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Differentiation and cryovolcanism on Charon: A view before and after New Horizons

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A B S T R A C T

Before the arrival of the *New Horizons* probe at the Pluto-Charon system, we developed a series of models that predicted that Kuiper Belt Objects, even as small and as cold as Charon, have experienced internal ice-rock differentiation and possibly cryovolcanism. Confronting these predictions is a wide array of spectroscopy, imagery, and other data from *New Horizons*. In this article we compare the predictions against the new observations, and find that they largely support the expected history of the Pluto system and the evolution of Charon. Following the collision of two partially differentiated impactors with radii ≈1000 km, a disk of material formed around Pluto, from which Charon and Pluto's other moons formed. Because the impactors did not completely differentiate, the disk contained rocky material from their crusts, explaining the moons' different densities and compositions. Long-lived radionuclides in Charon, assisted by ammonia antifreeze in the ice, melted ice and created a subsurface ocean that eventually refroze ≈1.7 – 2.5 Gyr ago. The freezing of this ocean would have created extensional stresses that possibly created Serenity Chasma, and could have led to widespread resurfacing, explaining the apparently younger age of Vulcan Planum. Buildup of radiogenic heat then created a second, smaller ocean that refroze 0.5–1.7 Gyr ago. As it froze, cryovolcanism would have been enabled, possibly creating Kubrick Mons. Charon's "moated mountains" such as Kubrick Mons have a natural explanation as cryovolcanoes depressing a thin lithosphere over a cryomagma chamber. We offer further predictions about other aspects of Charon's surface. Our previous predictions that Charon is a world shaped by geological activity have been largely borne out by *New Horizons* observations.

1. Introduction

For decades after Charon was discovered (Christy and Harrington, 1978), the strong expectation was that it would be a cold, dead world, perhaps akin to a large comet (Stern, 1989; Simonelli and Reynolds, 1989). The world that *New Horizons* would eventually visit was thought to be ancient, possibly even preserving information about the planetary building blocks of the outer Solar System (McKinnon and Mueller, 1988; Stern, 1989). With a surface temperature ≈55 K (Lellouch et al., 2011) and a pre-encounter radius 606 ± 8 km and density $1720 \pm 150\,\mathrm{kg\,m^{-3}}$ (Gulbis et al., 2006), this body was thought to be too small for cryovolcanism (Schubert et al., 2010), and possibly too small even to differentiate (Stern, 1989; Durand-Manterola, 2003); or, in later studies, too small if differentiated to maintain subsurface liquid in the recent past (Hussmann et al., 2006). Based on these studies, there was no reason to expect geological activity on Charon.

This view began to change in the last decade or so, as observations began to isolate the spectrum of Charon from that of Pluto. These observations revealed the presence of crystalline water ice on Charon's surface (Brown and Calvin, 2000; Buie and Grundy, 2000; Dumas et al., 2001; Cook et al., 2007; Merlin et al., 2010). Crystalline water ice is converted to amorphous form by irradiation from Galactic cosmic rays or even UV photons from the Sun, on relatively short timescales, $\sim 10^7$ year (Cook et al., 2007, and references therein). Crystalline water ice on KBO surfaces was interpreted to mean relative youth and therefore geological activity such as cryovolcanism (Brown and Calvin, 2000; Cook et al., 2007; Famá et al., 2010), as on Quaoar (Jewitt and Luu, 2004). A later theoretical study indicated that the heat of micrometeorite impacts on the surfaces of icy moons was probably sufficient to anneal the surface ice and counteract the amorphizing effects of radiation (Porter et al., 2010). This implies that the presence of crystalline water ice does not necessitate cryovolcanism, despite being suggestive of it.

In addition to crystalline water ice, ammonia hydrates on Charon's surface were detected with increasing certainty by Buie and Grundy (2000), Brown and Calvin (2000), Cook et al. (2007),

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Merlin et al. (2010), and DeMeo et al. (2015). Since ammonia hydrates also are expected to be destroyed on KBO surfaces by chemical processes initiated by energetic irradiation of roughly 100 eV per molecule, received on KBO surfaces on short (~20 Myr) timescales (Strazzulla and Palumbo, 1998; Cooper et al., 2004), the presence of ammonia hydrates has also been interpreted as requiring some sort of geological activity. As ammonia is a potent antifreeze, ammonia hydrates have been associated with cryovolcanism as that mechanism (Jewitt and Luu, 2004; Cook et al., 2007). It is to be noted, however, that the time to receive ≈100 eV dosages grows quickly with depth, and that ice at only several microns' depth would not receive sufficient irradiation to destroy ammonia hydrates (Fig. 5A of Cooper et al., 2004). Diffusion of NH_3 from the interior into the surface H_2O ice may also create ammonia hydrates (Cruikshank et al., 2015). Therefore, the presence of ammonia hydrates does not necessitate cryovolcanism, although it, too, is suggestive of it. Because of these alternative explanations for crystalline water ice and ammonia hydrates, there was no compelling reason to expect *New Horizons* to find Charon to be a geologically active world.

Motivated by the question of determining whether cryovolcanism is even possible in the past or present on bodies as small as Charon, our research group has built a series of increasingly sophisticated models. Desch et al. (2009) constructed a 1-D (spherically symmetric) model for the thermal internal evolution of KBOs, including the effects of ammonia and partial differentiation. Unlike previous models that assumed fully differentiated bodies (Hussmann et al., 2006), this model assumed KBOs accreted as homogeneous rock-ice mixtures, and that rock and ice within them separated only where and when heating from radioactive decay was sufficient. The predicted structure is a rocky core surrounded by an icy mantle, with liquid possible at the interface, underlying an undifferentiated crust of rock and ice too cold for rock and ice to separate. These undifferentiated rock-ice crusts were a robust prediction of the Desch et al. (2009) model, as was the fact that greater radiogenic heat released in the first 1–2 Gyr of a KBO's history can lead to increased heat flux today and a prolonged duration of subsurface liquid. The model of Desch et al. (2009) assumed that temperatures >176 K, the melting point of ammonia-water mixtures, was needed for rock and ice to separate. In later work, we investigated how these dense rock-ice crusts could overturn with the ice mantle below them via Rayleigh–Taylor instabilities; we determined that layers warmer than 140 ± 15 K would overturn but still would leave undifferentiated crusts tens of km thick on Charon-sized bodies (Rubin et al., 2014). Neveu et al. (2015a) investigated whether the rocky core would crack on small bodies; in most cases it does, allowing hydrothermal circulation through the core, with thermal and geochemical consequences. Neveu et al. (2015b) investigated which dissolved gases might arise in the subsurface ocean and how exolution of such gases might allow liquid to ascend through cracks and enable cryovolcanism. The thermal model was applied to Ceres in particular (Neveu and Desch, 2015) and, in two abstracts, to Haumea (Desch and Neveu, 2015b) and Charon (Desch and Neveu, 2015a). Desch (2015) investigated the state of the two KBOs that collided to form the Pluto-Charon system, demonstrating that their rock-ice crusts would have contributed to the circumplutonian disk from which Charon formed, increasing its density well above that of pure ice. The results of these models are detailed predictions of Charon's origins, composition, internal structure and thermal evolution, and the possibility for cryovolcanism and surface expression.

Other thermal models suggest differentiation and liquid in the Pluto-Charon system. Robuchon & Nimmo (2011) predict full differentiation and the possibility of present-day liquid inside Pluto. Very few thermal evolution models exist for Charon specifically. The models of Hussmann et al. (2006) assumed full separation of rock and ice in Charon, but nevertheless predicted that bodies as small as Charon could retain liquid for several Gyr. Thermal evolution models of Charon were also developed by Malamud and Prialnik (2015). These models also start off with an undifferentiated ice-rock mixture, but the differentiation process is modeled through the multiphase diffusive flow of water through porous rock. The heat of water-rock interaction is also accounted for, but no convective heat transfer occurs, whether in rock as hydrothermal circulation, in liquid, or in ice. The models of Malamud and Prialnik (2015) predict substantial differentiation, but in the absence of convective processes, Charon retains steep temperature gradients and substantial bulk porosity (near 25%) at depths up to 200–300 km. At such depths, temperatures allow water trapped in these poors to be liquid even at the present day.

Now these models and our models are confronted with new data: following its flyby of the Pluto-Charon system in July 2015, the *New Horizons* spacecraft has brought Charon into the realm of geology. Pluto's radius (1187 ± 4 km) and density ($1860 \pm 13\,\mathrm{kg\,m^{-3}}$ and Charon's radius (606 ± 3 km) and density ($1702 \pm 20\,\mathrm{kg\,m^{-3}}$) are now firmly established (Stern et al., 2015), and Charon and Pluto are found to be closer in density and composition than previously expected. Stern et al. (2015) have suggested this may imply that Charon formed as an intact moon from the collision of two undifferentiated impactors. Is the formation of Charon from a circumplutonian disk following a giant impact still consistent with these new compositions?

Imaging of Charon by *New Horizons*' Long-Range Reconnaissance Imager (*LORRI*) and its Multicolor Visible Imaging Camera (*MVIC*) of the *Ralph* instrument package have revealed a world that has been geologically active. A belt of chasmata circles a large fraction (if not all) of the moon, delimiting relatively ancient terrain to the north, and smooth, more sparsely-cratered plains to the south (Stern et al., 2015). The chasmata appear to be extensional features, often with graben features such as Serenity Chasma, consistent with dilation of Charon's ice shell resulting from freezing of a global subsurface ocean, a possibility predicted by Cruikshank et al. (1997) and Moore et al. (2003). From preliminary crater counts and estimates of cratering rates in the Kuiper belt (Schlichting et al., 2013; Greenstreet et al., 2015), the northern ancient terrains appear to be over 4 Gyr old, but Charon's younger equatorial plains (Vulcan Planum; we adopt in this paper the unofficial nomenclature used by the *New Horizons* team) may have been emplaced as early as ≈4 Gyr ago, or as late as 100–300 Myr ago (Stern et al., 2015). Could the chasms and the age dichotomy arise from a global resurfacing event related to the freezing of the subsurface ocean?

Several "moated mountains", including the remarkable Kubrick Mons, have been observed on Charon's limb, in which mountains kilometers high and wide are surrounded by depressions kilometers wide and deep. These mountains resemble the Hawaiian Islands, which are volcanoes depressing the surrounding lithosphere. Could these moated mountains on Charon be cryovolcanically emplaced and depressing their surrounding lithosphere?

Our models make specific predictions addressing each of these questions. In this article we compare our group's model predictions with *New Horizons* data. In Section 2 we use the updated densities of Pluto and Charon and our thermal evolution models for the impactors to argue for formation of Pluto's moons from an impact-generated disk. In Section 3 we discuss the state of Charon immediately after it forms from a disk. In Section 4 we present new calculations of the thermal evolution of Charon that support the existence of liquid water on Charon, at least in the past, and we calculate the timing of freezing of the surface ocean in an attempt to constrain the time of origin of Charon's Vulcan Planum and extensional chasmata, favoring times around 1.7–2.5 Gyr ago. In Section 5, we argue that Kubrick Mons and similar features are

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