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Detection of HCO\(^+\) towards Cygnus OB2 No. 12

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ABSTRACT
HCO\(^+\) has been detected for the first time towards the star Cygnus OB2 No. 12 through emission of the 1–0 rotational transition at 89 GHz. The CO\((J = 2 - 1)\) transition has also been observed. The observations are consistent with a model of dense regions embedded in a low-density clump gas. If actually present, the dense component would have an aggregate size \(L \leq 1300 \text{ au}\), in agreement with estimates of small-scale density fluctuations observed along diffuse lines of sight.

Key words: stars: individual: Cygnus OB2 No. 12 – ISM: abundances – ISM: clouds – ISM: molecules.

1 INTRODUCTION
The molecular ion H\(_2^+\) has been discovered in the apparently diffuse region of the interstellar gas in front of the star Cygnus OB2 No. 12 (McCall et al. 1998; Geballe et al. 1999) with an abundance comparable to that found for dense clouds (Geballe & Oka 1996). Geballe et al. (1999) constructed a model of the region with a hydrogen density of 10 cm\(^{-3}\) but they noted that it led to a long path length and did not explain observations of CO emission and C\(_2\) absorption (Gredel & Münch 1994). The low-density model is however consistent with ISO observations that have shown the presence of the 3.4-\(\mu\)m hydrocarbon feature, and the absence of the 3.0- and 4.27-\(\mu\)m features of H\(_2\)O and CO\(_2\) ices (Whittet et al. 1997).

In fact, the line of sight towards Cygnus OB2 No. 12 cannot be considered unusual. Millimetre-wave absorption measurements reveal that diffuse clouds have indeed a rich chemistry. As noted by Lucas & Lizst (1999), on the average abundance ratios are not so far from those in dark clouds. In particular, molecular species as HCO\(^+\), HCN, HNC, C\(_2\)H, as well as CS and CN are overabundant, relative to the standard diffuse cloud models, by about two orders of magnitude.

Recently, Cecchi-Pestellini & Dalgarno (2000) presented a model of the material in front of the star Cygnus OB2 No. 12 in which dense cold cores are embedded in diffuse clumps of gas. The model reproduces the measured abundances of H\(_2^+\), C\(_2\) and CO, and predicts a column density of about \(9 \times 10^{19} \text{ cm}^{-2}\) for HCO\(^+\). However, along typical diffuse lines of sight, excitation analysis of C, CO, and C\(_2\) energy level column densities derived from optical, ultraviolet and infrared absorption spectra suggest a density of a few times \(100 \text{ cm}^{-3}\) (although with a rather large uncertainty) and a temperature in the range 20–40 K. The difficulty raised by the diffuse cloud chemistry could be solved by a better understanding of both the excitation mechanisms of molecular tracers and the gas density structure. In this framework we have carried out a search for emissions of CO\((J = 2 - 1)\), CS\((J = 3 - 2)\) and HCO\(^+\)(\(J = 1 - 0\)) rotational transitions which are tracers of higher density gas. In sections 2 and 3 we describe the observations and results, while in the last section we discuss the conclusion we reached.

2 OBSERVATIONS
The millimetre-wave spectra were obtained with the IRAM 30-m telescope at Pico Veleta, Spain, in 1999 May 15–18. At the rest frequencies of 89 188.52 MHz HCO\(^+\)(\(J = 1 - 0\)), 146 969.05 MHz CS\((J = 3 - 2)\) and 230 537.98 MHz CO\((J = 2 - 1)\) the half-power beamwidths (HPBWs) are 29, 16 and 10 arcsec, the beam efficiencies 0.75, 0.53 and 0.39, and the system temperatures around 100, 250 and 300 K, respectively. Observations were made using position switching at 30 s on/off intervals with an array of three receivers set at the appropriate line frequencies. The spectrometers used are a 1 MHz filter bank and an autocorrelator. The first spectrometer, split into three parts of 256 and 512 channels, provides velocity resolutions of 3.4, 2.0 and 1.3 km s\(^{-1}\) at 89, 147 and 230 GHz, respectively. A second spectrometer provides velocity resolutions of 0.26, 0.15, and 0.10 km s\(^{-1}\) at the same frequencies. These spectrometers were used simultaneously so that each spectrum was recorded at two different resolutions. The pointing was checked every hour by observing either planets or continuum sources and was found to be accurate to within

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3 arcsec. The antenna temperature was calibrated with a standard chopper wheel method and the intensity of the spectra is expressed in units of main-beam brightness temperature ($T_{\text{MB}}$). The coordinates of Cygnus OB2 No. 12 were taken from McCall et al. (1998) as $\alpha_{1950} = 20^h30^m53^s.4$, $\delta_{1950} = +41^\circ03'52''$.

3 RESULTS

The millimetre-wave emission of CO($J = 2 - 1$) towards Cygnus OB2 No. 12 was mapped, in steps of $0.00\text{arcsec}^2$, around the position of the star (0,0) in a region of $40\times40\text{arcsec}^2$, which corresponds to $0.3\times0.3\text{pc}^2$, for a star at 1.7 kpc from the Earth (Torres-Dodgen, Carrol & Tapia 1991). Fig. 1 (upper panel) shows the spectrum of CO($J = 2 - 1$) taken at the coordinates of Cygnus OB2 No. 12. Three strong components are seen at LSR velocities of $-22, +7, +12\text{ km s}^{-1}$ and a weak one at $+0.3\text{ km s}^{-1}$. The features seen in absorption are artefacts owing to contamination from the reference position. Our results are in agreement with the observations made by McCall et al. (1998) with the James Clerk Maxwell Telescope (JCMT) of the same line. The peak emission relative to the observed region was seen at the (20,0) position. The derived spectral parameters are given in Table 1. They were obtained assuming for each line a Gaussian profile. If we compare the millimetre-wave emission of CO with the near-infrared high-resolution C2 spectra towards the same source taken by Gredel & Münch (1994) we find that the components at LSR velocities of $+7$ and $+12\text{ km s}^{-1}$ are common to both spectra and therefore they originate in the gas in front of Cygnus OB2 No. 12.

The CS($J = 3 - 2$) line was searched for towards Cygnus OB2 No. 12 in the same $40\times40\text{arcsec}^2$ region as the CO($J = 2 - 1$). It was not detected to a rms limit of 0.02 K. In the case of thermal emission in an optically thin gas we can derive an upper limit of $1.1\times10^{13}\text{ cm}^{-2}$ for the CS column density. The gas temperature is assumed to be 10 K.

The HCO$^+ (J = 1 - 0)$ line was also mapped in the same $40\times40\text{arcsec}^2$ region. It was detected in three positions including (0,0). The maximum emission was found at the (20,0) position. Fig. 1 (lower panel) shows the spectrum taken at the (0,0) position after 30 min integration on the source. The derived spectral parameters are shown in Table 1. Since the emission is centred at $+12\text{ km s}^{-1}$, it belongs to the foreground material.

Figure 1. Spectrum of the CO($J = 2 - 1$) transition (upper) and of the HCO$^+ (J = 1 - 0)$ transition (lower) towards Cygnus OB2 No. 12. The telescope pointing position corresponds to the coordinate of the star (see text).

Table 1. Molecular parameters from the observations towards Cygnus OB2 No. 12.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Position$^{(a)}$ (arcsec)</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>$\Delta v^{(b)}$ (km s$^{-1}$)</th>
<th>$T_{\text{MB}}$ (K)</th>
<th>$\int T_{\text{MB}}d\theta$ (K km s$^{-1}$)</th>
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<td>CO($J = 2 - 1$)</td>
<td>(+20, 0)</td>
<td>$+12.24(1)^{(c)}$</td>
<td>1.64(2)</td>
<td>7.1(1)</td>
<td>12.4(1)</td>
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<tr>
<td>HCO$^+ (J = 1 - 0)$</td>
<td>(+20, 0)</td>
<td>$+12.3(1)^{(c)}$</td>
<td>1.12(2)</td>
<td>0.09(2)</td>
<td>0.10(2)</td>
</tr>
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Notes:

$^{(a)}$ off-set position with respect to the coordinates of the star Cygnus OB2 No. 12;

$^{(b)}$ full width at half-maximum;

$^{(c)}$ the $1\sigma$ uncertainty in parentheses is in units of the last digit.
corresponding optically thin local thermodynamic equilibrium (LTE) column density is \( N_{\text{HCO}^+} = 1.0(2) \times 10^{11} \text{ cm}^{-2} \). The gas temperature is assumed to be 10 K.

McCall et al. (1998) also presented the spectrum of \( v = 1 - 0 \) lines of the fundamental vibration rotation band of CO near 4.65 \( \mu \text{m} \) towards Cygnus OB2 No. 12. The absorption profiles are centred at \( c_{\text{LSR}} = +15 \pm 4 \text{ km s}^{-1} \). This suggests that the CO absorption lines are produced largely by the \( +12 \text{ km s}^{-1} \) cloud. From the relative strengths of the infrared CO lines, Geballe et al. (1999) derived an excitation temperature of about 5–10 K and a total column density of CO of \( 3 \times 10^{16} \text{ cm}^{-2} \).

4 DISCUSSION

In the following we adopt both a Large Velocity Gradient (LVG) method and a method (ZVG) in which the velocity gradient is small in order to model the excitation condition of CO.

With the approximation that any emitted photon either escapes the medium completely or is locally absorbed, we may determine the CO level populations by solving the following rate equations

\[
f_i = \sum_{j>i} \left[ A_{ij} \beta_j [1 + J_{ij}(T_{bg}) + C_j] + \sum_{j<i} \left[ C_{ji} + A_{ji} \beta_j \frac{g_i}{g_j} J_{ij}(T_{bg}) \right] \right] \\
= \sum_{j>i} f_j A_{ij} \beta_j [1 + J_{ij}(T_{bg})] + \sum_{j<i} f_i \left[ C_{ji} + A_{ji} \beta_j \frac{g_i}{g_j} J_{ij}(T_{bg}) \right],
\]

where \( f_i \) is the fractional population of the \( i \)th energy level, subjected to the normalization condition \( \sum_i f_i = 1 \). In equation (1), \( A_{ij} \) is the Einstein coefficient for spontaneous emission, \( \beta_j \) the escape probability, \( C_j \) the de-excitation collision rate for the \( i \to j \) transition (Flower & Launay 1985), \( g_i \) the statistical weight of the \( i \)th level, and

\[
J_{ij}(T_{bg}) = \frac{1}{\exp(hv_{ij}/kT_{bg}) - 1}
\]

the background source. The escape probability for the LVG calculation is taken from Neufeld & Melnick (1987). In the ZVG case we use the escape probability of a quiescent slab of Capriotti (1965).

The solution of the radiative transfer equation gives the main-beam brightness temperature

\[
T_{\text{MB}}(v_i) = \frac{h v_i}{k} \left[ J_{ij}(T_{\text{ex}}) - J_{ij}(T_{bg}) \right] (1 - e^{-\tau_{ij}})
\]

where \( T_{\text{ex}} \) is the excitation temperature defined by the relation

\[
J_{ij}(T_{\text{ex}}) = \frac{1}{f_i g_i f_j g_j - 1} = \frac{1}{\exp(hv_{ij}/kT_{\text{ex}}) - 1}
\]

and \( \tau_{ij} \) the optical depth given by

\[
\tau_{ij} = \frac{c^3}{8 \pi v_{ij}^3} A_{ij} \left( f_i g_i - f_j g_j \right) N/\Delta v.
\]

In the LVG approximation \( N/\Delta v \) is the CO column density for unit velocity. The calculations were performed using a CO column density per unit velocity of \( 1 \times 10^{16} \text{ cm}^{-2}/(\text{km s}^{-1}) \) which implies a velocity step \( \Delta v = 3 \text{ km s}^{-1} \). In a static medium (ZVG) the optical depth is related to the column densities in the various levels and \( \Delta v \) is the FWHM (Table 1).

Fig. 2 shows the excitation temperature for the CO\((J = 2 - 1)\) rotational transition as a function of molecular hydrogen density.

The results of LVG modelling are consistent with the inferred excitation temperature (Geballe et al. 1999) if the density of molecular hydrogen is constrained below \( 500 \text{ cm}^{-3} \) for a gas temperature \( T_k = 15 \) and below \( 300 \text{ cm}^{-3} \) for \( T_k = 20 \). At those densities the main-beam brightness temperature (Fig. 3) is far from the observed value (Table 1). ZVG results imply an even larger gas density.

The best agreement between LVG results and both excitation and main-beam brightness temperature has been found choosing a gas temperature \( T_k = 12 \text{ K} \) and a density of the medium \( n_{\text{H}_2} = 2 n(\text{H}_2) \approx 10^4 \text{ cm}^{-3} \) (Fig. 3). Since the CO\((J = 2 - 1)\) critical density for \( \text{H}_2 \) collisions is about \( 6 \times 10^3 \text{ cm}^{-3} \) the emission should be close to LTE.

Whether the detected emission of \( \text{HCO}^+ \) is actually tracking a dense medium is not clear. Evans (1999) pointed out that the
detection of a particular emission transition does not necessarily imply a density of the medium close to the critical density. In fact, the effective density can be much lower. In particular, the density needed to produce a HCO\(^+\) (J = 1 – 0) rotational emission of 1 K can be as low as 560 cm\(^{-3}\), for an emitting gas with kinetic temperature \(T_k = 100\) K (Evans 1999). At these densities the fractional ionization, \(x_e\), can exceed 10\(^{-5}\) making electronic collisions important in the excitation processes. However, since the electron critical density of the \(J = 1 – 0\) transition of HCO\(^+\) is 4.6 cm\(^{-3}\) (Dickinson & Flower 1981) and being \(x_e = n_{e^+}/n_H = 1.4 \times 10^{-5}\), the carbon cosmic abundance (Cardelli et al. 1996), the level \(J = 1\) is sub-thermally populated.

Using a simple two-level system we may estimate the column density of HCO\(^+\) in the sub-thermal (low density) regime. The fraction of molecules in the \(J = 1\) rotational state is

\[
f_1 = n_1/n_{\text{HCO}^+} = \frac{2}{3 + n_e/n_{\text{coll}}},
\]

where \(n_e\) is the critical density and \(n_{\text{coll}}\) the number density of the collider. From equation (6) \(f_1^J = 0.6 \times 10^{-5} n_H\) in sub-thermal regime (S) and \(f_1^J = 0.7\) at thermal equilibrium (T).

In an optically thin gas the integrated main-beam temperature is proportional to the fractional population of the emitting level

\[
T_{\text{MB}} \Delta v \propto N_{\text{HCO}^+} \times f_1.
\]

Using equation (7) we can express the column density of HCO\(^+\) in the sub-thermal regime as

\[
N_{\text{HCO}^+}^S = n^S_{\text{HCO}^+} \times f_1^J / f_1^J,
\]

where \(n^S_{\text{HCO}^+}\) is the column density of HCO\(^+\) at LTE, which is \(1.0(2) \times 10^{11}\) cm\(^{-2}\). Then, substituting in equation (8) we have

\[
N_{\text{HCO}^+}^S = \frac{1.1 \times 10^{10}}{n_H}\text{ cm}^{-2},
\]

and the corresponding HCO\(^+\) fractional abundance along the line of sight results

\[
f_1^S = \frac{5.5 \times 10^{-8}}{n_H},
\]

using \(n_H = 2 \times 10^{22}\) cm\(^{-2}\) from McCall et al. (1998).

There are two alternative formation channels for HCO\(^+\), i.e. (i) the reaction of \(H_3^+\) with CO

\[
H_3^+ + CO \rightarrow HCO^+ + H_2 \quad (\text{R1})
\]

and (ii) a two-step mechanism involving the formation of CO\(^+\)

\[
C^+ + OH \rightarrow CO^+ + H \quad (\text{R2})
\]

followed by

\[
CO^+ + H_2 \rightarrow HCO^+ + H \quad (\text{R3})
\]

The major destruction channel is dissociative recombination

\[
HCO^+ + e \rightarrow H + CO. \quad (\text{R4})
\]

The resulting fractional abundances are

\[
f_{\text{HCO}^+}^{(i)} = \frac{k_{1} n_{H_2} f_{\text{CO}}}{k_{x_e}}, \quad (11)
\]

\[
f_{\text{HCO}^+}^{(ii)} = \frac{k_{2} f_{\text{OH}}}{k_{4}}, \quad (12)
\]

where \(k_{j}\) cm\(^3\) s\(^{-1}\) is the reaction coefficient of \(R_j\) reaction.

The fractional abundance of OH along diffuse lines of sight lies in the range \((1–3) \times 10^{-8}\) (Lizt & Lucas 1996). The fractional abundances of H\(^+_3\) and CO are \(2 \times 10^{-3}\) and \(1.5 \times 10^{-6}\) (McCall et al. 1998), respectively. Substituting these value in equations (11) and (12) we get \(f_{\text{HCO}^+}^{(i)} = 3.6 \times 10^{-13}\) and \(f_{\text{HCO}^+}^{(ii)} = (0.7–2) \times 10^{-11}\). In the previous derivation we use \(k_1 = 1.7 \times 10^{-9}\) cm\(^3\) s\(^{-1}\), \(k_2 = 7.7 \times 10^{-10}\) cm\(^3\) s\(^{-1}\), and \(k_4 = 1.1 \times 10^{-6}\) cm\(^3\) s\(^{-1}\) (Millar, Farquhar & Willacy 1997). The temperature was taken to be \(30\) K, derived by McCall et al. (1998) from the H\(^+_3\) ortho–para ratio.

It appears that in a diffuse medium the reactions (R1) is not efficient to produce HCO\(^+\). On the other hand, reactions (R2) and (R3) would lead to a fractional abundance of HCO\(^+\) comparable to that calculated from equation (10) for \(n_H \approx 100\) cm\(^{-3}\) (McCall et al. 1998; Cecchi-Pestellini & Dalgarno 2000) if the OH fractional abundances were larger (about a factor of 20) than generally assumed in diffuse regions. As the hypothesis of diffuse medium seems unlikely, an alternative approach to the problem is that offered by the model of Cecchi-Pestellini & Dalgarno (2000) which predicts a column density for HCO\(^+\) of \(9 \times 10^{10}\) cm\(^{-2}\) in small dense cores (\(n_H \approx 10^{3}\) cm\(^{-3}\)) along the line of sight. This prediction is in very close agreement with the value of \(1.0(2) \times 10^{11}\) cm\(^{-2}\) calculated in a LTE regime at \(T_B = 10\) K. The HCO\(^+\) (\(J = 1 – 0\)) critical density for H\(_2\) collisions is \(1.7 \times 10^{3}\) cm\(^{-3}\) and the LTE assumption in the derivation of the column density appears reasonable.

5 CONCLUSION

The present detection of HCO\(^+\) emission together with that of CO/(J = 2 – 1) by Geballe et al. (1999) is consistent with the presence of dense material along the line of sight to the star Cygnus OB2 No. 12.

The detections of CO (McCall et al. 1998), C\(_2\) (Gredel & Münch 1994), CH (Geballe et al. 1999) and HCO\(^+\) establish the existence of molecular material, besides H\(_3^+\), along the line of sight. Moreover, the detection of the HCO\(^+\) (\(J = 1 – 0\)) line could imply a density of the order of the critical density (i.e. \(n_H \approx 10^{4}\) cm\(^{-3}\)). The molecular observations suggest that a cloud exists in front of the star Cygnus OB2 No. 12 with dense regions contained in more diffuse clumps. A detailed continuum survey at 4.8GHz of the Cygnus OB2 association by Wendker, Higgs & Lendecker (1991) shows the existence of several approximately spherical regions of emission with diameters of about \(10\) pc at the distance of the star. A plausible scenario is one in which H\(_3^+\) ions exist in the clumps and other molecules in the condensations (Cecchi-Pestellini & Dalgarno 2000). Diffuse clumps have a typical visual extinction of less than 2 magnitudes. A limiting visual extinction of 2 magnitudes is consistent with the absence of ices in the ISO spectra towards the star (Whittet 1992).

In the dense condensations the hydrogen column density is \(N_{H} \approx 2 \times 10^{26}\) cm\(^{-2}\) consistent with a column density \(N_{\text{CO}} = 3 \times 10^{26}\) cm\(^{-2}\) derived from the observations of the lines at \(+12\) and \(+7\) km s\(^{-1}\) and an upper limit for CO fractional abundance of \(1.4 \times 10^{-4}\). It follows that the path length of the aggregate of the dense regions is \(L \approx 1300\) au (\(n_H \approx 10^{4}\) cm\(^{-3}\), from considerations on CO excitation), and the calculated H\(_3^+\) column density is \(N_{H_3^+} \approx 4 \times 10^{12}\) cm\(^{-2}\) (assuming \(n_{H_3^+} \approx 10^{-4}\) cm\(^{-3}\) appropriate for dense regions, McCall et al. 1999), so that the contribution of the aggregate of the dense cores to the total H\(_3^+\) column density along the line of sight to Cygnus OB2 No. 12 is negligible, compared with the clump contribution of \(3.8 \times 10^{14}\) cm\(^{-2}\) (McCall et al. 1998).
If a dense medium exists, it necessarily has a small aggregate transverse size. Since the covering factor cannot be small, dense regions should have a sheet-like geometry. Sheets produce smaller thermal pressure than other geometries (Heiles 1997). Therefore, morphology could have important implications on cloud energetics and stability.

The evidence for significant small-scale structures in diffuse interstellar clouds has been accumulating in the last few years. In particular through observations of Na\textsuperscript{i} D \textlambda 5890 and Ca\textsuperscript{ii} K \textlambda 3934 towards the binary star \mu Cru, Meyer & Blades (1996) inferred the existence of structures on scales less than the projected binary separation of 6600 au. The corresponding change in $N_{\text{H}}$ on this scale implies a density contrast larger than $10^3 \text{ cm}^{-3}$ (Meyer & Blades 1996), which in turn means the existence of a molecular cloud density in a very diffuse line of sight. The incorporation of density fluctuations, length-scale, and filling factor in theoretical models could be crucial for our understanding of diffuse cloud chemistry.

In conclusion, the recent discovery of H\textsubscript{3}\textsuperscript{+} towards Cygnus OB2 No. 12 (McCall et al. 1998) has raised new interest in the diffuse cloud in front of the star. Although the present results are solid, the problem is far from solved. Maps in 12CO, as well as 13CO, C\textsuperscript{18}O and HCO\textsuperscript{+}, would provide more accurate understanding of the morphology of the ambient gas. Multi-transitions studies of molecules with a wide range of critical densities can reveal density inhomogeneities. Therefore observations of other molecular high-density tracers would be instructive.

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