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ISO-SWS observations of solid state features towards RAFGL 7009S *

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Abstract. We report the detection of various solid state molecular features in the SWS01 spectrum of a protostellar object, RAFGL 7009S. Identified molecules include H_2O, CO, CO_2 together with $^{13}CO_2$ and CH_4. Other less firmly identified features are observed that appear in laboratory spectra of UV photolysed ices. We thus confirm the previous detection of CO_2 in the IRAS-LRS spectra of a number of embedded sources and present the detection of solid CH_4. In addition, we estimate the column densities of some solid state species towards RAFGL 7009S. Due to its extreme extinction this source represents a unique target for the detection of weak solid state absorption features, that are commonly observed in laboratory experiments.

Key words: ISM: molecules – ISM: abundances – ISM: dust, extinction – ISM: individual: RAFGL 7009S

1. Introduction

The presence of grain mantles made of simple ices such as H_2O, CO, CH_3OH, etc. has been confirmed by numerous ground based observations towards dense clouds (Willner et al. 1982, Grim et al. 1991). The primary astronomical targets for infrared spectroscopy of ices are protostars which contain circumstellar and cold foreground material. Energetic UV processing of icy grain mantles near protostars or in dense clouds enables the formation of new molecules and radicals. It has been shown that molecules like CO_2, H_2CO and others are easily formed in laboratory simulations of interstellar ice analogues (d'Hendecourt et al. 1986). Several molecules have been identified with ground based observations in comparison with laboratory spectra of astrophysically relevant ice mixtures (see Whittet 1993 for a review). However, many solid state features display their infrared transitions in regions obscured by the Earth atmosphere and the SWS instrument on-board ISO allows for the first time their detection.

Water ice, the most common constituent of interstellar grain mantles is observed around 3 μm (OH stretch), at 6 μm (OH bend) and with more difficulty at 13.5 μm (libration mode, Cox 1989). Other less abundant constituents detected up to now are CO, CH_3OH, as well as the general signature of hydrocarbons. In IRAS-LRS spectra, CO_2 has been detected towards a few protostars through its bending mode at 15.2 μm (d'Hendecourt & Jourdain de Muizon 1989) and re-analysis of IRAS spectra indicated that CO_2 is a widespread component in interstellar ices (d'Hendecourt & Ehrenfreund 1996). The detection of CO_2 was unambiguous thanks to laboratory simulations, where CO_2 is formed as a photoproduct from H_2O/CO ice mixtures. First ISO results led to fundamental new discoveries concerning the grain mantle composition. The ubiquitous presence of CO_2 has been confirmed through the strong stretching mode at 4.27 μm in different interstellar environments (de Graauw et al. 1996, this volume). In RAFGL 7009S, we report the detection of the following solid state molecular features: H_2O, CO, XCN, $^{12}CO_2$, $^{13}CO_2$ and CH_4. The presence of H_2CO and OCS (or CO_3) as well as various hydrocarbons is suggested by the overall identification with laboratory spectra of UV irradiated ices. We estimate column densities for some of the above mentioned molecules towards this extinct target.

2. Experimental

2.1. Laboratory spectroscopy

To produce interstellar ice analogues in the laboratory, gas mixtures were condensed in a high vacuum chamber on a cooled

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CsI window (12 K). The samples were photolysed with an UV lamp to simulate the interstellar radiation field. Infrared spectra were recorded with a Brucker FTS-IFS 66v spectrometer at a resolution of 2 cm^{-1}, well adapted for solid state features and compatible with our ISO-SWS data, allowing direct comparison.

2.2. Data reduction procedure

RAFGL 7009S has been observed on April 17th, 1996 with the SWS in mode AOT01 (full grating scan, speed 3). Manual data reduction started from SPD–level (Standard Processed Data) using the Interactive Analysis (IA) software as installed at the ISO Science Operations Center (SOC) in VILSPA. The reduction was done following the recommendations of the calibration scientists in the SWS Instrument Dedicated Team (IDT) and using the latest calibration files. The final spectrum was rebinned to a resolution of R=500. However, the calibration of the spectrum is still preliminary and fine tuning of the data will need further work.

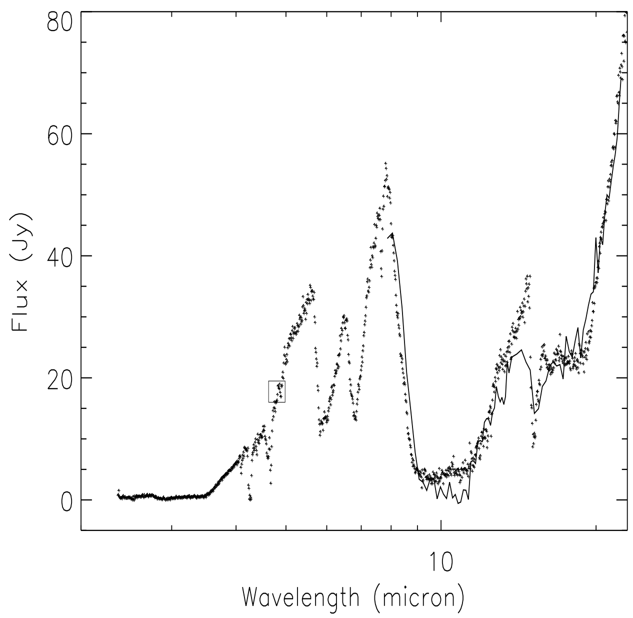

Fig. 1. A comparison between ISO SWS01 reduced spectrum of RAFGL 7009S (points) and the data already available for this source: a bandpass filter measurement at 4.8 μm (square) obtained at UKIRT and the IRAS-LRS spectra (full line). The agreement in flux is well within 10 %. Between the two strong silicate absorption features at 9.7 and 18 μm, the 15.2 μm absorption, somewhat smoothed out in LRS spectra, is quite prominent. Former identification of this feature with solid state CO_2 is further confirmed by the presence of the strong (saturated) absorption at 4.27 μm (stretching mode).

3. Results

The source RAFGL 7009S was selected on the basis of its 8–22 μm IRAS–LRS spectrum, showing the presence of a very deep, saturated, silicate feature, on the long-wavelength wing of which H_2O and CO_2 ice bands are clearly present. The infrared spectrum of RAFGL 7009S shows many similarities with that of W33A, a well-known protostellar-type object already thoroughly studied in the infrared. The depth of the water ice and silicate features in both sources, as well as the huge extinction evidenced from the near-infrared photometry make us believe that the two objects are very similar. From the IRAS colour-corrected flux densities, the far-infrared spectrum of RAFGL 7009S shows a ν dependence $f_\nu = \nu^\alpha$ with $-2.5 \leq \alpha \leq -2.0$, whereas for W33A it is $-3.5 \leq \alpha \leq -2.0$, in both cases α increasing with wavelength.

In Fig. 1 we present a comparison between the IRAS-LRS and the ISO-SWS01 spectra towards RAFGL 7009S. The comparison shows (i) that the solid CO_2 feature is readily identified and (ii) the flux calibration of both spectra agrees within 10 %. The SWS01 spectrum of RAFGL 7009S between 2.5 and 18 μm is displayed in Fig. 2. The source has such a high extinction that H_2O at 3 μm, CO_2 at 4.27 μm and the prominent silicate absorption at 9.7 μm are deeply saturated. The spectrum shows solid state features due to CO_2 and CH_4, H_2O, CO, XCN, H_2CO and a feature at 4.9 μm which can be attributed either to OCS or CO_3. Superimposed on the spectrum we display a laboratory spectrum of a photolysed polar ice mixture containing H_2O:CO:CH_4:NH_3:O_2=10:2:1:1:1. Between 4.6-4.7 μm the presence of the XCN feature (which may be contaminated by gaseous CO) together with the solid CO band is easily recognized in the astronomical source as well as in the laboratory spectrum (XCN somewhat smaller). The XCN band was first detected by Lacy et al. (1984) in the protostellar object W33A. A small feature at 4.9 μm looks similar to the one observed in W33A and may be due to OCS (Geballe et al. 1985, Palumbo et al. 1995). However, photolysis of CO_2 ice efficiently produces CO_3 which absorbs at the same wavelength (Gerakines et al. 1996). The OH bending mode of water ice at 6 μm and the unidentified 6.85 μm feature are prominent bands as seen towards many other protostellar sources. The match between the 6 μm feature obtained in the laboratory after UV photolysis is quite satisfactory. Compared to pure H_2O, the width and shape of the feature has been described in terms of production of C=O containing species, in particular H_2CO at 5.81 μm (d'Hendecourt et al. 1986). In the SWS-AOT06 spectrum of RAFGL 7009S (open time) H_2CO is clearly detected with an abundance of $\sim$ 3 % relative to water ice (d'Hendecourt et al. 1996). The 6.85 μm band, although present in the laboratory spectra and appearing upon photolysis (formation of saturated hydrocarbons) is weak and far from explaining the observed depth.

Fig. 3 a and b shows respectively the stretching mode of CO_2 at 4.27 μm (as well as $^{13}CO_2$ at 4.38 μm) and the ν_4 deformation mode of CH_4. Comparison is made with laboratory spectra. Note that in the astronomical source the CO_2 stretch appears saturated, so that a direct fit can only be obtained for the $^{13}CO_2$ band.

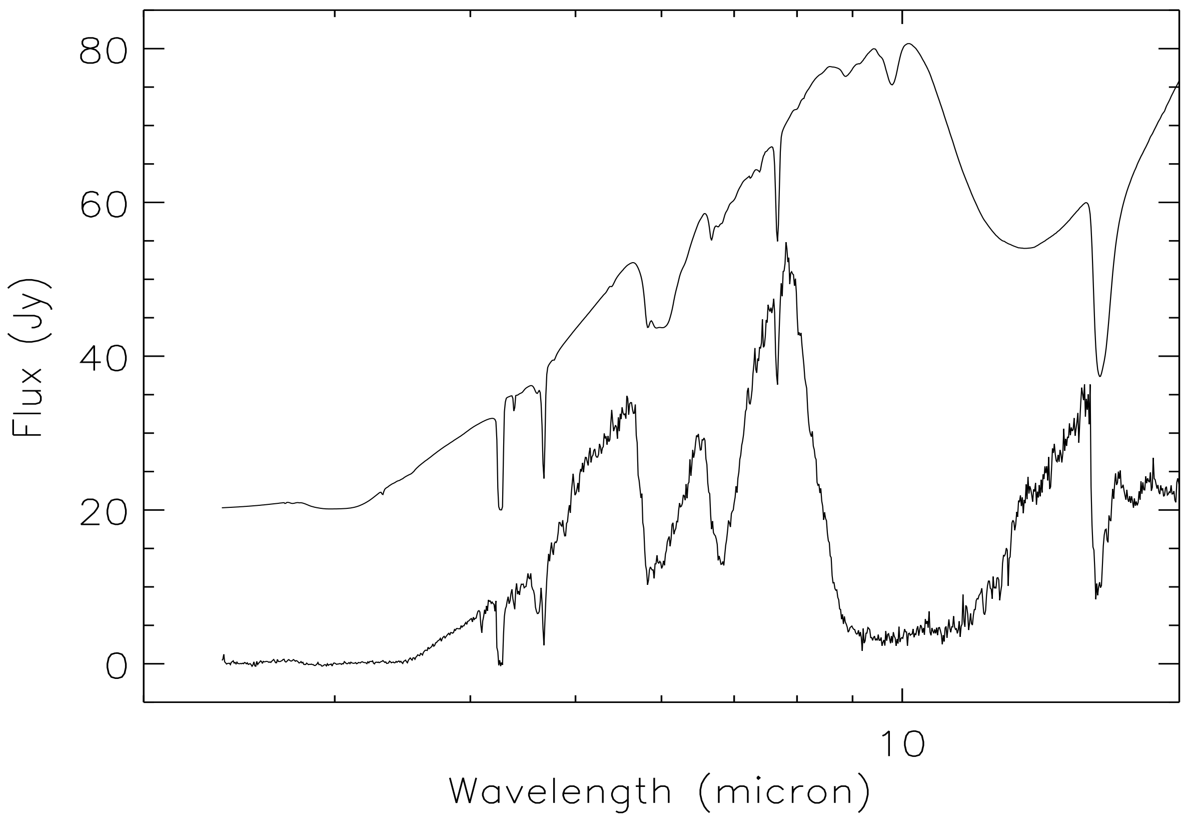

Fig. 2. SWS01 spectrum of the source RAFGL 7009S between 2.5 and 18 μm (bottom), compared with a laboratory spectrum of a photolysed ice mixture H_2O:CO:CH_4:NH_3:O_2=10:2:1:1:1 (top). Since the astronomical spectrum can be taken as a transmittance spectrum of a continuum through the cold dense medium, the laboratory spectrum has been multiplied by a 485 K black-body continuum. From left to right, the following absorptions can be noted: at 3 μm the H_2O ice band (totally saturated), at 4.27 μm the $^{12}CO_2$ and at 4.38 μm the $^{13}CO_2$ stretching mode. Between 4.6-4.8 μm the CO band appears together with the broad XCN component. The bending mode of H_2O at 6 μm is strongly modified by UV photolysis. The prominent 6.85 μm absorption, unidentified until now, is somewhat present in the laboratory mixture. At 7.7 μm a clear cut CH_4 absorption can be observed. The strong (saturated) silicate feature falls at 9.7 μm and its reproduction has not been attempted in our laboratory spectrum. The 13 μm libration mode of water ice is responsible for the dip between the two silicate features (at 10 and 18 μm). Finally the bending mode of CO_2 at 15.2 μm shows a three peak structure, indicating the presence of CO_2 in polar and apolar ices. The dip at 4.1 μm is an artefact and due to the overlap of the two AOT bands 1E and 2A. The laboratory spectrum has been shifted up by 20 Jy.

Comparing with laboratory measurements we derive abundances of some ice components towards RAFGL 7009S, listed in Table 1. The abundances from H_2O and $^{12}CO_2$ have been estimated from their respective bending modes and have a limited accuracy. The H_2O bending mode is contaminated by other molecules so that the derived column density represents an upper limit. The uncertainties in the continuum level at 15 μm might influence the abundance measurement of solid CO_2. The derived $^{12}CO_2$/$^{13}CO_2$ ratio of about 60 has to be further investigated. The improvement of reduction methods during the ISO mission will help to reveal important weak solid state features in this source.

4. Discussion

In this section we discuss the results in the general frame of the gas-grain chemistry in the dense interstellar medium. According to classical models, grains accrete mostly hydrates when the densities are low and H is dominant in the gas phase (d'Hendecourt et al. 1985). At late stage of cloud evolution, when atomic hydrogen is converted to H_2, molecules such as O_2, N_2 and CO populate the grain mantles. The subsequent evolution (thermal and UV photoprocesses) of the mantle leads to the formation of more complex molecules such as CO_2, H_2CO, CH_3OH and some hydrocarbons, which can be well simulated in the laboratory. Surface reactions creating CO_2 from CO and O, or formation of H_2CO by grain surface hydrogenation upon CO is another possible scenario considering the long timescales in interstellar space.

The spectrum of RAFGL 7009S displays a large number of solid state features, some of them for the first time detected in astronomical spectra. A large amount of solid CO_2 ($> 20\%$) has been detected towards RAFGL 7009S and addi-

Table 1. Column densities of solid state features towards RAFGL 7009S (using the measured band intensities A_m from Gerakines et al. 1995 for H_2O, CO and CO_2 and d'Hendecourt & Allamandola 1986 for CH_4).

Species	Wavelength	A_m	Column density
	μm	cm.mol^{-1}	cm^{-2}
H_2O	6.0	1.2 x 10^{-17}	1.1 x 10^{19}
CO	4.67	1.1 x 10^{-17}	1.8 x 10^{18}
$^{12}CO_2$	15.2	1.1 x 10^{-17}	2.5 x 10^{18}
$^{13}CO_2$	4.38	7.8 x 10^{-17}	4.0 x 10^{16}
CH_4	7.7	6.4 x 10^{-18}	4.3 x 10^{17}

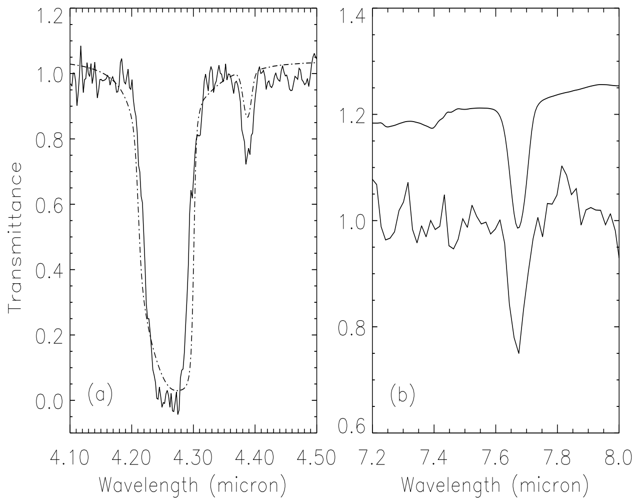

Fig. 3. A comparison between two laboratory features and those observed in RAFGL 7009S. (a) the $^{12}CO_2$ and $^{13}CO_2$ bands. For the $^{12}CO_2$ being saturated in the astronomical source, no precise match is attempted here. Note the strong absorption due to $^{13}CO_2$ which can be well fitted with an ice mixture H_2O:CO_2=2:1 (b) the deformation mode of CH_4 in the laboratory data (top) as compared to the astronomical feature. CH_4 resides in the polar phase, can be well matched with a mixture H_2O:CH_4=10:1

tionally solid CH_4 with an abundance of $\sim$ 4% compared to water ice. The profiles of CO and CO_2 indicate the presence of polar and apolar ices in the line of sight (Ehrenfreund et al. this volume, Ehrenfreund et al. 1996). A global comparison of the SWS01 spectrum of RAFGL 7009S with laboratory data is shown in Fig. 2. In this figure it is striking that most of the solid state features which are produced in the laboratory ices are found in the spectrum of RAFGL 7009S. The exceptions are naturally the two silicate features, not simulated in the laboratory. Another notable exception is the 6.85 μm band, whose exceptional depth cannot be produced in simple ices. The origin of this band has been suspected to come from hydrocarbons, CH_3OH, NH_4^+ and other candidates (Whittet 1993). Indeed, in our photolysed ices a weak 6.85 μm band does appear and can be attributed to the presence of various hydrocarbons. Another potential candidate for this band has been discussed by Hecht et al. (1986) and could be an amorphous mineral such as $MgCO_3$. Arguments against the carbonate identification have been discussed by Tielens & Allamandola (1987). Carbonates show additional weaker bands between 10-15 μm, which are up to now not observed in astronomical spectra. The strengths of those bands at longer wavelengths are however determined by the structural order of the carbonate and seem to be very weak in amorphous material (Knacke & Kraetschmer 1980). Due to the large amounts of solid CO_2 in the interstellar medium, reaction products such as carbonates, CO_3, O_3 and many others may play an important role in interstellar chemistry. We summarize that ISO-SWS observations have revealed for the first time a large number of important solid state features and many weak bands still await detection towards this extinct target RAFGL 7009S.

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