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WATER ICE ON KUIPER BELT OBJECT 1996 TO$_{66}$

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ABSTRACT

The 1.40–2.45 μm spectrum of Kuiper Belt object 1996 TO$_{66}$ was measured at the Keck Observatory in 1998 September. Its spectrum shows the strong absorptions near 1.5 and 2.0 μm that are characteristic of water ice—the first such detection on a Kuiper Belt object. The depth of the absorption bands and the continuum reflectance of 1996 TO$_{66}$ suggest the presence of a black- to slightly blue-colored, spectrally featureless particulate material as a minority component mixed with the water ice. In addition, there is evidence that the intensity of the water bands in the spectrum of 1996 TO$_{66}$ varies with rotational phase, suggesting a "patchy" surface.

Subject heading: minor planets, asteroids

1. INTRODUCTION

It is becoming increasingly clear that the remnant population of objects just beyond the orbit of Neptune is indeed representative of the small bodies (planetesimals) from which the planets accreted (Kuiper 1951; Edgeworth 1949). Kuiper Belt objects (KBOs), as they are sometimes called, are mostly beyond the range of planetary perturbations and too tightly bound to the Sun to be perturbed by passing stars (Kuiper 1951; Edgeworth 1949). Thus, KBOs are thought to be primitive remnants of the early solar system (Kuiper 1951; Edgeworth 1949) and may have unique surface compositional characteristics.

Studies of the physical properties and surface compositions of bodies in the outer solar system can give important clues to conditions existing in the early solar system. At the great heliocentric distances of the outer solar system, materials there are expected to be less modified by solar heating than materials in the region of the terrestrial planets. Thus, small bodies in the outer solar system are thought to preserve a more accurate record of the chemical and physical properties of the original material from which the solar system formed. Because our understanding of early solar system chemistry depends on our knowledge of the small bodies in the outer solar system, an important suite of bodies to study are the KBOs.

2. OBSERVATIONS

We report here on the near-infrared spectroscopy of the Kuiper Belt object 1996 TO$_{66}$ and discuss its implications. The data were obtained at the W. M. Keck Observatory in 1998 September 27 and 28 (Universal Time) using the Near Infrared Camera (NIRC). The measurements were made using the gr120 grism of the NIRC, which has an approximate wavelength range in first order of 1.35–2.55 μm and a spectral sampling interval of 0.00607 μm pixel^{-1}. The NIRC has an effective pixel size of 0″.15, and a slit width of 8.5 pixels (~1″.3) was used for all the spectral observations. An unresolved object defines the effective slit for spectroscopy when the physical slit used is larger than the seeing disk. For the circumstances of the observations reported here, the average seeing disk (about 3.5 pixels) was roughly the size of the fundamental resolution element of the spectrometer (about 2.5 pixels). A 1″.3 slit was chosen so as to facilitate checks of the alignment of the object's image within the slit without having to move the slit out of the optical train. This procedure resulted in an increase in observing efficiency over that which would have resulted if the NIRC were reconfigured each time the alignment of the image was checked. In addition, the use of a 1″.3 slit also ensured that no light was lost when the seeing disk of the object momentarily became larger than the physical slit (as is sometimes the case during a typical night at Mauna Kea Observatory). After each integration, the position of the object's image was checked through the broadband K_s filter (without the grism in the optical train), and if necessary, the object's image was recentered to its original position in the slit (which was fixed relative to the detector array). Because KBOs move so slowly, and because the Keck telescope tracks nonsidereal objects very well, after an integration the object's image was never more than ± 1 pixel from its original position. In addition, whenever an appropriate guide star was available, the spectrometer slit was aligned east-west so as to minimize drift of the object's image perpendicular to the slit. For our comparison asteroid, the exposure time was so short that there was no measurable drift of the object's image within the slit. Possible artifacts due to flat-field variations in the detector were eliminated by using the same two positions within the slit for all observations and applying flat-field frames obtained by imaging a specially illuminated section of the inside of the Keck dome. Atmospheric seeing on the night in question was about 0″.5 (FWHM) at 2.2 μm.

The KBO 1996 TO$_{66}$ was identified in images taken through the NIRC's K_s filter,[5] both by its motion as well as by its predicted position on the sky. Spectra were collected by centering the image of the object in the grism slit and obtaining pairs of images of 1200 s total exposure (15 separate exposures of 80 s co-added), with each exposure offset along the grism slit by 12″. A first-order subtraction of the sky background was accomplished by subtracting corresponding image pairs. Our spectra of 1996 TO$_{66}$ encompass 4800 s of integration on each of two nights.

Correction for telluric extinction and the solar color was

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[5] K_s is a filter whose passband encompasses the short-wavelength half of the standard K band and is centered at approximately 2.12 μm.

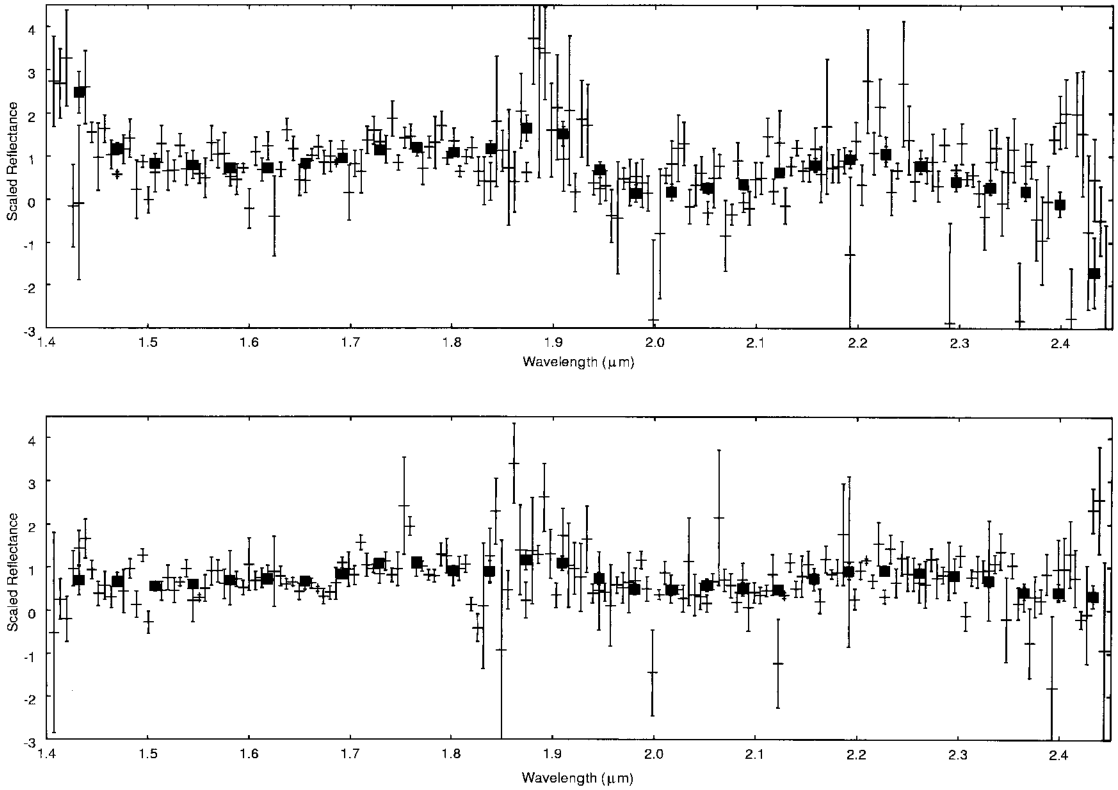

FIG. 1.—Spectra of 1996 TO_{66}. Both the original full-resolution data and the data convolved to lower resolution to improve the S/N are shown (see text). The data in the top panel are from 1998 September 27, and the data in the bottom panel are from 1998 September 28 (see text). The error bars were estimated from the repeatability of the measurements and propagated through the discrete convolution.

accomplished by using spectra of the C-type asteroid 329 Svea obtained on the same night and over the same air-mass range (1.03–1.13); 329 Svea was chosen because it has a flat spectrum with no spectral features over the wavelength range of the observations presented here (Tholen 1989; Bell et al. 1988). Flat-fielding of the images was accomplished by imaging a specially illuminated section of the inside of the Keck dome. Wavelength calibration was accomplished by using telluric absorption features in the raw spectra.

3. DISCUSSION

The resultant spectra are shown in Figure 1, both the original data and the same data convolved to lower resolution to enhance the signal-to-noise ratio (S/N). The convolution to lower resolution was done as a pure, discrete convolution. The purpose is to model how the data would look if obtained at intrinsically lower spectral resolution (with the associated increase in the S/N due to the larger spectral bandpass). Most grating spectrometers have Gaussian bandpasses; thus, we used a Gaussian convolution. In addition, using a Gaussian bandpass eliminates the Fourier spectral aliasing that would occur if one simply used a square bandpass to bin the data (i.e., convolve the spectrum with a square wave). The data are in good agreement with the broadband colorimetry of 1996 TO_{66} reported by Jewitt & Luu (1998). To facilitate comparison, the low-resolution data have been plotted separately in Figure 2. Strong absorption bands near 1.5 and 2.0 μm are readily apparent in the spectra from both nights. It can also be seen that the intensities of the absorptions near 1.5 and 2.0 μm substantially differ across the 2 nights' data, suggesting that varying areal coverage and/or the concentration of the absorbing material is revealed as the object rotates. The two absorptions near 1.5 and 2.0 μm are attributed to water ice on the surface of 1996 TO_{66}. To illustrate this, in Figure 3 we show the average of both nights' data at full resolution and the data convolved to lower resolution in the same manner as the spectra shown in Figures 1 and 2. Also shown in Figure 3 is a model spectrum of particulate water ice intimately mixed with neutral to bluish, but otherwise spectrally featureless, particulate material. The model spectrum was calculated using bidirectional reflectance theory (Hapke 1993), the known optical constants of water ice (Warren 1986; Toon et al. 1994), and a simulated dark material that is spectrally featureless but blue-colored over the wavelength region of our observations.

The grain sizes of the water ice and spectrally featureless material used in the model are 68 and 160 μm, respectively. These values are not unique, and one should not ascribe any great significance to them because the abundances and grains sizes of the two constituents can be varied within a wide range and still provide an acceptable match to the water-ice absorption bands in the spectrum.

The optical constants of water ice used in the spectral models here were taken from Warren (1986) and shifted in wavelength to agree with the data of Toon et al. (1994). The data of Warren were deemed to be more precise in the 1.4–2.4 μm wavelength region than those of Toon et al., but the central wavelengths of the absorption bands in the Toon et al. data corresponded more closely with those of water ice at the expected surface temperature of 1996 TO_{66}.

The optical constants for the blue material used here were derived by assuming a real index of refraction of 1.6 in the visual spectral region and by assuming a Lambert absorption

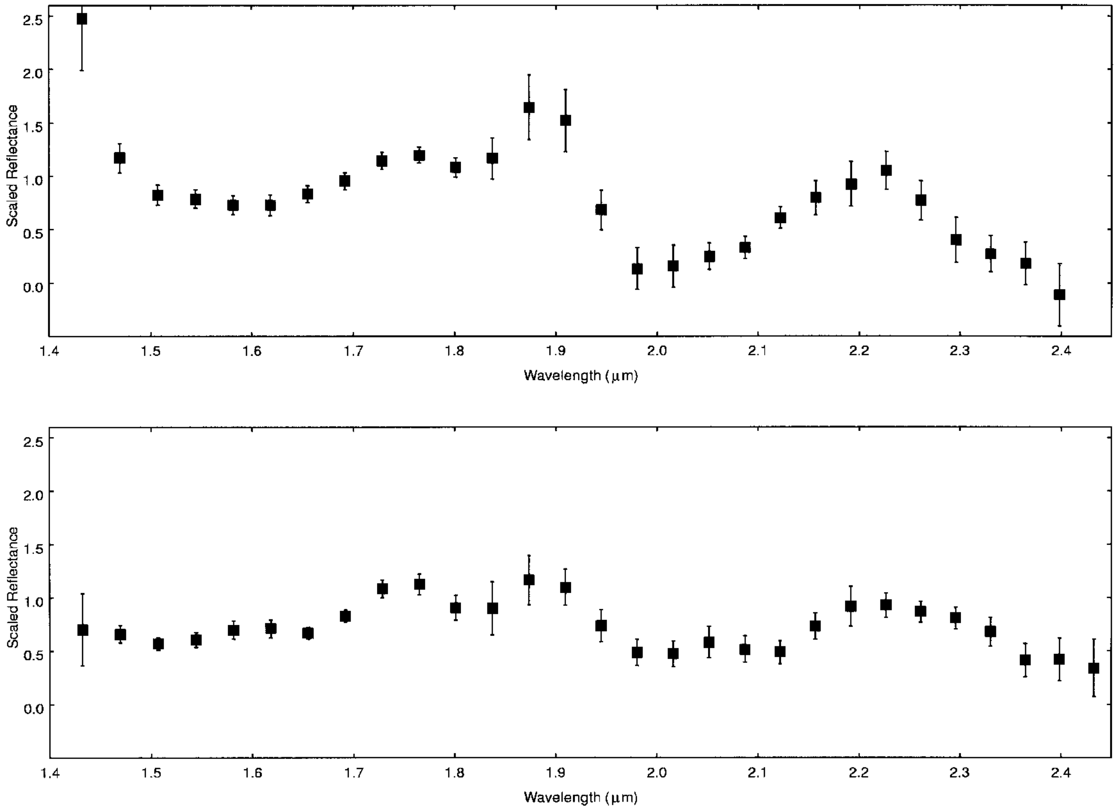

FIG. 2.—Spectra of 1996 TO_{66}. For clarity, just the data convolved to lower resolution to improve the S/N are shown (see text). Otherwise, the data here are exactly the same as those shown in Fig. 1.

coefficient that decreased linearly toward longer wavelengths. These quantities then served as inputs to a subtractive Kramers-Kronig algorithm that gave the spectrum of real indices of refraction corresponding to the defined imaginary indices and the real index in the visual. The calculated reflectance for 10 μm grains gives a roughly linear decrease in reflectance from 10% at 1.0 μm to 7% at 2.5 μm.

As can be clearly seen, both the model and the data show the strong 1.52 and 2.03 μm absorptions of water ice. The spectral match is strong enough that we consider water ice to be positively identified on the surface of 1996 TO_{66}. The simulated dark material in our model was chosen merely to improve the fit in the 1.4–2.45 μm spectral region. Whether the surface of 1996 TO_{66} actually contains material similar in color to the material used in our simulation cannot be uniquely determined from these data.

Although the model fits reasonably well, there are two rather significant discrepancies. The first is an apparent absorption band near 1.8 μm, the second is a mismatch between the model spectrum and the data beyond 2.2 μm. The apparent absorption near 1.8 μm is also seen in the spectrum of 1993 SC (Brown et al. 1997). To account for this absorption, if real, would require an additional molecular component on the surface of 1996 TO_{66} besides H_2O. Nevertheless, we cannot be certain whether the absorption is real or an artifact of incomplete extinction correction in the neighborhood of the strong 1.9 μm telluric water vapor absorption.

The mismatch between the model and the data beyond 2.2 μm is a bit more interesting because there are no strong telluric absorptions in the 2.2–2.4 μm wavelength region, suggesting that the drop in reflectance of the data relative to the model is real. It is not clear from these data whether the discrepancy is due to another molecular component on 1996 TO_{66} or a difference in the actual optical constants of the water on 1996 TO_{66} versus those measured in the laboratory (Warren 1986; Toon et al. 1994).

Notable also is the weakness or absence of the 1.65 μm absorption that is partially blended with the 1.52 μm absorption in crystalline water ice (Fink & Larson 1975). The weakness or absence of this band in our data is consistent with amorphous water ice rather than crystalline water ice on 1966 TO_{66}, although certainty demands more precise data.

It is interesting that the spectrum of the Centaur 1997 CU_{26} (Brown et al. 1998) shows water-ice absorptions and little else except red, spectrally featureless material. In contrast, a well-studied Centaur Pholus (Cruikshank et al. 1998) shows an absorption band at 2.03 μm attributed to water ice on its surface, and its overall red color has been attributed to the presence of red, organic material (Sagan, Khare, & Lewis 1984; Cruikshank 1997). Pholus also shows evidence of light organic compounds such as methanol (CH_3OH) (Cruikshank et al. 1998). The spectrum of the KBO 1993 SC (Brown et al. 1997) shows evidence of light hydrocarbons on its surface, but none for water ice. Finally, Chiron, another Centaur whose orbit crosses that of Saturn and Uranus, has a weak coma and undergoes episodic gas releases like a comet. Its spectrum from 1.4 to 2.45 μm is featureless and nearly flat, similar to that of a C-type asteroid (Cruikshank 1997).

The spectral differences and similarities among the Kuiper Belt objects and the Centaurs suggest both populations are compositionally diverse groups of objects. Many recent studies of solar system dynamics conclude that the Kuiper Belt is the

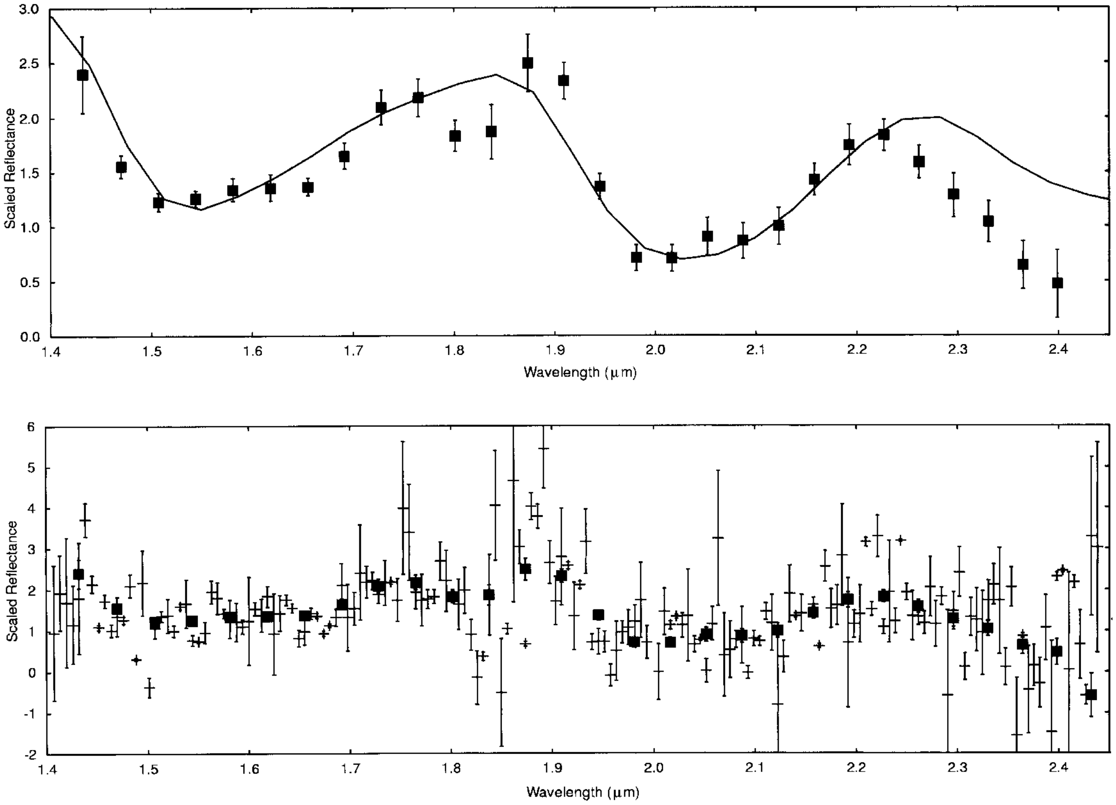

FIG. 3.—Spectra of 1996 TO$_{66}$ from both nights' data averaged together. The data in the bottom panel are at full resolution, and the data in the top panel have been convolved to lower resolution. The error bars were estimated from the repeatability of the measurements and propagated through the discrete convolution. A model was fitted to the data and is represented by the solid line (see text).

source of the Centaurs and the short-period comets (Duncan, Quinn, & Tremaine 1988; Gladman & Duncan 1990; Holman & Wisdom 1993; Luu, Jewitt, & Cloutis 1994; Irwin, Tremaine, & Zytkow 1995). The data presented here and the spectral evidence gathered to date (although sparse) are supportive of that view.

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