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LETTER

Letter to the Editor

The hot core of the solar-type protostar IRAS 16293−2422: H_2CO emission

C. Ceccarelli[1], **L. Loinard**[2], **A. Castets**[3], **A.G.G.M. Tielens**[4], **and E. Caux**[5]

[1] Laboratoire d'Astrophysique, Observatoire de Grenoble, B.P. 53, 38041 Grenoble cedex 09, France
[2] Institut de Radio Astronomie Millimétrique, 300 rue de la piscine, 38406 St. Martin d'Hères, France
[3] Observatoire de Bordeaux, B.P. 89, 33270 Floirac, France
[4] SRON, P.O. Box 800, 9700 AV Groningen, The Netherlands
[5] CESR CNRS-UPS, B.P. 4346, 31028 Toulouse cedex 04, France

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Abstract. We model the H_2CO and $H_2^{13}CO$ line emission observed towards the solar-type protostar IRAS16293-2422. Based upon previous analysis of the physical structure of the envelope surrounding IRAS16293-2422, we develop a model in which the H_2CO lines are emitted by two components: a cold H_2CO-poor outer envelope and a warm H_2CO-rich core. We find that the model reproduces successfully all the available H_2CO and $H_2^{13}CO$ data for a H_2CO abundance equal to $(1.1 \pm 0.3) \times 10^{-9}$ in the outer and $(1.1 \pm 0.4) \times 10^{-7}$ in the inner regions of the envelope respectively. We interpret this increase of the H_2CO abundance as due to the evaporation of the grain mantles when the dust temperature exceeds 100 K at about 150 AU from the center, forming a hot core like region. Assuming that all mantle constituents evaporate and are detected in the gas phase, we derive that the H_2CO-ice abundance is about 3% of the H_2O-ice abundance. This is the first measurement of the H_2CO abundance in grain mantles around a low-mass protostar.

Key words: stars: formation – ISM: jets and outflows – ISM: individual objects: – infrared: ISM: lines and bands

1. Introduction

Massive protostars are known to possess hot cores enriched in complex molecules which are undetected in cold molecular clouds (e.g. Wamsley 1992). The most accepted view is that the grain mantles evaporate close to the central star, injecting in the gas phase the molecules constituting such ices (Millar 1997; Tielens & Charnley 1997). Those molecules are then transformed in other molecules by endothermic reactions, in the so called high temperature driven chemistry (e.g. Charnley, Tielens & Rodgers 1997).

Low mass protostars, on the contrary, were thought to be not luminous enough to have a hot core like region around (e.g. van Dishoeck & Blake 1998). Yet, in Ceccarelli et al. (2000; hereinafter CETAL00), we recently modeled the observed line spectrum of the H_2O, O and SiO towards IRAS16293-2422 (hereinafter IRAS16293), a 27 $L_\odot$ protostar, and found that there is a region where the dust temperature exceeds 100 K: in this warm region the water ice and the silicon trapped in dirty ices evaporate and the gas phase H_2O and SiO abundances increase by a factor of ~ 10 and ~ 4000 respectively, with respect to the relevant abundances in the outer region of the envelope. The derived SiO abundance in the warm region is $\sim 1.5 \times 10^{-8}$, very similar to what found in the hot cores of high luminosity protostars.

In this Letter we add support to the presence of a hot core like region around IRAS16293. We analyze several transitions of H_2CO and $H_2^{13}CO$ obtained towards IRAS16293 by van Dishoeck et al. (1995) and Loinard et al. (2000) and, by means of an accurate model, we show that also H_2CO abundance is drastically enhanced in the warm inner part of the envelope surrounding IRAS16293. The Letter is organized as follows: after a short summary of the observational framework, we interpret the observations by a detailed model which takes into account the physical structure of the envelope around IRAS16293 (§ 2), and finally we discuss the implications of the modeling results (Sect. 3).

2. The collapsing envelope model

IRAS16293 has been target of several observations of $H_2^{13}CO$ and H_2CO line emission. Van Dishoeck et al. (1995) report the detection of twelve H_2CO lines in the 230 and 350 GHz bands; the observed lines span a relatively large range of upper level energies from ~ 15 cm^{-1} to ~ 200 cm^{-1}. More recently Loinard et al. (2000) carried out a higher sensitivity survey of five H_2CO and $H_2^{13}CO$ lines, from which the relevant line opacities can be accurately derived. Finally, large scale maps of the region shows that H_2CO line emission is extended over a region larger than $\sim 40''$ (Van Dishoeck et al. 1995; Ceccarelli et al. in prep).

Send offprint requests to: Ceccarelli.Cecilia@obs.ujf-grenoble.fr

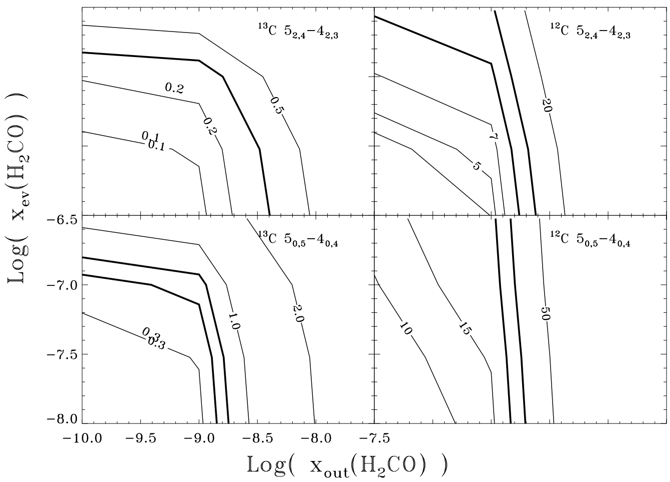

Fig. 1. Computed $\int \mathrm{T_{mb}}$ dv in K km s^{-1} of the observed p-H_2CO lines, after convolution with the telescope beam, as function of the total (ortho+para) H_2CO abundance in the outer and in the evaporation regions respectively. In these computation the ortho to para ratio is assumed equal to 3. Left panels show the ^{13}C isotope, while right panels show the ^{12}C isotope. The thick line in the upper left panel shows the observed ^{13}C $5_{2,4} - 4_{2,3}$ upper limit. The two thick lines in the other panels show the lower and higher bound to the observed values.

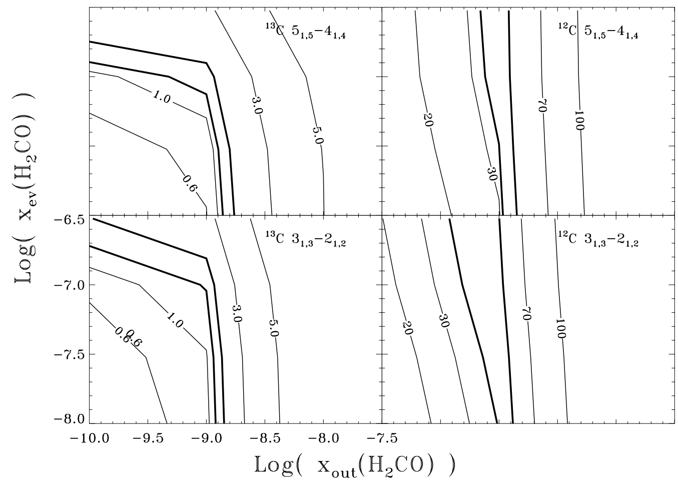

Fig. 2. Same as Fig. 1 for the observed o-H_2CO lines.

Ceccarelli, Hollenbach & Tielens (1996; hereinafter CHT96) developed a model which computes self-consistently the thermal structure and the O, H_2O and CO line spectrum of the collapsing envelopes around low-mass protostars within the "inside-out" framework (Shu 1977). In CETAL00 we applied this model to the observations of O, H_2O and SiO line emission towards IRAS16293 and we derived the physical structure of the envelope around this source, namely the gas density, temperature and velocity profiles. We found that at ~ 150 AU from the center the grain icy mantles evaporate, injecting large amounts of H_2O and SiO in the gas phase. Here we use the physical structure derived in CETAL00 to interpret the H_2CO and $H_2^{13}CO$ observed lines.

We developed a model which computes the H_2CO line emission using the density, temperature and velocity profiles for the envelope as derived in CETAL00. The envelope consists of two regions: in the cold outer region the abundance $X_{\rm out}$(H_2CO) is taken close to the values found in cold clouds. Closer to the center an extra–amount $X_{\rm ev}$(H_2CO) is injected into the gas phase by the evaporation of the dirty ices at $\mathrm{T_{dust}} \geq 100$ K. The abundances $X_{\rm out}$(H_2CO) and $X_{\rm ev}$(H_2CO) are free parameters. We solved the statistical equilibrium equations simultaneously with the radiative transfer (following the CHT96 method) to compute the level populations at any radius; the model considers the first 40 and 37 levels of the ortho and para H_2CO respectively. The Einstein coefficients were derived from the JPL catalogue (Pickett et al. 1998) and the collisional coefficients from Green (1991). The H_2CO ortho to para ratio is initially assumed to be 3:1. We adopted a $H_2^{12}CO$ to $H_2^{13}CO$ ratio equal to 60, as supported by theoretical (Langer et al. 1984) and experimental (Keene et al. 1998) studies.

In Fig. 1 and 2 we show the computed $H_2^{12}CO$ and $H_2^{13}CO$ line fluxes as a function of the two free parameters $X_{\rm out}$(H_2CO) and $X_{\rm ev}$(H_2CO), after convolution of the theoretical signal with the relevant beam profile, for the p-H_2CO and o-H_2CO lines observed by Loinard et al. (2000). Comparison between the model predictions and observations gives two different values for the total (ortho+para) H_2CO abundance when the o-H_2CO and the p-H_2CO lines are considered. This implies an ortho to para ratio which is different from the assumed 3:1. The derived o-H_2CO and the p-H_2CO abundances are respectively (note that Fig. 1 and 2 refer to the total H_2CO abundance):
$X_{\rm out}$(o-H_2CO) = $(7 \pm 2) \times 10^{-10}$,
$X_{\rm ev}$(o-H_2CO) = $(9 \pm 3) \times 10^{-8}$,
$X_{\rm out}$(p-H_2CO) = $(4 \pm 1) \times 10^{-10}$,
$X_{\rm ev}$(p-H_2CO) = $\leq 2 \times 10^{-8}$.
From these values we can derive the H_2CO ortho-to-para ratios in the outer and in the evaporation regions, which result equal to 2 ± 1 and $\geq$3 respectively. The total H_2CO abundance in the outer and evaporation regions are:
$X_{\rm out}$(H_2CO) = $(1.1 \pm 0.3) \times 10^{-9}$,
$X_{\rm ev}$(H_2CO) = $(1.0 \pm 0.4) \times 10^{-7}$.

Fig. 3 shows the ratio between the observed and predicted fluxes of all the detected lines as function of the upper level energy, for the model with the above parameters. In the same figure we also report the ratio between the observed and predicted line fluxes for a model in which we set $X_{\rm ev}$(H_2CO)=0 to test the robustness of the existence of the evaporation region. The figure clearly shows that the model with no evaporation region grossly underestimates the fluxes from the ^{13}C and the ^{12}C high lying lines. In order to reproduce them an inner region with a larger abundance of H_2CO is definitively necessary.

Fig. 4 shows the contribution to the observed flux for selected H_2CO lines, as a function of the radius. Our model predicts that the emission from low-lying H_2CO lines is extended over about 5000 - 6000 AU, i.e. over a region of $40''$ around IRAS16293, as observed in large scale maps of the region (see the beginning of paragraph). Among all observed transitions of H_2CO, the $H_2^{13}CO$ $5_{2,4} - 4_{2,3}$ transition penetrates deepest in

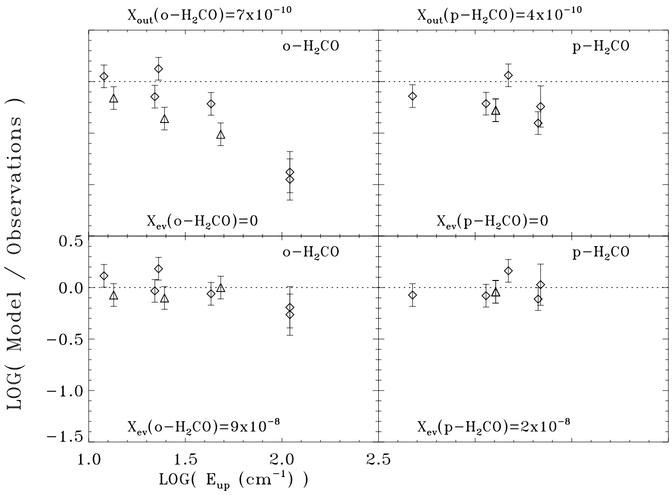

Fig. 3. Ratio between the observed and predicted line fluxes as function of the upper level energy for a model with the parameters described in the text (bottom panels) and for a model with no evaporation in the inner region (top panels). The diamond represent the $H_2^{12}CO$ lines while the triangles the $H_2^{13}CO$ lines. Note that the upper level energies of the $H_2^{13}CO$ lines have been shifted by 0.05 to make the points distinguishable in the plot.

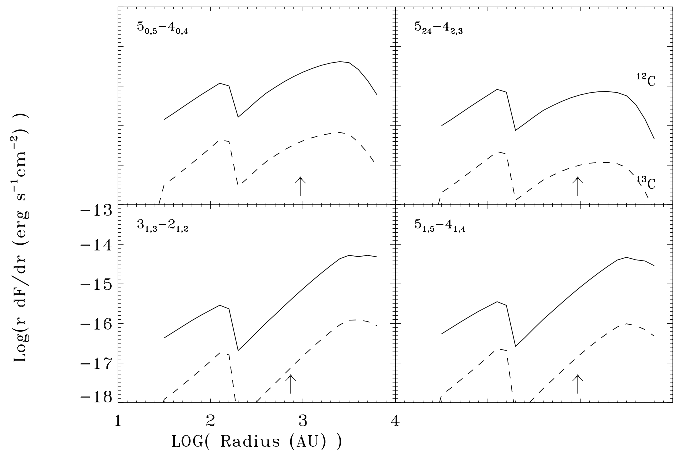

Fig. 4. r(dF/dr) versus the radius r of the observed o-$H_2^{12}CO$ lines. F is the observed flux in the lines; the beam FWHMs of the observations by Loinard et al. (2000) are marked by arrows.

the envelope and probes the inner regions. Although an accurate modeling of the line profiles is beyond the scope of this Letter, looking at Fig. 4 we do not expect that the abundance dichotomy between the inner hot core and the outer collapsing envelope would show up particularly pronounced in the profile.

3. Discussion

IRAS16293 is undoubtedly a complex region, where many components coexist (e.g. see the review by van Dishoeck et al. 1995). Nevertheless, in our opinion the envelope which surrounds the two known objects ($4''$ apart; Wootten 1989) dominates the line emission from several of the observed molecules. In CETAL00 we successfully modeled the H_2O, O and SiO line emission as originating in an envelope collapsing towards 0.8 $M_\odot$ at a rate of 3.5×10^{-5} $M_\odot$ yr^{-1} and discussed why we think that the emission from those molecules is likely to originate in the envelope rather than in the outflow shock (see also Ceccarelli et al. 1999). In this Letter we add formaldehyde to this list. Although in the past the observed H_2CO emission has been attributed to an outflow shock (e.g. van Dishoeck et al. 1995), we showed in the previous paragraph that the emission is well reproduced by a model which attributes the emission to the collapsing envelope. The warm component enriched in H_2CO which was observed at $\leq 3''$ scale by van Dishoeck et al. and attributed to a gentle shock, in our model is indeed a hot core like region caused by the evaporation of grain mantles because of the heating of the dust by the central 27 $L_\odot$ source. Our model is able to reproduce simultaneously 12 far infrared lines from H_2O and O, and 23 sub/millimeter lines from SiO and H_2CO, all of them covering a large interval of upper level energies. Furthermore, the model correctly predicts the observed extent and widths of the sub/millimeter lines. Although we cannot exclude the shock hypothesis, we think that the collapsing envelope with an hot core region hypothesis is very strongly supported by all the considered data and a possibility much more probable to us. In the following we pursuit the implications of this interpretation.

Emission from low-lying lines from this molecule extends up to $40''$, tracing the outer region of the envelope up to 6000 AU of distance from the center. The H_2CO abundance (1.1×10^{-9}) is somewhat larger than what is expected by gas phase chemical models which tends to predict a lower abundance (e.g. Lee, Bettens & Herbst 1996). It has already been proposed that H_2CO is mainly produced onto the grain surfaces via hydrogenation of depleted CO (Tielens 1983; Federman & Allen 1991) and our previous observations of a high D_2CO over H_2CO ratio ($\sim 5\%$) certainly support this idea (Ceccarelli et al. 1998; Loinard et al. 2000).

Whatever is the origin of H_2CO, the derived H_2CO abundance in this cold region is similar to what is found in molecular clouds (Minn & Greenberg 1993), as is the SiO abundance (4×10^{-12}) and the H_2O abundance (5×10^{-7}). Yet all these abundances increase dramatically in the inner, warmer and denser regions of the envelope: H_2CO jumps by about a factor 100, SiO by $\sim$ 4000 and H_2O by $\sim$ 10. This abrupt change occurs at about 150 AU, when the dust temperature exceeds 100 K and the grain mantles evaporate, injecting in the gas phase the molecules that constitute the mantle themselves. The values we obtain for the H_2CO and SiO abundances in the evaporation region are similar to what is found in the hot cores of massive protostars (Mangum et al. 1990; Wright, Plambeck & Wilner 1996), suggesting the presence of an hot core like region around IRAS16293, whose dimensions are clearly smaller than those of massive protostars, but whose chemical behavior is similar. Table 1 gives a summary of the abundances observed towards IRAS16293, the Orion Hot Core and the observed ice abundances of the same species.

The composition of the grain mantles in the envelope of IRAS16293 can therefore be derived by the gas phase prod-

Table 1. [a]Ices are given with respect to the measured H_2O-ice column density.
H_2O, H_2CO and SiO abundances (with respect to H) towards IRAS16293 (CETAL00 and this Letter) and Orion (Mangum et L. 1990; Wright et al. 1996) in the warm (through observations of the evaporated ices) and cold regions respectively. Sixth column reports the abundances of the same species in the ices, as derived towards W33A and NGC7538-IRS9 (van Dishoeck & Blake 1998 updated with the data from Keane et al. 2000). Seventh column reports the values observed towards cold molecular clouds (Minn & Greenberg 1993; Ziurys, Friberg & Irvine 1989; Snell et al. 2000).

Species	IRAS16293		Orion		Ices	Clouds
	warm	cold	warm	cold		
H_2O	3×10^{-6}	5×10^{-7}	$\geq 10^{-5}$	$\leq 10^{-7}$	100 [a]	$10^{-9} - 10^{-7}$
H_2CO	1×10^{-7}	1×10^{-9}	1×10^{-8}	1×10^{-9}	3-6	2×10^{-9}
SiO	1.5×10^{-8}	4×10^{-12}	3×10^{-8}	$\leq 5 \times 10^{-10}$		$\sim 10^{-12}$

ucts of the evaporation. Note that since IRAS16293 is such an obscured, cold and low luminosity object, it is not possible to observe directly the near infrared ice absorption features (from which ice abundances are derived), as it is usually done in high mass protostars. Therefore the study of the line emission from evaporated molecule is the only way to reconstruct the mantle composition in similar low mass cold protostars. Following the findings of the present and CETAL00 works, in IRAS16293 the formaldehyde is about 3% of iced water, assuming that all icy mantle evaporates. As already mentioned, that formaldehyde is a major constituent of grain mantles was already expected by the supporters of H_2CO formation via active grain chemistry. Nevertheless the search for iced H_2CO towards high mass protostars has been rather frustrating (e.g. Grim et al. 1991; Allamandola et al. 1992) and only recently iced H_2CO has been observed at a level of $\sim 3-6\%$ towards some high luminosity protostars (Keane et al. 2000), comparable with what we find in IRAS162293.

4. Conclusions

The main conclusions of this work are:
- a hot-core-like region exists in IRAS16293 with a size ~ 150 AU, where grain mantles have evaporated injecting ice-species such as H_2CO into the gas phase;
- the abundance of H_2CO in the evaporation region is $(1.0 \pm 0.4) \times 10^{-7}$, i.e. 100 times more than in the outer envelope and comparable to the H_2CO abundance in the hot cores of massive protostars;
- iced H_2CO is about 3% of iced H_2O in the mantles of the grains around IRAS16293, comparable to the values found in the mantles of massive protostars.

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