CRYOVOLCANISM ON CHARON AND OTHER KUIPER BELT OBJECTS. **S. J. Desch**, **J. C. Cook**, **W. Hawley** and **T. C. Doggett**, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287. (steve.desch@asu.edu).

Kuiper Belt Objects (KBOs) are the coldest objects in the Solar System, and are often considered to be geologically dead [1]. Despite this, many KBOs show clear evidence for crystalline water ice on their surfaces, from absorption of sunlight at 1.65 μm, including Charon [2,3], Quaoar [4], and 2003 EL_{61} [5]. Absorption at 2.21 μm due to ammonia hydrates has also been observed on Charon [2,3] and Quaoar [4]. Cosmic rays, and especially solar ultraviolet radiation, should amorphize crystalline ice on the surfaces of KBOs within $< 10^5$ years [3]; ammonia hydrates should also be destroyed by cosmic rays on $< 10^7$ year timescales [6]. The presence of crystalline water ice and ammonia hydrates on KBOs provide strong evidence for cryovolcanism [4,3]. But how is cryovolcanism, the upwelling of liquid water onto the surface, even possible on KBOs, whose surfaces hover around 50 K? In this abstract we present calculations of the internal thermal evolution of KBOs, and show that liquid water can exist today in objects the size of Charon and larger, and can be brought to the surface.

Before proceeding, the one KBO which has been directly imaged is Triton. *Voyager 2* imaging of Triton (presumably a captured KBO) shows strong evidence for cryovolcanism in its cantaloupe terrain, with dark lobate flows [7] and young ($t < 0.5$ Gyr) uncratered surface [8], despite a surface temperature of less than 40 K. For that matter, the uranian satellites Miranda and Ariel likewise possess terrains younger than $\sim 10^8$ years [9,10] that speak to extensive resurfacing, not to mention the continuing eruption of material from Enceladus, consistent with the presence of liquid water there [11]. It should not be suprising to discover cryovolcanism on KBOs, although it remains to be understood.

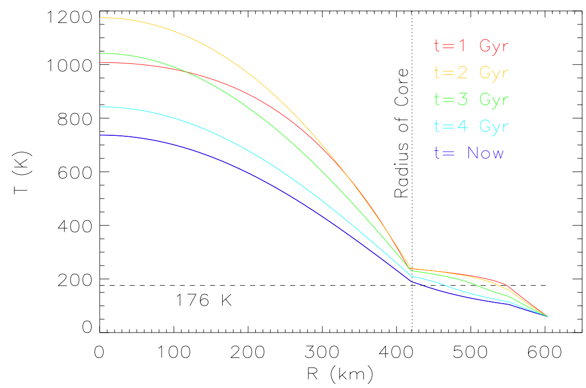
The first requirement for cryovolcanism is that liquid water be maintained at depth. While the surface temperatures of KBOs are typically 40-60 K, radioactive decay (especially of ^{40}K) warms deeper material to temperatures that are sensitive to the thermal conductivity of the surface layers. Models of the temperatures inside KBOs have been developed by [12] assuming steady state and completely differentiated bodies. In these models, radioactive decay in the rocky core of the KBO drives a heat flux through a liquid ammonia-water ocean and an outer shell of water ice. Assuming sufficient NH_3 is driven into the liquid, the liquid layer is held at the water-ammonia eutectic at 176 K. These models predict that liquid water can exist on bodies the size of Titania or larger (i.e., radii $R > 800$ km); notably, on Charon ($R = 604$ km) and Quaoar ($R = 650$ km) no liquid can be maintained at the present-day radiogenic heating rate.

We have improved on these models with new, time-dependent models for the interior temperatures of KBOs such as Charon. We start at $t = -4.5$ Gyr with undifferentiated (rock/ice), cold ($T = 50$ K) bodies, with $NH_3/H_2O \approx 0.10$, heated by an initially strong but monotonically decreasing radioactive decay as per [13]. Energy diffuses through the body according to the 1-D spherical heat conduction equation, with $T = 50$ K an imposed outer boundary condition and $\partial T/\partial r = 0$ at $r = 0$:

$$\rho c_{\rm P}(T)\,\frac{\partial T}{\partial t} = +\rho q(t) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa(T)\frac{\partial T}{\partial r}\right), \quad (1)$$

where ρ is the material density, $c_{\rm P}(T)$ and $\kappa(T)$ are its temperature-dependent effective heat capacity and thermal conductivity, and q is the rate of radiogenic heat release per gram of material. While the material is originally a mixture of rock and ice, we assume the rock and ice have differentiated at a given location if the temperature there has ever exceeded 176 K. This results in a rocky core, a liquid or frozen ammonia and water mantle, and a shell of undifferentiated rock and ice. Latent heats associated with phase changes are incorporated into the effective heat capacity. Standard heat capacities for rock (olivine) and water ice were used. The temperatures we compute in our models are *highly* sensitive to the thermal conductivities of rock which, unfortunately, are not well constrained. We have adopted a constant value $\kappa(T) = 1.5\,{\rm W\,m^{-1}\,K^{-1}}$ for rock, which is appropriate for a partially compacted L chondrite [14]. Where ice and rock are intimately mixed, we add heat capacities linearly, and combine thermal conductivities using the geometric mean. Thermal conductivities in the liquid layer are set so that the heat flux is carried by convection. The results of our calculation for the case of Charon are presented in Figure 1.

In contrast to the conclusions of [12], we find that a subsurface liquid reservoir is possible on



Charon, today. Unfortunately, the extent of such a subsurface ocean, even its existence, are sensitive to the assumed thermal conductivity, depending critically on whether κ is closer to 1.0 or 2.0 W m^{-1} K^{-1}. For our imposed value $\kappa = 1.5$ W m^{-1} K^{-1}, the thickness of the water-ammonia ocean (33% NH_3 by weight) is about 20 km, corresponding to a mass $\approx 4 \times 10^{22}$ g, a little less than 10% of the entire mass of ices on Charon. Charon appears to be within a few $\times 10^8$ years of seeing all of its liquid freeze. Still, Charon was not predicted to retain liquid water at all according to the steady-state models. There are two reasons why time-dependent models are more favorable for the retention of water. First, these models show that KBOs generally do not completely differentiate, leaving an undifferentiated outer layer of mixed rock and ice. The thermal conductivity in this layer is dominated by rock, the value for which is in the range $\kappa = 1$ - 2 W m^{-1} K^{-1}, but certainly lower than the thermal conductivity of ice conductivity (e.g., $\kappa = 3.3$ W m^{-1} K^{-1} assumed by [12] or $\kappa = 5.67$ W m^{-1} K^{-1} for ice at 100 K). This helps keep the heat of radioactive decay in the body. Second, some radioactive heat generated during the first ≈ 2 Gyr of a KBO's evolution is consumed as latent heat of melting as the liquid ocean is created, but is then released as latent heat of freezing thereafter as the ocean refreezes. As $\approx 3 \times 10^{23}$ g of liquid (the amount in Charon at $t = 2$ Gyr) freezes over 3 Gyr, the latent heat of freezing released contributes ≈ 0.2 erg cm^{-2} s^{-1} to the surface flux. This is a non-negligible fraction of the radiogenic heat flux at the present day, which we calculate to be ≈ 1.3 erg cm^{-2} s^{-1}. Combined, these effectively lower the minimum size KBO that can have liquid water today from $R \approx 800$ km [10] to $R \approx 600$ km. Significantly, this includes Charon and Quaoar.

If liquid water exists on Charon and Quaoar, can it resurface? An important consequence of the melting and re-freezing of ice is that as the liquid refreezes it must displace about 7% of its volume (even accounting for the presence of NH_3; [3]). The expansion of the ice is expected to drive extensional stresses and create cracks; if cracks develop as a result of these stresses at the base of the ice layer, with lengths of several km, then these cracks will be self-propagating because the rock/ice layer above the liquid is denser than the liquid itself [15] This positive buoyancy does not exist for bodies like Europa, where the water/ice and rock have completely differentiated, but is a natural consequence of the incomplete melting of KBOs. A self-propagating crack should reach the surface within about an hour, producing a water-ammonia geyser that spills onto the surface and freezes into the crystalline state. Given the total amount of liquid melted on Charon and then refrozen over 3 Gyr, $\approx 3 \times 10^{23}$ g, the volume of displaced water is equivalent to a surface layer about 5 km thick, or about 16 cm per 10^5 years. This is easily compatible with the presence of crystalline water ice.

Our time-dependent thermal models of KBOs show that it is possible for Charon and Quaoar to retain liquid water to the present day; this water may escape to the surface, providing possibly the only explanation for crystalline water ice and ammonia hydrates on the surfaces of those bodies. If Charon is experiencing cryovolcanism we expect to find lobate flows and uncratered areas similar to those seen on Triton. Direct imaging by *New Horizons* in 2015 should provide conclusive evidence for or against cryovolcanism on Charon.

References: [1] McKinnon, WB, 2002, in *Proceedings of Asteroids, Comets, Meteors - ACM 2002.*, 29. [2] Brown, ME & WJ Calvin, 2000, Science, 287, 107. [3] Cook, JC, SJ Desch, T Roush, T Geballe & C Trujillo, 2007, ApJ in revision. [4] Jewitt, A & J Luu, 2004, Nature, 432, 731. [5] Barkume, KM, ME Brown & EL Schaller, 2006, ApJL, 640, L87. [6] Cooper, JF, ER Christain, JD Richardson, C Wang, 2003, Earth, Moon and Planets 92, 261. [7] Croft, SK, 1990, LPSC 21, 246. [8] Strom, RG, SK Croft & JM Boyce, 1990, Science 250, 437. [9] Plescia, JB, 1987, Nature, 327, 201. [10] Plescia, JB, 1988, Icarus, 73, 442. [11] Porco, CC et al., 2006, Science, 311, 1393. [12] Hussmann, H, F Sohl & T Spohn, 2006, Icarus, 185, 258. [13] Lewis, JS, 1997, in *Physics and Chemistry of the Solar System*, 250. [14] Yomogida, K & T Matsui, 1983, JGR, 88, 9513. [15] Crawford, GD & DJ Stevenson, 1988, Icarus, 73, 66.