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## Water Ice on Triton

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## ABSTRACT

We report the spectroscopic detection of H<sub>2</sub>O ice on Triton, evidenced by the broad absorptions in the near infrared at 1.55 and 2.04  $\mu\text{m}$ . The detection on Triton confirms earlier preliminary studies (D. P. Cruikshank, R. H. Brown, and R. N. Clark, *Icarus* 58, 293-305, 1984). The spectra support the contention that H<sub>2</sub>O ice on Triton is in a crystalline (cubic or hexagonal) phase. Our spectra (1.87-2.5  $\mu\text{m}$ ) taken over an interval of nearly 3.5 years do not show any significant changes that might relate to reports of changes in Triton's spectral reflectance (B. Buratti, M. D. Hicks, and R. L. Newburn, Jr., *Nature* 397, 219, 1999), or in Triton's volatile inventory (J. L. Elliot et al., *Nature* 393, 765-767, 1998).

## INTRODUCTION

The near-infrared spectral region 1.0-2.5  $\mu\text{m}$  is rich with diagnostic absorption bands of simple ices; it is in this region that many of the ices detected on planets and satellites by remote sensing spectroscopy have been found. Brown and Cruikshank (1997) have recently reviewed the physical basis for the spectral behavior of ices in the near-infrared, while Schmitt et al. (1998) have reviewed the optical properties of ices of planetary interest. Three other reviews (Roush et al. 1995, Cruikshank et al. 1998a, 1998b) present current information on the ices identified on several planetary satellites and Pluto.

Previous studies of the near-IR spectrum of Triton have revealed the ices of N<sub>2</sub>, CO, CH<sub>4</sub>, and CO<sub>2</sub>, listed here in order of decreasing volatility (Cruikshank et al. 1993). Details of the discoveries and the implications of each ice for the atmosphere and its exchange with the surface have been reviewed recently (Brown et al. 1995; Yelle et al. 1995) and will not be repeated here.

This paper presents new observational results which reveal the clear presence of solid H<sub>2</sub>O on Triton. Solid H<sub>2</sub>O was included in the models of Triton's reflectance spectrum calculated by R. N. Clark for the paper by Cruikshank et al. (1984) to account for the continuum shape in spectra of low resolution and low signal precision. The limitations of those data lent only modest confidence to the identification of H<sub>2</sub>O ice, and this material was largely ignored in subsequent discussions of Triton's surface. The present work is in a sense a rediscovery of H<sub>2</sub>O ice on Triton. A thorough analysis of all the spectroscopically identified components of Triton's surface, including H<sub>2</sub>O, is presented in the thesis by Quirico (1995) and the paper by Quirico et al. (1999).

One of the spectral features of H<sub>2</sub>O ice of special interest in planetary spectroscopic studies occurs at 1.65  $\mu\text{m}$ . It is present in the spectra of all of the icy satellites of Jupiter, Saturn, and Uranus (e.g., Cruikshank et al. 1998a). This feature is unique to crystalline H<sub>2</sub>O ice, and its strength and band center are strongly temperature-dependent (Fink and Larson 1975, Grundy and Schmitt 1998). Water ice has been found in the near-infrared spectra of comet C/1995O1 (Hale-Bopp) (Davies et al. 1997), the Centaur 1997 CU<sub>26</sub> (Brown et al. 1998), and on Kuiper Disk object 1996 TO<sub>66</sub> (Brown et al. 1999). The

apparent absence of the 1.65- $\mu\text{m}$  feature on the comet and on 1997 CU<sub>26</sub> led the authors to suggest that the H<sub>2</sub>O in these two objects is amorphous, as it is in interstellar ices in the grains surrounding protostars (R. G. Smith et al. 1989). However, Lellouch et al. (1998) found crystalline H<sub>2</sub>O ice grains in the coma of comet Hale-Bopp from far-infrared emission bands observed with the ISO spacecraft when the comet was 2.9 AU from the Sun. The Brown et al. (1999) spectrum of Kuiper Disk object 1996 TO<sub>66</sub> may weakly show the 1.65  $\mu\text{m}$  band

## NEW OBSERVATIONS

The observations reported here were made with the cooled grating array spectrometer (CGS4) of the United Kingdom Infrared Telescope (UKIRT) in May, 1995, and October, 1998. The circumstances of the observations are given in Table I. In 1995, CGS4 was equipped with a 150 mm focal length camera, giving a pixel size of 1.23 by 1.23 arcsec, and a 75 line/mm grating. The slit width was 1.23 arcsec. This configuration yielded a spectral coverage of 0.66  $\mu\text{m}$  for a single setting of the grating in first order. In 1998, CGS4 contained a 300 mm focal length camera (0.61 arcsec/pixel), a slit width of 0.61 arcsec, and a 40 line/mm grating, giving a spectral coverage of 0.64  $\mu\text{m}$  in first order. Both of these represent a considerable increase in spectral coverage over the configuration when our first Triton work was accomplished with this instrument (Cruikshank et al. 1993). The improvement results primarily from the implementation of a larger InSb array of 256 x 256 pixels. The smaller pixels of this array result in higher spectral resolution; at 1.65  $\mu\text{m}$  the resolving power was 630, and at 2.2  $\mu\text{m}$  it was 840 in 1995, and 880 in 1998.

In two nights in May 1995, we used two settings of the grating to cover the region 1.42 – 2.53  $\mu\text{m}$  with a wavelength overlap (1.87 – 2.09  $\mu\text{m}$ ). In October 1998, we covered the spectral region 1.87 – 2.51  $\mu\text{m}$  in a single grating setting. In addition to the absorption bands of the ices previously identified, this spectral region includes the broad bands characteristic of solid H<sub>2</sub>O that are seen in the reflectance of numerous satellites of Jupiter, Saturn, and Uranus (e.g., Clark et al. 1986; Roush et al. 1995; Cruikshank et al. 1998a).

The broad H<sub>2</sub>O ice bands lying in the region 1.42 - 2.52  $\mu\text{m}$  are significantly shifted to longer wavelengths than the water vapor bands seen in the transmission spectrum of the Earth's atmosphere, although there is some overlap in wavelength in the band wings. The spectral regions of telluric water vapor absorption are largely avoided in ground-based observations, and this can cause broad ice bands to be overlooked; detection of the water ice bands requires wide and continuous wavelength coverage. Furthermore, in the case of Triton, other strong absorbers (N<sub>2</sub> and CH<sub>4</sub>) overlap with portions of the water ice bands, making the latter less distinct. It is for these reasons that the H<sub>2</sub>O ice bands were not seen in earlier spectra of Triton in the observational program that began in 1991 with CGS4 (Cruikshank et al. 1993). However, with the broader wavelength coverage afforded by

the new configuration of CGS4 (described above), and with special care to correct for the telluric absorption bands, it became possible to discern clearly the broad ice bands

Table I. Observations of Triton

Object	Date and Universal Time	Wavelength $\mu\text{m}$	Average Airmass	Triton's Position angle $\theta$ (deg)
BS 6998	1995 May 13, 1400	1.87 - 2.53	1.33	-
Triton	1995 May 13, 1420	1.87 - 2.53	1.33	242
BS 6998	1995 May 15, 1330	1.42 - 2.08	1.32	-
Triton	1995 May 15, 1400	1.42 - 2.08	1.32	356
Triton	1998 Oct. 28, 0500	1.87 - 2.51	1.4	246
BS 7994	1998 Oct. 28, 0625	1.87 - 2.51	1.29	-

diagnostic of  $\text{H}_2\text{O}$  ice on Triton. With the exception of a small spectral interval near 1.85  $\mu\text{m}$ , where telluric absorption is strongest, we satisfactorily determined the shape of Triton's spectrum with a precision easily sufficient to show the characteristic shapes of the  $\text{H}_2\text{O}$  ice bands centered at  $\sim 1.55$  and 2.04  $\mu\text{m}$ .

Figure 1 presents the composite spectrum of Triton from the data of 1995 May 13 and 15, and 1998 October 28, shown as geometric albedo, with the principal absorption bands identified. Also shown is a spectrum of crystalline  $\text{H}_2\text{O}$  ice computed for 5- $\mu\text{m}$  particles from a Hapke scattering model, using complex refractive indices measured for a thin film at  $T=40\text{K}$  (Grundy and Schmitt 1998). The spectrum of amorphous  $\text{H}_2\text{O}$  ice was similarly calculated from refractive indices obtained in the laboratory of B. Schmitt. The coincidence of the laboratory and the Triton spectra between 1.90 and 2.09  $\mu\text{m}$ , where there are only weak, narrow absorption bands of  $\text{CO}_2$  on Triton, is particularly diagnostic of the presence of  $\text{H}_2\text{O}$ . Between 1.45 and 1.60  $\mu\text{m}$  there is a similar coincidence that supports the  $\text{H}_2\text{O}$  identification.

The abundance of  $\text{H}_2\text{O}$  ice on Triton cannot be determined without a full evaluation of the effects of all the other known components on the spectrum. In their analysis of the September, 1995 data, Quirico (1995) and Quirico et al. (1999) found that in the best-fitting (but not unique) models of Triton's spectrum the  $\text{H}_2\text{O}$  component is spatially segregated from a terrain consisting of the much more volatile solid solution of  $\text{N}_2:\text{CH}_4:\text{CO}$ . In the preferred model the  $\text{H}_2\text{O}$  (100  $\mu\text{m}$  grains) is mixed at a granular level with  $\text{CO}_2$  (500  $\mu\text{m}$  grains) in the fractions 87% and 13%, respectively. The  $\text{H}_2\text{O}:\text{CO}_2$  terrain covers about 45% of the surface of the Triton hemisphere visible at the time of the observations. The remaining 55% of the surface is covered by the  $\text{N}_2:\text{CH}_4:\text{CO}$  molecular mixture in "grains" nearly 10 cm in size, corresponding to a compact crystalline solid, as described by Eluszkiewicz (1991).

## THE NATURE OF H<sub>2</sub>O ICE ON TRITON

Solid H<sub>2</sub>O at low pressure can exist in at least four phases: amorphous (vitreous) ice in a high (Iah) and a low density (Ial) configuration (Jenniskens et al. 1995), and the crystalline cubic (Ic) and hexagonal (Ih) phases. The phase depends upon the temperature and other conditions of formation, the thermal annealing history, and the elapsed time. Water ice that forms at  $T < 100$  K is amorphous, and when formed at  $T < 30$  K it is Iah. The transformation Iah  $\rightarrow$  Ial occurs at about 38 K (Jenniskens and Blake 1996), and in the absence of irradiation (e.g., electrons or UV) is irreversible. The transition Ial  $\rightarrow$  Ic occurs quickly at  $T \sim 150$  K, but in time it will occur at somewhat lower temperature. Schmitt et al. (1989a, 1989b, 1992) found that the crystallization time of amorphous ice is less than 10 years at  $T = 110$  K, and about 1000 years at  $T = 100$  K. In the absence of irradiation this transition is also irreversible. Ice formed at  $T > \sim 190$  K is hexagonal, and transitions to Ic or the amorphous phases do not occur, even if the ice is cooled to lower temperatures.

The spectroscopic signatures of the various phases of ice in the wavelength region of interest here have not been fully explored, although there is considerable information on the hexagonal phase and its spectral variation with temperature (Grundy and Schmitt 1998). Because of technical difficulties in preparing thick samples of amorphous and cubic ice, the near-infrared spectrum of the amorphous phase has been studied only in thin films (Fink and Sill 1982, Schmitt et al. 1998).

On Triton the  $2\nu_3$  absorption in CH<sub>4</sub> dissolved in N<sub>2</sub> ice occurs at 1.665  $\mu\text{m}$ , with a weaker component at 1.65  $\mu\text{m}$  that is coincident with the 1.65  $\mu\text{m}$  band in H<sub>2</sub>O ice. With the existing data it is not easy to distinguish between crystalline and amorphous phases. In Figure 2 we show two model spectra for Triton, one using crystalline and the other using amorphous H<sub>2</sub>O ice. Each model has two spatially segregated components, as does model A of Quirico et al. (1999), except that the grain size for CO<sub>2</sub> is 500  $\mu\text{m}$ . Specifically, one component covering 55% of the surface consists of N<sub>2</sub> ice in which 0.08% CH<sub>4</sub> and 0.05% CO are dissolved; the grain size is 11 cm and the Henyey-Greenstein phase function parameter  $g = -0.4$  (see Quirico et al. 1999). The second spatial component covering 45% of the surface consists of CO<sub>2</sub> and H<sub>2</sub>O ices mixed at the granular level; the CO<sub>2</sub> grains are 500  $\mu\text{m}$ , the H<sub>2</sub>O grains are 160  $\mu\text{m}$  in diameter, and  $g = -0.4$ . The difference between the two models in Figure 2 is that one uses the optical constants of amorphous ice at  $T = 38$  K, and the other is pure crystalline ice. The effect of the band in crystalline ice is seen in Figure 2 to increase the depth of the 1.65  $\mu\text{m}$  component of the CH<sub>4</sub> band in the model spectra.

We have compared the ratios of the depth of the 1.65  $\mu\text{m}$  component of the CH<sub>4</sub> band to the depths of the 1.72 and 1.79  $\mu\text{m}$  CH<sub>4</sub> bands for both models and for Triton in Table II. The values for Triton are greater than those for the model with amorphous ice, but less than those for the model with crystalline ice. This trend suggests, but does not prove, that the H<sub>2</sub>O ice on Triton is crystalline.

Table II Band Depth Ratios on Triton and in Models

	Ratio 1.65 $\mu\text{m}$ to 1.72 $\mu\text{m}$	Ratio 1.65 $\mu\text{m}$ to 1.79 $\mu\text{m}$
Amorphous H <sub>2</sub> O model	0.80	0.81
Triton	1.00	0.93
Crystalline H <sub>2</sub> O model	1.09	1.11

### CHANGES ON TRITON?

The spectral reflectance of Triton in the photovisual region is known to be variable (e.g., B. A. Smith et al. 1989, Brown et al. 1995). Buratti et al. (1998, 1999) have reported a recent abrupt change from a relatively neutral and colorless reflectance (in the region 0.35-0.95  $\mu\text{m}$ ) to a distinct red color, and then back to neutral over an interval of about seven months. At the same time, results from stellar occultations by Triton have led Elliot et al. (1998) to conclude that the atmospheric surface pressure (mostly due to gaseous N<sub>2</sub>) on Triton has increased by a factor of about three since the Voyager encounter of 1989, perhaps as a result of an overall warming of the surface.

The spectra in Figure 1, obtained over an interval of nearly 3.5 years and encompassing the times of both the Buratti et al. (1998) and some of the Elliot et al. (1998) observations, show no discernible change in the reflectance of Triton from 1.87 to 2.50  $\mu\text{m}$ . The relevant data in Figure 1 were obtained for the same longitude on Triton. This spectral range includes absorption bands of N<sub>2</sub>, CO, and CH<sub>4</sub>, the most volatile species known on Triton. Minor differences in the spectra at 1.90 and 2.00  $\mu\text{m}$  are regarded as insignificant because of difficulties in correcting for telluric absorption features at those wavelengths, and the albedo levels are the same to the precision of the spectrophotometry (about  $\pm 5\%$ ). Thus, there does not appear to be spectral evidence in our data to support either a gross change in reflectance or a difference in the distribution of volatiles on Triton's surface.

Continued monitoring of Triton's spectrum appears to be warranted.

### ACKNOWLEDGMENTS

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## FIGURE CAPTIONS

Figure 1. The spectrum of Triton, 1.4-2.5  $\mu\text{m}$ . Spectrum a is a composite of two data sets recorded on 1995 May 13 and May 15 (see Table I). Spectrum b (offset downward by 0.25) was recorded on 1998 October 28. The spectrum of hexagonal  $\text{H}_2\text{O}$  ice is from Grundy and Schmitt (1998), while the spectrum of amorphous  $\text{H}_2\text{O}$  ice is from Schmitt et al. (1998).

Figure 2. Two models of the Triton spectrum, after Model A of Quirico et al. (1999). In the model with amorphous  $\text{H}_2\text{O}$  ice, the 1.65  $\mu\text{m}$  band component in the model is due entirely to  $\text{CH}_4$  dissolved in  $\text{N}_2$ , but in the model with crystalline  $\text{H}_2\text{O}$ , the 1.65  $\mu\text{m}$  band depth is enhanced by the addition of the 1.65  $\mu\text{m}$  band in  $\text{H}_2\text{O}$ .

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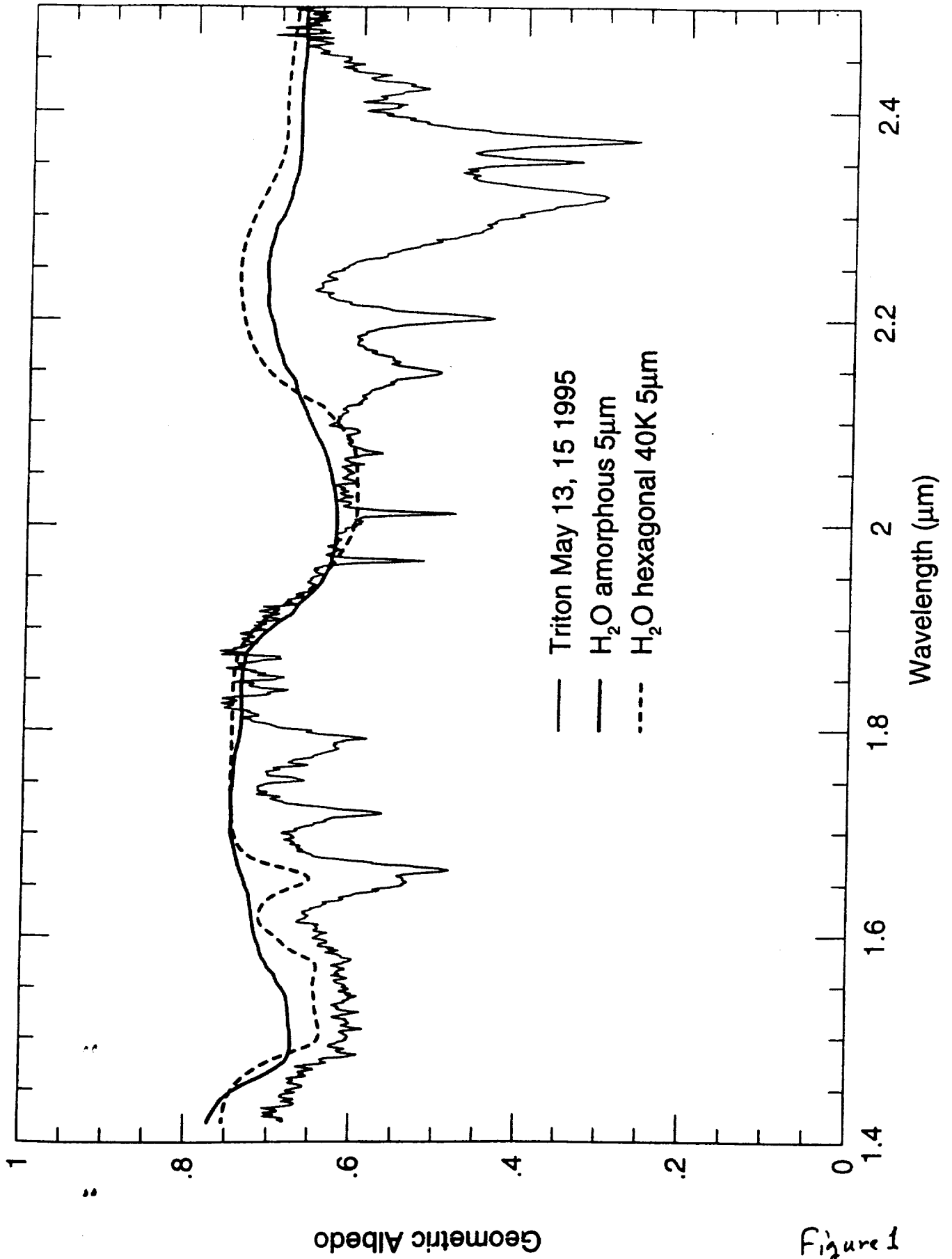


Figure 1

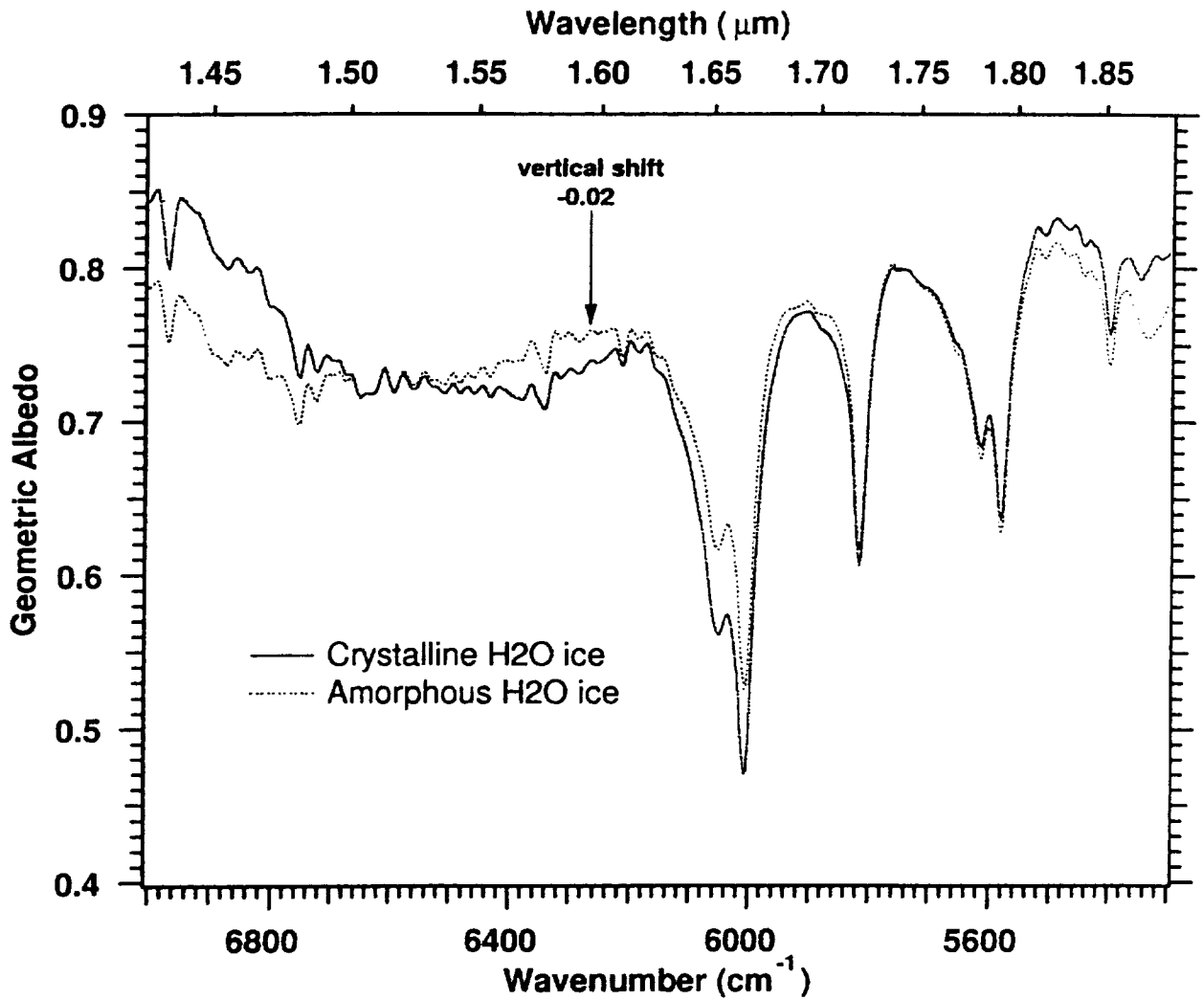


Figure 2

