NEAR-INFRARED SPECTRA OF KUIPER BELT OBJECTS: MORE THAN JUST WATER ICE.

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Introduction: Remote sensing via near-infrared (NIR) spectroscopy is the only method available to examine the surface composition of Kuiper Belt Objects (KBOs). Crystalline water ice, which requires $T > 100$ K for formation, has been observed on several KBOs including Charon. In addition to water ice, ammonia hydrates have also been seen on Charon [1], and possibly Quaoar [2]. Both ices have relatively short lifetimes (few Myrs, 1) when exposed on the surface [1] and requires a mechanism like cryovolcanism [1-3].

Observations: Understanding whether or not cryovolcanism occurs on Charon and KBOs requires obtaining NIR spectra of KBOs, preferably similar in size to Charon ($r \approx 606 \pm 8$ km; 4). [2] obtained spectra of (50000) Quaoar ($r \approx 630 \pm 90$ km; 5) from 0.9 to 2.5 μm using the CISCO spectrograph on Subaru. The spectrum shows a red slope of $27 \pm 1\%/1000$ Å, and features due to crystalline water ice at 1.5, 1.65 and 2.0 μm. [2] also suggested the presence of a feature at 2.21 μm, like that seen on Charon. Unpublished K-band observations found in the Subaru archive from 2005 show this feature is present and it shifts from night to night suggesting ammonia hydrate is found in several hydration states. Fig. 1 shows the average observations from 2004 and 2005. The data are rebinned to 60 Å/pix, and shown with 3σ error bars.

Spectra from 1 to 2.5 μm of (90482) Orcus ($r \approx 473 \pm 36$ km; 6) were originally obtained by [7] using the ISAAC instrument on the VLT. The spectrum has a neutral to blue slope similar to Charon. [7] reported the presence of the 1.5 and 2.0 μm features of water ice, but lacked the signal to positively identify the 1.65 and 2.21 μm feature. Additional Orcus data from 2005 were found in the Gemini North archives using the NIRI spectrograph. These observations showed large features near 1.23 and 2.23 μm, the later suggests pure NH_3. These data were observed on only one occasion and appear weak when averaged with the 2004 data. If these features are real, they suggest Orcus has a patchy surface. The data from both runs are combined in Fig. 2 at 60 Å/pix resolution with 3σ error bars.

Finally, spectra of (55636) 2002 TX_{300} were obtained using the Gemini North NIRI spectrograph in August 2003. While the signal-to-noise of this data is quite low, it is an improvement in signal over what was originally reported by [8]. Like Orcus, the NIR slope of 2002 TX_{300} is neutral-to-blue [9]. These spectra show deep water ice features, and strongly suggest crystalline ice is present. A depression in the spectrum around 2.25 μm suggests ammonia may also be present here too, but higher quality data are clearly needed to make a definitive detection. The observations of 2002 TX_{300} are shown in Fig. 3 at a resolution of 60 Å/pix resolution with 3σ error bars.

Hapke Models: Hapke models were developed for each KBO. The spectral components were broken into three groups of materials: ices, blue and red absorbers. The ices examined included amorphous and crystalline water ice [10,11,12], NH_3 [13] and its hydrate [14], CO_2 [15,16], and CH_3OH [17]. The blue materials included the Charon dark neutral absorber (*dna*, 18), the phyllosilicates: montmorillonite [19], kaolinite [20], and serpentine [21], and the salt, mirabilite [22,23]. The Charon *dna* was originally developed by [18] to improve fits to Charon's spectrum. *Dna* likely represents a composite of several materials which is slightly red at $\lambda < 1.9$ μm, and blue elsewhere. The phyllosilicates and salt all have different blue slopes, and all except mirabilite lack any identifiable features other than those at 1.4 and 1.9 μm due to the presence of water in these minerals. The red materials include amorphous carbon [24], the silicate olivine [25], and Triton, Titan and Ice I tholins [26-28].

Initial models of Quaoar mix water ice, one blue and one red material. These models minimize χ^2 for a mixture of water ice, Triton tholin and *dna*. This model is shown as the blue curve in Fig. 1. Additional models were then developed substituting *dna* for other red and blue components until a similar, if not smaller, χ^2 was found. A mixture of water ice, Triton and Titan tholins, kaolinite, and ammonia hydrate best matched the spectrum of Quaoar (red curve in Fig. 1). The various other ices had little, if any, effect. Similar procedures were followed for Orcus and 2002 TX_{300}. The Orcus model use mixture of water ice, Triton tholin, montmorillonite, and ammonia hydrate, and the 2002 TX_{300} model uses a mixture of amorphous and crystalline water ice, montmorillonite and mirabilite.

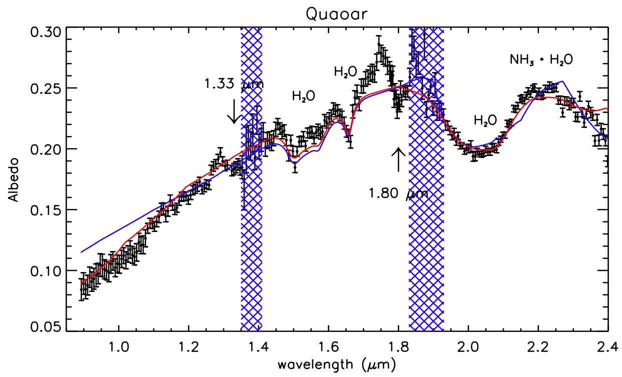

Fig. 1 NIR spectrum of Quaoar.

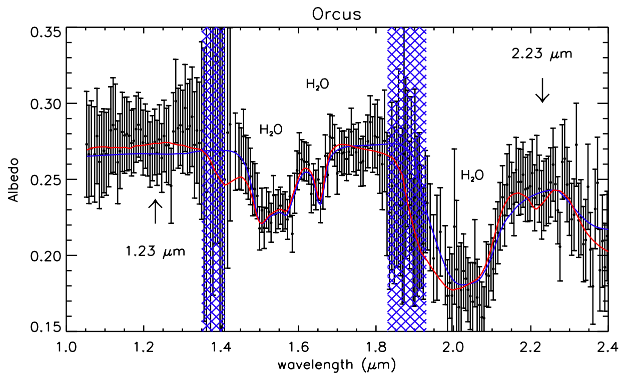

Fig. 2 NIR spectrum of Orcus.

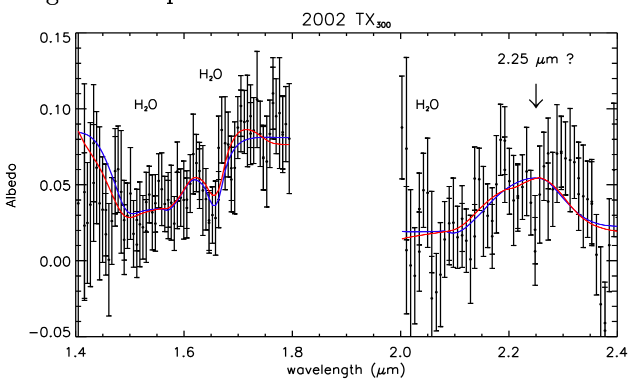

Fig. 3 NIR spectrum of 2002 TX_{300}.

Discussion: Absent from the fits are the features seen at 1.80 and 1.33 μm on Quaoar and 2.23 and 1.23 μm on Orcus. The 1.23 and 1.33 μm features are near H_2O features, but do not make a match. The feature at 1.80 μm on Quaoar appears close to the edge of an optical window, but maintains a signal representative of most of the data. The feature also does not appear to be an artifact of removing the telluric and solar spectra and it is present in two grating positions. [2] likely did not report it because they lacked the additional 2005 data. The asymmetric shape of this feature resembles montmorillonite and mirabilite features, however shifted blueward 0.1 μm and redward 0.03 μm, respectively. [29] measured the effects of temperature on several salts and showed the 1.77 μm feature of mirabilite shifts to shorter wavelengths at colder temperatures, opposite from what is needed. However, a similar feature in $MgSO_4 \cdot 12H_2O$ shifts to 1.79 at 50 K but the observations do not match other features of this salt. If true, KBOs might not only have water ice and ammonia hydrate on the surface, but phyllosilicates and/or salts. Such materials can only be formed in the presence of liquid water, and strongly suggest cryovolcanism is a likely resurfacing mechanism.

References: [1] Cook, JC et al., 2007, ApJ, in press. [2] Jewitt, D & Luu, J, 2004, Nature, **432**, 731. [3] Desch, SJ et al., LPSC, **#38**, 1901. [4] Gulbis, AAS et al., 2006, Nature, **439**, 7072. [5] Brown, ME, Trujillo, CA., 2004, AJ, **127**, 2413. [6] Stansberry, J. et al., 2007, in *Kuiper Belt Objects*, in press. [7] de Bergh, C et al., 2005, A&A, **437**, 1115. [8] Licandro, J et al., 2006, A&A, **457**, 329. [9] Grundy, WM et al., 2005, Icarus, **176**, 184. [10] Schmitt, B, et al., 1998, Optical Properties of Ices from UV to Infrared, in *Solar System Ices*, p. 199. [11] Roush, TL, 1997, Lunar and Planetary Science Conference, **28**, 199. [12] Grundy, WM & Schmitt, B, 1998, J. Geophys. Res., **103**, 25809. [13] Martonchik, JV et al., 1984, Applied Optics, **23**, 541. [14] Brown, RH et al., 1988, Icarus, **74**, 262. [15] Hansen, G, 1997, Adv. in Space Research, **20**, 1613. [16] Hansen, G, 1997, JGR, **102**, 21569. [17] Cruikshank, DP et al., 2005, Icarus, **175**, 268. [18] Buie, MW & Grundy, WM, 2000, Icarus, **148**, 324. [19] Roush, TL, 2005, Icarus, **179**, 259. [20] Egan, WG & Hilgeman, TW, 1979, Optical Properties of Inhomogeneous Materials: Applications to Geology, Astronomy, Chemistry, and Engineering, p. 105. [21] Bauer, JM et al., 2002, Icarus **158**, 178. [22] Crowley, JK, 1991, Journal of Geophys. Res., **96**, Issue B10, 16231. [23] Clark, RN et al., 2003, USGS Digital Spectral Library splib05a, U.S. Geological Survey, Open File Report 03-395. [24] Rouleau, F, & Martin, PG, 1991, ApJ., **377**, 526. [25] Fabian, D et al., 2001, A&A, **378**, 228. [26] Khare, BN et al., 1984, Icarus, **60**, 127. [27] Khare, BN et al., 1993, Icarus, **103**, 290. [28] Khare, BN et al., 1994, Bull. Am. Astron. Soc., **26**, 1176. [29] Dalton, JB et al., 2005, Icarus, **177**, 472.