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The reflectance spectrum of water ice: Is the 1.65 μm peak a good temperature probe?

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Abstract. Water ice is an ubiquitous material in space, on the surface of planets and their moons, in comets and interstellar dust grains. The structure of water ice strongly depends on the deposition temperature. It can be amorphous if deposited at low temperature, i.e. 16 K, or crystalline if the deposition temperature is higher than 140 K (in the laboratory). In previous works we have studied the effects induced by fast ions and UV Lyman-a photons on the structure of the water ice by means of IR transmission spectra in the 3 μm region. Here we report on the study of the reflectance spectrum in the range 1.3-2.5 μm, where water ice exhibits two bands at 1.5 and 2 μm with a peak at 1.65 only present if the structure is crystalline. In the Solar System the reflectance features of water ice have been observed on many objects, among which icy surfaces of satellites. We will report on the temperature and ion irradiation dependence of the reflectance spectrum of water ice in the 1.3-2.5 μm range and its possible use as a surface temperature probe.

Key words. Planets and satellites: general – Methods: laboratory – Techniques: spectroscopic – Planets and satellites: individual: Asbolus, Europa, Callisto, Ganymede, 2004 DW, Quaoar

1. Introduction

Water ice is largely present in the Solar System in a number of surfaces of planets, moons, comets and rings (Schmitt et al. 1998a). At heliocentric distances larger than 5 AU water ice becomes one of the most important component of surfaces. Water ice has a number of strong features in the infrared spectrum, bands due to O-H stretching and bending modes at 3 μm and 6 μm respectively, the libration band at 12 μm, a band at 4.5 μm attributed to the combination of bending and libration, and a lattice band at 45 μm. Because of the asymmetry at the surface or inside pores, small bands arise from molecules that do not saturate their possible bonds, so H and O dangling bonds appear in the 2.7-2.8 μm range. Extensive reviews on the topic can be found in Boutron & Alben (1975); Hagen et al. (1983); Jenniskens et al. (1995); Westley et al. (1998); Devlin (2001); Baragiola (2003); Leto & Baratta (2003). The spectral properties of water ice are subjected to relevant variations indicating also variation of the structural properties of the ice if it has been irradiated with electrons (Dubochet

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& Lepault 1984), or with ions (Baratta et al. 1991; Strazzulla et al. 1992; Moore & Hudson 1992; Hudson & Moore 1992, 1995; Leto et al. 1996). Leto & Baratta (2003) have demonstrated that UV photolysis does alter the water ice structure in a way that resembles what the ions do. The NIR spectrum of water ice does also show interesting features that are in some circumstances sensitive to the temperature. In particular, in the range 1.5-2.5 μm the spectrum depends on the sample structure, if it is amorphous appears smooth and the central peak positions are shifted towards higher wavenumbers, if the structure is crystalline the spectrum does show an additional peak at 1.65 μm whose intensity is high at low temperature and decreases as the temperature increases (Schmitt et al. 1998b; Grundy & Schmitt 1998).

In the Solar System water rich icy surfaces have been detected in many objects by means of reflectance spectra. Grundy et al. (1999) have studied the possibility to use the 1.65 μm feature seen in reflectance spectra obtained by ground based observation to evaluate the temperature of surfaces on satellites of Jupiter, Saturn and Uranus. Kern et al. (2000) studied compositional variation of the surface of Centaur 8405 Asbolus, finding indication of the presence of the 1.65 μm. Also in the reflectance spectrum of Miranda Bauer et al. (2002) have found indication of crystalline water ice. Hansen & McCord (2004) have studied the reflectance spectra of Galilean satellites, they found that the three outermost satellites have surface ice layers whose lattice structure is predominantly amorphous in the case of Europa, crystalline for Callisto and for Ganymede they found sites that shows different crystallinity. It is also worth to notice that the water ice features have been also observed in TNO's. Fornasier et al. (2004) observed 2004 DW, a plutino class TNO whose diameter is about 1600 km, using the Italian Telescopio Nazionale Galileo (TNG). They revealed the clear signature of water ice in the range 1.5-2.5 μm. Recently Jewitt & Luu (2004) observed a large Kuiper belt object, Object (50000) Quaoar, with the Subaru telescope. They obtained the spectrum of Quaoar in the range 0.4-2.5 μm and found the clear signature of crystalline water ice at 1.65 μm.

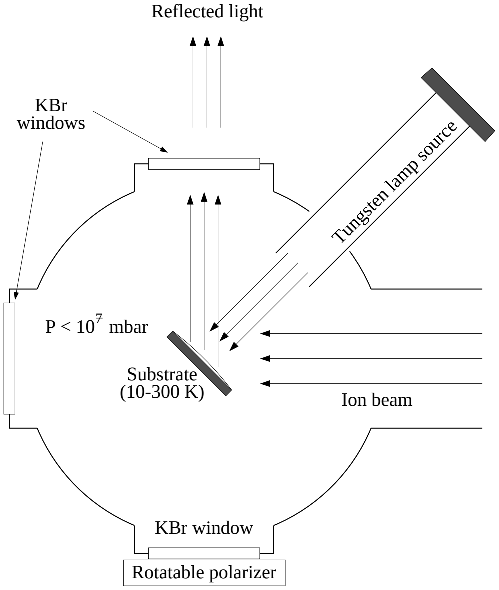

Fig. 1. Schematic view of the experimental apparatus used for in situ IR reflectance spectroscopy of frozen gases.

2. Experimental setup

The experiments here reported have been carried out in the laboratory at Catania Astrophysical Observatory. The experimental setup allows in situ IR spectroscopy of frozen gases and refractory materials before, during and after irradiation with fast ions.

2.1. Infrared spectroscopy

The in situ IR reflectance spectroscopy is performed in a stainless steel vacuum chamber (see Fig. 1) facing an FTIR spectrometer (Bruker Equinox 55). Inside the vacuum chamber the pressure is kept below 10^{-7}mbar. An IR transparent substrate (crystalline silicon) is placed in thermal contact with a cold finger whose temperature can be varied between 10 K and 300 K. A needle valve is used to admit pre-prepared gases (or mixtures) into the chamber where they freeze on the substrate. The sub-

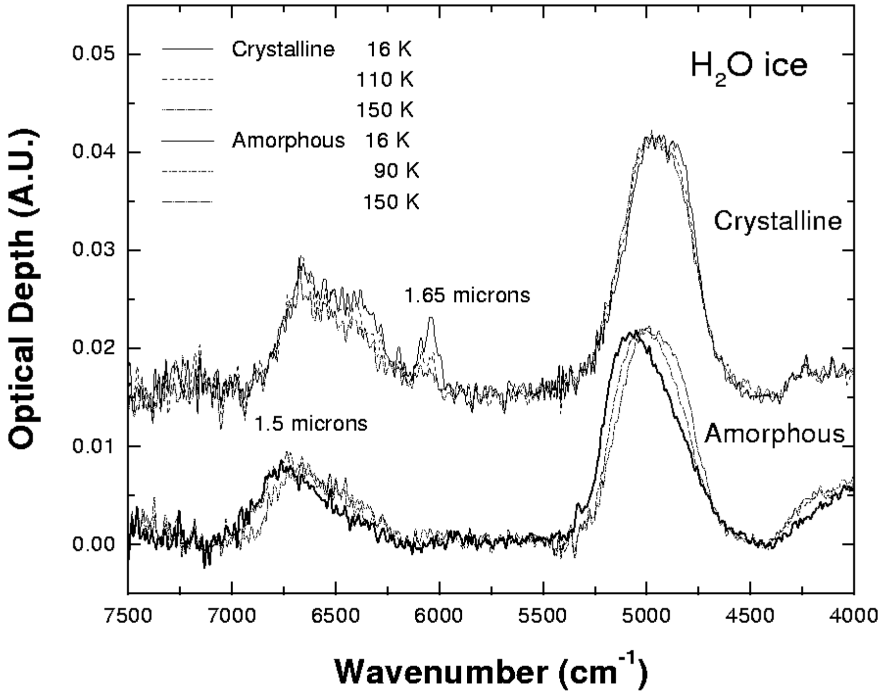

Fig. 2. The reflectance spectrum of crystalline and amorphous water ice at various temperatures. The bands considered for the subsequent analysis are indicated.

strate holder forms a 45^o angle with both the IR beam and the ion beam, so that sample spectra can be taken in situ, even during irradiation with ions without tilting the sample. For this purpose the IR spectrometer is positioned (by a movable optical bench) so that the IR beam is transmitted by the substrate through a hole in the sample holder. In order to obtain reflectance spectra a light source is placed in front of the sample position. The reflected light from the sample surface is then collected by the spectrometer optics at 45^o.

2.2. *Ion irradiation*

The ion implanter is a Danfysik 1080-200 accelerator from which ions with energy up to 200 keV (400 keV for double ionizations) can be obtained. The ion beam produces a 1 cm^2 spot on the target and current ranges between 100 nA/cm^2 and tens of μA/cm^2.

3. Results

3.1. *Reflectance spectrum of water ice between 1.3-2.5 μm (7500 and 4000 cm^{-1})*

We have studied the spectra of water ice obtained by deposition from the gas phase. Water ice is accreted from the background on a cold surface at various temperatures. First we prepared a crystalline sample depositing at temperature of 150 K; the resulting spectra is shown in Fig. 2 along with the spectra ob-

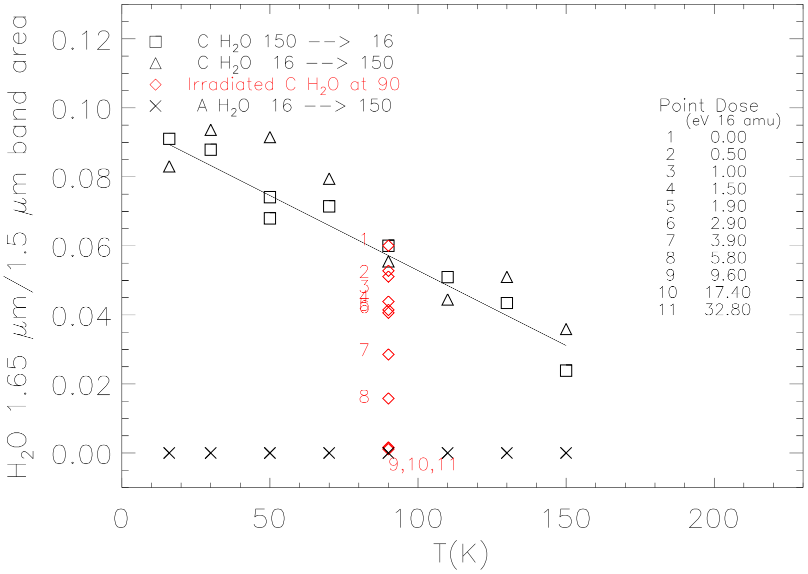

Fig. 3. The 1.65 μm band area ratioed to the area of the 1.5 μm band.

tained after the sample has been cooled down to 110 and 16 K. In the same figure the spectrum obtained by depositing the gas phase water at low temperature (16 K) is also shown. In this case the ice is amorphous. Spectra taken after the temperature of the sample is rised to 90 and 150 K are also shown. As can be easily seen the feature at 1.65 μm (6061 cm^{-1}) is only present when the lattice structure is crystalline. It is also clear that it is sensitive to the temperature, in fact at high temperature, say 150 K, the 1.65 μm band is barely appreciable but, as soon as the temperature decreases the peak becomes higher and the band area increases. In the case of the amorphous sample the 1.65 μm band is not present at any temperature; even when the temperature reaches 150 K and the crystallization occurs the band is not appreciable because has weak absorbance.

3.2. *A thermometer in the lab*

We have used the band areas of the 1.65 μm and the other water bands present in the spectra of crystalline water to search a way to make use of the temperature dependence of the 1.65 μm band to probe the temperature of the ice. In Fig. 3 we show a plot in which the 1.65 μm band area has been ratioed to the area of the 1.5 μm (6667 cm^{-1}) band. The plot shows that the ratio correlates with the temperature of the sample and it is possible to estimate the temperature of the sample just evaluating the band area ratio.

3.3. *Ion irradiation of crystalline water ice*

It is well known that a water ice layer undergoes lattice structure transition if exposed to ion irradiation, or UV photolysis (Baratta et al. 1991; Strazzulla et al. 1992; Moore & Hudson 1992; Hudson & Moore 1992, 1995; Leto et al. 1996; Leto & Baratta 2003). We have performed irradiation experiments at 90 K to study the evolution of the water ice features after irradiation at various doses. The results are plotted in the same Fig. 3. The amorphyzation of the ice layer that is induced by the irradiation do diminish the 1.65 μm band area. The final result is that the irradiated sample gives a decreasing band area ratio starting from the value that it has at 90 K.

The result gives us the indication that only in the case of an ice layer that has not been exposed to ion irradiation the reflectance spectrum of water ice can give reliable hints on the temperature of the surface. We would like to notice that UV photons do amorphyze a crystalline ice sample (Leto & Baratta 2003) as well, that is, also the exposition to UV photons do produce the same effect.

4. Conclusion

We have studied the reflectance spectrum of water ice in the range 1.3-2.5 μm. We demonstrated that, in the laboratory, it is possible, by using some band area ratio, to obtain the temperature of the studied sample. We have also demonstrated that if the sample has been exposed to ion irradiation the correlation between band area ratio and temperature is lost. So assuming that an ice layer has been thermally processed it is possible to retrieve information on the temperature of the layer by means of the band areas. But as soon as a process like ion irradiation do alter the ice the thermometer fails. An intriguing puzzle is the one that has been raised by the observations of Jewitt & Luu (2004). They observed object (50000) Quaoar (a Kuiper Belt object) and obtained the full spectrum in the range 0.4-2.5 μm. They found the signature of crystalline water ice at 1.65 μm. Given the distance from the Sun (~43 AU) a value of 50 K for the radiation temperature at Quaoar distance is estimated. The radiation temperature at Quaoar is much less then the critical value T_c necessary to enable crystalline transition that can be estimated in at least 105 K. At 40 AU the timescale for the complete amorphization of the surface ice layer responsible for the observed spectra can be estimated to be of $\sim 10^7$ yr, knowing the amount of cosmic rays and solar wind ions flux (Cooper et al. 2003). That time is much less than the Solar System age and imply that Quaoar surface must have been resurfaced with new crystalline ice or has suffered a surface temperature rise during the last 10^7 yr. We agree with those argumentation and support the authors hypothesis that resurfacing mechanism must exists on Quaoar, probably cryovolcanism.

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