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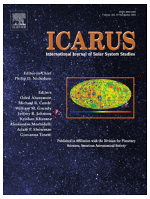

Implications of the observed Pluto–Charon density contrast

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ABSTRACT

Observations by the New Horizons spacecraft have determined that Pluto has a larger bulk density than Charon by 153 ± 44 kg m^{-3} (2σ uncertainty). We use a thermal model of Pluto and Charon to determine if this density contrast could be due to porosity variations alone, with Pluto and Charon having the same bulk composition. We find that Charon can preserve a larger porous ice layer than Pluto due to its lower gravity and lower heat flux but that the density contrast can only be explained if the initial ice porosity is $\gtrsim 30\%$, extends to $\gtrsim 100$ km depth and Pluto retains a subsurface ocean today. We also find that other processes such as a modern ocean on Pluto, self-compression, water-rock interactions, and volatile (e.g., CO) loss cannot, even in combination, explain this difference in density. Although an initially high porosity cannot be completely ruled out, we conclude that it is more probable that Pluto and Charon have different bulk compositions. This difference could arise either from forming Charon via a giant impact, or via preferential loss of H_2O on Pluto due to heating during rapid accretion.

1. Introduction

The New Horizons spacecraft has provided a wealth of new information about the Pluto system (Stern et al., 2015) and has spurred a number of modeling efforts to understand these observations. Desch (2015) and Desch and Neveu (2016) have modeled the process of differentiation on early Pluto and Charon (or their precursors in the case of an impact formation). Malamud et al. (2016) modeled the role serpentinization may play in the extensional tectonics observed on Charon (Beyer et al., 2016). Hammond et al. (2016) used thermal modeling to show that if Pluto's subsurface ocean froze completely ice II may have formed, causing contraction. Given that no contractional features are observed on Pluto's surface they infer that Pluto must still have a subsurface ocean today. In this work we apply a thermal model similar to these to examine the implications of the bulk density difference between Pluto and Charon.

Bulk density is one of the most important measurements for determining the first order structure and composition of any world. Prior to 2015, bulk density measurements of Pluto and Charon were limited by the poorly known radius of Pluto (Tholen and Buie, 1997; Lellouch et al., 2009). This uncertainly was large enough that it could barely be determined whether Pluto and Charon had any difference in density at the 2σ level (Brozović et al., 2015). With the images acquired by New Horizons, the radius of Pluto has been measured with an error of less than two kilometers (Stern et al., 2015; Nimmo et al., 2016). These results show that Pluto and Charon have distinct bulk densities (1854 ± 11 and 1701 ± 33 kg m^{-3} respectively). This difference in density raises the question of whether Pluto and Charon must be compositionally distinct, or if this observation could be consistent with bodies that have the same bulk composition.

This observed difference in density ($\Delta\rho_{PC} = 153 \pm 44$ kg m^{-3}) at first glance appears small given that it is ~10% of Pluto and Charon's bulk density. The changes needed to achieve this density contrast without a difference in bulk composition, however, are dramatic. To give some sense of the scale of change required, it would require melting Pluto's entire ice shell to match the observed density contrast (McKinnon et al., 2017).

Determining if Pluto and Charon have different rock/ice ratios is an important constraint on formation models of the Pluto-Charon system (Nesvorný et al., 2010; Canup, 2005; 2011). There are two primary models for how Pluto and Charon might have formed. One is that Pluto and Charon may have formed in-situ via gravitational collapse (Nesvorný et al., 2010). In this scenario there is no obvious mechanism which might cause one body to preferentially accrete rock or ice; it therefore predicts that Pluto and Charon should have the same initial bulk composition. Alternatively, Charon could have been formed in a giant impact, analogous to the Earth-Moon forming impact. Published models support a low velocity impact between partially differentiated impactors (Canup, 2011). In this sce-

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Table 1
Parameters used.

	Symbol	Nominal value	Units	Variation range
Reference Viscosity	η_0	10^{14}	Pa s	$10^{13} - 10^{17}$
Viscosity Reference Temperature	T_0	270	K	
Activation Energy	Q	60	kJ/mol	
Ice Thermal Conductivity	k_{ice}	$0.4685 + 488.12/T$	W/(m K)	
Core Thermal Conductivity	k_c	3.0	W/(m K)	1.0 – 4.0
Initial Porosity	ϕ_0	0.2		0.0-0.3
Empirical porosity-conductivity coeff.	a	4.1		
Empirical porosity-conductivity coeff.	b	0.22		
Empirical porosity-conductivity coeff.	ϕ_p	0.7		
Surface Temperature	T_s	40.0	K	
Initial Temperature	T_0	150.0	K	150–250
Ice Specific Heat	Cp_{ice}	1930	J/(kg K)	
Core Specific Heat	Cp_c	1053	J/(kg K)	
Ice Density	ρ_{ice}	950	kg/m^3	950
Ocean Density	ρ_w	1000	kg/m^3	
Core Density	ρ_c	3500	kg/m^3	2500–3500
Latent Heat of Ice	L_H	3.33×10^5	J/kg	

nario there is a grazing impact where a remnant of the impactor is captured (Charon) and a disk of ice-dominated material is created. Some of this disk reaccretes onto Charon and some of the disk may go on to form the smaller outer moons (Canup, 2011), resulting in a Charon that may be ice-rich relative to Pluto.

In this work, we investigate whether the observed bulk density difference *requires* a difference in composition. We examine a number of sources of density contrast to determine if any of those could explain the magnitude of difference observed. We consider density contrasts due to differences in porosity, subsurface oceans, self-compression, water-rock interactions (i.e. serpentinization), and volatile loss. We focus on porosity as it is the mechanism capable of producing the largest density contrast. We find that to match the observed density contrast Charon must have an ice shell with ~30% porosity to ~100 km depth. We also present arguments why this large porous layer is unlikely to exist and instead favor a compositional difference between Pluto and Charon to explain the density contrast.

2. Thermal evolution and pore closure model

To test if the density contrast between Pluto and Charon can be explained by differences in the thickness of a porous layer we used a 1D conductive thermal model based on Nimmo and Spencer (2014). We set the same initial rock to ice ratio for Pluto and Charon and model their thermal evolution in order to determine if the density contrast can be explained without differences in composition. The key effects that generate density contrast are changes in the porous structure and the final state of a subsurface ocean.

To fully test porosity as an explanation for the observed density contrast we focus on the most favorable initial conditions. In our model Pluto and Charon are differentiated; this is consistent with the observation that both Pluto and Charon show no compressional features that would be expected from high-pressure ice phases forming at depth if they were not differentiated (Stern et al., 2015; Moore et al., 2016; McKinnon et al., 2017). The initial porosity extends from the surface to the base of the ice shell and has a constant value ψ_0. Having such a thick initial porous layer after differentiation, even if full differentiation follows a giant impact, may or may not be likely but provides an important end-member case. Although we do not explicitly include impact-generation of porosity at later epochs (Milbury et al., 2015), the depth to which such porosity extends will probably be limited to ~10 km at most because of the low velocity and restricted sizes of likely impactors (discussed in Section 4.1). Porosity of the silicate core is unlikely to affect the overall bulk density for reasons discussed in Section 3.2 below.

The start time for thermal evolution is after the decay of short-lived isotopes like ^{26}Al (Kenyon, 2002). Our model takes into account the decay of the long-lived isotopes ^{238}U, ^{235}U and ^{40}K. The abundances of these elements in the core is assumed to be the chondritic value using the abundances of Robuchon and Nimmo (2011). We adopt a cold (150 K), isothermal initial state and assume that a specified porosity initially extends throughout the entire ice mantle. Differentiation probably requires temperatures higher than 150 K, but higher initial temperatures would permit ice flow and reduce the initial porosity. The initial temperature assumed is not very important for the long-term porosity evolution, because the long-term evolution is determined mainly by the energy associated with radioactive decay (Robuchon and Nimmo, 2011). Sensitivity tests found that lowering the initial temperature from 150 K to 50 K lowered the final density of Charon by ~15 kg/m^3 because slightly more porosity was preserved.

We assume both Pluto and Charon have conductive ice mantles (the effect of ice convection is discussed in Section 2.1.2). The local melt temperature of each layer is pressure-dependent following Leliwa-Kopystyński et al. (2002). For all the runs presented here we assume there is no ammonia present (discussed in Section 2.1). We modify the original code of Nimmo and Spencer (2014) to include the variable thermal conductivity of water ice (Petrenko and Whitworth, 2002; Hobbs, 1974; Hammond et al., 2016), the effect of porosity on thermal conductivity, as well as conservation of mass (Appendix A). The model self-consistently adjusts the thermal conductivity (k) for each grid point (i) as pore closure proceeds. We modify the conductivity according to the lower bound derived by Shoshany et al. (2002),

$$k_i(\phi) = k_{ice}(T)\left(1 - \frac{\phi}{\phi_p}\right)^{(a\phi+b)} \tag{1}$$

where ϕ is the layer porosity and T is the temperature in Kelvin. $k_{ice}(T)$ and the constants a, b, and ϕ_p are given in Table 1. The effect of porosity on thermal conductivity is generally less than that of the temperature but does become important for high porosity cases ($>20\%$). The temperature dependence of specific heat (Cp) was not included as sensitivity tests found its effect on the long term evolution negligible (less than 0.1% change in the final density for a factor of four change in Cp).

To account for the radial variation in conductivity, layer thickness (Δz), and density (ρ) of each grid point (subscript i), we update the discretized heat conduction equation from Nimmo and Spencer (2014) to use to that of Kieffer (2013) modified to the spherical geometry. The following equation is derived in