DIFFERENTIATION AND CRYOVOLCANISM IN THE PLUTO-CHARON SYSTEM. S. J. Desch[1] and M. Neveu[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe AZ 85287-1404 (steve.desch@asu.edu)

Introduction: Previous models developed by our research group of the Pluto-Charon system have predicted the following: (1) Long-lived radionuclide decay in KBOs ~1000 km in radius leads to rock-ice separation within ~10^7 yr, but differentiation is only partial—a rock and ice crust tens of km thick should remain [1]. (2) Subsurface liquid, aided by ammonia antifreeze, may persist to the present day on Pluto-sized bodies. On Charon-like bodies liquid is likely to have frozen in the last ~1 Gyr [1]. (3) Subsurface liquid can erupt cryovolcanically, perhaps aided by exsolution of gases during ascent [2]. (4) Formation of Charon and the other moons from an impact-generated disk is likely and is not ruled out by the high density of Charon [3].

Data from *New Horizons* supports these predictions. Here we show that: (1) Densities of Pluto and Charon are consistent with formation from the impact of partially differentiated KBOs; (2) Ice-rich Nix, Hydra and Kerberos are consistent with formation from the icy mantles of the impactors; (3) Geologic resurfacing of Charon (and some areas on Pluto) may be cryovolcanic; (4) Tectonic features on Charon may arise from freezing of a global subsurface ocean ~2 Gyr ago; (5) the 'Mountain-in-a-Moat' may be a cryovolcano that sank into its magma chamber.

Disk generated by impact of two partially differentiated bodies: The Pluto-Charon system likely formed by impact [4]. Canup [4] found that formation of Charon from a circumplutonian disk may require impact of differentiated (rocky core / icy mantle) bodies, making the disk too icy to explain Charon's density (1.702 g cm^{-3} [5]); [4] therefore favored Charon being the intact impactor. Desch [3] showed impactors must be only *partially* differentiated with crusts of rock and ice (Fig. 1). The disk will then contain rock, thereby explaining and Charon's density. Differentiated bodies may demand a disk scenario.

We update the model of [3] using the latest *New Horizons* data. Pluto and Charon match observed densities (1.860 g cm^{-3}, 1.702 g cm^{-3} [5]) if impactors have equal densities 1.84 g cm^{-3} and radii 994 km; 4% of the mass escapes (consistent with [4]); and their undifferentiated crusts are 46 km thick. Our thermal evolution models [1] including ammonia, with bulk density 1.84 g cm^{-3}, T_{diff} = 145 K [9], T_{surf} = 60 K, predict crustal thickness 45 km.

We suggested [3] Pluto's other moons are fragments of the icy mantles of the impactors. Nix and Hydra have albedos ≈0.5, consistent with 'relatively clean water ice' [5], and Kerberos and Styx albedos appear similar. The orbital resonances among the moons may demand origin in a disk [6]. Formation in a disk, and the icy moons, both suggest differentiated impactors.

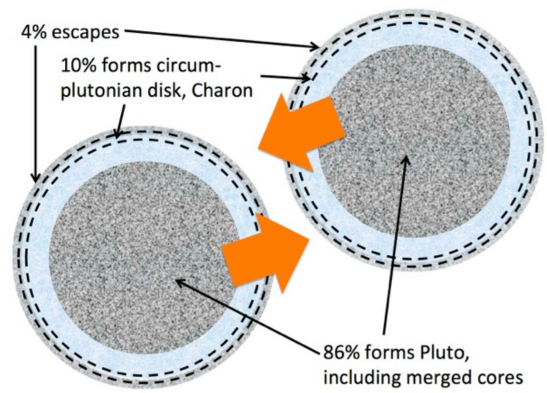

Figure 1: Impact of two partially differentiated Kuiper Belt Objects can produce a disk such that Charon forms with density 1.70 g cm^{-3}.

Freezing of a global ocean: Our models [1,3] predicted a thin global water/ammonia eutectic subsurface ocean on Charon with mass ~2 x 10^{22} g, that froze about 2-3 Gyr ago (Fig. 2). A 7% volume increase upon freezing could increase Charon's radius by 300 m, possibly causing Serenity and Macross Chasmata; and/or cryolava could be emplaced to a global depth of 300 m, possibly explaining variable cratering across Charon's surface and the youth of Vulcan Planum.

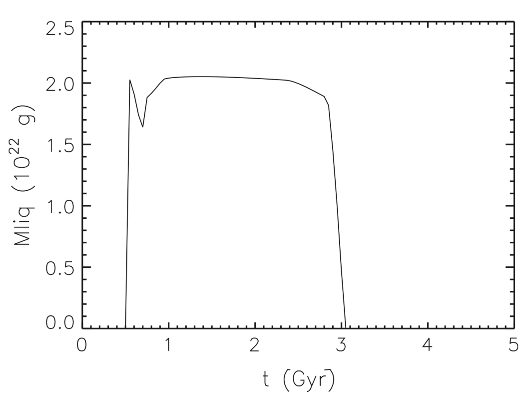

Figure 2: Mass of liquid inside Charon over time, assuming the ice is ~1wt% ammonia [3].

The ‘Mountain in a Moat’: Lithosphere deforming under a cryovolcano? *New Horizons* images of Charon show that “several large peaks of unknown origin extend 2 to 4 km above the rolling plains and are surrounded by moat-like depressions 1 to 3 km deep. The most prominent of these, Kubrick Mons, is 20 x 25 km across and 3 to 4 km high.” [5]. We interpret these as rapidly emplaced cryovolcanoes weighing down on and deforming the surrounding lithosphere, like the island of Hawaii, as depicted in Figure 3.

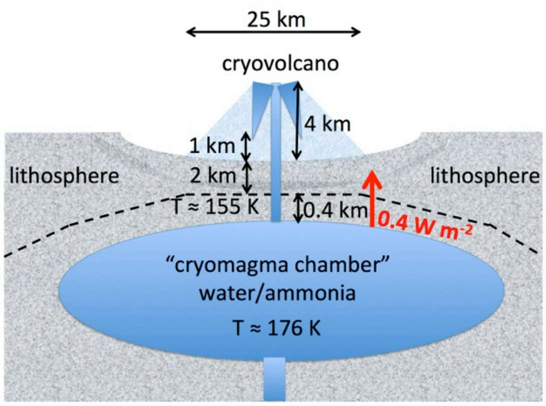

Figure 3: Schematic of Mountain in a Moat, Kubrick Mons, as a cryovolcano that sank into its cryomagma chamber and deformed the surrounding lithosphere.

We estimate the lithosphere thickness following [7]. Crustal deformation over lengthscales $\alpha \approx 300$ km for Hawaii, $\alpha \approx 30$ km for Kubrick Mons, implies a much lower rigidity D on Charon than on Earth, with $D_{\text{Charon}} = 1.2 \times 10^{-6}\, D_{\text{Earth}}$., using $\alpha = (4D / (\rho_m - \rho_w) g)^{1/4}$ and

$$\left(\frac{\alpha_{\text{Charon}}}{\alpha_{\text{Earth}}}\right)^4 = \left(\frac{D_{\text{Charon}}}{D_{\text{Earth}}}\right)\left(\frac{g_{\text{Charon}}}{g_{\text{Earth}}}\right)^{-1}\left(\frac{(\rho_m-\rho_w)_{\text{Charon}}}{(\rho_m-\rho_w)_{\text{Earth}}}\right)^{-1}$$

The lithosphere thickness h is found from rigidity D and Young’s modulus E, using $D = E\, h^3 / [12(1-\nu^2)]$. We assume a Poisson’s ratio ν identical on both Charon and Earth. On Earth, E=70 GPa, h=40 km. For ammonia-rich ice on Charon we adopt E=0.5 GPa [8] and infer ***h*=2.2 km** to the base of the lithosphere, using

$$\left(\frac{D_{\text{Charon}}}{D_{\text{Earth}}}\right) = \left(\frac{E_{\text{Charon}}}{E_{\text{Earth}}}\right)\left(\frac{h_{\text{Charon}}}{h_{\text{Earth}}}\right)^3$$

The base of the lithosphere is where crust flows with strain rate ~(1 Myr)$^{-1}$ due to ~1 MPa stresses from the cryovolcano’s weight. This requires T>155 K [9], temperatures usually reached only at depths ≈50 km [1].

This suggests a localized, transient cryomagma chamber. A temperature T=155 K only 2.2 km below the surface at 60 K demands a heat flux of ≈0.4 W m^{-2}. For comparison, on Enceladus $\alpha \approx 3.1$ km, h=0.3 km, and the heat flux is 0.25 W m^{-2} [10]. A chamber with volume ~(30 km)^3 will freeze in ~0.3 Myr. A cryovolcano formed within 1 Myr sometime in the past could have sunk into the cryomagma chamber and deformed the surrounding lithosphere, but the region would be frozen today.

We note that the discovery of ammonia-bearing ices by *New Horizons* is consistent with our earlier findings that Charon contains ammonia that can facilitate cryovolcanism, but which is rapidly destroyed on the surface by radiation [11].

Conclusions: We find that multiple aspects of the Pluto-Charon system are consistent with differentiated bodies and cryovolcanism, as our group predicted [1-3,9, 11]. The densities and compositions of the moons are consistent with the impact of already partially differentiated bodies that formed a disk. Charon’s tectonic features and resurfaced plains are possibly related to freezing of a global ocean ~2 Gyr ago. Kubrick Mons and other similar features may be cryovolcanoes that date to that same time, that deformed the surrounding lithosphere as they formed, before freezing. The detection of the antifreeze ammonia on Charon’s surface further supports the idea of cryovolcanism.

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References: [1] Desch, SJ, Cook, JC, Doggett, TC & Porter, SB (2009) *Icarus* 202, 694. [2] Neveu, M, Desch SJ, Shock, EL & Glein, CR (2015) *Icarus* 246, 48. [3] Desch, SJ (2015) *Icarus* 246, 37. [4] Canup, RM (2005) *Science* 307, 546. [5] Stern, SA et al. (2015) *Science* 350, aad1815. [6] Ward, WR & Canup, RM (2006) *Science* 313, 1107. [7] Lambeck, J & Nakiboglu, SM (1980) *JGR* 85, 6403. [8] Lorenz, RD & Shandera, SE (2001) *GRL* 28, 215. [9] Rubin, ME, Desch, SJ & Neveu, M (2014) *Icarus* 236, 122. [10] Giese, B et al. (2008) *GRL* 35, L24204. [11] Cook, JC, Desch, SJ, Roush, TL, Trujillo, CA & Geballe, TR (2007), *ApJ* 663, 1406.