Astron. Astrophys. 334, 1056–1059 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Solid CO_2 towards NGC7538 IRS1*

G. Strazzulla[1], B. Nisini[2], G. Leto[3], M.E. Palumbo[1], and P. Saraceno[2]

[1] Osservatorio Astrofisico di Catania, V.le A. Doria 6, I-95125 Catania, Italy
[2] CNR Istituto di Fisica dello Spazio Interplanetario, CP27, I-00044 Frascati, Italy
[3] CNR Istituto di Radioastronomia, Stazione di Noto, Siracusa, Italy

Received 22 October 1997 / Accepted 19 February 1998

Abstract. We report the observation of the young infrared source NGC7538 IRS1 with the Short Wavelength Spectrometer (SWS) onboard the ISO satellite in the 2.4-45 μm range. The spectrum exhibits several absorption features due to silicates and to molecular species frozen on the refractory dust. In particular the stretching and bending mode of solid CO_2 have been identified. In this paper we present a comparison of the observed absorption band at about 15.1 μm (660 cm^{-1}) attributed to the bending mode of solid CO_2 with laboratory spectra of ion irradiated ice mixtures.

Key words: ISM: molecules – dust, extinction – infrared: ISM: lines and bands – ISM: individual objects: NGC7538 IRS1

1. Introduction

Infrared observations have clearly shown the presence of absorption features (e.g., at 3.1, 4.67, 4.9, 6.0, 6.8, μm) along the line of sight of embedded young stellar objects and field stars obscured by dense molecular clouds. These features are characteristic of simple molecules such as H_2O, CO, OCS, CH_3OH in the solid state. These molecules are believed to be frozen in icy grain mantles formed by accretion (e.g., CO) or reaction of gas phase species (e.g., H and O to form H_2O) onto preexisting refractory grain cores.

On the basis of laboratory experiments and theoretical calculations it has been possible to predict the presence of solid CO_2 in icy grain mantles (Tielens & Hagen 1982; d'Hendecourt et al. 1985). However because of telluric absorption its detection is impossible with ground-based and airborne telescopes. D'Hendecourt & Jourdain de Muizon (1989) have reported the detection of the CO_2 bending mode at about 15.2 μm with the low resolution spectrometer (LRS) on board IRAS along the line of sight of 3 infrared sources. Whittet & Walker (1991) carried out a systematic search of the LRS database for sources known to have the 3 μm absorption feature and found no discernible 15.2 μm absorption band except the ones already studied by D'Hendecourt & Jourdain de Muizon (1989).

With the Infrared Space Observatory it is now possible to observe both the stretching and bending modes of solid CO_2. In fact solid CO_2 has already been detected with ISO-SWS and ISOPHOT-S along the line of sight of several embedded sources (de Graauw et al. 1996a; Whittet et al. 1996; Gürtler et al. 1996) showing that it is a ubiquitous constituent of icy grain mantles in molecular clouds.

NGC7538 is a complex of HII regions and molecular clouds of about one degree of diameter situated in the Perseus spiral arm at $\sim$2700 pc. South-east of the centre of the visible nebula three very compact HII regions called NGC7538 IRS1, IRS2, and IRS3 are found. IRS1 has infrared properties characteristic of pre-main sequence objects and appears to be the youngest and the most luminous (more than 10^4 $L_\odot$) of the three sources. Being a very luminous source still embedded in the dense dusty envelope in which the star is forming, IRS1 is a perfect candidate for studying interstellar absorption features. Indeed, features of H_2O (at 3 μm), CO (at 4.67 μm) and CH_4 (at 7.6 μm) ices have been observed towards this source from the ground (Willner et al. 1982; Lacy et al. 1984, 1991).

2. Observations and data reduction

The observations were obtained with the Short Wavelength Spectrometer (SWS; de Graauw et al. 1996b) on board the ISO satellite (Kessler et al. 1996). A complete spectrum (2.4 to 45 μm) of NGC7538 IRS1 has been taken in grating mode AOT01 at speed 2 with an effective resolution of about 250, during revolution 91 pointing at $23^h 11^m 36.6^s$ $61^\circ 11' 49.0''$, 1950.

The raw data were reduced using the standard ISO-SWS reduction procedure (OLP version 5.1); subsequent analysis consisted in removing spurious signals due to cosmic ray impacts and rebinning the data at the instrumental resolution. To reduce the noise due to inaccuracies in the flux calibration of the different detectors, before rebinning the detector scans were scaled to each other by fitting straight lines and multiplying each scan to the mean level.

Send offprint requests to: M.E. Palumbo

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.

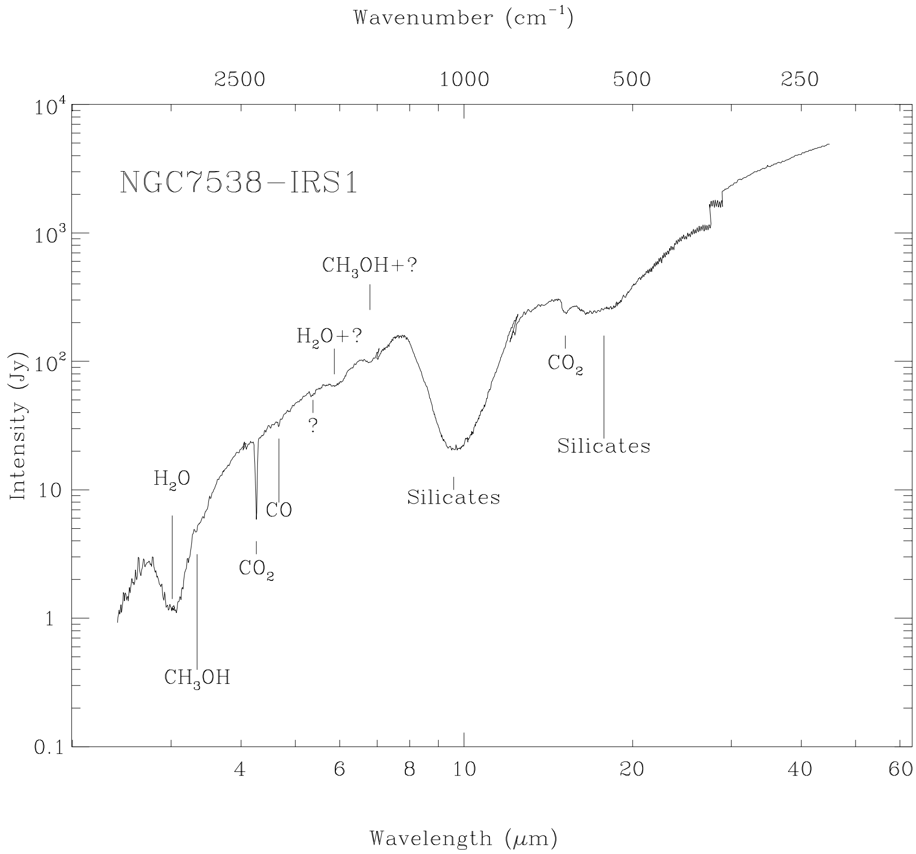

Fig. 1. SWS spectrum of NGC7538 IRS1 in the 2.4-45 μm region. Labels refer to solid state absorption features.

3. Results

Fig. 1 shows the whole SWS spectrum of NGC7538 IRS1 in the 2.4-45 μm region. The spectrum presents several absorption features attributed to silicates and to frozen species such as H_2O, CO, CH_3OH while other features still remain unidentified.

The absorption bands at about 4.27 μm (2340 cm^{-1}) and 15.1 μm (660 cm^{-1}) are attributed to the stretching and bending mode of solid carbon dioxide (CO_2) respectively. We have estimated from both bands an abundance of solid CO_2 of about 3.4×10^{17} molecules/cm^2 (using the integrated absorbance values A=7.6×10^{-17} cm/molecule and 1.28×10^{-17} cm/molecule for the stretching and bending mode respectively; Yamada & Person 1964) and from the 3 μm band an abundance of solid H_2O of about 1.5×10^{18} molecules/cm^2 (using A=2×10^{-16} cm/molecule; Hagen et al. 1981) which give a relative abundance of carbon dioxide to water ice of about 22%. This is similar to the values observed towards other sources (de Graauw et al. 1996a; Gürtler et al. 1996).

Because of the low resolution of our spectrum, the only ice band that we can compare with laboratory spectra is the bending mode of CO_2. In fact in this spectral region resolution is about 2 cm^{-1}. This band shows a double structure with peaks centered at 656 cm^{-1} and 662 cm^{-1}.

Preliminary comparisons of laboratory spectra of icy mixtures containing CO_2 with the ISO spectra (de Graauw et al. 1996a) have shown that it is not possible to find a single spectrum which fits the CO_2 observed bands and it has been suggested that the observed features are due to the sum of at least two independent components. In particular a combination of a polar mixture (dominated by H_2O) with a nonpolar mixture (dominated by CO_2) has been used. However these fits do not attempt to reproduce narrow substructure in the profiles of the bending mode. In fact it is not possible to find different laboratory spectra which fit each subpeak separately and most laboratory spectra of CO_2 in several mixtures do not show substructure in the bending profile. Among astrophysically relevant mixtures, only the bending mode of pure CO_2 and O_2:CO_2 mixtures show a substructure. However in the case of pure CO_2 particle shape effects modify the band profile and good fits to the observed bands are only obtained for a very restrictive set of parameters (de Graauw et al. 1996a), similarly in O_2:CO_2 mixtures subpeaks are very sensitive to matrix conditions and concentrations. In particular Ehrenfreund et al. (1997) have studied several ice mixtures containing CO_2. As an example in CO:O_2:CO_2 mixtures the bending mode shows two peaks which shift from 658.7 and 661 cm^{-1} in a 100:50:4 mixture at 10 K to 658.2 and 662.2 cm^{-1} in a 100:50:32 mixture and in some cases also a third peak at 662.7 appears. In H_2O:CO_2 mixtures (Sandford & Allamandola 1990) the peak position of the CO_2 bending mode shifts from 653.3 cm^{-1} in a 50:1 mixture to 654.7 in a 1:1 mixture. When CO_2 is produced after ion irradiation of ice mixtures (Palumbo et al. 1998) the peak position of the bending mode varies from 651 cm^{-1} in a H_2O:CH_3OH=2:1 mixture to 661 cm^{-1} in a CO:N_2=1:1 mixture. The CO_2 bending mode observed towards obscured objects shows subpeaks at about 656 cm^{-1} and 662

cm^{-1} (de Graauw et al. 1996a; this work). In the case of GL 2136 also a third peak at about 649 cm^{-1} appears (de Graauw et al. 1996a). It is interesting to note that the relative intensity of these peaks changes from source to source suggesting that different components (polar, nonpolar, other?) give a different relative contribution along different lines of sight probably depending on the different thermal and energetic processing of the dust.

We have compared the band due to the bending mode in NGC7538 IRS1 with several laboratory spectra of ion irradiated mixtures[1]. CO_2 is in fact easily produced by ion irradiation of ice mixtures containing C-bearing and O-bearing species (Strazzulla et al. 1997; Palumbo et al. 1998). Again, in most cases, the bending mode of CO_2 produced doesn't show subpeaks. This is not the case when CO_2 is produced after ion irradiation of CO:O_2 mixture (see Fig. 3 in Palumbo et al. 1998). Fig. 2 shows the profile of the CO_2 bending mode produced after ion irradiation of CO at 10 K and warmed up to 20 K and 40 K. It is interesting to note that the band profile changes significantly at 40 K. At this temperature most of the original CO has sublimated; most CO_2 produced leave the target with CO while some is left over trapped in a suboxides matrix (Palumbo et al. 1998). The profile of the bending mode band in this case shows a substructure which however is different from that of pure CO_2.

Fig. 3 shows a comparison of the observed feature (crosses) with the laboratory spectra of CO_2 produced after ion irradiation of CO at 10 K and warmed-up to 40 K (dashed line) and of CO_2 produced in a H_2O:CH_3OH mixture (100 K; dotted line). The solid line is the sum of the two independent components. Also in this case it is then possible to separate a nonpolar and a polar component which contribute comparably to the optical depth of the observed feature. Furthermore the substructure in the profile seems to be well reproduced.

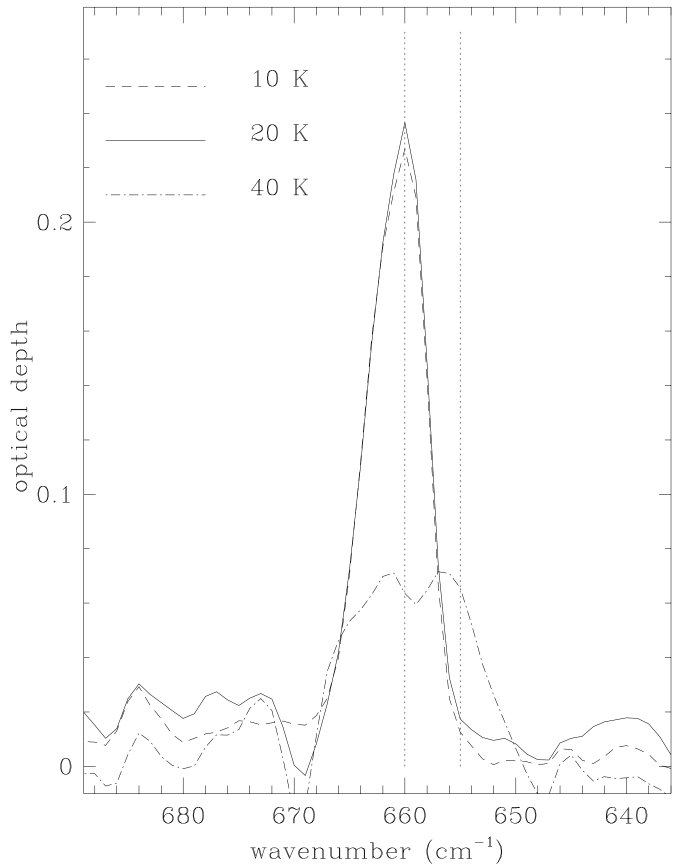

Fig. 2. Laboratory spectra of the CO_2 bending mode produced after ion irradiation of CO at 10 K (12 eV/16amu; dashed line) and after warmup to 20 K (solid line) and to 40 K (dot-dash line). Dotted lines at 660 cm^{-1} and 655 cm^{-1} which indicate peak positions of the bending mode in pure CO_2 (Sandford & Allamandola 1990) have been drawn for reference.

4. Discussion

CO_2 is not predicted to have appreciable abundance in the gas phase in the interstellar medium (e.g., Herbst & Leung 1986) so that its condensation on interstellar grains can be neglected. Thus its presence may be due to reaction of gas-phase species on grain cores or to energetic processing such as UV and particle irradiation. Indeed laboratory experiments have shown that CO_2 is produced after UV and ion irradiation of astrophysically relevant ices (Gerakines et al. 1996; Palumbo et al. 1998). The comparison reported in Fig. 3 shows that along the line of sight of NGC7538 IRS1 ice mantles could have suffered energetic processing and warmup. This latter is probably due to the temperature gradient along the circumstellar envelope caused by the forming star which is heating up its surroundings. The former, simulated in laboratory by ion irradiation, could be caused by particle irradiation due to stellar flares and/or low energy cosmic rays (Teixeira et al. 1998 and references therein). Another possibility could be UV irradiation. However in this case the UV photons emitted by the embedded object are not able to penetrate the thick envelope and are absorbed by the material close to the star, then the UV field inside the cloud would be responsible for the processing of icy grain mantles. If this is the case the same processing should occur in quiescent interstellar clouds. In this view it would be very interesting to compare the profile of the CO_2 bands along the line of sight of embedded objects with those to be observed towards field stars in order to evaluate the relative importance of energetic processing (UV vs ions) on ice mantles.

Furthermore also fits of the solid CO band profile observed towards several obscured infrared objects have pointed to ice mantles that could have suffered energetic processing and warmup (Palumbo & Strazzulla 1993; Teixeira et al. 1998). In addition the observed CO bands have been fitted with the same laboratory mixtures used above. A further support to these results will be given by the simultaneous comparison of the high resolution profile of the stretching and bending modes of CO_2 and CO towards NGC7538 IRS1 and all other sources with the same laboratory spectra. This will be done when ISO high resolution spectra are available to the scientific community.

[1] A description of the experimental apparatus, the data analysis, and the laboratory infrared spectra can be found in Palumbo et al. (1998)

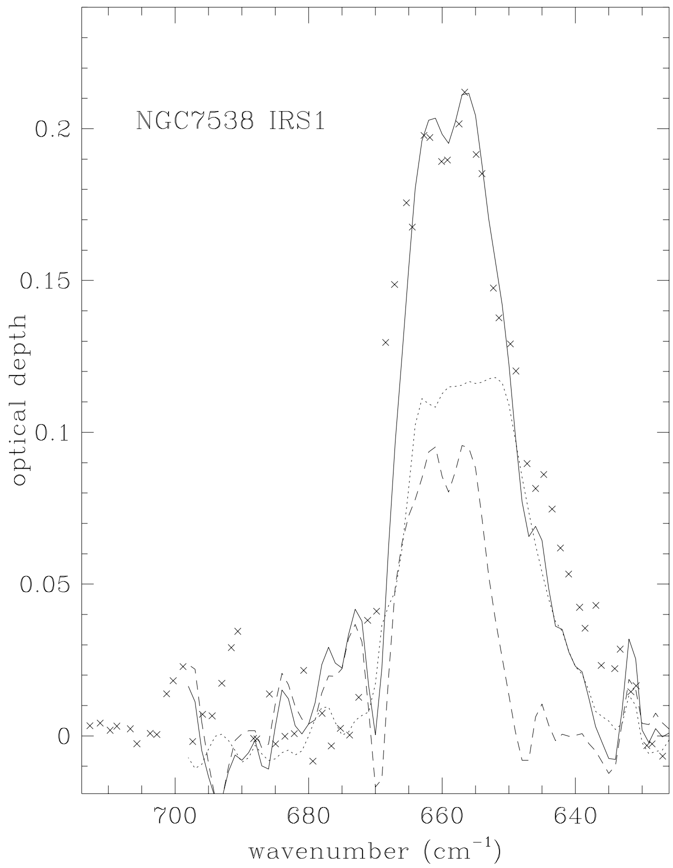

Fig. 3. Comparison of the observed bending mode (crosses) with laboratory spectra of CO_2 produced after ion irradiation of CO at 10 K and warmed-up to 40 K (dashed line) and of CO_2 produced in a H_2O:CH_3OH mixture (100 K; dotted line). The solid line is the sum of the two components.

Finally, it has often been pointed out that composition of ice mantles in the interstellar medium might be similar to that of comets (e.g., Mumma et al. 1993), suggesting that comets are a direct aggregate of interstellar dust after a modest processing in the solar nebula. After the estimation of the abundance of CO_2 in icy mantles (15-20% with respect to water) which is significantly higher than that observed in comets (a few percent with respect to water) this model on the origin of comets seems to have an additional problem.

Acknowledgements. These observations are part of the LWS-Guaranteed Time Program and as such are the results of a joined effort of all the ISO-LWS team. B. Nisini wishes to thank the SRON in Groningen for its hospitality for processing the data, and in particular Adwin Boogert for his kind assistance in the data reduction. This research has been financially supported by the Italian Space Agency (ASI), the italian Consiglio Nazionale delle Ricerche (CNR) and the Ministero dell'Università e della Ricerca Scientifica e Tecnologica (MURST).

References

de Graauw Th., Whittet D.C.B., Gerakines P.A., et al., 1996a, A&A, 315, L345
de Graauw Th., Hasen L.N., Beintema D.A., 1996b, A&A, 315, L49
d'Hendecourt L.B., Allamandola L.J., Greenberg J.M., 1985, A&A 152, 130
d'Hendecourt L.B., Jourdain de Muizon M.J., 1989, A&A 223, L5
Ehrenfreund P., Boogert A.C.A., Gerakines P.A., et al., 1997 A&A 328, 649
Gerakines P.A., Schutte W.A., Ehrenfreund P., 1996, A&A 312, 289
Gürtler J., Henning Th., Kömpe C., et al., 1996, A&A 315, L189
Hagen W., Tielens A.G.G.M., Greenberg M.J., 1981, J. Chem. Phys. 75, 4198
Herbst E., Leung C.M., 1986, MNRAS 222, 689
Kessler M.F., Steinz J.A., Anderegg M.E., et al., 1996, A&A 315, L27
Lacy J.H., Baas F., Allamandola L.J., et al., 1984, ApJ 276, 533
Lacy J.H., Carr J.S., Evans II N.J., et al., 1991, ApJ 376, 556
Mumma M.J., Weissman P.R., Stern A., 1993, in Planets and Protostars III, Levy E.H., Lunine J.J., and Matthews M.S., (eds.), Univ. of Arizona Press, Tucson, 1177
Palumbo M.E., Strazzulla G., 1993, A&A 269, 568
Palumbo M.E., Baratta G.A., Brucato J.R., et al., 1998, A&A in press
Sandford S.A., Allamandola L.J., 1990, ApJ 355, 357
Strazzulla G., Brucato J.R., Palumbo M.E., Satorre M.A., 1997, A&A 321, 618
Teixeira T.C., Emerson J.P., Palumbo M.E., 1998, A&A 330, 711
Tielens A.G.G.M., Hagen W., 1982, A&A 114, 245
Whittet D.C.B., Walker H.J., 1991, MNRAS 252, 63
Whittet D.C.B., Schutte W.A., Tielens A.G.G.M., et al., 1996, A&A 315, L357
Willner S.P., Gillett F.C., Herter, T.L., et al., 1982, ApJ 253, 174
Yamada H., Person W.B., 1964, J. Chem. Phys. 41, 2478