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Density of Charon formed from a disk generated by the impact of partially differentiated bodies

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ABSTRACT

Formation of Pluto's moon Charon from an impact-generated circumplanetary disk has been considered unlikely because of its composition. Such a disk is created by the collision of two similarly sized, differentiated impactors; the disk would contain material from the impactors' outer portions; and that material has been presumed to be pure water ice. Charon has been predicted to have a density $\sim$1000 kg m^{-3} if formed from a disk, much lower than its observed density $\approx$1630 kg m^{-3}. Here we reconsider the composition of the circumplanetary disk. We draw on previously presented models to calculate the thermal evolution and internal structure of the impactors, each assumed to have radii $\approx$972 km and mean densities $\approx$2000 kg m^{-3}. We show such bodies retain crusts of rock and ice on their surfaces about 46 km thick, comprising about 13% of the impactors' mass; the outer layers are *not* pure ice. Provided $\approx$6% of the total mass of the impactors escapes the system, an escape fraction supported by numerical simulations, the observed densities of Pluto and Charon are reproduced in a scenario involving a circumplanetary disk. Charon's density does not rule out an origin from an impact-generated disk. We calculate the thermal evolution of Charon if it formed late from an impact-generated disk. While Charon is less heated by radioactive decay than if it formed earlier, the heat of its accretion causes its complete differentiation. Subsurface liquid and cryovolcanism may have existed on Charon, but only until 1.5 Gyr ago. These predictions may be tested by data returned by the *New Horizons* mission.

1. Introduction

The fascinating Pluto system is unique in the Solar System. No object in the Solar System, save the giant planets, has as many satellites as the 5 seen in the Pluto system: Charon (Christy and Harrington, 1978); Nix and Hydra (Weaver et al., 2006); and Kerberos (Showalter et al., 2011) and Styx (Showalter et al., 2012). Charon is the most massive satellite, with $M_c = 1.52 \times 10^{21}$ kg, which is a fraction $M_c/M_p = 0.117$ of Pluto's mass, 13.02×10^{21} kg. Nix and Hydra each possess masses of a few $\times 10^{17}$ kg (Weaver et al., 2006), and Kerberos and Styx are smaller still. The orbits of all the satellites are prograde and coplanar, and the orbital periods of the four other satellites are very near mean motion commensurabilities with Charon (Tholen et al., 2008). Nix and Hydra are near the 4:1 and 6:1 commensurabilities, and Kerberos and Styx are near the 3:1 and 5:1 commensurabilities, respectively. These properties are most readily explained if the smaller satellites and Charon formed together in a circumplanetary disk, even though the details of where they formed and how they their orbits subsequently evolved are debated (Canup, 2005, 2011; Stern et al., 2006; Ward and Canup, 2006; Lithwick and Wu, 2008; Kenyon and Bromley, 2013). The most natural explanation for the circumplanetary disk is that it arose following a giant impact, similar to the protolunar disk around the Earth (McKinnon, 1989; Canup, 2005, 2011; Kenyon and Bromley, 2013). Models of Pluto's satellites' origins might be used to probe the dynamical evolution of the Kuiper Belt and the internal structure of Kuiper Belt objects (KBOs), and could provide insights into how the Earth and Moon formed.

The formation of Charon in particular speaks to these issues. How Charon formed is not currently understood. Canup (2005) explored two possible scenarios. In the first scenario, equal-sized, fully differentiated bodies collide at about the escape velocity $v_{\rm esc} \approx 0.73$ km s^{-1}, at an oblique angle (normalized impact parameter $b' > 0.8$). Each impactor has a mass M_i just slightly larger than half the mass of the system, i.e., $\gamma \equiv M_i/(M_p + M_c) \approx 0.5$. Before the collision, the two impactors are in prograde rotation with periods of perhaps 3–7 h. The bodies are assumed to have fully differentiated, forming an inner core of iron surrounded by an outer core of dunite, surrounded by an ice mantle. The temperatures in the body are assumed to be $\approx$150 K near the surface, rising to 800 K at the core. Over the course of the impacts, the cores of the two bodies

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merge, even as a bar-type mode forms and launches spiral arms from the outermost parts of the bodies (i.e., the ice mantles). A small fraction, typically 1–8% depending on the specific parameters, of the total mass escapes the system altogether. Over time the material is expected to form a disk from which Charon (and presumably Nix, Hydra, etc.) can form. The material in this disk will either accrete into a satellite or onto the planet. In a typical example, 70% of the disk's mass was on equivalent circular orbits exterior to the Roche limit. Canup (2005) estimated the mass of Charon using scaling relations developed for understanding the Moon-forming impact, which include knowledge of the disk's mass and angular momentum. Based on these estimates, Canup (2005) found the mass ratio between the satellite and planet was often $q \equiv M_s/M_p \approx 0.12$, the observed value. Canup (2011) subsequently modeled how Nix and Hydra might simultaneously form in this scenario.

The other scenario explored by Canup (2005, 2011) involves a larger target ($\gamma = 0.5–0.7$) and smaller impactor ($\gamma = 0.5–0.3$), again hitting at a low speed $v_{\rm imp} < 1.2\ v_{\rm esc}$ (corresponding to $v_\infty < 0.9\ {\rm km\ s^{-1}}$), at a very grazing angle (normalized impact parameter $b' > 0.8$). Under these conditions the impactor emerges as an intact moon in orbit around the new planet. Smaller impactors ($\gamma \approx 0.3$) require larger impact parameters ($b' \approx 0.96$) to impart the required angular momentum. The formation of an intact moon was found to be highly correlated with the differentiation state of the impactor and target, requiring undifferentiated bodies, e.g., homogeneous spheres of serpentine (hydrated silicate). For the same physical parameters, differentiated bodies tended to form disks.

To understand the Pluto–Charon system and use it to probe the Kuiper Belt, it is important to determine which of these two scenarios led to Charon's formation. Canup (2005) used arguments about the resultant satellite's density to distinguish between these models. She strongly favored intact moon scenarios: in these scenarios a larger range of input parameters yield a system with $q \approx 0.1$ and the Pluto–Charon system angular momentum; and in disk scenarios she considered, the disk would be composed almost entirely from the icy mantles of the impactors, and Charon would have a density of pure water ice $<1000\ {\rm kg\ m^{-3}}$. Canup (2011) only considered intact moon scenarios, investigating only whether sufficient mass existed in an auxiliary disk to form Nix and Hydra. Canup (2005) acknowledged that bodies as large as the impactors she considered were unlikely to remain undifferentiated, but still strongly favored the intact moon scenarios.

The thermal evolution and differentiation of KBOs has been investigated by Desch et al. (2009) and Rubin et al. (2014), and their results can be used to judge the two Charon formation scenarios. In these one-dimensional, spherical models, bodies are assumed to accrete as homogeneous mixtures of rock and ice (water ice, but also containing ammonia dihydrate). The bodies accrete cold with temperatures characteristic of the Kuiper Belt ($\approx$40 K) and are then heated by decay of long-lived radionuclides. In only tens of millions of years, temperatures inside these bodies are sufficient to melt water ice, allowing separation of ice and rock. After a rocky core forms, central temperatures can exceed 1200 K, even on small, Charon-like bodies with mean density $\bar{\rho} = 1630\ {\rm kg\ m^{-3}}$ and radius 600 km. Differentiation of ice and rock is assumed to take place whenever the temperature in a shell exceeds a critical temperature, $T_{\rm diff}$. Inside the radius at which $T = T_{\rm diff}$, all rock is assumed to settle into a core, surrounded by a thin layer of water/ammonia liquid, surrounded by a thick mantle of pure water ice. The largest radius at which the temperature ever exceeds $T_{\rm diff}$ is termed $R_{\rm diff}$. In the shells with $r > R_{\rm diff}$, temperatures remain cold enough that ice and rock never separate.

Desch et al. (2009) assumed $T_{\rm diff} = 176$ K, because the viscosity of ammonia-bearing ice drops 5 orders of magnitude above this temperature (Arakawa and Maeno, 1994), allowing Stokes flow of meter-sized rock through the ice on geological timescales. On a Charon-like KBO they found $R_{\rm diff} = 515$ km. Rubin et al. (2014) assumed separation of ice and rock had to proceed through Rayleigh–Taylor (RT) instabilities at the ice-crust interface. The rock-ice crust is denser than the underlying ice mantle and will sink through it if RT instabilities can operate; the rock-ice crust is then carried to warmer depths where ice and rock can easily separate. RT instabilities are suppressed, however, where the temperature is too low and the viscosity too high. For Charon-like bodies with radius 600 km, Rubin et al. (2014) calculated that differentiation requires temperatures higher than $T_{\rm diff} = 150$ K, and found $R_{\rm diff} = 542$ km. The outermost 58 km of a Charon-like body never melts, never overturns, and remains an undifferentiated mixture of rock and ice. Both Desch et al. (2009) and Rubin et al. (2014) robustly predict the existence of undifferentiated crusts of mixed ice and rock on the exteriors of KBOs.

This prediction is significant in the context of Charon forming from an impact-generated circumplanetary disk. Charon's composition will match the composition of the disk. Because the ejected material contains undifferentiated crust of rock and ice, the disk will not be pure water ice. The Charon that forms from the disk is potentially denser than pure ice. In fact, we can estimate the density of Charon by keeping track of the ejected material. Some of the material escapes the Pluto–Charon system; considering the geometry of the impact and the spiral arms that are generated, we consider it likely that this escaping material derives from the crust. The remaining crust and some portion of the ice mantles will form Charon, and some portion of the ice mantles and rocky cores of the impactors will form Pluto. It is therefore possible for Charon to accrete from an impact-generated disk and yet have a density intermediate between the impactors and pure water ice.

In this article we test this hypothesis and judge the likelihood that Charon formed from a circumplanetary disk. In Section 2 we first calculate the likely differentiation states of impactors with the relevant size ($\approx$972 km in radius) and density ($\approx 2000\ {\rm kg\ m^{-3}}$). We find that they should retain undifferentiated crusts of about 46 km in thickness (containing 13% of the total mass), which means a substantial amount of rocky material should end up in the impact-generated disk. In Section 3 we calculate the composition of the disk as a function of the mean densities $\bar{\rho}$ of the impactors, and the fraction of material that escapes, $f_{\rm esc}$. For impactors with $\bar{\rho} = 2000\ {\rm kg\ m^{-3}}$, radii $R = 972$ km, and assuming $f_{\rm esc} = 6\%$ of the material escapes, we find that the density of Charon is reproduced if the crustal thickness of the impactors is 46 km. For these parameters, the crustal thickness predicted by thermal evolution models is exactly the crustal thickness needed to explain the density of Charon formed from a circumplanetary disk. In Section 4 we discuss the consequences of these results for the origin of Charon. We conclude that an origin of Charon from an impact-generated disk should *not* be ruled out based on density. In fact, given that the undifferentiated impactors apparently necessary for the intact moon scenario are unlikely, formation of Charon from a disk may be the *more* likely scenario.

2. KBO thermal evolution and internal structure

Since the work of Canup (2005), a greater understanding of the internal thermal and structural evolution of KBOs has been developed. It is widely appreciated that KBOs may differentiate and even maintain subsurface liquid (e.g., Hussmann et al., 2006). Desch et al. (2009) considered the thermal evolution of KBOs that are heated by long-lived radionuclides (^{40}K, ^{232}Th, ^{235}U and ^{238}U, in chondritic abundances relative to Si, according to Lodders (2003)), and which contain ammonia hydrates as part of their com-