scenarios for growth of KBOs (Kenyon et al., 2008), the 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. It is therefore reasonable to adopt the same initial composition, which reduces the number of free parameters. Volatile loss related to tidal heating can also be excluded for KBOs.

There remain six KBOs in the appropriate size range: 2002 UX_{25}, Salacia, Orcus, Quaoar, Charon and Haumea (listed according to size in ascending order). Large KBOs that exclusively have small satellites – Quaoar, Haumea and Eris – have been suggested to have undergone giant impact events after their formation. Interestingly, these objects have higher densities than any other measured KBO. Haumea is even known to have an entire family of icy objects surrounding it. This would indeed seem to be the result of impacts, which removed ice from a differentiated mantle, although the nature of these collisional events remains an open question (Brown, 2012). Quaoar and Haumea therefore represent a population of high density KBOs, with a bulk density which was probably altered due to a past cataclysmic event. Considering the unclear circumstances involving this past event, we prefer not to include these two objects in the sample. The bulk density of 2002 UX_{25} was very recently measured. With a radius of about 325 km, this object has the surprisingly low bulk density of only 0.82 g/cm^3, making it the largest known object in the Solar System with a bulk density lower than the specific density of water (Brown, 2013). It is difficult to reconcile this very low bulk density with the high rock/ice mass ratio that is normally associated with KBOs. One possibility is that the bulk porosity of this object is at least 60%, more like the porosity expected of a comet, but this would be unrealistic for an object of this size. Another possibility is that for some reason, its rock/ice mass ratio is atypical, and much lower compared to other known KBOs. Perhaps the explanation is related to the fact that 2002 UX_{25} is a member of the hot classical population of KBOs, characterized by highly inclined, more eccentric orbits (Noll et al., 2008). Or, perhaps the high ice abundance of 2002 UX_{25} is also a consequence of a past cataclysmic event, although there is no evidence for it. Whatever the reason, we choose to exclude 2002 UX_{25} from the sample.

The three remaining KBOs: Salacia, Orcus and Charon can be considered a coherent sample. Salacia is the larger object in a binary, and it has a radius of 427 ± 22 km. Its satellite Actea, has a much smaller radius of 143 ± 12 km (Fornasier et al., 2013). The mass of the system was first determined by Grundy et al. (2011) to be $4.66 \pm 0.22 \times 10^{23}$ g, and more recently refined by Stansberry et al. (2012) to be $4.38 \pm 0.16 \times 10^{23}$ g. Adopting mean values, the corresponding bulk densities of the system are 1.37 g/cm^3 and 1.29 g/cm^3. Stansberry et al. (2012) derived a lower bulk density of 1.16 g/cm^3, adopting the former mass estimation, yet larger values for the sizes of Salacia and Actea. We adopt the median value of 1.29 g/cm^3, which also corresponds to the most recent estimates of mass and radii of the system. Orcus is the larger object in a binary, with a radius of 459 ± 12 km, slightly larger than that of Salacia. Its satellite Vanth has a radius of 138 ± 9 km, slightly smaller than that of Actea (Fornasier et al., 2013). The mass of the Orcus-Vanth system was determined by Brown et al. (2010) to be $6.32 \pm 0.05 \times 10^{23}$ g. Adopting mean values, the bulk density of the system according to Fornasier et al. (2013) is 1.53. Brown et al. (2010) derived a bulk density of about 1.6 g/cm^3 assuming an identical albedo for Orcus and Vanth. Unlike Salacia, however, Orcus has an unusually high albedo of about 0.27 (Lim et al., 2010), so Brown et al. (2010) derived a bulk density of about 1.5 g/cm^3, assuming a low albedo for Vanth. We adopt the newest estimate of 1.53 g/cm^3, which falls between the other two. Note that in both binary systems the measured bulk density is derived from the total mass of the system, implying that the KBO and its satellite have the same rock/ice mass ratio and also the same porosity, although it might be more reasonable to assume the larger body to have lower porosity and hence higher density. The size of Charon was determined from the stellar occultation of July 11, 2005. Buie et al. (2006) reported a radius of 603.6 ± 1.4 km and derived Charon's individual bulk density of 1.65 g/cm^3 (since the Charon-to-Pluto mass ratio is known). Person et al. (2006) similarly reported a radius of 606.4 ± 1.5 km and a slightly lower bulk density of 1.63 g/cm^3. From the 4 June, 2011 stellar occultation, a radius of 602.4 ± 1.6 km was reported (Sicardy et al., 2012). The latter is in better agreement with the radius measured by Buie et al. (2006).

As inferred from their densities, most mid-sized icy objects are known to be composed of a mixture of different materials, with rock and water being the most abundant by far. The term 'rock' is used in this paper generally, with reference to two distinct phases of silicates: processed rock, which is chemically altered by interacting with water, and unprocessed rock which is unaffected by aqueous alterations. Depending on conditions, the

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