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Extended D_2CO emission: The smoking gun of grain surface-chemistry

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Abstract. We present new observations of the H_2CO and D_2CO emission around IRAS16293-2422, a low mass protostar in the ρ Ophiuchus complex. Bright H_2CO and D_2CO emission is detected up to $40''$ from the center, corresponding to a linear distance of ∼5000 AU. The derived H_2CO abundance profile has two jumps at $r \leq 150$ AU and $r \leq 700$ AU, where the dust temperature reaches 100 K and 50 K respectively. The measured $[D_2CO]/[H_2CO]$ abundance ratio in the envelope is between 0.03 and 0.16, an extremely high value. We demonstrate that the present new observations can only be explained if the D_2CO (and H_2CO) are formed during the previous cold pre-collapse phase, stored in the grain mantles, and released in the gas phase during the pre-collapse phase. We consider the two main competing theories for mantle formation, i.e. pure accretion against grain surface chemistry, and we conclude that the former theory cannot explain the present observations, whereas grain active chemistry very naturally does. We found that the mantles are evaporated because of the thermal heating of the grains by the central source and that in the outer cold envelope H_2CO and D_2CO molecules are embedded in CO-rich mantles which sublimate when the dust is warmer than 25 K. Finally, the present day H_2CO and D_2CO abundances very probably reflect the mantle composition. We argue that mantles have likely formed in an onion-like structure with the innermost ice layers more enriched in H_2CO molecules and we give estimates of the CO hydrogenation efficiency across the envelope and/or in different ices.

Key words. ISM: abundances – ISM: molecules – stars: formation – ISM: individual: IRAS 16293−2422

1. Introduction

Doubly deuterated formaldehyde was discovered towards Orion by Turner (1990). The measured $[D_2CO]/[H_2CO]$ abundance ratio ∼0.3% made Turner claim that the formaldehyde is mainly synthesized on the grain surface. Subsequently Ceccarelli et al. (1998) and Loinard et al. (2000; hereinafter LCCT2000) discovered an even larger $[D_2CO]/[H_2CO]$ ratio, ∼5% toward the solar type protostar IRAS16293-2422 (hereinafter IRAS16293) and ∼26% toward the younger protostar 16293E (Loinard et al. 2001). As in the case of Orion, the large $[D_2CO]/[H_2CO]$ abundance ratio was interpreted as proof that D_2CO is formed on the grain surfaces during the cold and dense pre-collapse phase and released in the gas phase because of the heating of the dust during the collapse. These first works implicitly assumed that the D_2CO line is emitted either in the innermost warm regions close to the central object, where the dust temperature reaches the ice evaporation temperature (∼80 K for H_2O ices), or in shocks associated with the outflow emanating from the young source, where the mantle molecules are sputtered into the gas phase. However, LCCT2000, analyzing the absorption of the D_2CO and H_2CO lines observed towards IRAS16293, found that between us and the source there must be an absorbing layer of H_2CO and D_2CO gas. This gas is relatively cold (∼20 K) and enriched in D_2CO. We estimated that the $[D_2CO]/[H_2CO]$ abundance ratio in this gas is ∼12%; i.e. even larger than the ratio observed towards the source itself (LCCT2000).

In order to clarify the situation we obtained a map of the D_2CO emission around IRAS16293. Our goal was to determine the region where the D_2CO line is emitted and to understand the origin of this emission. The outline of the paper is the following: after reviewing the source background in Sect. 2, we present the new observations in Sect. 3. The discussion and implications of these new observations are reported in Sects. 4 and 5.

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2. Source background

IRAS16293 is a 15 $L_\odot$ protostar embedded in the small molecular cloud L1689N, in the ρ Ophiuchus complex at 120 pc of distance (Knude & Hog 1998). The gas in L1689N seems to be anomalously deficient in CO (by about a factor ten with respect to the usual assumed CO abundance in clouds) and overabundant in atomic oxygen (Caux et al. 1999). IRAS16293 has been the target of several studies, triggered by the claim of Walker et al. (1986) that the envelope around IRAS16293 is collapsing towards the center (see also Zhou et al. 1995; Narayanan et al. 1998). IRAS16293 has been classified as a Class 0 source (André et al. 1993) and it is very probably in a very early stage of its evolution (Bontemps et al. 1996; Saraceno et al. 1996). An unbiased line survey in the 215 and 350 GHz bands showed the existence of several components in a 30″ region centered on IRAS16293 (Blake et al. 1994; van Dishoeck et al. 1995): an ambient molecular core, a rotating and infalling envelope, an outer cold disk, two warm circumstellar disks and finally a multiple outflow. The outflows have been traced in several molecular species: CO (Walker et al. 1986; Mizuno et al. 1986), O (Ceccarelli et al. 1997), SiO (Hirano et al. 2000). Recently Castets et al. (2001) obtained large scale maps of H_2CO, SiO and O emission. All these tracers give a well defined picture of three outflows emanating from the three sources housed in L1689N (Castets et al. 2001). The structure (i.e. the density and temperature profiles as well as the abundances of the main gas coolants) of the envelope surrounding IRAS16293 has been recently reconstructed based on multifrequency H_2O, SiO, O, and H_2CO line observations (Ceccarelli et al. 2000a,b). The envelope is formed by gas, whose abundance is similar to typical molecular cloud abundances in the outer regions ($\geq$150 AU). In the inner regions ($\leq$150 AU) the abundances of H_2O, SiO and H_2CO jump to abundances typical of the hot cores of massive protostars. Finally, there is additional evidence that heavier and more complex molecules are also present in this hot-core like region (Ceccarelli et al. 2000c).

3. Observations and results

Using the IRAM 30 meter telescope, we obtained $60'' \times 80''$ maps of the D_2CO $4_{0,4}-3_{0,3}$ (at 231.410 GHz) and H_2CO $3_{1,3}-2_{1,2}$ (at 211.211 GHz) emission around IRAS16293. Smaller maps of the central $30'' \times 30''$ region were obtained in the D_2CO $4_{1,4}-3_{1,3}$ and $2_{1,2}-1_{1,1}$ (at 221.192 and 110.837 GHz respectively) transitions. In addition we observed the $H_2^{13}CO$ $3_{1,3}-2_{1,2}$ (at 206.132 GHz) transition towards the central position and towards two other positions offset by (0″, −10″) and (−10″, −10″) respectively. Finally, we observed the H_2CO $2_{1,2}-1_{1,1}$ (at 140.839 GHz) transition towards the position at offset (0″, −20″), with the goal of measuring the gas temperature at this position (see below).

The observations were performed in January 1999 and August 2000. The telescope beam efficiencies and beamwidth at 3 mm and 1.3 mm are equal to 0.8 and 0.48, and 22″ and 11″ respectively. The four receivers were connected to units of the autocorrelator set to provide spectral resolutions of 40 and 80 kHz at 110 and 230 GHz respectively. All frequencies of interest here the velocity resolutions are of the order of 0.1 km s^{-1}. The map spacing is 10″. All observations were performed in the position switching mode with an OFF position offset equal to (−180″, 0″). Typical integration times at each position are of few minutes for the H_2CO lines and up to 1 hour for the D_2CO lines.

Figures 1 and 2 show the maps of the integrated intensity $\int T_{\rm mb}\ \Delta v$ of the D_2CO $4_{0,4}-3_{0,3}$ and H_2CO $3_{1,3}-2_{1,2}$ lines respectively. The D_2CO $4_{1,4}-3_{1,3}$ and $2_{1,2}-1_{1,1}$ maps are similar to the $4_{0,4}-3_{0,3}$ map in the central region and therefore are not shown. We detected $H_2^{13}CO$ $3_{1,3}-2_{1,2}$ emission only towards the central position (see LCCT2000); in the two other observed positions we obtained upper limits to the peak $T_{\rm mb} \leq 0.03$ K.

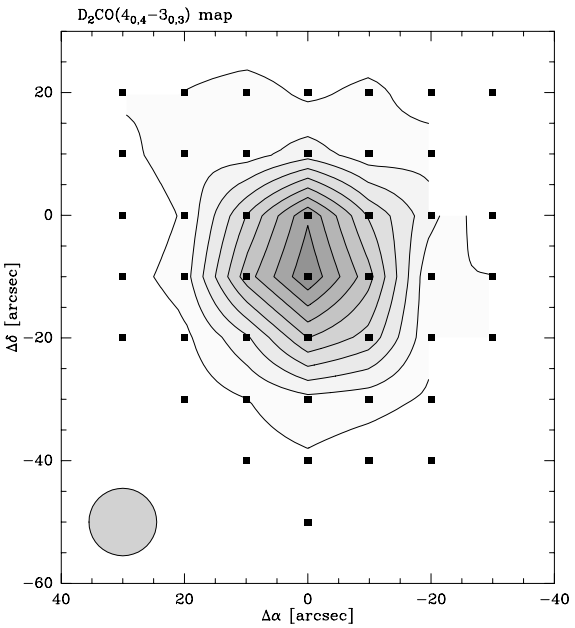

Fig. 1. D_2CO: $4_{0,4}-3_{0,3}$ line intensity $\int T_{\rm mb}\ \Delta v$, integrated over the −20 to +25 km s^{-1} velocity interval. Contour levels start at 0.3 K km s^{-1} and increase by steps of 0.3 K km s^{-1}. The last contour is 2.7 K km s^{-1} and the highest value is 2.95 K km s^{-1}. The (0″, 0″) position corresponds to $\alpha(2000) = 16^{\rm h}24^{\rm m}22^{\rm s}.6$, $\delta(2000) = -24°28'33''.0$.

Both H_2CO and D_2CO emission is extended over the observed region. The H_2CO line traces the envelope that surrounds IRAS1629, slightly elongated towards the south (see van Dishoeck et al. 1995; Castets et al. 2001). The $H_2^{12}CO$ line opacities derived from the $H_2^{13}CO$ observations are relatively small: at the central position, where the absorption is stronger, $\tau \sim 1$ (LCCT2000), while at the two other observed positions τ is less than unity.

Surprisingly, the D_2CO emission is extended ∼40″ towards the South. It seems to peak some 10″ South

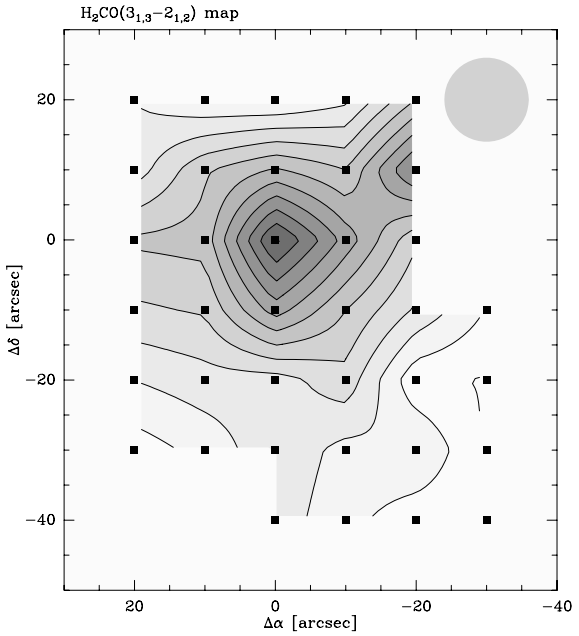

Fig. 2. H_2CO: $3_{1,3}-2_{1,2}$ line intensity $\int T_{\rm mb}\ \Delta v$, integrated over the −20 to +25 km s^{-1} velocity interval.

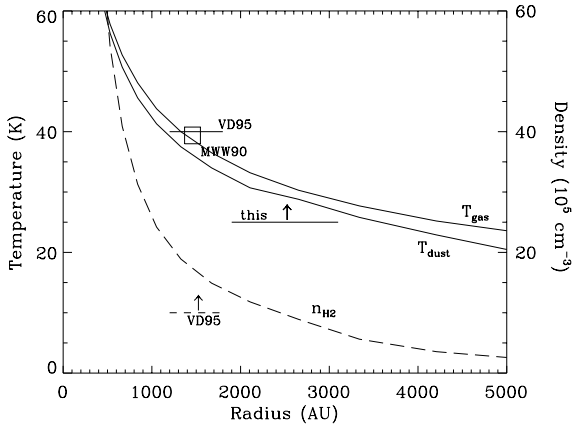

Fig. 3. Profiles of the dust and gas (solid lines) temperatures, and of the gas density (dashed line) as function of the distance from the center, as computed by the CCC2000 model. Note that the density is in 10^5 cm^{-3} units, as marked the right y-axis. The square shows the estimate of the gas temperature by Mundy et al. (1990); the lines marked VD95 are the temperature and density estimates by van Dishoeck et al. (1995); the lower limit marked "this" is this work.

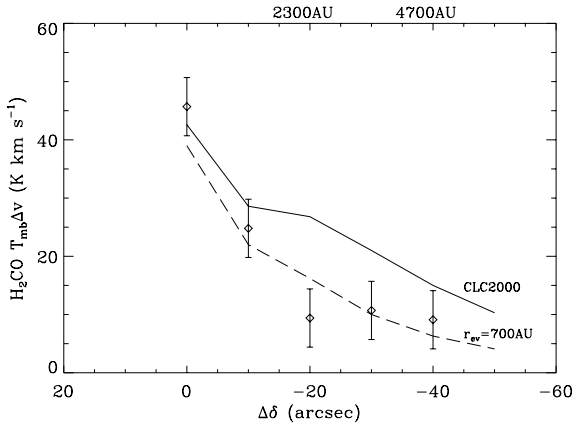

Fig. 4. Profiles of the H_2CO $\int T_{\rm mb}\Delta v$ line intensity as function of the distance from the center: diamonds show the observations, solid line the CLC2000 model predictions and the dashed line a model with a decrease of the H_2CO abundance outside $r_{\rm ev} = 700$ AU. In the upper panel we report the linear distance in AU, i.e. $20'' = 2300$ AU and $40'' = 4700$ AU.

of the source center, although the difference in the line intensity in the two points is only 20% and therefore only marginally significant. The linewidth is somewhat larger ($\sim$5 km s^{-1}) towards the center than in the remaining positions, where the D_2CO line is narrow ($\sim$2 km s^{-1}). This is qualitatively consistent with the picture of D_2CO emission originating in the envelope surrounding IRAS16293 and collapsing towards the center (Ceccarelli et al. 2000a,b). The observations toward the central position would intercept both the relatively static outer envelope and the innermost collapsing regions, giving rise to an enlarged line profile, while the observations in the other positions only intercept the static outer envelope.

Finally, the H_2CO multifrequency observations at the position ($0''$, $-20''$) from the center give a rotational temperature of 25 K (see LCCT2000 for a discussion of how this value is computed).

4. Discussion

4.1. The H_2CO extended emission

In Ceccarelli et al. (2000a; hereinafter CCC2000) and Ceccarelli et al. (2000b; hereinafter CLC2000) we used the observed H_2O, SiO, H_2CO and atomic oxygen lines to reconstruct the physical structure of the envelope surrounding IRAS16293, i.e. the density and temperature profiles as well as the H_2CO abundance profile. To help the reader follow the discussion, Fig. 3 reports the CCC2000 results together with some independent estimates of the gas density and temperature at different distances from the center, which all agree with the CCC2000 model predictions. Specifically, the CLC2000 model predicts that the H_2CO abundance is $\sim10^{-9}$ in the outer cold envelope and 100 times higher in the "hot-core" like region at 150 AU. We emphasize that the model predictions are based on multifrequency H_2CO observations *towards the central position*, i.e. the present new observations are an independent test to this model. The CLC2000 model predicts that the H_2CO $3_{1,3}-2_{1,2}$ emission extends about 4000 AU, in rough agreement with our present observations. Figure 4 shows the cross scan of the observed $\int T_{\rm mb}\Delta v$ along the North-South direction and the emission predicted by the CLC2000 model. The comparison between the observed and predicted line intensity suggests that the H_2CO abundance varies as function of the radius also in the outer envelope. In fact, a better fit to the observations is obtained if the H_2CO abundance is 4×10^{-9} at $\geq$700 AU, when the

dust exceeds 50 K, and 4×10^{-10} at larger distances. Both the H_2CO abundance values and where the jump occurs are rather well constrained by the present observations. Incidentally, the new proposed model fits all the previous H_2CO observations towards the central position, as does the CLC2000 model. In effect, the IRAS16293 envelope consists of three regions:

i) $r \leq 150$ AU: a *hot core like region*, where the dust temperature exceeds 100 K;
ii) $150 \leq r \leq 700$ AU: a *warm envelope*, where the dust temperature is between 50 K and 100 K;
iii) $r \geq 700$ AU: a *cold envelope*, where the dust temperature is colder than 50 K.

In the hot core and warm envelope regions the gas phase H_2CO abundance is dominated by mantle desorption.

4.2. The D_2CO extended emission

In LCCT2000 we analyzed six transitions of H_2CO, $H_2^{13}CO$ and D_2CO respectively to derive the average rotational temperature (45 K) and H_2CO column density (3.8×10^{14} cm^{-2}) towards the central position. The derived [D_2CO]/ [H_2CO] ratio, corrected for the H_2CO line opacities, is 0.05 ± 0.01.

The two H_2CO and D_2CO transitions that we used for the maps shown in Sect. 3 have similar upper level energies ($\sim$20 cm^{-1}). Because the lines are essentially optically thin, this implies that both lines are excited at approximatively the same temperature and density and therefore we can consider their $\int T_{\rm mb}\ \Delta v$ ratio as a measure of the [D_2CO]/[H_2CO] abundance ratio in the mapped region. Figure 5 shows the [D_2CO]/[H_2CO] abundance ratio, as derived from the $\int T_{\rm mb}\ \Delta v$ line ratio. The [D_2CO]/[H_2CO]

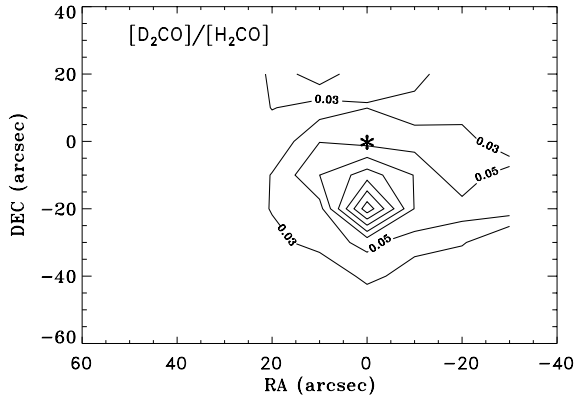

Fig. 5. [D_2CO]/ [H_2CO] abundance ratio. Contour levels start at 0.03 and increase by steps of 0.02. The highest value is 0.16 measured at (0″, −20″).

abundance ratio has a peak at (0″, −20″), where it reaches the value 0.16, and then it decreases outwards to 0.03 at (0″, −40″), the last point where we detected D_2CO emission. It is very unlikely that opacity effects can really reverse this trend, since the H_2CO line opacity is less than unity, except in the central position. As already noticed in our previous works (Ceccarelli et al. 1998 and LCCT2000) the observed [D_2CO]/[H_2CO] value $\geq$0.03 is extremely high.

4.3. Origin of deuteration

One key question is: *what causes the observed high degree of deuteration of the gaseous formaldehyde?* In principle, there are two possibilities: either abundant D_2CO is formed *now* by chemical reactions in the gas phase or it was formed *previously* in the colder and denser pre-collapse phase, stored in the grain mantles, and released in the gas phase now, during the collapse. As already argued in our previous works (Ceccarelli et al. 1998; LCC2000; Loinard et al. 2001), it is very unlikely that D_2CO is a present-day gas phase product. The observation of a large deuteration at $\sim$20″, where the gas temperature is higher than $\sim$30 K, strengthens our previous claims. In fact, at such gas temperatures, even the single deuteration of molecules in the gas phase is predicted to be an order of magnitude smaller than that observed by us for D_2CO (e.g. Millar et al. 1989) because of the destruction of H_2D^+ by H_2 collisions (Watson 1976). Supporting these theoretical arguments, the [DCO^+]/[HCO^+] ratio, which traces the [H_2D^+]/[H_3^+] ratio, was observed toward IRAS16293 to be 0.009 (van Dishoeck et al. 1995). Likewise, the [DCN]/[HDN] ratio, which ultimately derives from the [CH_2D^+]/[CH_3^+] fractionation, observed in IRAS16293 is 0.013 (van Dishoeck et al. 1995). Both these values are an order of magnitude less than the [HDCO]/[H_2CO] ratio (LCCT2000), hence implicating a different origin. *Thus our first conclusion is that the abundant D_2CO observed in the IRAS16293 envelope must have been formed during the pre-collapse phase, stored in the ice grain mantles and released in the gas phase during the collapse.*

There are two competing theories of mantle formation. Either the mantle is formed by mere accretion of molecules synthesized in the gas phase (e.g. Roberts & Millar 2000) or molecules are formed via active grain chemistry on the grain surfaces themselves (e.g. Tielens & Hagen 1982). The first theory predicts high molecular deuteration when the gas is strongly depleted of CO (e.g. Brown & Millar 1989; Willacy & Millar 1998; Roberts & Millar 2000). Recently Roberts & Millar (2000) argued that the [D_2CO]/[H_2CO] abundance ratio can reach 10% when CO is depleted by at least a factor 30 (see their Fig. 10). The problem with this interpretation is that, given the required high depletion, the highly deuterated gas accreting into the mantles would be a small fraction of the total accreted material, reducing the fractionation of the observed evaporated molecules. Conversely, active grain chemistry offers a simple and more viable explanation. Models of grain surface chemistry predict in a natural way high deuteration and high double deuteration of formaldehyde (Tielens 1983; Charnley et al. 1997). In these models, H_2CO and D_2CO are formed via hydrogenation of the CO on the

grain mantles. The molecular fractionation is set by the atomic [D]/[H] ratio in the gas phase at the moment of the mantle formation. This ratio can reach unity in dense ($\geq 10^5$ cm^{-3}) gas and hence a relatively high fractionation can be achieved (Tielens 1983). *Hence our second conclusion is that the high abundance of H_2CO, HDCO, and D_2CO in the envelope surrounding IRAS16293 supports models in which – in a previous cold, dark cloud phase – accreted atoms and molecules react on grain surfaces to form hydrogenated (and oxidized) species such as H_2CO and their deuterated counterparts.*

4.4. Mantle desorption

Now the second question is: *what causes the desorption of the grain mantles at distances up to ∼4000 AU?*

The comparison between IRAS16293 and the pre-collapse core L1544 can help to enlighten this point. L1544 is a dense ($\sim 10^6$ cm^{-3}) and cold (∼10 K) core suspected to be on the verge of collapsing (Tafalla et al. 1998). Caselli et al. (1999) observed a large CO depletion (≥10) towards the center of L1544. The density of the IRAS16293 envelope at 3000 AU is $\sim 10^6$ cm^{-3}, comparable to the density towards the center of L1544. Observations of H_2CO and D_2CO emission towards this pre-stellar core give an abundance ratio [D_2CO]/[H_2CO] ∼0.1 (Loinard et al. in preparation), similar to that found in IRAS16293. The H_2CO column density towards L1544 derived by these observations is $\sim 3 \times 10^{12}$ cm^{-2}. Taking the H_2 column density estimated by Ward-Thompson et al. (1999), 1.3×10^{23} cm^{-2}, gives an H_2CO abundance $\sim 3 \times 10^{-11}$ in L1544. This value is more than ten times smaller than the abundance we measured in the envelope of IRAS16293. This confirms that H_2CO in L1544 is as depleted as CO. But note that although mantles (as seen in the gas phase) seem to have the same D_2CO enrichment in IRAS16293 and L1544, much less of the mantles are found in the gas phase in L1544 than in IRAS16293. Therefore, whereas cosmic rays may be responsible for the partial evaporation of the grain mantles in L1544, a more efficient mechanism evaporates the grain mantles in the envelope of IRAS16293. This mechanism must have to do with the *onset* of the collapse, or more specifically, with the *presence of a protostar inside* the envelope.

Obviously, thermal evaporation of polar ices is excluded, since the dust temperature at 4000 AU is less than the needed 80 K (e.g. Tielens & Allamandola 1987). In principle, a shock associated with the outflow emanating from the central object could cause a partial desorption of the grain mantles. But our observations do not show any evidence of such a shock at the place (south) where we detect abundant D_2CO. On the contrary, an outflow extending in the direction north-east to south-west is well documented in the literature (see Sect. 2), and our D_2CO map does not show any strong emission in that direction. SiO emission maps, believed to trace the shocks in the region strengthen this affirmation. Strong

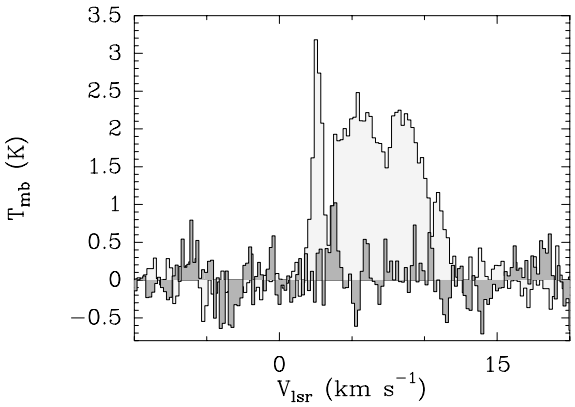

Fig. 6. H_2CO (light grey) and D_2CO (dark grey) line emission at $(-20'', +20'')$ from the center. The H_2CO line profile shows very strong emission between 4 and 12 km s^{-1}, probing the presence of outflowing gas. On the contrary, the outflow is not visible in the D_2CO line.

SiO emission is observed at the CO emission peaks of the outflow where the outflow impacts the surroundings, whereas no trace of SiO emission is observed towards the direction where D_2CO is bright (Hirano et al. 2000; Castets et al. 2001). Actually, the non detection of D_2CO emission at $(-20'', +20'')$, where a bright red wing is observed in H_2CO (Fig. 6) puts a stringent limit to the [D_2CO]/[H_2CO] ratio in this position: ≤0.003.

Accretion shocks may occur along the disk even at thousands of AUs, but they are predicted to be too weak (∼1 km s^{-1}) to cause an appreciable sputtering of the grain mantles. Model computations argue that in order to inject in the gas phase 1% of the mantle, a shock velocity of at least 10 km s^{-1} is needed (e.g. Caselli et al. 1997), which seems very unlikely in this case.

A simple and straightforward explanation of the extended D_2CO emission is that iced H_2CO and D_2CO molecules are embedded in a matrix rich in CO, or other non-polar, volatile molecules, which are evaporated at ∼4000 AU, where the dust temperature exceeds 25 K. Analysis of the detailed profile of the solid CO fundamental at 4.67 μm have shown that much of the solid CO is in an ice phase, which is non-polar in character; i.e., consists mainly of CO, N_2, and/or O_2 molecules (Tielens et al. 1991; Chiar et al. 1996). This non-polar ice mantle is distinct from the H_2O-rich ice phase which carries the 3.0 μm ice band and dominates the global ice composition in molecular clouds. The importance of ice segregation and thermal processing has also been inferred from the analysis of the detailed profiles of the $^{12}CO_2$ bending mode, the $^{13}CO_2$ stretching mode and the $^{12}CO_2$ overtones (Chiar et al. 1998; Boogert et al. 2000). This segregation of ice mantle molecules into components with different volatility is now generally attributed to the heating action as the newly formed central star increases its energy output.

The ensemble of our observations is consistent with the hypothesis that at ∼4000 AU CO-rich mantles evaporate, injecting in the gas phase traces of H_2CO and D_2CO.

For example, the H_2CO abundance in the cold envelope of IRAS16293 is at least four times larger than that measured in L1689N (the cloud hosting IRAS16293), which is $\leq 10^{-10}$ (Castets et al. 2001). Besides, CO itself seems depleted in the L1689N cloud by more than a factor 10 (Caux et al. 1999), whereas no CO depletion is observed towards IRAS16293 (Mundy et al. 1990).

At a somewhat smaller distance, ∼700 AU, a second layer of the mantle including ten times more H_2CO molecules evaporates: the dust temperature is about 50 K, very close to the 45 K evaporation temperature of pure H_2CO ices (Tielens & Allamandola 1987). Finally at ∼150 AU a third layer of the mantle, formed mainly by water molecules, evaporates, injecting another factor of 25 more of H_2CO molecules in the gas phase. *Our third conclusion is therefore that thermal heating of the dust releases the grain mantle constituents in the gas phase.* The mantles either have formed in an "onion-like" structure (predominantly H_2O ices covered by H_2CO ices which are themselves coated by predominantly CO ices) or are more enriched in H_2CO molecules going inwards. The observations so far available do not allow us to draw a conclusive picture of the mantle formation. There are several distinct possibilities which could explain the observations. For example, the observed non-polar, CO-rich mantles could be on a separate dust component, e.g. the large grains versus the small grains, due to size-dependent outgassing. It could also be due to a difference in the history of mantles formed in different places in the cloud.

4.5. Mantle formation

Once injected in the gas phase, H_2CO and D_2CO would undergo chemical reactions which may change their initial abundances. Charnley et al. (1992) estimated that the time scale for the conversion of H_2CO first into more complex molecules and then back into CO by gas phase chemical reactions in a dense ($\geq 10^6$ cm^{-3}) and hot ($\geq$100 K) core is $\geq 10^4$ yr, comparable to the IRAS16293 presumed age[1]. Deuterated formaldehyde abundance will also be changed by gas phase reactions on a time scale of $\sim 10^4$ yr (Charnley et al. 1997). Thus, at first approximation, the gas phase H_2CO and D_2CO abundances reflect their mantle abundances. In the previous paragraphs we demonstrated two facts:

a) formaldehyde fractionation increases going inwards: outside the envelope it is at least ten times smaller than inside the envelope;

b) larger amounts of H_2CO molecules are injected in the gas phase going inwards.

This behavior is qualitatively and quantitatively in agreement with what is expected if H_2CO results from CO hydrogenation on the grain mantles, i.e. with active grain chemistry model predictions. Charnley et al. (1997) showed that, when the accreting gas is dense ($\geq 10^5$ cm^{-3}) [H]/[CO] $\ll 1$, and the mantle $[D_2CO]/[H_2CO]$ abundance ratio depends quadratically on the accreting [D]/[H] ratio, i.e. $[D_2CO]/[H_2CO] \propto ([D]/[H])^2$. On the other hand, the gas phase [D]/[H] ratio depends almost linearly on the density of the gas (e.g. Tielens 1983), which implies that the $[D_2CO]/[H_2CO]$ abundance ratio depends approximatively on the square of the accreting gas density: $[D_2CO]/[H_2CO] \propto n^2$. Applying these results to the IRAS16293 envelope (where $n \propto r^{-3/2}$) gives a $[D_2CO]/[H_2CO]$ abundance ratio which decreases approximately with the cube of the radius r, i.e. $[D_2CO]/[H_2CO] \propto r^{-3}$. This is roughly consistent with our observations which show that the $[D_2CO]/[H_2CO]$ ratio decreases by about a factor of five going from 20″ to 40″. It is also consistent with the observed $[D_2CO]/[H_2CO]$ inside and outside the envelope. In fact, the $[D_2CO]/[H_2CO]$ ratio $\leq$0.003 (Sect. 4.4) outside the envelope (where the density is $\sim 5 \times 10^4$ cm^{-3}; Caux et al. 1999), is at least a factor ten lower than the $[D_2CO]/[H_2CO]$ ratio = 0.03 (Sect. 4.2) at the border of the envelope (where the density is $\sim 5 \times 10^5$ cm^{-3}).

The fact that the fractionation decreases to 0.05 in the $\leq$20″ region can be explained by the more efficient protonation, followed by dissociative recombination, of the D_2CO, which proceeds at a rate roughly proportional to the square density.

Finally, the amount of evaporated H_2CO in the three regions we identified (hot core, warm envelope, cold envelope) can be used to estimate the efficiency of CO hydrogenation across the envelope and/or in different ices. Assuming a CO abundance of 10^{-4}, the $[H_2CO]/[CO]$ results are: 10^{-3} in the hot core, 4×10^{-5} in the warm envelope and 4×10^{-6} in the cold envelope. These values reflect the efficiency with which CO is hydrogenated in the ices (Tielens & Hagen 1982): in polar ices (hot core) the efficiency is ∼250 times higher than in non-polar ices (cold envelope).

5. Conclusions

We presented a 60″ × 80″ map around IRAS16293 of the H_2CO and D_2CO line emission. We detected H_2CO and D_2CO emission up to 40″ from the center, corresponding to a linear distance of ∼5000 AU.

We used the observed H_2CO emission to reconstruct the H_2CO abundance profile across the envelope. We identified three regions:

i) in the inner "hot-core like" ($r \leq 150$ AU) region the H_2CO abundance is 10^{-7}, in agreement with our previous claims;
ii) in the intermediate "warm envelope" ($150 \leq r \leq 700$ AU) region the H_2CO abundance is 4×10^{-9};
iii) in the outer "cold envelope" ($r \geq 700$ AU) region the H_2CO abundance is 4×10^{-10}.

[1] IRAS16293 has at its center a 0.8 $M_\odot$ protostar accreting at a rate of 3.5×10^{-5} $M_\odot$ yr^{-1} (Ceccarelli et al. 2000a). Assuming that the accretion rate is constant, the age of the protostar is $\sim 2 \times 10^4$ yr.

The measured $[D_2CO]/[H_2CO]$ abundance ratio is 0.03 at the border of the envelope and increases going inwards, with a peak at 20″ where it is 0.16. This extremely high formaldehyde deuteration cannot be a present-day gas phase product. On the contrary, D_2CO must have been formed on the grain mantles during the previous cold *pre-collapse phase* and it has been injected in the gas phase during the warm *collapse phase*. We discussed the possibilities that such mantles are formed because of either pure gaseous D_2CO accretion or D_2CO formation via CO hydrogenation on the grain surfaces. The former theory cannot account for the observed values in a consistent way. In contrast, active grain chemistry successfully accounts for both the absolute observed fractionation and the observed gradient across the envelope.

We demonstrated that mantles are evaporated because of the thermal heating of the grains by the central source. In the "cold envelope" H_2CO and D_2CO molecules are embedded in CO-rich mantles which evaporate when the dust is warmer than ∼25 K, at ∼4000 AU. In the "warm envelope" a layer of apparently pure H_2CO ice is evaporated and, finally, prevalently H_2O ices are evaporated in the innermost 150 AU region. The measured H_2CO abundances in the three regions have been used to estimate the efficiency of CO hydrogenation across the envelope and/or in different ices. CO is hydrogenated 250 times more efficiently in H_2O-rich ices than in CO-rich ices.

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