# Cryovolcanism on Charon and other Kuiper Belt Objects

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**Introduction**: Kuiper Belt Objects (KBOs) are the coldest objects in the solar system, and are often considered to be geologically dead, with no evidence for geological activity on their surfaces [1]. Nevertheless, a large number of KBOs show clear evidence for crystalline water ice on their surfaces, from absorption of sunlight at 1.65 um, including Charon [2,3], Quaoar [4], and 2003 $EL_{61}$ [5]. Absorption at 2.21 um due to ammonia hydrates has also been observed on Charon [2,3] and Quaoar [4]. Since cosmic rays are predicted to amorphize crystalline water ice on geologically short timescales < 1 Myr, and solar UV photons may amorphize it even more rapidly [3], the implication is that the water ice is being annealed or replenished. Cook et al. (2007) [3] calculated the rate at which ice could be annealed on the surfaces of KBOs and concluded that no known process could anneal ice faster than it would be amorphized by cosmic rays, and interpreted the presence of crystalline water ice as requiring replenishment of surface water ice by cryovolcanism. Annealing by heating by micrometeorite impacts was found by [3] to be nearly as fast as amorphization by cosmic rays, however, so if the flux of interplanetary dust particles near KBOs were an order of magnitude higher than measured by *Pioneer 10*, then it is possible that micrometeorite impacts could be the cause of the crystallinity of water ice on KBOs. At this point in time, the evidence in support of cryovolcanism is controversial. At the same time, strong evidence exists to support the possibility of cryovolcanism operating on even small, cold, icy bodies such as KBOs and Charon. *Voyager 2* imaging of Triton shows strong evidence for cryovolcanism in its cantaloupe terrains, with dark lobate flows [6] and young (t < 0.5 Gyr) uncratered surface [7], despite a surface temperature < 40 K. The uranian satellites Miranda and Ariel likewise possess terrains < 100 Myr old [8,9] that speak to extensive, recent resurfacing. None of the above objects is currently experiencing obvious tidal heating, and the mechanism for their recent surface renewal demands explanation.

We have constructed internal thermal evolution models of KBOs to judge whether they could contain subsurface liquid. Here we describe those calculations and present the results of a parameter study aimed at determining the minimum size of body that could retain subsurface liquid to the present day. This subsurface liquid could be brought to the surface via self-propagating cracks as described by [10]. We conclude that cryovolcanism is a viable mechanism for brining subsurface liquid to the surfaces of KBOs as small as about 500 km in radius.

**Model:** We model KBOs as spherically symmetric bodies that are mixes of rock and ice. The rock/ice ratio is found from the mean density using a rock density 3.6 g/cm3, and ice density 0.94 g/cm3. Ice is considered to be a mixture of water ice and ammonia dihydrate; the ratio of NH3 mass to combined mass of NH3 and H2O is denoted X. Thus the ice component is potentially 4 phases: water ice, ammonia dihydrate (ADH), liquid water and liquid ammonia. Standard heat capacities from the literature are assumed and are combined linearly weighted by mass fractions. Latent heats due to phase transitions are treated as effective heat capacities over a limited (5 K) temperature range centered on the temperature of the transition. We assumed a thermal conductivity of water is k(T) = 567/T W/m/K, and a temperature-independent k = 1.2 W/m/K for ADH, based on [11]. These are combined within the ice phases using volume fractions and the geometric mean. Any region containing more than 5% liquid is assumed to be convective, and will support only a very shallow temperature gradient.
We assign such regions the large but finite thermal conductivity k = 40 W/m/K. This typically leads to temperature gradient across a 30 km-thick liquid layer of < 1.5 K. The actual temperature gradient supported by convection would be smaller, consistent with k > 1000 W/m/K, but by retaining the lower value we capture the same physical behavior on a coarser grid without violating the Courant condition. We also allow for the use an effective thermal conductivity to include solid-state convection, but the viscosities on KBOs are so high (due to the cold temperatures) that the Rayleigh number is never found to exceed ~ 100. and convection is never initiated. For the heat capacities and thermal conductivities of rock, we use the values at low temperatures (< 100 K) measured by [12] for ordinary chondrites, which we regard as superior analogs to any terrestrial rocks at room temperature. The thermal conductivity of cold ordinary chondrites is roughly independent of temperature and is ~ 1 W/m/K. Thermal conductivities of combined rock and ice are combined using volume fractions and the formalism of [13].
With these inputs, we solve the standard heat flux equation. Our bodies are assumed to accrete cold. Radioactive heating is assumed to take place only in the rock material, due to decay of 40K, 235U, 238U and 232Th only.

While the KBO 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, since (if X > few percent) this implies a signficant amount of liquid melt. The study of [14] shows that the effective viscosity is reduced in such ices to ~ $10^{11}$ P, allowing Stokes flow of meter-sized rocks across a typical cell size (5 km) in the short time of only 30 kyr. Differentiation results in a rocky core surrounded by a liquid or solid water/ammonia mantle, surrounded by an undifferentiated crust of rock and ice. The surface temperature is maintained at a constant value (e.g., 60 K for Charon).

The results of our calculations for Charon (assuming X = 0.05) are presented in Figures 1 and 2, which show the predicted internal temperatures and distribution of phases. We predict that Charon contains a rocky core (solid line) of radius 330 km, surrounded by a slushy layer about 30 km thick containing a mix of ADH and liquid water and ammonia. Above this layer is a layer of solid water ice (dashed line) from 360 to 470 km, surrounded by an undifferentiated crust of rock, water ice and ADH (dash-dot line), about 130 km thick. Only about half of the mass of Charon ever experiences differentiation. Our thermal evolution models suggest that within a few x $10^8$ yr, the subsurface liquid will freeze entirely. We have repeated these calculations for a variety of KBO mean densities (rock/ice fractions) and radii to find the combination of bodies that could retain liquid water to the present day. The results are shown in Figure 2. We conclude that objects with a densities similar to Pluto and Triton, 2.0 g/cm3, as small as 500 km in radius, could retain liquid to the present day.

Our time-dependent thermal models of KBOs show that it is possible for Charon and Quaoar and many other small KBOs to retain liquid water to the present day. As liquid freezes and increases in volume, self-propagating cracks will be initiated, allowing subsurface liquid to be driven to the surface. Thus cryovolcanism is a viable mechanism for delivering liquid to the surfaces of KBOs such as Charon. Direct imaging by *New Horizons* in 2015 should provide conclusive evidence for or against cryovolcanism on Charon.

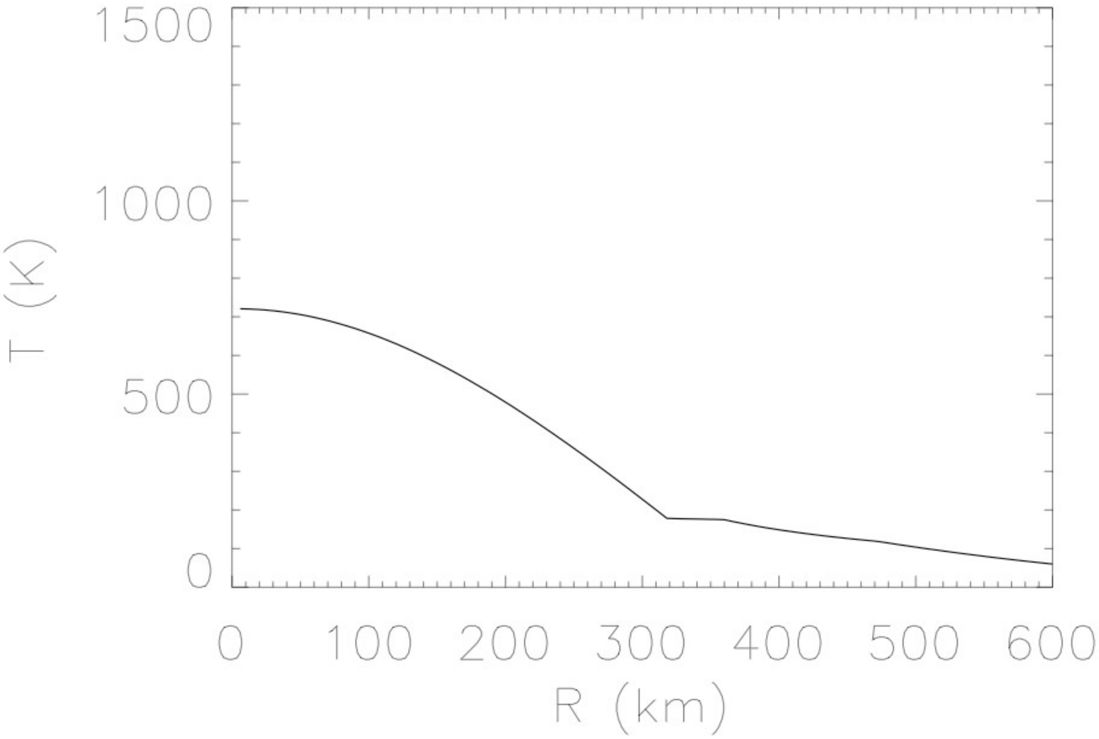

**Figure 1**: Present-day temperature inside Charon.

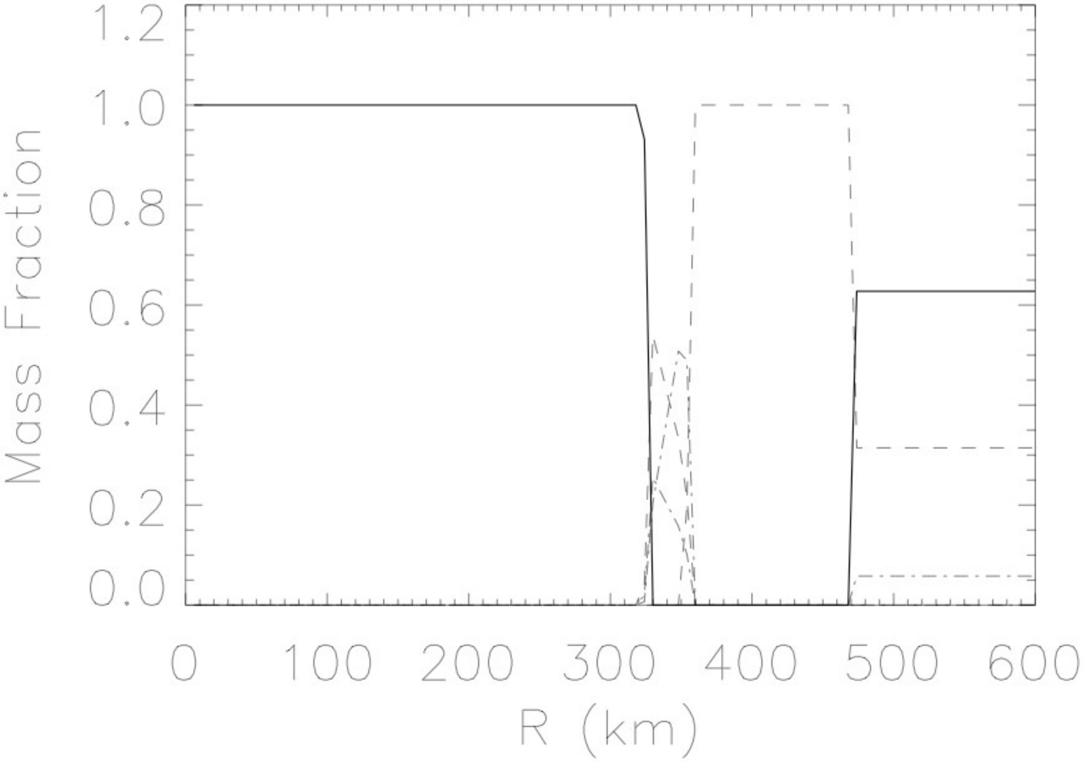

**Figure 2:** Present-day distribution of rock (solid line), water ice (dashed line), ammonia dihydrate (dash-dot line), and liquid phases (other) inside Charon.

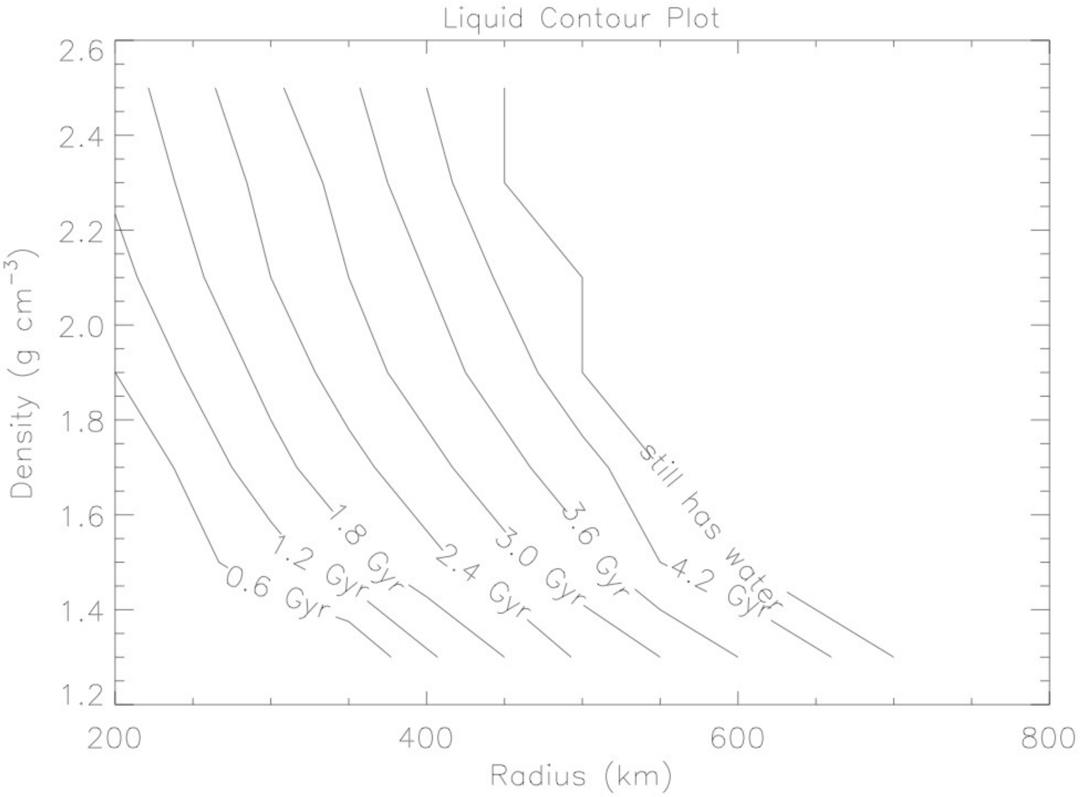

**Figure 3:** Combination of mean density and radius of a KBO to retain subsurface liquid to the present day. For smaller or icier bodies, the times denote the age of the solar system when subsurface liquid last existed.

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