Examination of the K-band Spectrum of Charon: Possible Evidence for Multiple Ammonia Ices.

J. C. Cook[1], **C. B. Olkin**[1], **S. J. Desch**[2], **R. M. Mastrapa**[3], **T. L. Roush**[3], **A. J. Verbiscer**[4] [1]Southwest Research Institute, Boulder, CO, 80301 (jccook@boulder.swri.edu), [2]Arizona State University, Tempe, AZ, 85287, [3]NASA Ames, Moffett Field, CA 94035, [4]University of Virginia, P.O. Box 400325, Charlottesville, VA 22904

Introduction: Remote sensing via near-infrared (NIR) spectroscopy is the only method available to examine the surface composition of Kuiper Belt Objects (KBOs). NIR spectra of Charon, and possibly several other KBOs, have led to the detection of a feature near 2.21 μm, commonly identified as ammonia hydrate [1–5]. This is somewhat surprising since ammonia ice, which was predicted to be present on icy bodies in the outer solar system, has not been detected. NH_2, the photodisassociated product of NH_3, is seen in the comae of comets, of which 95% is expected to have originated as NH_3 [6]. Based on comets originating from the Kuiper belt and Oort cloud, the NH_3/H_2O is around 0.5% [7]. Alternatively, infrared observations of protostars [8, 9], the rheology of icy satellites [10], the nitrogen isotopes of Titan's atmosphere [11] all suggest initial ratios ∼5-20% which agree well with chemical equilibrium models [12–14]. So the question is: "Where is the ammonia on icy bodies?" Can ammonia take on other forms, such as ammonium (NH_4^+)? We present new observations from 2008 combined with previous observations from 2005 of Charon in K-band (1.9-2.4 μm) to reach a resolution.

Observations & Data Reduction: We obtained NIR spectra of Charon using NIRI and Altair, the adaptive optics instrument, on the 8-m Gemini North telescope on Mauna Kea. The observations were made over several nights in May and June 2008 when the observed longitude was 300°. The goals of the observations were to determine whether or not αN_2 ice or hydrocarbon ices were present on Charon, as had been suggested by Verbiscer et al. [15] in previous observations at a similar longitude. The slit width and position of Pluto and Charon was identical to the data collected in 2005 [see 16, for details]. Their position in the slit was dithered in an $ABBA$ pattern. The total integration time was 120 minutes (2008 only), of which about 75% were done under good conditions. During these observations, Charon was 0.8″ from Pluto and their spectra were not blended.

The spectra were extracted from the 2D images using programs written in IDL following the method of optical extraction [17]. We deviated from this method slightly for the removal of the sky lines using a double subtraction method rather than modeling the sky lines. AB image pairs were first subtracted to remove the sky lines. The five minute individual exposures generally left residual sky lines. We removed the residual sky lines by subtracting the $B-A$ image from the $A-B$ image after aligning the positive spectra of each image. Careful consideration was given to the wavelength calibration before the second step. The sky lines were used to map the distortion seen in the wavelength direction, which was measured up to 40 Å or 9 pix. The IDL bilinear interpolation program was used to make the reconstructed $B-A$ image with a distortion pattern corresponding to the $A-B$ image. This assured proper removal of sky lines and consistent wavelength calibration. This method was applied to the 2005 data for the first time, producing slightly different results than published previously. The spectrum presented in Fig. 1 is a combination of all the observations. We will present at the meeting this spectrum along side the longitudinally resolved spectra and our comparative analysis.

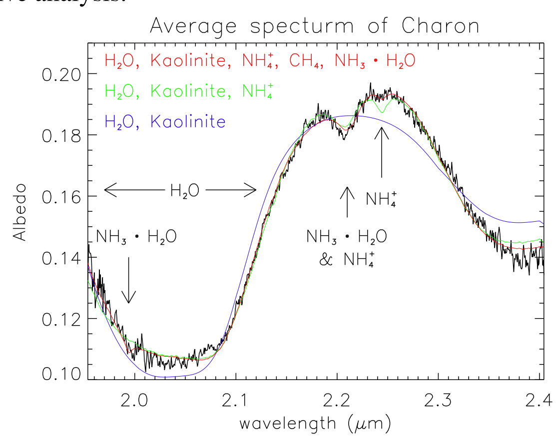

Figure 1: Fig. 1 Average K-band spectrum of Charon and model fits.

Hapke Models: Since the publication of Cook et al. [16], new lab spectra of ammonia, its hydrates and irradiated remnants have become available [18]. These spectra cover a range in temperature between 10 K and 150 K which includes the amorphous to crystalline transition of pure NH_3, mixtures of H_2O/NH_3 between 0 and 57 which includes ammonia mono- and hemihydrate ices, and irradiated samples up to 7 eV molec^{-1} which produces features attributable to ammonium (NH_4^+) ice. They showed that as the fraction of H_2O increases at a given temperature, the 2.00 and 2.24 μm features of pure NH_3 ices migrate to shorter wavelengths, approaching 1.99 and 2.21 μm respectively. We use their relative absorbance spectra to derive optical constants (n and k) for the ices. These optical constants are used in modeling the spectrum of Charon.

As has been previously reported [2], the addition of a nearly neutral material is needed to improve the Hapke model fits to Charon. Cook et al. [16] had used the optical constants for an unknown dark neutral absorber (dna) from Buie & Grundy [2]. In this analysis, we examine models which include either dna or the phyllosilicates serpentine [19] and kaolinite [20]. All the absorbers examined have blue spectral slopes in this wavelength range, lack identifiable features and differ largely in albedo. The results show a preference for kaolinite. Observations of Charon at longer wavelengths are needed to determine if kaolinite is the best match.

Besides the materials discussed above, we also include crystalline water ice at 50 K [21] and searched for HCN, CH_4, C_2H_4, C_2H_6, CH_3OH, N_2 (α and β phases), CO_2 and CO [22–27]. Except for H_2O and CH_4, all these ices are searched for in the final step because they would have weak features, and can be ignored until the end.

Discussion: Here we will discuss how we determined the best model and the significance of that model. We first model the spectrum as a mix of H_2O ice, one neutral absorber and either NH_4^+ or CH_4 ice and determine which model minimizes the goodness of fit parameter, χ^2_ν. We use these two ices because they have features near 2.21 μm. Of these six models, there is a clear preference for a mix of H_2O, kaolinite and NH_4^+. This model gives χ^2_ν=4.4 and matches the feature at 2.21 μm and the possible secondary feature near 2.24 μm (see green curve in Fig. 1). All models which included CH_4 had larger χ^2_ν values than the NH_4^+ counterpart, and produced little or no absorption near 2.21 μm. We then add one of six other ices: pure NH_3 ice (crystalline, amorphous and transitional phases), $NH_3{\cdot}H_2O$, $2NH_3{\cdot}H_2O$, or CH_4 and found that CH_4 best reduced χ^2_ν to 3.5 but still did not significantly modify the fit near 2.20 μm. Rather most of the improvements were made at wavelengths longward of 2.3 μm (see the red curve in Fig. 1). We followed the same procedure with the five remaining ices and found the addition of $NH_3{\cdot}H_2O$ reduces χ^2_ν to 2.9 and mainly produces a feature near 1.99 μm. Our best fit model is a mix of H_2O, kaolinite, NH_4^+, CH_4 and $NH_3{\cdot}H_2O$ with mass fractions 7.0%, 7.3%, 0.7%, 83.5% and 1.5% and grain diameters 0.15, 0.25, 0.09, 8.7 and 0.07 mm, respectively. None of the additional ices produced a significantly better fit (reducing $\chi^2_\nu > 10\%$).

Methane is included because it has a feature near 2.20 μm, which is similar to the feature seen on Charon. However, the modeled CH_4 grain size is extremely large (diameter$\sim$10 mm), which effectively makes CH_4 a dark absorber lacking the common CH_4 features at 2.20, 2.32 and 2.38 μm. We interpret the significance of this fit to mean that there may be a layer of hydrocarbons on Charon's surface, perhaps heavier than C_2H_6. We plan to explore this possibility further by using hydrocarbons like those examined by Clark et al. [28].

This is the first time NH_4^+ has been suggested on the surface of Charon. Ammonium may be formed from NH_3 under two conditions: irradiation [18] or by acid-base reactions [18, 29]. While we assume irradiation is the likely formation mechanism, there is no evidence to rule out acid-base reaction, particularly if Charon is cryovolcanically active [16]. In the very least, these observations reveal Charon may have a much more diverse surface than previously thought. These observations of Charon also suggest that NH_3 may be present elsewhere in the solar system, but in forms such as NH_4^+, ammonia hydrates or maybe ammonia enriched silicates like buddingtonite or tobelite.

References

[1] Brown, M. E., Calvin, W. M., 2000, Science, **287**, 107
[2] Buie, M. W., Grundy, W. M., 2000, Icarus, **148**, 324.
[3] Dumas, C. et al., 2001, AJ., **121**, 1163
[4] Jewitt, D. C., Luu, J., 2004, Nature, **432**, 731.
[5] Barucci, M. A. et al., 2008, A&A, **479**, 13.
[6] Feldman, P. D et al., 2004, in *Comets II*, 425.
[7] Kawakita, H., Watanabe, J-I., 2002, ApJ, **572**, L177.
[8] Taban, I. M. et al., 2003, A&A, **399**, 169.
[9] Dartois, E. et al., 2002, A&A, **394**, 1057.
[10] Fortes, A. D., 2004, PhD Thesis, Univ. of London.
[11] Hunten, D. M. et al., 1984, in *Saturn*, 671.
[12] Lodders, K., 2003, ApJ, **591**, 1220.
[13] de Pater, I, Lissauer, J. J, 2001, in *Planetary Sciences*.
[14] Lewis, J. S., 1997, in *Physics and Chemistry of the Solar System*, 249.
[15] Verbiscer, A. J. et al., 2007, LPI Contribution #1357, 144.
[16] Cook, J. C. et al., 2007, ApJ, **663**, 1406.
[17] Horne, K., 1986, PASP, **98**, 609.
[18] Moore, M. H. et al., 2007, Icarus, **190**, 260.
[19] Bauer, J. et al., 2003, Icarus, **158**, 178.
[20] Egan, W. G., Hilgeman, T. W., 1979, Optical Properties of Inhomogeneous Materials: Applications to Geology, Astronomy, Chemistry, and Engineering, Academic Press, New York, 235 pp., p. 105
[21] Grundy, W. M., Schmitt, B., 1998, JGR, **103**, 25809.
[22] Khare, B. N. et al. 1994, DPS Meeting #26, 1176.
[23] Grundy, W. M. et al., 2001, Icarus, **155**, 486.
[24] Quirico, E., Schmitt, B., 1997, Icarus, **127**, 354.
[25] Cruikshank. D. P. et al., 2005, Icarus, **175**, 268.
[26] Grundy, W. M. et al., 1993, Icarus, **105**, 254.
[27] Hansen, G., 1997, Adv. in Space Research, **20**, 1613.
[28] Clark, R. N. et al., 2009, JGR, in press.
[29] Moore, M. H., et al., 2003, Icarus, **161**, 486.