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Detection of an absorption feature at the position of the 4.27-μm band of solid CO_2*

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Abstract. We report observations of 13 young infrared sources associated with molecular clouds with ISO's spectrophotometer ISOPHOT-S in the wavelength range from 2.5 to 11.6 μm. In addition to a number of well-known interstellar bands due to various molecular ices, a new band at 4.27 μm was detected, which is very likely attributed to C=O stretching vibrations of solid CO_2. This new band is seen in all our sources. Thus, CO_2 seems to be a common constituent of icy grain mantles in molecular clouds. The strength of the band increases with the strengths of the CO and H_2O bands. We estimate that CO_2 and CO may be present in comparable amounts in the mantles. The implications for the models of interstellar chemistry are briefly discussed.

Key words: ISM: dust, extinction – infrared: ISM: lines and bands

1. Introduction

The near- and mid-infrared spectral regions have turned out to be a bonanza for the investigation of the composition of interstellar dust grains. A common aspect of current dust models is that grains in molecular clouds acquire mantles of volatile material around their refractory cores. Many solids that are considered important as components of interstellar dust, such as silicates and various ices including H_2O, CO, CO_2, NH_3, and CH_4, show bands in the near and mid infrared. In recent years, spectroscopy from the ground, aircraft and space has continuously improved our knowledge of the composition of interstellar grains in molecular clouds and enlarged the list of compounds identified as their constituents (see, e. g., Dorschner & Henning (1995) for a recent review).

An important open question is the abundance of CO_2 in the grains. Its detection in astronomical sources with ground-based or air-borne instruments is made impossible by absorption due to telluric CO_2. Model calculations of grain surface chemistry predict appreciable amounts of this molecule, but the precise reaction path leading to this molecule is still open to debate (Tielens & Hagen 1982; d'Hendecourt et al. 1985; Hasegawa, Herbst & Leung 1992). Laboratory experiments involving energetic processing (UV irradiation, particle bombardment) of interstellar ice analogues containing CO easily produce CO_2, yet the role of such energetic processes for the composition of grain mantles is unclear.

D'Hendecourt & Jourdain de Muizon (1989) reported the detection of a band at 15.2 μm in the IRAS LRS spectra of the three infrared sources AFGL 961, AFGL 989, and AFGL 890, which they attribute to C=O bending vibrations of CO_2. However, this identification has been controversial, and it remained unclear how widespread this feature is in the interstellar medium (Whittet & Duley 1991).

The Infrared Space Observatory (ISO) with its spectrographic capabilities for the first time provides the opportunity to search for the strongest mid-infrared band of CO_2, which is due to C=O asymmetric stretching vibrations and lies near 2340 cm^{-1} (4.27 μm). The Short-Wavelength Spectrometer (SWS) offers high spectral resolution and is well suited for the detailed investigation of band profiles. The ISOPHOT-S grating spectrometer is, because of its significantly higher sensitivity, ideal for the survey of larger numbers of sources. Here we report on the detection of a band at 4.27 μm in the ISOPHOT-S spectra of 13 infrared sources associated with molecular clouds.

2. Observations and data reduction

The observations were carried out using the spectrophotometer subsystem of ISO's imaging photo-polarimeter ISOPHOT. This subsystem consists of two low-resolution grating spectrometers

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covering the wavelength ranges from 2.5 to 5 μm (PHT-SS) and from 5.8 to 11.6 μm (PHT-SL). Each spectrometer has a linear array of 64-element Si:Ga detectors. The common entrance aperture is $24'' \times 24''$. The spectral resolution is about 85 for PHT-SS and about 95 for PHT-SL. For a more detailed description of the instrument see Lemke et al. (1996). The data processing was done using the PHT Interactive Analysis (PIA) software made available by the ISOPHOT Data Centre of the Max-Planck-Institut für Astronomie, Heidelberg.

3. Results and discussion

The goal of this study was to investigate the composition of interstellar dust grains in molecular clouds. For this purpose, we observed 13 infrared sources associated with molecular clouds. These sources have been selected because their spectra show both a deep 10-μm silicate band (measure for amount of refractory dust) and the water ice band at 3.0 μm (indicator of grain mantels). Figure 1 presents the spectrum of W33A and Cepheus A as illustrative examples. All our spectra clearly show a number of absorption bands due to various ices; these features are listed in Table 1. Most of these features are already known from ground-based or airborne observations. The spectral resolution of PHT-S is not sufficient to separate clearly the 'XCN' at 4.62-μm from the generally stronger CO band at 4.67 μm. The presence of the OCS band at 4.9 μm is also difficult to check because of the wavelength gap in the spectrum between 5.0 and 5.8 μm.

An new, relatively narrow feature has been detected at 4.27 μm. This band is visible in the spectra of each of our sources, implying that its carrier is a very common constituent of interstellar dust in the environment of embedded sources. Based on the laboratory data from Sandford & Allamandola (1990) and the current ideas of interstellar grain chemistry it seems very likely that this newly detected absorption feature can be identified with C=O asymmetric stretching vibrations of solid CO_2. It is clear that an identification based on our data alone has to be considered as preliminary. However, observations with ISO's Short-Wavelength Spectrometer have confirmed our assignment (de Graauw et al. 1996). The detection of the 4.27-μm CO_2 band in the spectra of all our sources indicates that CO_2 is a very common constituent of icy interstellar dust grains.

Quantitative estimates for the optical depths or the equivalent widths of the 4.27-μm band are difficult to make because the spectral resolution of ISOPHOT-S is not high enough. From the observed spectra, we can derive the *apparent* optical depth defined by

$$\tau_{\rm app} = -\ln \frac{\Phi_{\rm obs}(\lambda_{\rm c})}{\Phi_{\rm c}(\lambda_{\rm c})},$$

where $\Phi_{\rm obs}(\lambda_{\rm c})$ is the observed flux, $\Phi_{\rm c}(\lambda_{\rm c})$ is the flux of the undisturbed continuum within the absorption band, interpolated by means of a 3rd-order polynomial fitted to the adjacent continuum, and $\lambda_{\rm c}$ is the central wavelength of the pixel in question. We list the apparent optical depths and their rms errors in Table 2. The observed fluxes $\Phi_{\rm obs}(\lambda_{\rm c})$ were deconvolved with the

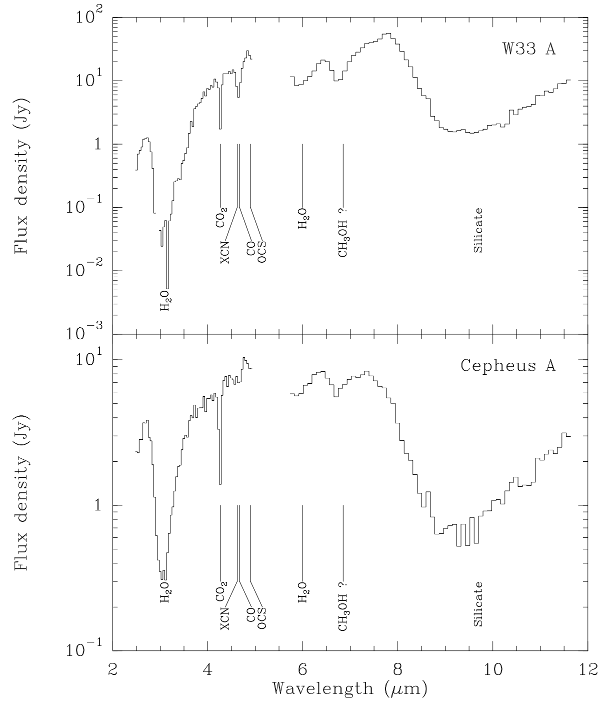

Fig. 1. Spectrum of W33A (upper panel) and Cepheus A (lower panel) taken with ISOPHOT-S. The expected positions of absorption features due to CO_2, other ices, and silicate are indicated.

spectral bandpass of the instrument and assuming a Gaussian band profile with a FWHM of 20 cm^{-1}. Note that laboratory studies have shown that the band width depends on the composition of the ice mantles (Sandford & Allamandola 1990). It is evident that this introduces an additional uncertainty to our values. The deconcolved optical depths are also given in Table 2.

In Table 2, we list the optical depths for the 3.0-μm H_2O and 4.67-μm CO ice bands and for the 9.7 μm silicate feature taken from the literature in order to be compared with our CO_2 values. In the case of the CO one has to keep in mind that the interstellar CO band consists of at least two components. A narrow component with its precise peak position and halfwidth varying somewhat among the sources is attributed to CO in a non-polar (probably H_2O-poor) matrix, while the broad component is related to CO in a polar (H_2O-rich) matrix.

It is well known that there is no correlation between the depth of the silicate band and the depth of the ice features. This is also true for the 4.27-μm band. Obviously the amount of condensed ices is determined by the physical conditions in the interstellar clouds. We find from our data that the 4.27-μm band tends to be deeper with more H_2O or CO present on the grains. From our numbers, we derive a mean ratio of $\tau_{\rm corr}(CO_2)/\tau_{\rm nonp}(CO)$ of about 3. Using the integrated absorption cross sections measured by Gerakines et al. (1995) and 20 cm^{-1} and 6 cm^{-1} as FWHM for the CO_2 and CO bands, respectively, we find that comparable amounts of CO_2 and CO should be present in the grain mantles. This result agrees with the conclusion by d'Hendecourt &

Table 1. Identified dust features. The question mark indicates possible identifications.

IRAS	Other name	3.08 μm H_2O	4.27 μm CO_2	4.67 μm CO	6.0 μm H_2O	6.7 μm -CH_3, -CH_2-	9.7 μm silicate
11072−7727	Ced111–IRS5	+	+	+			
	WL–6	+	+	+	+		+
18018−2426	M8E–IRS	+	+				+
18117−1753	W33A	+	+	+	+	+	+
18196−1331	AFGL 2136	+	+	+	+	+	+
18274+0112	S68–IRS1 = SVS 20	+	+	+	+	+	
	SVS 4	+	+	+	?	?	+
	S68–IRS2	+	+		?		+
	HH100–IRS	+	+	+	+	+	+
20275+4001	AFGL 2591		+	?			+
22176+6303	S140–IRS1	+	+		+	?	+
22543+6145	Cep A	+	+	+	+	+	+
23118+6110	NGC 7538–IRS9		+	+	+	+	+

Table 2. Optical depths of selected dust bands. For the 4.27-μm band the apparent and deconvolved optical depths derived in this paper are given. The + in column 3 indicates the presence of the feature, but no meaningful optical depth could be derived due to the low S/N ratio. The other values are from the literature.

IRAS	Other Name	$\tau(CO_2)$ app.	$\tau(CO_2)$ deconv.	τ(CO) non-polar	τ(CO) polar	Ref.	$\tau(H_2O)$	Ref.	τ(sil)	Ref.
11072−7727	Ced 111–IRS5	+								
	WL–6	2.1 ± 1.6	8	1.8	-	1	2.1	2		
	M8E–IRS	0.2 ± 0.1	0.4				0.18	3	2.60	3
18117−1753	W33A	1.8 ± 0.6	6.5	1.2	0.43	4	>5.4	3	7.84	3
18196−1331	AFGL 2136	0.9 ± 0.4	2.0	-	0.2	4	2.72	3	5.07	3
18274+0112	S68–IRS1 = SVS 20	1.1 ± 0.3	2.6	1.21		5	1.00	5		
	S68–IRS2 = CK 2	1.0 ± 0.7	2.3	3	0.45	6	1.86	5		
	HH 100–IRS	1.1 ± 0.6	2.6	0.89	0.22	7	1.44	7	1.21	7
20275+4001	AFGL 2591	+		<0.05	-	4	0.69	3	4.14	3
22176+6303	S140–IRS1	1.0 ± 0.8	2.3	0.1:	-	4	1.28	3	3.97	3
22543+6145	Cep A	1.5 ± 0.5	4.5							
23118+6110	NGC 7538–IRS9	+		2.6	0.43	4	3.28	3	4.46	3

References: 1. Kerr et al. (1993); 2. Tanaka et al. (1990); 3. Willner et al. (1982); 4. Tielens et al. (1991); 5. Eiroa & Hodapp (1989); 6. Chiar et al. (1994); 7. Whittet et al. (1996)

Jourdain de Muizon (1989) from their identification of the 15.2 μm CO_2 band.

Whereas CO is, next to H_2, the most abundant interstellar molecule in the gas phase and the solid CO observed in the grain mantles may result from freezing out, models for the interstellar gas-phase chemistry do not predict an appreciable abundance of CO_2 (e.g. Herbst & Leung 1986). Our finding of $N(CO_2)/N(CO) \approx 1$ implies that CO_2 forms on grain surfaces and that, because CO and CO_2 have very different sublimation temperatures, the dust grains have to remain cold ($<$ 20 K). Several possibilities have been discussed in the literature how CO_2 may be form on grain surfaces. Experimental studies have shown that CO_2 is readily produced in laboratory ice analogues containing CO by UV irradiation or particle bombardement (d'Hendecourt et al. 1986; Sandford & Allamandola 1990; Palumbo & Strazzulla 1993). The reaction $CO + O \rightarrow CO_2$ has been used by Tielens & Hagen (1982) in their modelling of the grain surface chemistry, while Mitchell (1984) suggested O + HCO $\rightarrow$ CO_2 + H as an alternative possibilty. The question of how the CO_2 molecules in the grain mantles actually form is still open to debate.

4. Conclusions

In addition to a number of well-known ice fetures, we have detected a new interstellar absorption band at 4.27 μm. As high-resolution observations by ISO's SWS spectrometer have confirmed, this band is due to solid CO_2. This new band is present in the spectra of all 13 objects observed. This indicates that CO_2 is a common component of the mantles of dust grains in molecular clouds. Comparing the optical depths of the 4.27- μm (CO_2) and 4.67-μm (CO) bands, we estimate that both molecules are present in the grain mantles in comparable amounts. This implies that CO_2 forms on the surfaces of the dust grains effectively either by chemical reactions or by energetically processing (e.g. UV radiation, particle bombardment) of the mantle material.

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