

A SEARCH FOR INTERSTELLAR GAS-PHASE CO₂

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1. Introduction

CO₂ is one of the simplest carbon- and oxygen-containing molecules, for which little is known in interstellar space, because of its high abundance in the Earth's atmosphere. Only indirect searches of the chemically related HOCO⁺ ion have been possible from the ground (Thaddeus et al. 1981; Minh et al. 1988, 1991). The ISO Short Wavelength Spectrometer (SWS) (de Graauw et al. 1996a) opens up the possibility to search for the infrared-active asymmetric stretch and bending modes of gas-phase CO₂ around 4.3 and 15.0 μm toward bright infrared sources.

The detection of abundant interstellar solid CO₂ (de Graauw et al. 1996b) suggests that CO₂ could be a particularly sensitive probe of gas-grain chemistry. The observed abundance of solid CO₂ with respect to hydrogen of about $\sim (1-5) 10^{-6}$ is a factor of 10 larger than that predicted by cold gas-phase models. Comparison of the observed gas/solid CO₂ ratios with those of other species known to be abundant in icy mantles, especially H₂O and CO, will allow us to address the formation route of CO₂.

2. Observations and analysis

We searched for gas-phase CO₂ in the spectra of four deeply embedded young stellar objects. Mitchell et al. (1989, 1990) have measured near-infrared absorption lines of gas-phase ¹²CO and ¹³CO at high spectral resolution from the ground, which indicate the presence of both cold, $T_{\text{kin}} = 15 - 60$ K, and warm, $T_{\text{kin}} = 120 - 1000$ K, gas along the lines of sight. The same sources are also observed by Helmich et al. (1996, this volume) and van Dishoeck & Helmich (1996) for gas-phase H₂O absorption.

Figure 1 shows the observed spectrum between 4.1 and 4.7 μm toward GL 2591. It clearly illustrates the difference between the spectrum of a

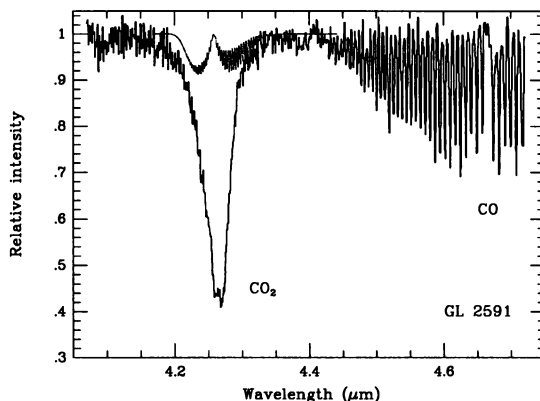


Figure 1. ISO-SWS spectrum toward GL 2591 in the 4.1–4.7 μm region. Broad absorption due to the ν_3 band of solid CO_2 is seen at 4.26 μm , as well as a forest of *R* and *P*-branch lines due to the warm, gas-phase CO $\nu=1-0$ band between 4.4 and 4.7 μm .

gas-phase and a solid-state species, and indicates a very different chemical behavior for the two species: most of the CO is in the gas phase, whereas most of the CO_2 is in solid form. In order to constrain the amount of gas-phase CO_2 , simulated spectra have been made following Helmich (1996). The adopted Doppler parameters b and excitation temperatures are based on the infrared observations of warm gaseous CO (Mitchell et al. 1990). Figure 1 includes a simulated spectrum (dotted line) of gas-phase CO_2 for a column density of $5 \cdot 10^{16} \text{ cm}^{-2}$, $b=7.5 \text{ km s}^{-1}$, and $T_{\text{ex}}=250 \text{ K}$, which is the maximum column density that could be hidden underneath the solid CO_2 feature.

More stringent constraints on the gas-phase CO_2 can be deduced from the strong *Q*-branch in the ν_2 bending mode. Figure 2 shows the ISO-SWS spectra of the four sources around 15 μm , with model CO_2 spectra included. It is seen that in all four sources, a $3-4\sigma$ absorption feature is present at the position of the CO_2 ν_2 *Q*-branch, which tentatively suggests the presence of gas-phase CO_2 , especially toward GL 2136 and NGC 7538.

The column densities of $\sim 10^{16} \text{ cm}^{-2}$ derived above correspond to gas-phase CO_2 abundances with respect to total H_2 of at most $\sim 10^{-7}$. These abundances are more than an order of magnitude below the limits derived from HOCO^+ (except for Galactic Center clouds), and a factor of a few lower than predicted by pure gas-phase steady-state models. Typically less than 5% of the CO_2 is in the gas phase, in strong contrast with CO and H_2O (see Table 1).

The large fraction of CO in the gas phase is not surprising, because solid CO readily evaporates at dust temperatures above 20 K. The mystery

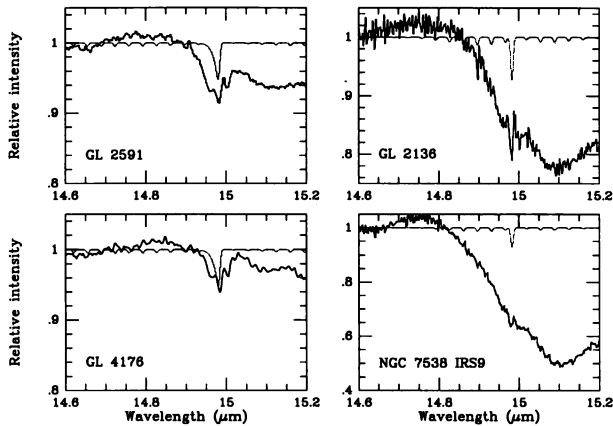


Figure 2. Normalized ISO-SWS grating spectra toward four embedded young stellar objects around 15 μm . The broad absorption feature starting around 14.8 μm is due to solid CO₂. The light (dotted) lines indicate the model absorption spectra of gas-phase CO₂ for $N(\text{CO}_2)=1.10^{16} \text{ cm}^{-2}$.

TABLE 1. Gas/solid state abundance ratios

Object	CO	CO ₂	H ₂ O
NGC 7538 IRS9	10	0.01	<0.04
GL 2136	200	0.02	0.4
GL 2591	>400	0.04	1.1
GL 4176	>400	0.04	2.2

is why the gas to solid ratio of H₂O is so much larger than that of CO₂ in three of the sources, because its sublimation temperature of $\sim 45\text{--}72$ K is lower than that of H₂O (>90 K). Several possible explanations for this problem are discussed by van Dishoeck et al. (1996). The most plausible scenario is that a large fraction of the observed gas-phase H₂O does not originate only from icy mantles but also from high-temperature gas-phase reactions in shocks or radiatively heated gas.

In summary, the ISO-SWS observations demonstrate that gas-phase CO₂ is not abundant in interstellar clouds, in spite of the ubiquitous presence of solid CO₂. They also show the potential of ISO to obtain reliable gas to solid state abundance ratios, which should provide insight into the physical and chemical evolution during star formation.

Acknowledgements

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Discussion

Buch: Is the assignment of solid CO₂ certain?

van Dishoeck: Yes, see the chapter by Tielens & Whittet in this volume.

Smith: As I understand, the proposed mechanism for formation of CO₂ in ices is the reaction of CO with O atoms. In the gas phase this spin-forbidden reaction has an appreciable activation energy and there seems little reason to suppose that this will be substantially reduced if the species are simply physisorbed on the surface of interstellar ice grains. Have laboratory experiments confirmed the proposed mechanism for CO₂ formation?

van Dishoeck: The formation of CO₂ in ices is discussed at several places in this volume, see Tielens & Whittet and the discussion following Schutte.

Tielens: Comment. Our laboratory experiments show that O can be stored at 10 K in a CO matrix. Upon warm-up, CO₂ is immediately formed. Probably the reaction is inhibited by a steric factor and/or small energy barrier. The difference with the earlier experiment by d'Hendecourt et al. likely reflects his much higher O₂/CO ratio. Under these conditions, atomic O prefers to react with O₂ rather than CO. Beating the drum of grain surface chemistry (again), it should be remembered that on a grain surface an O atom has a day the time to react with CO as compared to 10⁻⁵ s in the lab. Thus, these experiments show that, depending on the O/O₂ ratio in the accreting gas, CO can be oxidized to CO₂ on a grain surface.