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Ices on the Surface of (50000) Quaoar

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ABSTRACT

The 1.4 - 2.4 μm spectrum of the large Kuiper belt object (50000) Quaoar obtained at the Keck observatory shows distinct absorption features of crystalline H_2O ice and CH_4 and possibly other molecules. CH_4 is unexpected on Quaoar because of its high volatility. The CH_4 absorption is shifted slightly to shorter wavelengths than is expected for a pure ice, as has been seen on Pluto and Triton where it is attributed to the CH_4 being in solution with N_2 ice. N_2 should not be stable on the surface of Quaoar and its spectral signature is not observed, so we hypothesize that the CH_4 is trapped in another ice on the surface where it can survive in spite of its volatility. Additional telescopic and laboratory data are required in order to positively identify all of the features seen in the spectrum of Quaoar.

Subject headings: comets: general – infrared: solar system – minor planets

1. Introduction

The recently discovered Kuiper belt object (KBO) Quaoar, with an R magnitude of approximately 18.6 and a size of 1250 ± 200 km (Brown & Trujillo 2004), is the largest and brightest KBO discovered to date, and, as such, offers the best opportunity for the detailed study of the surface composition of one of these distant objects. KBOs were initially expected to be among the least processed objects remaining in the solar system, with their compositions reflecting the initial formation conditions. Some of the earliest observations of the physical characteristics of KBO surfaces showed, however, a large variation in surface color, which led to the belief that some sort of modification, such as that due to collision or radiation darkening, is an important current surface process (Luu & Jewitt 1996). Recent work suggested that the largest of the KBOs, such as Quaoar, should have suffered sufficient internal heating to have undergone significant processing and volatile loss (de Sanctis et al. 2001; McKinon 2002 ; de Sanctis et al. 2002; Choi et al. 2002). The study of the bright objects such as Quaoar offers the opportunity to observationally determine the surface composition of the largest objects still remaining in the outer solar system and to examine processes affecting surfaces in this region.

Infrared spectroscopy is the most suitable technique for remote study of KBO surface ices (e.g. Brown & Cruikshank 1997), but owing to the extreme distance and small size of KBOs, few reliable infrared spectra have been obtained. To date, the only definitively identified material on the surface of a KBO has been H_2O ice (Brown et al. 1999; Licandro et al. 2001) which has broad absorption bands that can be identified in relatively low signal-to-noise data. The detection of H_2O ice was widely expected, as H_2O ice should be the most abundant material in small bodies from Jupiter onward. Extremely volatile ices, such as those seen at Pluto and Triton, for example, have proved elusive, but it is not clear if the non-detections are because the ices are non-existent or simply too difficult to detect without higher quality spectra. The continued discovery and high-quality characterization of the brightest KBOs should lead to a dramatic increase in our understanding of these surfaces.

2. Observations

Near-infrared spectra of the KBO (50000) Quaoar were obtained on 12 July 2002 using the facility near infrared spectrograph NIRSPEC (McLean et al. 1998) on the Keck telescope. At the time of observations, the object was 43.4 AU from the sun, 42.7 AU from the earth, at a phase angle of 0.86 degrees, and moving at a rate of approximately 2 arcsec hr^{-1} with respect to the background stars. We identified Quaoar in direct images through the slit viewing camera both by its motion with respect to nearby stars and by a comparison to Digitized Sky Survey images, and we centered it in the 0.57 arcsec wide spectral slit. Sequences of three spectra were obtained with the object offset along the slit by about 10 arcseconds between each exposure. Three grating settings were required to completely cover the spectral region from 1.4 to 2.5 μm at resolutions ($\lambda/\Delta\lambda$) between 2000 and 3000. Before and after each setting, we obtained comparison spectra of the nearby G2V star HD 151450. The wavelength range from 2.10 to 2.53 μm was covered in 18 exposures of 200 seconds each at airmasses from 1.22-1.24 and 1.44-1.55; 1.44 to 1.73 μm was covered in 6 exposures of

200 seconds each at airmasses from 1.24-1.28; and 1.70 to 2.13 was covered in 6 exposures of 200 seconds each at airmasses from 1.33-1.49. In all cases, the comparison spectrum of HD 151450 was taken within 0.1 airmasses and immediately preceding or following the target spectrum. Data reduction followed the procedure outlined by Brown (2000) with the exception that spectral regions containing individual bright emission lines were clipped out of the spectra and appear as blank regions.

Figure 1 shows the resulting spectrum of Quaoar. The absolute value of the infrared albedo is obtained from the R albedo of $0.092^{+0.036}_{-0.023}$ (Brown & Trujillo 2004) , the V-R color of 0.64 ± 0.04 (Trujillo and Brown, in prep), and an estimated V-J color of 2.1 ± 0.2 using typical values found by McBride et al. (2003). Errors in the overall absolute albedo calibration are of the order of 30% and are dominated by the uncertainty in the optical albedo. The resulting signal-to-noise in the spectrum ranges from 5-10 per pixel in the most ideal regions. This spectrum shows the very distinct signature of H_2O ice, including the unique 1.65 μm absorption which indicates that (at least some of) the H_2O is in crystalline, rather than amorphous, form.

We first attempt to model the spectrum of Quaoar with a mixture of H_2O ice and a dark featureless material. Such modeling has been sufficient to describe the spectra of all KBOs observed to date and is a useful first starting point. Figure 2 shows Quaoar, now smoothed to a resolution of 200 by a gaussian convolution of the original data and resampled at twice the resolution, compared to a best-fit H_2O ice plus dark material model. The model is created from a least-squares best fit Hapke model (Hapke 1981) of a spatially segregated mix of crystalline H_2O ice grains (Grundy & Schmitt 1998) and a dark red material in which the fractional abundance of ice, the grain size of the ice, and the color of the dark material are allowed to vary. The best fit parameters have little unique meaning, as many different values could give similar fits, but, for comparison, they are a grain size of 22 μm, an ice fraction of 33%, and a spectral slope of 20% per 1 μm for the dark material. A comparison of the spectrum of Quaoar and the model shows a good fit to the major H_2O features, but a weaker than expected 1.65 μm absorption, perhaps indicative of the existence of a mixture of both crystalline and amorphous H_2O ice.

Absorptions appear in the spectrum of Quaoar that do not appear in the simple H_2O model. Most prominently, a distinct absorption occurs at 2.20 μm and a series of broad absorptions occurs beyond 2.25μm. In Fig. 2 we compare the spectrum of Quaoar to that of the centaur Pholus (Brown 2000) and the satellite Charon (Brown & Calvin 2000), two outer solar system bodies which also have H_2O spectra combined with longer wavelength absorptions. The long wavelength portion of the spectrum of Quaoar resembles the spectra of neither of the other bodies, nor does it resemble any known spectrum in the solar system.

Surprisingly, however, these long wavelength features correspond closely to the strongest features that would be expected from the presence of CH_4 on the surface of Quaoar. We test this possibility, we construct a best-fit model allowing the inclusion of methane. This model is also shown in Fig. 2, and the match to the 2.20μm feature and the longer wavelength absorption is good. The model consists of 15 μm grains which are an intimate mix of 62% H_2O ice and 38% CH_4 ice (Grundy et al. 2002) combined with a spatial mix of 65% dark material. Again, we do not place any particular significant on the specifics of this non-unique model, we simply show that all of the major features in model are matched in the Quaoar spectrum.

We do not consider the identification of CH_4 on Quaoar secure unless we can show that each absorption line expected to be present is indeed detected. We show in Figs. 3, 4, and 5 the full resolution data compared to the H_2O+CH_4 model. The signal-to-noise ratio of the data does not permit detection of the extremely weak absorptions at 1.72 and 1.80μm, though the presence of these features in higher quality data could be used to verify the presence of CH_4. Lines at 2.20 and 2.32μm are clearly detected. The only prominent CH_4 line which does not appear in the spectrum of Quaoar is that at 2.38μm. Beyond about 2.35μm, however, the Quaoar spectrum is corrupted by large numbers of bright terrestrial emission lines, so we place no weight on the appearence or non-appearence of any narrow spectral features in this region. We thus conclude that all expected features of CH_4 are present at their expected strengths and that CH_4 is therefore positively identfied on Quaoar.

Careful examination of Quaoar's CH_4 absorption shows that the most distinct feature, at 2.20 μm is slightly shifted with respect to the modeled feature position (the precision of the wavelength scale has been checked from the positions of known sky emission lines and is better than a fraction of a pixel). The 0.007 μm shift of the band center between the laboratory data and the Quaoar spectrum is almost identical to that seen at Triton (Fig. 5), where it is attributed to the CH_4 being dissolved in a matrix of N_2 ice (Quirico & Schmitt 1997). Triton shows the distinct 2.15 μm nitrogen quadrupole absorption, so dissolution of CH_4 in this N_2 seems reasonable on this body. At Quaoar, however, no hint of a N_2 feature at 2.15μm appears. Part of this region is obscured by a terrestrial atmospheric emission line, and a comparison to the spectrum of Triton shows that N_2 at that relative level would be difficult to observe. Triton also has a distinct absorption at 2.35 μm of CO, of which there is no evidence on Quaoar. The presence or absence of N_2 on Quaoar remains unknown and awaits more detailed observations. Understanding the physical state of the CH_4 on Quaoar is critical to assessing the thermal history of the body and will be discussed below.

The other main region of the spectrum showing clear absorptions is the trough of the H_2O ice absorption between 1.95 μm and 2.13 μm (Fig. 4). This spectral region suffers from absorption due to terrestrial CO_2, so identification of any Quaoar lines in this region will have to await higher quality spectra.

Several other small features seen throughout the spectrum, such as those at 2.240, 2.263 and 2.342 μm, and possibly more, are not explained by the presence of only H_2O and CH_4. A search through laboratory spectra for other matches, including all simple combinations of H,C, O, and N and the complex organics examined by Quirico et al. (1999) and Cruikshank et al. (1998), has yielded no matches, though we note that most complex organics have absorption features in the 2.3 μm region where many of the unidentified lines are. We suspect that these complex organics may be present and may have formed from UV and cosmic ray interaction with the surface CH_4 and H_2O. Higher signal-to-noise spectroscopy will be required to confirm the reality and precise shapes of these features and additional laboratory data may be required to make positive identifications.

3. Discussion

The spectrum of Quaoar contains signatures of crystalline H_2O ice, CH_4 ice, and perhaps more complex organic materials. H_2O is the main non-volatile ices at these distances in the solar system, so its existence is expected even if the object has been extensively thermally processed. The presence of the H_2O in crystalline form, rather than purely amorphous form, and the detection of the much more volatile CH_4 contains important information about the thermal history and current state of Quaoar.

H_2O ice condensed at the low temperatures expected in the outer solar system or directly incorporated from typical ISM grains should exist in amorphous form (Jenniskens et al. 1998). Such H_2O ice will stay in amorphous form unless heated to $\sim$90 K, where it will crystallize to cubic form (Jenniskens & Blake 1996). The presence of the 1.65 μm absorption band of H_2O demonstrates the presence of at least some crystalline H_2O ice on the surface of Quaoar and thus suggests the possibility of high surface temperatures in Quaoar's history. Such high surface temperatures do not appear to be the result of the effects of initial radiogenic heating of a large object; current detailed models even including the effects of ^{26}Al do not show surface temperatures higher than $\sim$60 K on Quaoar-sized bodies (Choi et al. 2002). The existence of crystalline H_2O ice on Quaoar and on bodies such as Charon (Brown & Calvin 2000) remains unexplained.

The discovery of CH_4 on the surface of Quaoar is likewise unexpected. CH_4 should be quickly vaporized at the temperatures required for crystallization of H_2O ice. For larger objects of the size of Pluto and Triton, vaporization leads to the formation of an atmosphere and abundant CH_4 surface frosts. Quaoar, in contrast, is approximately the size of Charon, on which the gravitational pull is too small to maintain an atmosphere and volatiles are absent. We thus expect that any initial near-surface CH_4 on Quaoar should have been lost. Irradiation of an H_2O – CO_2 ice mixture – which may be present – is unlikely to create CH_4, though it could be the cause of the unidentified longer wavelength absorptions potentially attributable to more complex organics (Wu et al. 2003).

The small wavelength shift in the CH_4 absorption gives an important clue to the state of CH_4. On Pluto and Tritan such a shift has been interpreted as a dilution of CH_4 in N_2, the dominant ice on these bodies. N_2 has a vapor pressure $\sim 10^6$ times that of CH_4 at these surface temperatures, so its presence on Quaoar is unlikely. An alternative is that CH_4 is trapped in another ice where it can be preserved even in the face of some heating. CH_4 has been seen to become trapped in amorphous H_2O ice in low temperature laboratory experiments (Bar-Nun et al. 1985). However, recent laboratory data (M. Bernstein, private communication) suggests that little shifting of the relevent spectral features occurs in this trapping. A definitive identification of the state of the CH_4 is not currently possible.

The composition and physical state of the ices on the surface of Quaoar contain important clues to the thermal history of such large objects in the outer solar system. Priority should be placed on obtaining higher signal-to-noise spectra of Quaoar in order to verify the additional low-level absorption features potentially present and to better measure the shapes and positions of the absorption lines identified in order to accurately assess the physical state of the ices.

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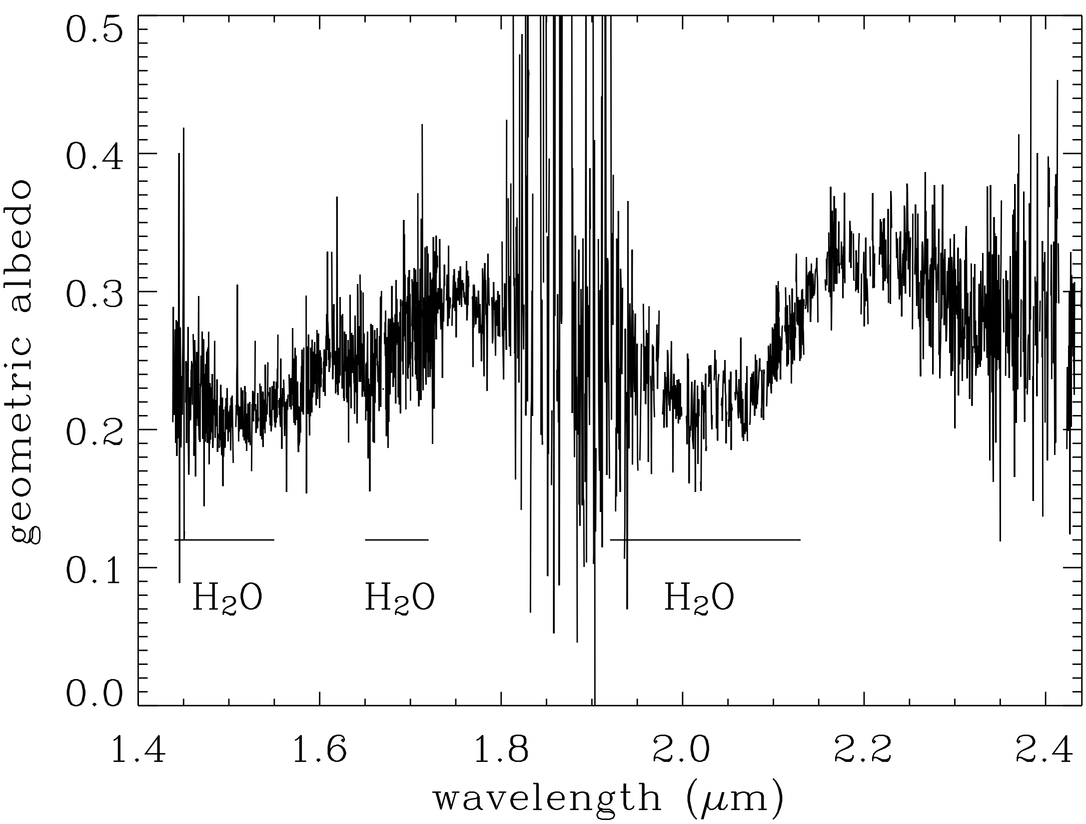

Fig. 1.— The infrared spectrum of (50000) Quaoar. Gaps in the spectrum occur where strong sky emission lines obscure the data. The signature of crystalline H_2O ice is dominant.

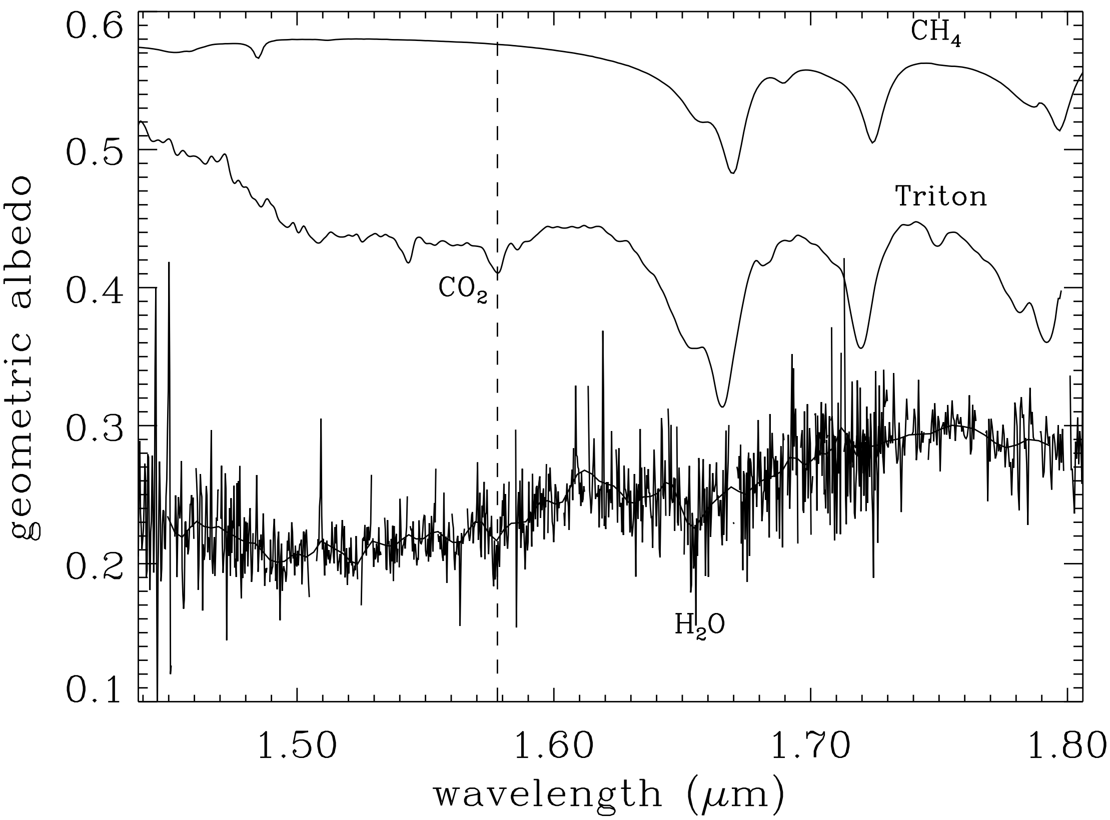

Fig. 2.— The spectrum of Quaoar, smoothed to a resolution of 200, compared to the spectra of the centaur Pholus (offset +0.1 in albedo) and the satellite Charon (offset −0.1), both of which have absorptions beyond 2.1 μm, but neither of which resembles the spectrum of Quaoar. All spectra are compared to a best-fit water-ice-plus-dark-material models (dashed lines) to show the nature of the deviation from water ice. Quaoar's long wavelength region is best fit by a model that adds CH_4 ice intimitely mixed with the H_2O (thin solid line).

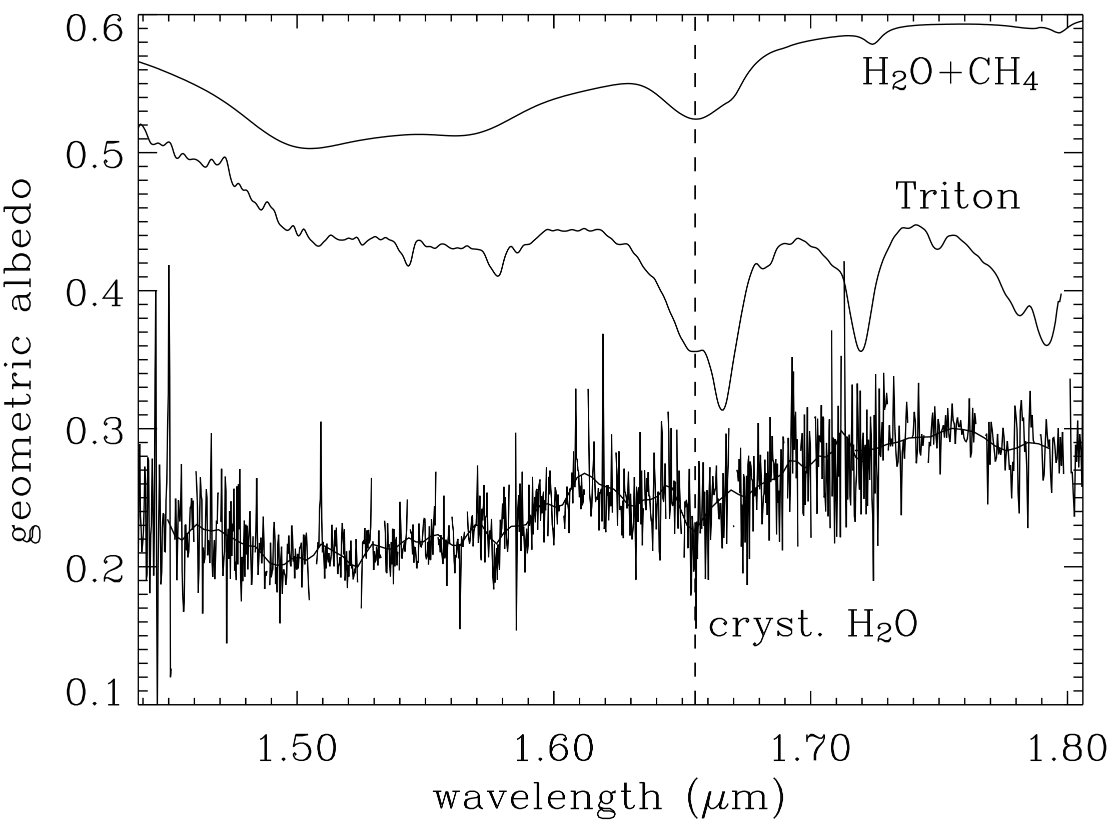

Fig. 3.— The full resolution short wavelength spectrum of Quaoar compared to the spectrum of Triton (Quirico et al. 1999) (offset +0.03) and the H_2O - CH_4 ice mix model (offset +0.3). The smooth line through the Quaoar data shows the smoothed spectrum of Fig. 2. The CH_4 absorptions at 1.67, 1.72, and 1.79 μm, which are clear on Triton, are too weak to be expected to appear in this spectrum.

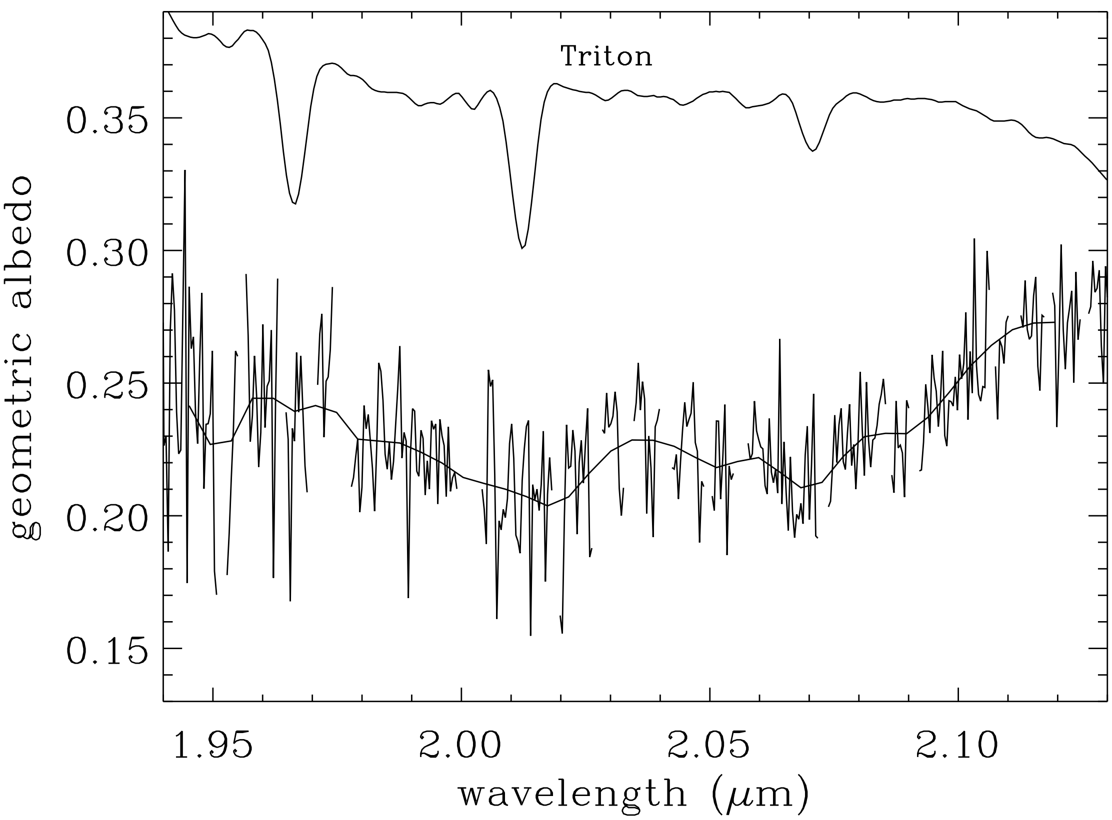

Fig. 4.— The full resolution medium wavelength spectrum of Quaoar compared to the spectrum of Triton (offset +0.03). The H_2O+CH_4 spectrum is not shown as no distinct absorptions appear in this region. The absorptions on Triton are due to CO_2 which is not apparent in the Quaoar spectrum.

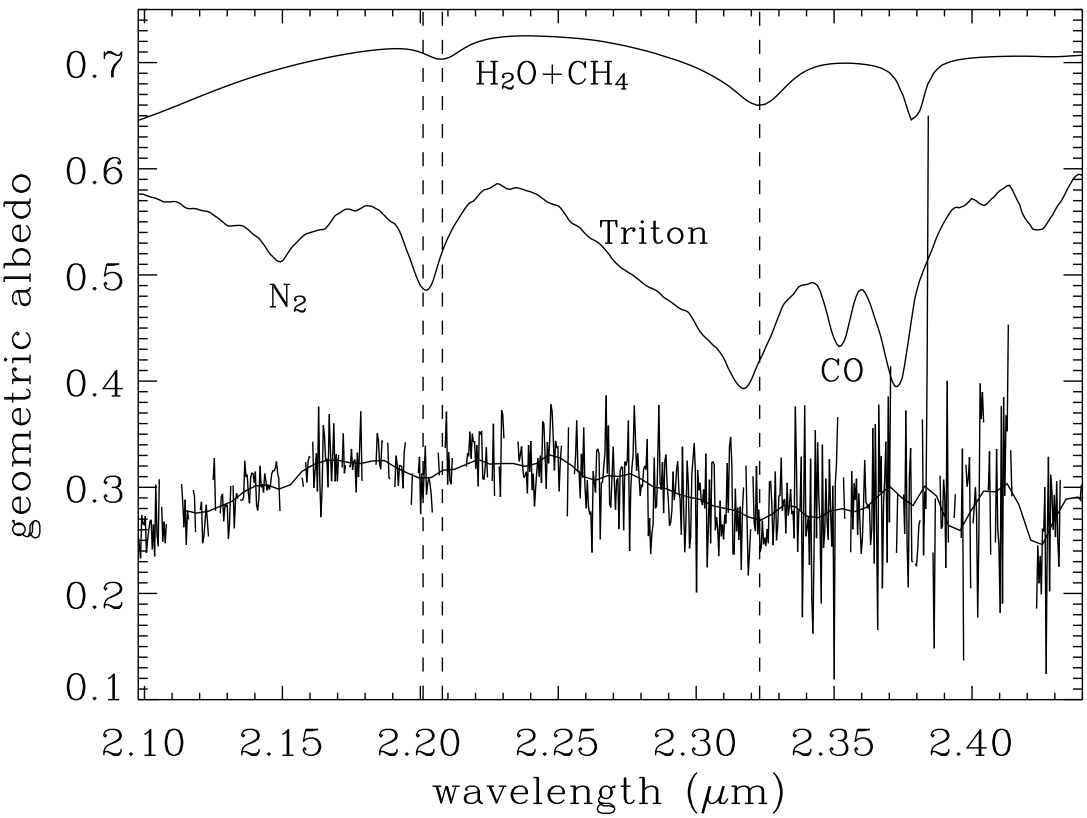

Fig. 5.— The full resolution long wavelength spectrum of Quaoar compared to the spectrum of Triton (offset +0.25) and the H_2O+CH_4 ice mix model (offset +0.4). The 2.20 and 2.32 μm absorptions of methane appear on both Triton and Quaoar. The 2.37 μm absorption of CH_4, apparently missing in Quaoar's spectrum, is in a region of the spectrum highly disturbed by telluric emission and would not be expected to be visible. Quaoar's 2.20 μm CH_4 absorption is shifted to shorter wavelengths by an amount equal to that seen at Triton, where it is attributed to dissolution in N_2. No evidence is seen on Quaoar of a feature due to N_2 or CO, both seen on Triton, though both lines are in regions heavily corrupted by telluric emission lines.