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Formaldehyde absorption and visual extinction in the dark cloud L 1709 in the ρ Ophiuchi region

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Summary. We have mapped the 4.83 GHz H_2CO line in the dark cloud L 1709 in the ρ Oph complex and compared it with the distribution of visual extinction derived from star counts. The contours of the H_2CO and the shape of the dark cloud show a remarkable similarity. The H_2CO column density and visual extinction have a positive linear correlation with a slope of $0.9 \cdot 10^{13}$. The threshold value of visual extinction from which H_2CO can be detected in this cloud is $A_v > 0.9$ mag. There is a suggestion of a turnover of the relation between the H_2CO column density and A_v at high A_v . Although the limited amount of data does not allow us to draw any definite conclusions as to the cause, depletion on grains is a possibility. The ratios, $N_{1,1}(\text{H}_2\text{CO})/A_v$ and $N_{1,1}/N_{\text{H}_2}$, the volume density and the total mass of the cloud are derived. The radial velocity distribution indicates the presence of independently moving subclouds.

Key words: dark clouds – interstellar molecules – visual extinction – formaldehyde – interstellar dust

1. Introduction

While it is generally known that molecules are abundant in higher density clouds (as indicated by higher dust extinction) the current theories for the formation and depletion of, for example, H_2CO and its relationship to the dust are still under development. Whether the H_2CO molecules are formed by gas phase reactions alone (Herbst and Klemperer, 1973; de Jong et al., 1980) or by reactions including those within and on the dust grains (Greenberg, 1976, 1979; Greenberg et al., 1979, d'Hendecourt et al., 1985) is a problem which is being actively pursued.

Langer (1976) made a calculation on the fractional abundance for formaldehyde, $X(\text{H}_2\text{CO})$, in model clouds exposed to the interstellar radiation field. For a hydrogen density of 10^4 cm^{-3} , Langer found a nearly constant $X(\text{H}_2\text{CO})$ at large optical depths, but a sharp drop of the fractional abundance below a quite well-defined optical depth value (4–6) depending on the value of the fractional abundance of metal oxides. De Jong et al. (1980) have taken grain accretion into account in a model of L134 and have shown that for sufficiently long cloud lifetimes the abundance of H_2CO drops rapidly. Time dependent chemistry in molecular clouds combining both continuous gas phase and grain

surface reaction along with accretion, photochemistry, and explosive grain mantle desorption shows that for a cloud density $\eta_{\text{H}_2} = 10^4 \text{ cm}^{-3}$ and $A_v = 4$ mag the value of $N_{\text{H}_2\text{CO}}/N_{\text{H}_2}$ peaks up to $\sim 10^{-7}$ (rather higher than observed) at times $t \simeq 10^6$ yr and then drops by a factor of 100 at $t \simeq 10^7$ yr (d'Hendecourt et al., 1985; Greenberg, 1985). For lower densities $\eta_{\text{H}_2} = 10^3 \text{ cm}^{-3}$ and $A_v = 2$ mag the theoretical maximum $\sim 10^{-10}$ is achieved only for $t \gtrsim 10^7$ yr. If explosions are not included, unimpeded accretion leads to a “total” disappearance of H_2CO out of the gas and into the grain mantles for $t \gtrsim 10^6$ yr (Iglesias, 1977; Greenberg, 1977; d'Hendecourt et al., 1985). It is clear that accretion plays a role in gas phase abundances but its effects are complicated by processes of ultraviolet processing (d'Hendecourt et al., 1986), and desorption (Greenberg and Yench, 1973; d'Hendecourt et al., 1982; Leger et al., 1985) as well as surface reactions (Grim and d'Hendecourt, 1986). Thus the theoretical possibility of a lack of linear correlation between H_2CO and dust at high extinctions is demonstrated although the dependence of this effect on local conditions and cloud evolution has yet to be fully explored. Bernes and Sandqvist (1977) calculated the probability of photodissociation of H_2CO in dark clouds for various density distributions. They found that in the ρ Oph cloud complex, higher opacities than those implied by star counts are necessary if photodissociation of formaldehyde by interstellar radiation in the outer parts of the cloud is not to occur.

A number of mappings of the 4.8 GHz H_2CO line in dark clouds have been published (Sume et al., 1975; Myers and Ho, 1975; Brooks et al., 1976; Dickel et al., 1977; Myers et al., 1978; Few and Booth, 1979; Minn and Greenberg, 1979; Sandqvist and Bernes, 1980). A general correspondence between the distributions of formaldehyde and extinction seems to be apparent, but in a few clouds no detailed correlation is found (Dickel et al., 1977; Minn and Greenberg, 1979). In fact, the latter authors found that $N_{\text{H}_2\text{CO}}/A_v$ seemed to be decreasing with increasing extinction beyond about $A_v = 4$ mag in clouds near NGC 2264. This effect was later noted also by Wooten et al. (1980) in studies of 13 molecular clouds using measurements of H_2CO (140.8 GHz) and HCO^+ (89.2 GHz). In the clouds characterized by higher density and temperature but lower abundances a negative slope was found for the correlation between $N_{\text{H}_2\text{CO}}$ and the spatial density.

Thus although it appears obvious that we observe formaldehyde molecules in a variety of regions where extinction is well determined, it also appears useful to observe not only the general correlation of dust and H_2CO but also to observe the correlation of the shapes and boundaries of well-defined dark

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clouds with those of the molecular distribution to help discriminate among the various grain-gas interactions which have been proposed. What is the relative importance of local dust density and of ultraviolet penetration in the balance between H_2CO production and destruction?

L1709 is one of the dark clouds in the ρ Oph complex. Lynds (1962) gives the size and opacity of this cloud as 0.099 deg^2 and 6 respectively. We mapped not only L1709 but also the region of about 0.4 deg^2 surrounding it. This area contains an additional small dark cloud, L1704. The L1709 region is well suited for detailed mapping because it has both a sharp boundary and a reasonable angular dimension for 4.8 GHz H_2CO line observations. This cloud is the upper arm of two elongated streamers extended to the east from the central region of the ρ Oph complex where H II regions, infrared sources, radio recombination lines, and millimeter wavelength molecular lines were found and active star formation is in progress (Loren and Wootten, 1986). It is also the cloud where measurements of optical and infrared polarization by Vrba et al. (1976) show that the magnetic field is generally lined up with the direction of elongation.

We have mapped the cloud in the 4.83 GHz absorption line of H_2CO and derived extinction by the method of star counts. We then made a detailed comparison of the two results.

2. Observations

The 6-cm H_2CO line observations were made with the NRAO¹ 43-m telescope. The half-power beamwidth of the antenna was $6.6'$ and beam efficiency was $\sim 80\%$. The 413-channel autocorrelator receiver with a cooled 6-cm parametric amplifier was used. The system noise temperature was $\sim 70 \text{ K}$. The effective resolution was 3.94 Hz (0.24 km s^{-1}). Forty minute integrations on and off sources were performed, yielding an rms noise 0.07 K . We used the value of 4829.660 MHz for the rest frequency of H_2CO . The data were Hanning smoothed before the line parameters were measured. All velocities were measured with respect to the local standard of rest assuming the standard solar motion. The measurements were made at forty-four points for the mapping with $6'$ grid intervals in both right ascension and declination.

3. Star counts and extinction

The stars were counted in the region of 1.8×1.0 on an enlarged red print of the Palomar Observatory Sky Survey (POSS). The red print is chosen rather than the blue simply because it gives better statistics provided by the greater number of stars seen on the print (Encrenaz et al., 1975; Tucker et al., 1976). A grid of contiguous squares of size $6.6 \times 6.6'$ were used to match the beamwidth of the H_2CO observations. Stars were counted in over 150 square fields to obtain the extinction map. We used the following analytic formula to derive the red and visual extinction, A_R and A_V , from the star counts (see Dickman, 1978; Encrenaz et al., 1975).

$$A_V = 1.21 A_R \simeq 3.4 \log \frac{N_R^{\text{ref}}}{N_R},$$

where N_R^{ref} and N_R are the number of stars counted in the reference field and the field where extinction is to be measured respectively. The values of the ratio of total to selective extinction $R_V = 3.2$ (Harris, 1973), and the slope of the plot, $\log(N_R^{\text{ref}}/N_R)$ vs $\log(N_B^{\text{ref}}/N_B)$ at various points, $s = 1.6$, which comes from the general extinction law are used in our analysis.

The highest value of extinction obtained by this method is 6.1 mag which is considerably lower than the value obtained by Vrba et al. (1976) in the same region by optical and infrared photometry of stars. As already discussed by Minn and Greenberg (1979), the star counting method generally provides a lower limit to the extinction.

4. Comparisons of H_2CO distribution with the visual appearance and extinction map of the cloud

A contour map of the antenna temperature of the H_2CO line is superimposed on the POSS red print in Fig. 1. The figure shows that the shapes of the H_2CO and dust clouds are generally well correlated as the contour lines follow the outline of the visual dark cloud and the peaks of $T_A = -0.30$ fall in the darkest areas of the cloud. However, the lowest contour line of $T_A = -0.1$ falls considerably outside the apparent boundary of the dark cloud as delineated on the POSS red print. A substantial, though slightly less distinct obscuration than the principal portion of the cloud is also clearly extended outward on the POSS blue print, matching the H_2CO distribution. A contour map of the integrated line intensity $W = \int T_A dV$ of H_2CO is shown in Fig. 2. The line opacity is generally far less than 1.0, so that we can take W as proportional to the column density of the lower state H_2CO with the usual assumption that excitation and background temperatures are constant throughout the region. Here the contour line shape resembles the T_A distribution except that it shows only one peak which is shifted to the north-eastern side of the darkest part of the cloud. The H_2CO cloud seems to extend beyond the dark cloud we mapped toward another dark area in the upper left side of the map, while in the western side of the cloud the H_2CO cloud appears to be terminated even though a considerable amount of obscuration exists beyond the edge of the cloud forming a link with the major cloud in the ρ Oph region.

Figure 3 shows the distribution of visual extinction, A_V , derived from star counts. The visual extinction map appears to be more complex than the H_2CO distribution and the visual appearance of the cloud. The two maxima with $A_V = 6.1$ and 5.3 lie in the central part of the cloud along the major axis. The positions of these maxima correspond closely with the T_A peaks in Fig. 1 rather than with the peak position of W .

In order to compare the distributions of extinction and H_2CO , we plotted as dashed lines, in Fig. 3, the contour lines of $W = 0.1$ and $0.2 \text{ km s}^{-1} \text{ K}$ shown in Fig. 2. The contour line of $W = 0.1 \text{ km s}^{-1} \text{ K}$ generally follows closely the contour line of $A_V = 2.0$ mag on the northern and southern sides. But on the eastern side, H_2CO is detected in the region of lower extinction, while on the western side, H_2CO has dropped to $W = 0.1$ even though there exists a region of higher extinction. We did not continue our mapping into this adjacent dark cloud. Myers et al. (1978) also noted that in the numerous positions of high extinction near to and west of HD 147889 in the ρ Oph region, the H_2CO line could not be detected. This is part of a larger cloud of high extinction and there is no obvious a priori reason for the reduction in the H_2CO line strength in this region.

¹ Operated by Associated Universities, Inc. under contract with the National Science Foundation

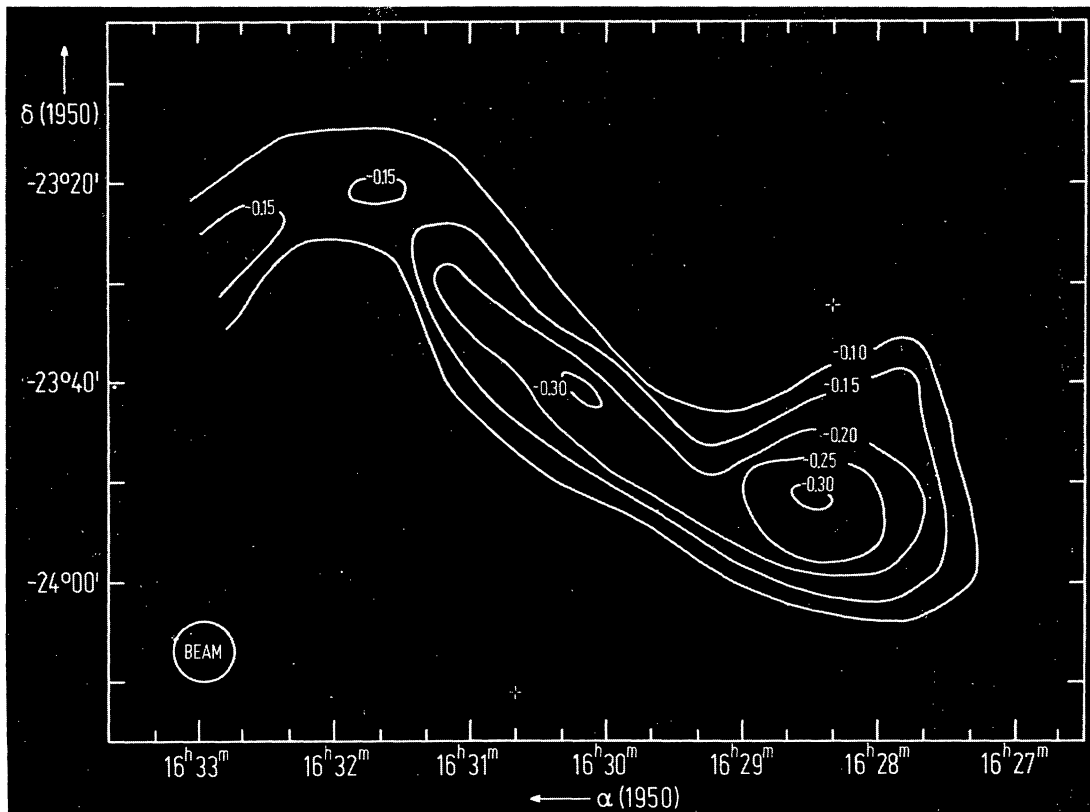


Fig. 1. A contour map of the cloud in the H₂CO line antenna temperature superimposed on the Palomar Sky Survey red print. The contour unit is K

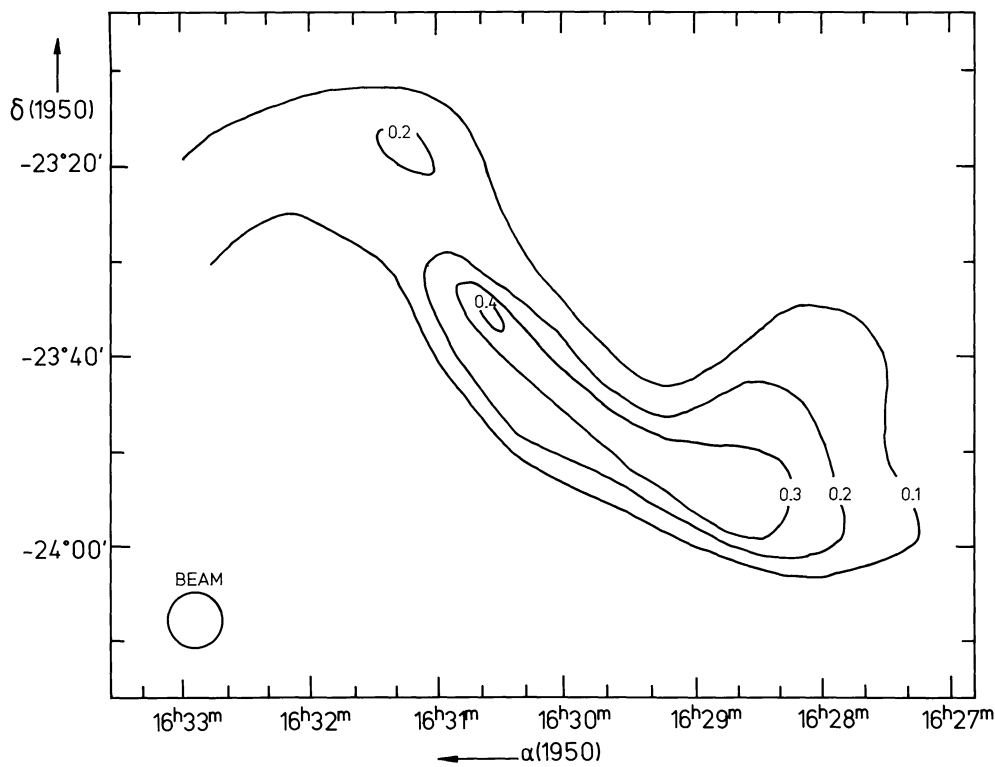


Fig. 2. A contour map of the observed integrated intensity, $\int dv T_A$, of the H₂CO absorption line. The contour unit is $\text{km s}^{-1} \text{K}$

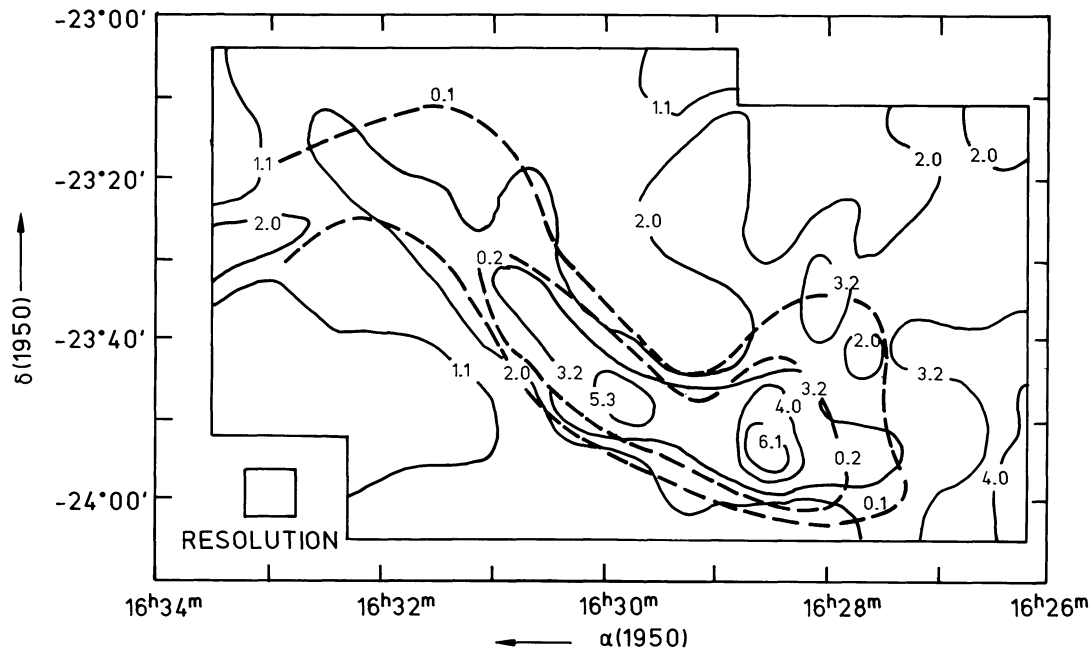


Fig. 3. Distribution of visual extinction derived from red star counts. The contour unit is mag. The two outer contour lines of 0.2 and 0.1 km s^{-1} K of $\int dv T_A$ are shown in dashed lines

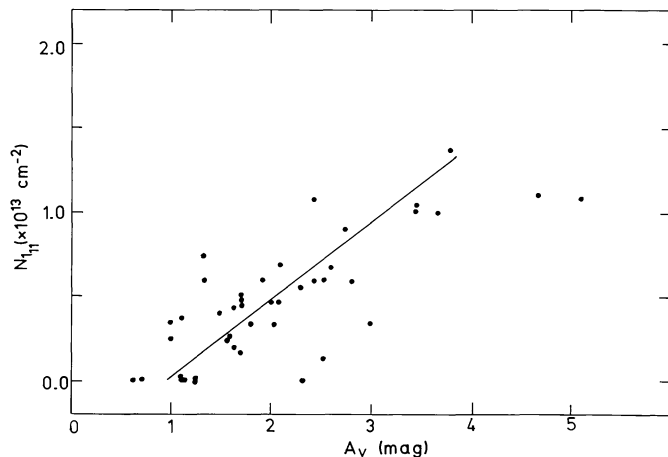


Fig. 4. The lower column density N_{111} of H_2CO as a function of visual extinction toward the cloud

5. Correlation of H_2CO and extinction

We calculated the H_2CO column density in the $J_{K-K^+} = 1_{11}$ state, N_{111} , at each position observed assuming a constant excitation temperature $T_{\text{ex}} = 2.0$ K over the whole cloud and that H_2CO completely fills the beam. The excitation temperatures for the transition $1_{10} \leftarrow 1_{11}$ of formaldehyde have been derived by a few authors (Heiles, 1973; Downes et al., 1976; Sandqvist and Bernes, 1980) for various clouds from their observations. The excitation temperatures they found vary from 0.5 K to 2.4 K from cloud to cloud. Evans et al. (1975) and Garrison et al. (1975) derived T_{ex} as a function of density of the cloud for different kinetic temperatures. Implications of varying T_{ex} on the H_2CO column density have been fully examined by Javanaud (1980). We adopted $T_{\text{ex}} = 2.0$ K as did Sume et al. (1975) and Sherwood and Wilson

(1981). This value of T_{ex} is consistent with the calculations made by Garrison et al. (1975) for a hydrogen density in the range $N_{\text{H}_2} \approx 5 \cdot 10^3$ to $1.5 \cdot 10^4 \text{ cm}^{-3}$, which is approximately consistent with our final result. The uncertainty in T_{ex} leads to an uncertainty in the column density. But, as pointed out by Sherwood and Wilson (1981), the likely variation of T_{ex} (1.7–2.0 K) in this cloud gives only a factor of 2 uncertainty in the column density. The maximum value of N_{111} we derived in this cloud is $1.38 \cdot 10^{13} \text{ cm}^{-2}$. The values of the H_2CO column density are a little lower than the column densities in the ρ Oph cloud derived by Myers et al. (1977), mainly due to the narrower line halfwidth ($\lesssim 1.0 \text{ km s}^{-1}$). The H_2CO column density of the lower level, N_{111} , is plotted as a function of visual extinction in Fig. 4. A considerable scattering of points is shown as may be expected from a large scale comparison. However, a general positive linear correlation appears to exist between the H_2CO column density and the visual extinction, if we ignore the two points at high extinction. A similar positive linear correlation was obtained in the Taurus dark clouds by Kutner (1973), in the ρ Oph cloud by Myers et al. (1977), and in dark clouds near NGC 2264 by Minn and Greenberg (1979).

The best linear fit to the data points in Fig. 4 is

$$N_{111}(\text{H}_2\text{CO}) = 0.9 \cdot 10^{13} (A_v - 0.9 \text{ mag}).$$

Minn and Greenberg (1979), Sherwood and Wilson (1981), and Pöppel et al. (1983) derived similar relations for dark clouds near NGC 2264, Cloud 2 and the Taurus cloud. The slopes range from 0.6 to $1.5 \cdot 10^{13}$. Javanaud (1979) also found that $N_{\text{H}_2\text{CO}}/A_v$ is constant over $2.5 < A_v \leq 7.1$ mag, which is consistent with our result. Our threshold value of A_v from which the H_2CO molecule can be detected is $A_v > 0.9$ mag. It has been found to vary from cloud to cloud with a range of $A_v = 0 \sim 2.1$ mag (Kutner, 1973; Myers, 1975; Myers et al., 1978; Minn and Greenberg, 1979; Sherwood and Wilson, 1981). Myers et al. (1978) obtained $A_v = 0.9$ mag in the ρ Oph cloud which is the same value as ours. The threshold value of A_v for ^{13}CO is found within a range similar

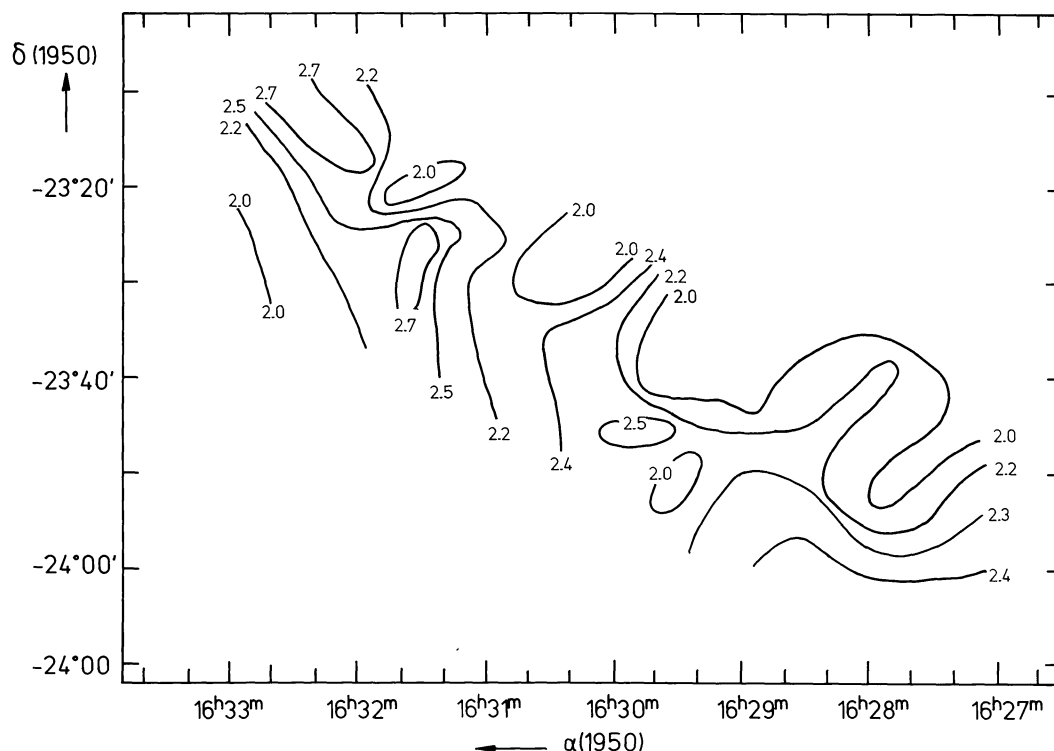


Fig. 5. Distribution of the observed radial velocity of the H₂CO line. The unit is km s⁻¹

to that for H₂CO (Frerking et al., 1982; Dunert et al., 1986; Bachiller and Cernicharo, 1986), but the threshold A_v for CH seems to be a bit lower than those for H₂CO and ¹³CO since CH is concentrated in the outer parts of dark clouds as shown by Mattila (1986).

The two points at high extinction (A_v near 5 mag) in Fig. 4 imply that the H₂CO column density does not increase linearly at high extinction but rather tapers off. This result is based on too little data to be more than suggestive. But, if it is confirmed, it could be interpreted either as the result of the lack of H₂CO due to accretion of molecules on the grains or some more subtle effect involving grain-gas interactions, or increased population of the higher levels of the H₂CO molecules in these densest regions as can be shown to occur from millimeter H₂CO line observations in L1318b-c (Dickel et al., 1977). Contrary to this, Javanaud (1979) argued that based on the calculations of the lifetime of H₂CO by Sandell and Mattila (1975), $N_{\text{H}_2\text{CO}}/A_v$ must increase by an order of magnitude as A_v increases from 2.5 to 7.1 mag due to a reduced rate of destruction of H₂CO by photodissociation. But Javanaud's observations show a constant ratio of $N_{\text{H}_2\text{CO}}/A_v$ over the entire extinction range. Frerking et al. (1982) found a similar turnover in C¹⁸O and C¹⁹O and discussed the possible causes of the reduction of column density at high extinction. In order to determine an accurate value of $N_{\text{H}_2\text{CO}}/A_v$ which is so important in the discussion of formation and destruction of H₂CO, we need a more accurate method to determine extinction than star counts which give somewhat lower values of A_v . Bernes and Sandqvist (1977) studied the photo-dissociation rate of formaldehyde by interstellar radiation and concluded that higher opacities than those implied by star counts are necessary. The average value of $N_{1,1}/A_v$ in our analysis is $0.26 \cdot 10^{13} \text{ cm}^{-2} \text{ mag}^{-1}$. This agrees well with the value of Javanaud ($0.268 \cdot 10^{13} \text{ cm}^{-2} \text{ mag}^{-1}$ for beam efficiency, $\eta = 0.6$).

If we use the value of $N_{\text{H}_2}/A_v = 0.94 \cdot 10^{21} \text{ cm}^{-2}$ (Bohlin et al., 1978) the ratio of H₂CO column density in the lower state to total hydrogen is $N_{1,1}/N_{\text{H}_2} = 1.0 \cdot 10^{-9}$. This compares well with Javanaud's value. The ortho to para ratio of H₂CO as discussed by Javanaud is still unknown to uncertainties of an order of magnitude. However, if we assume the ratio equals 3 to 1 (Scoville et al., 1972; Thaddeus et al., 1971), the ratio, $N_{\text{H}_2\text{CO}}/N_{\text{H}_2}$, is similar to those of Kutner (1973) and Evans et al. (1975).

If we take the distance to the ρ Oph complex, $D = 200 \text{ pc}$ (Bok and Cordwell, 1971), to be the distance of the cloud, we obtain the mean volume density $n = 1.3 \cdot 10^3 \text{ cm}^{-3}$ and a total mass of $5.2 \cdot 10^2 M_\odot$ assuming that hydrogen is mostly in the molecular form and the above mentioned ortho to para ratio of H₂CO. The cloud core could well have a density 5 to 10 times higher so that the relative decrease of H₂CO observed at higher extinctions would be consistent with the decrease predicted by d'Hendecourt et al. (1985) if the cloud lifetime is $\sim 10^7 \text{ yr}$.

5.1. Line velocity

The radial velocity distribution in the cloud (given in Fig. 5) ranges from 2.0 to 2.7 km s⁻¹ at the upper end. The radial velocity of the H I absorption line in this region varies from 3.0 to 3.5 km s⁻¹ (Minn, 1981). The Figure shows no systematic pattern. However, the contour lines can be divided into two groups, north and south. In the southern part the lower region has the more positive velocity, while in the northern part the cloud center along the long axis has the largest positive velocity. The contour lines run along the long axis of the cloud. There are a few isolated velocity centers which might be an indication of the existence of subclouds moving independently. The velocity distribution in the cloud implies that there are large scale turbulent or random motions in the cloud even though the magnetic fields as indicated

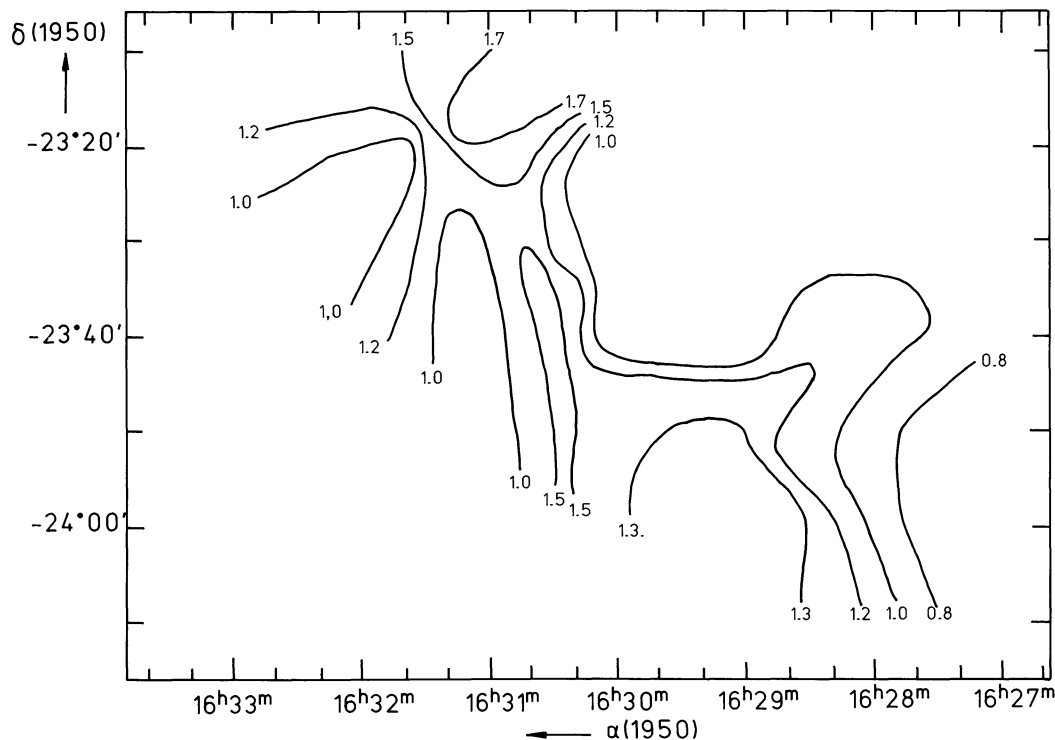


Fig. 6. Distribution of the observed H_2CO line halfwidth. The unit is km s^{-1}

Table 1. Derived H_2CO parameters

Median velocity (km s^{-1})	2.2
Median line halfwidth (km s^{-1})	1.2
Angular dimension (arcmin)	52×10
Linear dimension (pc)	3.0×0.6
Median column density (cm^{-2})	$2.76 \cdot 10^{13}$
Median volume density (cm^{-3})	$1.5 \cdot 10^{-5}$
Total mass (M_{\odot})	10^{-5}

from optical polarization measurements (Vrba et al., 1976) are well aligned with the long axis of the cloud.

5.2. Line halfwidth

Figure 6 shows the distribution of the H_2CO line halfwidth. It varies between 1.7 km s^{-1} at the upper east side and 0.8 km s^{-1} at the west side of the cloud. The variation, however, shows no systematic trend such as the increase of the line width toward the center of the cloud complex in the direction near NGC 7538 (Minn and Greenberg, 1975). This irregularity of the line halfwidth could be due either to random motions of molecules in the cloud or variation of the cloud depth along the line of sight. There is no correlation between the line width and star count or between the line width and line temperature. The derived parameters of the H_2CO cloud based on the assumed distance of 200 pc are given in Table 1.

6. Conclusions

From a detailed mapping of H_2CO in an isolated quiescent cloud L1709 in the ρ Oph region we note that:

1) There is an excellent correlation of the shapes of the H_2CO contours with the visual boundary of the cloud and the extinction contours obtained from star counts.

2) There exists a linear relation between the H_2CO column density and visual extinction in the range $0.9 \lesssim A_v \lesssim 4 \text{ mag}$.

3) A preliminary result, based on limited data, indicates that the H_2CO number density decreases not only relatively but absolutely at high extinction ($A_v > 4.6 \text{ mag}$).

4) The nonuniformity of the velocity and line width implies large scale turbulent motions or subclouds within the cloud.

5) The mean value of the ratio of formaldehyde to hydrogen is $N_{\text{H}_2\text{CO}}/N_{\text{H}_2} = 1.42 \cdot 10^{-9}$.

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