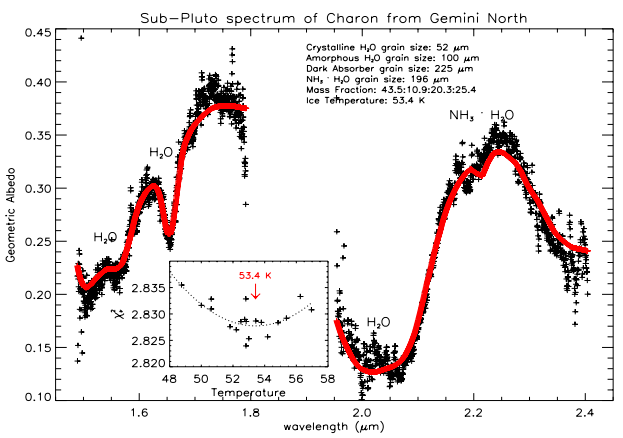
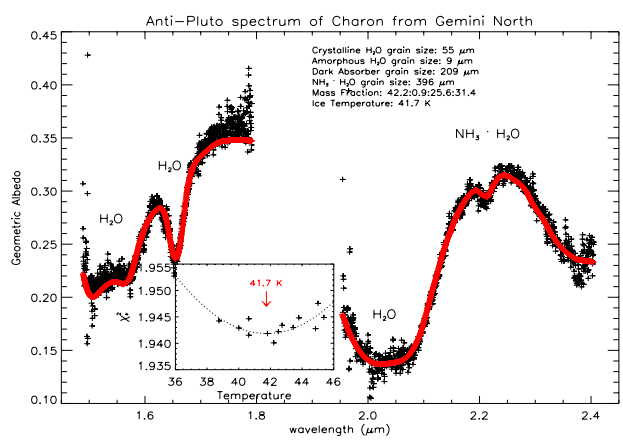
NEAR-INFRARED SPECTRA OF CHARON: SUPPORT FOR CRYOVOLCANISM ON KUIPER BELT OBJECTS?. **J. C. Cook**[1], **S. J. Desch**[1], **T. Roush**[2], **T. R. Geballe**[3] and **C. A. Trujillo**[3] [1] Dept. Physics and Astronomy, Arizona State University, Tempe, AZ 85287 [2] NASA Ames Research Center MS 245-3, Moffett Field CA, 94035 [3] Gemini Observatory, 670 North A'ohoku Place, Hilo HI 96720 (jason.cook3@asu.edu) .

We present near-infrared (NIR) reflectance absorption spectra of Charon (Figure 1) which show unambiguously the presence of crystalline water and ammonia hydrate. The presence of these components suggests geological activity. The presence of ammonia hydrate enables cryovolcanism by lowering the melting point of water. We propose a model for present-day cryovolcanism on Charon and discuss consistencies with our observations. Most icy moons and Kuiper Belt Objects at least as large as Charon may be geologically active.

Observations





We obtained $1.5 - 2.4\,\mu$m reflectance spectra of Charon's hemispheres facing Pluto ("sub-Pluto"; Figure 1a) and facing away from Pluto ("anti-Pluto"; Figure 1b) using the NIRI camera and the Altair adaptive optics (AO) system at the Gemini North observatory on Mauna Kea, on four nights when Charon was at minimum separation from Pluto, ≈ 0.44". This separation is at the limit of non-AO seeing but using AO we resolved the pair, significantly reducing the contamination from Pluto in Charon's spectrum from $\sim 10\%$ of Charon's flux in [1] to $\ll 1\%$. The spectra are of significantly higher resolution ($R \sim 650 - 800$) than previous studies (e.g., $R \sim 200$ of [2]). The quality of these data have allowed us to constrain the composition and (crystalline water ice) temperature of Charon's surface.

We fit the spectra using a Hapke model including amorphous H_2O ice I_a, crystalline H_2O ice I_h, "ammonia-water" ice (H_2O plus 3% $NH_3 \cdot H_2O$), and a neutral "dark absorber". A single temperature is assumed for all components, which will affect the shape of the crystalline water ice features, especially the $1.65\,\mu$m feature [3], as well as the amorphous ice features. For the sub-Pluto hemisphere, our optimal fit assigns the following mass fractions and grain sizes to the components: 43.5% H_2O I_h crystalline ice ($52\,\mu$m), 10.9% amorphous H_2O I_a ice ($100\,\mu$m), 20.3% dark absorber ($225\,\mu$m), 25.4% $NH_3 \cdot H_2O$ ($196\,\mu$m), and a best-fit temperature 53.3 K. For the anti-Pluto hemisphere, our optimal fit assigns the following mass fractions and grain sizes to the components: 42.2% H_2O I_h crystalline ice ($55\,\mu$m), 0.9% amorphous H_2O I_a ice ($9\,\mu$m), 25.6% dark absorber ($209\,\mu$m), 31.4% $NH_3 \cdot H_2O$ ($396\,\mu$m), and a best-fit temperature 41.7 K. Based on variations in χ^2_ν, we estimate the uncertainties in T to be about 1.5 K, but note that an admixture of amorphous and crystalline ices at a single temperature may spectroscopically resemble a more cyrstalline ice at higher temperature [5]. Our inferred mass fractions resemble those of [1]. The high abundance of crystalline water ice on Charon has been noted by [4,5,1]. Like [5], we also find no evidence for N_2, CO or CH_4 on Charon, ices detected on Pluto [6]. We also exclude significant quantities of pure NH_3, but find evidence for substantial quantities ($> 1\%$) ammonia hydrate based on the depth of the $2.2\,\mu$m absorption.

We find hemispheric dichotomies in the compositions, and in the temperatures of the (crystalline)

ice. Visual-wavelength maps of Charon [7] show it is mostly dark except for a large, bright (albedo ~ 0.9) polar cap mostly on the anti-Pluto side, and a larger bright (albedo ~ 0.75) patch on the equator on the sub-Pluto side. We presume these bright patches are water ice overlaying darker material, which is consistent with our observation of more dark absorber on the anti-Pluto hemisphere. The 2.21 μm feature on the anti-Pluto hemisphere is well fit by ammonia monohydrate, but the feature is shifted blueward to 2.18 μm on the sub-Pluto side. As the NH_3:H_2O ratio is decreased in an ammonia hydrate, the peak absorption is shifted blueward (M. Moore, personal communication), so we conclude that ammonia is relatively depleted on the sub-Pluto hemisphere. Crystalline water ice observed on the sub-Pluto hemisphere is at higher temperature (53 K) than the anti-Pluto side (41 K). These temperatures are qualitatively explained if the temperatures reflect local conditions in thermally isolated patches of ice, in which case we predict $T = 70.85\,(1-a)^{1/4}\,(\cos\theta)^{1/4}$ K, where a is the albedo at visual wavelengths and θ is the local angle between the Sun and the zenith. The sub-observer latitude on Charon is currently $-33°$, so the equatorial patch of ice on the sub-Pluto side has $a \approx 0.75$, $\theta \approx 30°$ and $T = 48$ K. The south polar ice cap at latitudes $\approx -70°$ likewise has $a \approx 0.9$, $\theta \approx 40°$, and $T = 37$ K. These are reasonably close to the observed temperatures, so we conclude that crystalline ice is warmer on the sub-Pluto side because it most of it lies at the equator, while on the anti-Pluto side it is at the south pole.

Geologic Activity?

The presence of crystalline water on Charon's surface has been cited before as evidence of geological activity, since it should be amorphized by solar UV radiation on geologically short timescales [1]. In light of its small size ($R_c = 605$ km [8]), and because Charon experiences no tidal dissipation, geological activity has remained speculative [9]. Here we discuss conditions under which cryovolcanism is actually likely. Assuming Charon is made of ice plus serpentine, we calculate a rock mass fraction of 0.71, with an ice shell 127 km thick. If ^{40}K in the rock is present at solar abundances [10], its radioactive decay should drive a heat flux through the ice shell $F \sim 1.5\,(R_c/r)^2\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The temperature therefore should increase with depth with a gradient $dT/dr = -F/\kappa$, where $\kappa(T)$ is the temperature-dependent thermal conductivity in the ice. It is straightforward to integrate for T from the surface temperature $\equiv 50$ K, once κ is specified. The commonly adopted $\kappa = 567\,\mathrm{W\,m^{-1}}/T$ (which yields $T = 79$ K at the base of the ice shell) is only appropriate for pure crystalline I_h ice. The thermal conductivity of ice is reduced significantly, to $\kappa \sim 1\,\mathrm{W\,m^{-1}\,K^{-1}}$, if the ice contains $\sim 10-20\%$ NH_3 [11], or is amorphous [12]. Using the thermal conductivity for amorphous ice, we find temperatures exceed the ≈ 175 K melting point for an ammonia-water eutectic in the lowermost ≈ 25 km of the ice shell, suggesting a cryomagma may exist at depth. Above this layer, amorphous ice is expected to transform incompletely, and reversibly, to cubic ice I_c above the glass temperature ≈ 129 K, and to behave as a viscous liquid [13]. The material strength of water would be weakened further by the addition of 10-20% NH_3 [11], also aiding cryovolcanism. Amorphous ice on Charon is not expected to crystallize: it is kinetically inhibited over the age of the Solar System below about 100 K [13], and the presence of $\sim 2\%$ impurities like NH_3 renders crystallization endothermic [14]. The significant abundance of ammonia hydrates we have observed on Charon render it likely that Charon experiences cryovolcanism, if its ice is amorphous.

If Charon experiences cryovolcanism, we expect liquid water-ammonia cryomagma at $T > 175$ K to periodically spill over its surface. As the liquid cools, NH_3 is preferentially lost from the melt, especially when the spill is over Charon's warmer equatorial regions. Because of the high temperature of the melt, it should crystallize directly to the I_h state. Our observations are therefore consistent with the idea that the crystalline ice observed on Charon's surface are equivalent to lunar maria. The presence of crystalline ice on the surfaces of other Kuiper Belt Objects, e.g., Quaoar [15], may be due to cryovolcanism as well if they also contain ^{40}K and NH_3.

References: [1] Brown ME & Calvin WJ 2000 Science 287, 107 [2] Dumas C et al 2001 AJ 121, 1163 [3] Grundy WM & Schmitt B 1998 JGR 103, 25809 [4] Dumas C et al 1999 [5] Buie MW & Grundy WM 2000 Icarus 148, 324 [6] Grundy WM & Buie MW 2001 Icarus 153, 248 [7] Buie MW, Tholen DJ & Horne K 1992 Icarus 97, 211 [8] Sicardy B et al 2006 Nature 439, 52 [9] Rainey ES & Stevenson DJ 2003 AGUFM P51B-0447 [10] Lodders K 2003 ApJ 591, 1220 [11] Lorenz RD & Shandera SE 2001 Geophys Res Lett 28, 215 [12] Andersson O & Suga H 2002 PhysRevB 65, 140201 [13] Jenniskens P & Blake DF 1996 ApJ 473, 1104 [14] Kouchi A & Sirono S 2001 GeophysResLett 28, 827 [15] Jewitt DC & Luu J 2004 Nature 432, 731