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Letter to the Editor

Detection of [C I] 492 GHz emission from a high-latitude translucent cloud

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Abstract. The [C I] $^3P_1 - {}^3P_0$ 492 GHz fine structure line has been detected in the high-latitude cloud toward HD 210121 using the James Clerk Maxwell Telescope. The measured [C I] line strengths vary between $T_{\rm MB} = 0.6 - 1.6$ K and appear correlated with the CO $J = 1 - 0$ emission. The inferred [C I] column densities can be well explained by models with densities $n_{\rm H} \simeq 500 - 5000\,{\rm cm}^{-3}$ and a low incident radiation field, which causes the C$^+$, C $\rightarrow$ CO transition zone to be shifted to lower A_V values. The derived N(C)/N(CO) ratio is about 3 – 6, significantly larger than found in dense PDRs. Cooling by [C I] is larger than that by CO in this cloud and may be comparable to that by [C II] within a factor of a few.

Key words: ISM: abundances – atoms – clouds: HD 210121 – Radio lines: ISM

1. Introduction

An important chemical aspect of translucent clouds, i.e. clouds with $A_V \simeq 1-5$ mag, is that they lie in the region where carbon is transformed from atomic to molecular form, C$^+$ $\rightarrow$ C $\rightarrow$ CO. Model calculations have shown that small changes in the physical parameters like total hydrogen density and column density may cause large variations in the CO abundance (van Dishoeck & Black 1988, 1989). The abundance of neutral carbon, C, is sensitive to these parameters as well, but has been much less investigated for translucent clouds, both observationally and theoretically. With the advent of sensitive SIS detectors at 492 GHz, it has now become possible to observe the weak [C I] $^3P_1 - {}^3P_0$ line in such clouds. We report here a successful search for this line in a high-latitude translucent cloud.

The cirrus cloud toward HD 210121, a star with $A_V \simeq 1$ mag, is one of the best characterized high-latitude clouds to date. Optical absorption line studies of e.g. CH, CN, and C_2 (de Vries & van Dishoeck 1988, Gredel et al. 1992) and atomic lines (Welty & Fowler 1992) have been used to put stringent limits on the physical conditions along the pencil beam line of sight. CO 1 – 0, 2 – 1, and 3 – 2 (sub)millimeter emission lines from this cloud have been studied in detail by Gredel et al. (1992) and van Dishoeck et al. (1991). The observations can be matched by a kinetic temperature $T_{\rm K} \simeq 15^{+10}_{-5}$ K and a density $n_{\rm H} \simeq 500 - 5000\ {\rm cm}^{-3}$ at the center of the cloud. At the edge, the temperature may be somewhat higher. The lower density has been derived from the absorption line observations, whereas the higher densities are needed to reproduce the CO data. The inferred CO column densities $N({\rm CO}) = 10^{15} - 10^{16}$ cm^{-2} throughout the cloud are somewhat lower than those of dark clouds but still indicate that of the order of 2 – 10% of the carbon is already in molecular form, even for such low A_V. This can be explained by a low incident intensity of the radiation field at high galactic latitude which causes the C$^+$, C $\rightarrow$ CO transition zone to be shifted to lower A_V (van Dishoeck & Black 1988). Since the atomic carbon column densities are also sensitive to density and radiation field, observations of the [C I] line would form significant tests of the models. Also, searches for [C I] emission from such clouds are interesting to determine its cooling rate compared to that of the [C II] 158 μm and CO rotational lines.

The [C I] $^3P_1 - {}^3P_0$ line at 492 GHz has been widely observed in dense ($n_{\rm H} \simeq 10^4 - 10^6$ cm^{-3}) photon-dominated regions (PDRs) which are exposed to intense radiation fields that are enhanced by factors $I_{\rm UV} = 10^3 - 10^5$ with respect to the general interstellar radiation field. Here the [C I] line is usually found to be very strong, $T_{\rm MB} > 10$ K, even deep inside the clouds, and seems to correlate well with the ^{13}CO emission (Keene et al. 1985). This has been interpreted to indicate that interstellar clouds are not homogeneous but have a clumpy structure through which the radiation can penetrate (Stutzki et al. 1988). Since cirrus clouds clearly have a filamentary and clumpy structure as seen on high resolution optical images (Stark 1993), the [C I] emission of these low density PDRs may have a distribution similar to that of the dense PDRs. With the new large submillimeter telescopes and improved receivers, it is now possible to extend the study of the [C I] line to much higher angular resolution and to much weaker lines, such as expected for high-latitude clouds. Furthermore, no confusion from em-

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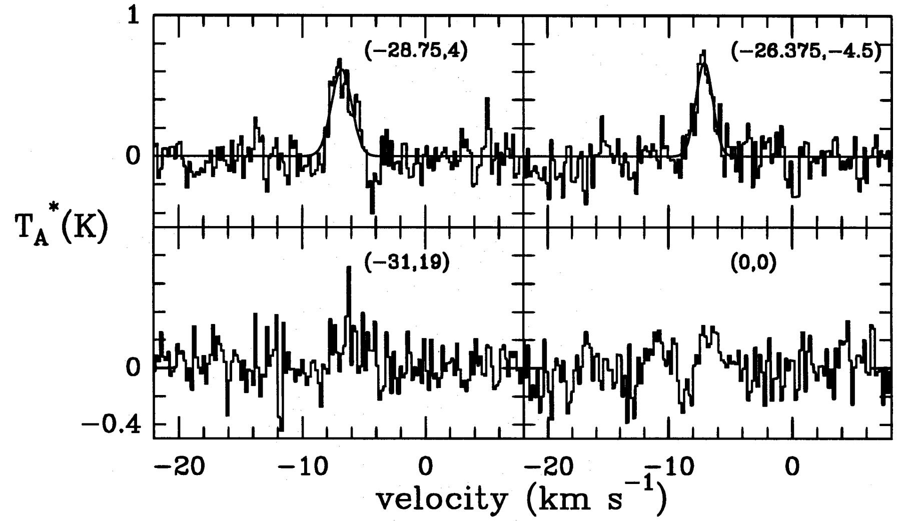

Fig. 1. Observed [C I] 492 GHz spectra in the cloud toward HD 210121. Offset postions are in arcmin with respect to the star

Table 1. Observations of the [C I] $^3P_1 - {}^3P_0$ 492 GHz line in the high-latitude cloud toward HD 210121

$\Delta\alpha, \Delta\delta^a$ (arcmin)	$T_{\rm MB}$ (K)	$V_{\rm lsr}$ (km s^{-1})	ΔV (km s^{-1})	I (erg cm^{-2} s^{-1} sr^{-1})	N(C) (cm^{-2})
−31, 19	0.6 ± 0.3:	−6.1 ± 0.3	2.4 ± 0.5:	(1.9 ± 0.9)(−7):	2(16) − 7(16):
−28.75, 4.0	1.4 ± 0.3	−6.8 ± 0.1	1.9 ± 0.2	(3.4 ± 0.3)(−7)	4(16) − 2(17)
−26.375, −4.5	1.6 ± 0.3	−7.1 ± 0.1	1.6 ± 0.2	(3.3 ± 0.3)(−7)	4(16) − 2(17)
0, 0	<0.6			<1.9(−7)	<7(16)

^{a} offset with respect to the star HD 210121 at α(1950)=22:05:36.1; δ(1950) = −3:46:35.5

bedded sources or background emission exists for these clouds. The [C I] 492 GHz line has been detected previously in only one diffuse cloud, that toward ζ Oph. Here $T_{\rm MB} \simeq 0.2$ K was found using the Kuiper Airborne Observatory (Keene et al. 1987).

2. Observations and results

Using the 15m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, we observed the [C I] $^3P_1 - {}^3P_0$ line at 492.1607 GHz on November 20, 1993. The beam size at this frequency is 10″ and the main beam efficiency $\eta_{\rm MB}$ = 0.43. The SIS receiver RxC2 had a double side band receiver noise temperature of 300 K, resulting in system temperatures including the atmosphere of about 2000 – 2500 K. The backend consisted of the Digital Autocorrelation Spectrometer (DAS) with a bandwidth of 250 MHz and a spectral resolution of 189 kHz, corresponding to 0.11 km s^{-1} at 492 GHz. The DAS configuration and the RxC2 parameters are described by Dent (1993). Since the [C I] is likely to be extended, the observations were carried out in position switching mode, switching by 3 – 12′ to offsets chosen on the basis of existing CO and H I maps. The total integration time (on & off) at each position was 60 min, resulting in a rms noise around 0.2 K per resolution element. The data were smoothed to 0.2 km s^{-1} resolution. The calibration was performed with the chopper-wheel method, carried out every 20 min. The absolute calibration was checked by observing the Orion Bar, which showed $T_A^* \simeq 8.3$ K at the position α(1950)=05:32:54, δ(1950)=−05:27:15.

We observed [C I] at four positions selected from the ^{12}CO 1−0 map of Gredel et al. (1992). Three positions are located near peaks of the integrated CO emission in clumps B, D, and E; the fourth position is toward the star HD 210121 itself. At two of the three positions in clumps B and E, [C I] is clearly detected with $T_{\rm MB} \simeq 1.6$ K, whereas the third position (−31′,19′) shows a 2σ feature with $T_{\rm MB} \simeq 0.6$ K. Toward HD 210121, a 2σ upper limit $T_{\rm MB} < 0.6$ K is reported. The [C I] spectra are presented in Fig. 1. The results from a Gaussian analysis together with the calculated line intensities, using the Rayleigh-Jeans convention, are listed in Table 1. Table 2 shows the corresponding ^{12}CO and ^{13}CO emission parameters observed with the SEST in a 43″ beam at the same positions. The central velocities of the [C I] lines agree well with those of the ^{12}CO and ^{13}CO emission. The widths of the two detected [C I] lines are comparable to those of ^{12}CO, but appear broader than those of ^{13}CO. However, the observed [C I] line widths are likely to be upper limits to the true line widths, because the frequency instability of the receiver introduces an instrumental broadening of about 0.5 km s^{-1}. The lack of [C I] emission at the stellar position, and the detection at other positions suggests that the [C I] intensity roughly scales with ^{12}CO and/ or ^{13}CO line intensity.

Table 2. Observations of the ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$ lines in the high-latitude cloud toward HD 210121

$\Delta\alpha, \Delta\delta$ (arcmin)	$T_{\rm MB}(12)$ (K)	$T_{\rm MB}(13)$	$V_{\rm lsr}(12)$ (km s^{-1})	$V_{\rm lsr}(13)$	$\Delta V(12)$ (km s^{-1})	$\Delta V(13)$	$I(12)$ (erg cm^{-2} s^{-1} sr^{-1})	$I(13)$	$N(12)$ (cm^{-2})	$N(13)$
−31, 19^a	5.7	1.9	−6.2	−6.4	1.1	0.8	1.1(−8)	2.2(−9)	6(15) – 6(16)	1(15) – 4(15)
−28.75, 4.0	4.7	1.4	−6.5	−6.5	1.8	1.1	1.4(−8)	2.2(−9)	8(15) – 6(16)	1(15) – 4(15)
−26.375, −4.5	5.5	1.0	−7.1	−7.1	1.3	0.9	1.2(−8)	1.3(−9)	7(15) – 6(16)	8(14) – 2(15)
0, 0^a	2.0	0.1	−6.2	−5.9	2.1	1.7	0.7(−8)	0.3(−9)	4(15) – 1(16)	2(14) – 3(14)

^{a} from Gredel et al. (1992)

3. Analysis

Statistical equilibrium calculations were performed to determine the population distribution over the ground triplet levels of C, using an escape probability method for the radiative transfer. This set of equations has been solved to find the excitation conditions for a range of C column densities, kinetic temperatures, and molecular hydrogen (the main collision partner) densities. A background radiation field with $T_{\rm bg} = 2.73$ K was included. A large range of the parameter space (N(C), n(H$_2$), $T_{\rm K}$) matches a given radiation temperature. In Table 1 we list the inferred range in C column densities for $T_{\rm K} = 15 - 50$ K and $n({\rm H_2}) \approx 1/2\ n_{\rm H} = 250 - 2500$ cm^{-3}. The upper limits on the column densities correspond to the low end of the kinetic temperature and density range. The lower limits correspond to high-density cases where the excitation temperature approaches $T_{\rm ex} = \Delta E/k = 23.6$ K, where ΔE is the energy difference between the C $J = 0$ and 1 levels and k is the Boltzmann constant. The 492 GHz line was always found to be optically thin for the above listed range of physical parameters.

In order to determine the total cooling by [C I], we need to estimate the strength of the [C I] ^{3}P$_2$ – ^{3}P$_1$ 809 GHz line. This line is very sensitive to the kinetic temperature since $\Delta E_{21}/k$ = 62.5 K. Its strength varies between 0.4 – 3 times the intensity of the ^{3}P$_1$ – ^{3}P$_0$ line for $T_{\rm K} = 15 - 50$ K respectively. The total cooling provided by the [C I] line at positions where the [C I] is detected therefore varies between $5 \times 10^{-7} - 1 \times 10^{-6}$ erg cm^{-2} s^{-1} sr^{-1}. The total cooling by CO including estimates for the higher, unobserved transitions ranges from 1×10^{-7} to 7×10^{-7} erg cm^{-2} s^{-1} sr^{-1} for the density, temperature and column density range of Table 2.

The derived C column densities in clumps B and E are at least an order of magnitude larger than those found from ultraviolet observations in diffuse clouds such as those toward ζ Oph and ζ Per (Jenkins et al. 1983). The derived column density ratio N(C)/N(CO) ranges from 3 to 6 at both positions where [C I] has been detected. The range in this ratio is much smaller than that in the individual column densities, since N(CO) and N(C) scale similarly with physical parameters like n and T. Thus, most of the carbon in this cloud is not bound in CO, contrary to dense PDRs which have ratios of about 0.1 – 0.2 (Keene et al. 1985). In order to investigate the sensitivity of the C column densities to the physical conditions, we have extended the models of van Dishoeck & Black (1988) to the high-latitude cloud regime. The main parameters affecting N(C) are the total hydrogen density $n_{\rm H} = n({\rm H}) + 2n({\rm H_2})$, the total column density $N_{\rm H}$, the scaling factor for the incident radiation field $I_{\rm UV}$, and the gas-phase carbon abundance. The models assume a plane parallel geometry for the cloud and a homogeneous density and kinetic temperature. Compared with the van Dishoeck & Black (1988) paper, the new models use a larger H$_3^+$ dissociative recombination rate of $\sim 5 \times 10^{-8}$ cm^3 s^{-1} at low temperatures and have reduced shielding of the H$_2$ lines on the carbon photoionization.

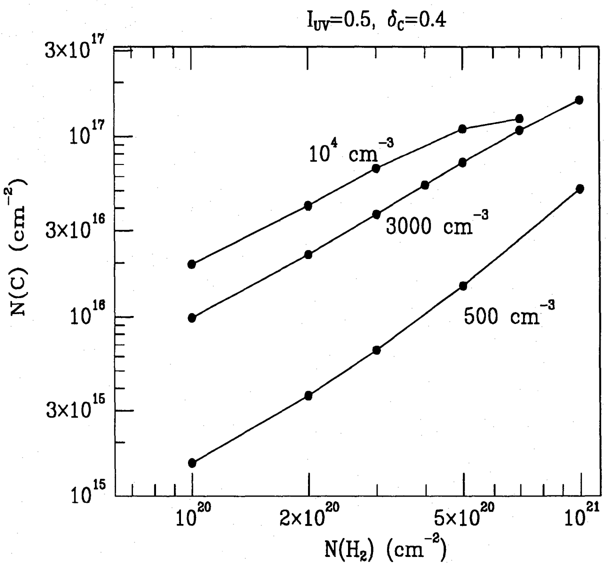

Fig. 2. Calculated atomic carbon column densities as functions of H$_2$ column densities for models with densities $n_{\rm H}$ ranging from 500 to 10^4 cm^{-3}. $N({\rm H_2}) \simeq 8 \times 10^{20}$ cm^{-2} corresponds to $A_V \simeq 1$ mag

The resulting C column densities as functions of total H$_2$ column density (or A_V) are presented in Fig. 2 for densities $n_{\rm H}$ ranging from 500 to 10^4 cm^{-3}. The gas-phase carbon abundance is kept at 40% of the solar carbon abundance in these models, comparable to that found toward ζ Oph (Cardelli et al. 1993). The radiation field is taken to be $I_{\rm UV} = 0.5$, which should be appropriate for high-latitude clouds within a factor of two. It is seen that the C column density increases not only strongly with total column density, but also with density due to the enhanced C$^+$ recombination rate. Indeed, the observed C column densities of 4×10^{16} cm^{-2} or larger can readily be obtained at $A_V \simeq 1$ mag for densities larger than about 2000 cm^{-3}. If $I_{\rm UV} < 0.5$, the density could be even lower. For densities as low as 500 cm^{-3}, however, the total column density needs to be $> 10^{21}$ cm^{-2} ($A_V > 1$ mag) to reproduce the observed N(C).

4. Discussion and conclusions

The HD 210121 cloud shows widespread low-level ^{12}CO emission extended over an area of about 1 square degree in which some distinct peaks or "clumps" are embedded (Gredel et al. 1992). The ^{13}CO emission around these maxima has a smaller extent and a steeper gradient toward the boundaries of the clumps. From a comparison between the optical surface brightness and the CO emission in a sample of cirrus clouds, Stark (1993) finds that an increase in ^{12}CO column density is most likely due to the filamentary structure of the cloud, which results in an increase in the length of the line of sight through the cloud with the density remaining approximately constant. On the other hand, the ^{13}CO emission appears to be caused by localized space density enhancements or "clumps" along the line of sight which are shielded from the radiation field. The optical surface brightness of the HD 210121 cloud is particularly low compared with other high-latitude clouds at similar galactic latitude, which indicates that the intensity of the illuminating radiation field is lower than the average field (Stark 1993), consistent with the low value of $I_{\rm UV}$ adopted in Fig. 2.

The fact that the [C I] emission is detected at the positions of the strongest ^{12}CO and ^{13}CO emission is consistent with the above interpretation, since both an increased column density and increased density will enhance the [C I] (Fig. 2). However, much more sensitive limits toward other positions, in particular those without significant ^{13}CO emission such as the (0,0) position, are needed to determine whether the [C I] has a stronger correlation with ^{13}CO than with ^{12}CO. Also, the fact that the beam size for the CO observations is 4 times larger than that for the [C I] data may affect the correlations. Finally, it should be recalled that the current observing strategy uses the position switching technique. This favors detection of the [C I] associated with the denser clumps, while a widespread uniform [C I] component associated with the filaments may be much harder to detect. Observations of CO transitions at the same spatial resolution as the [C I] observations in frequency switching mode are necessary to circumvent these problems and determine the true origin of the [C I] emission.

The cooling by [C I] is larger than the cooling by CO for $T_{\rm K} = 15 - 50$ K, $n_{\rm H} = 500 - 5000$ cm^{-3} (Sect 3). This is in agreement with the global values from the *COBE* measurements for the diffuse gas in our Galaxy (Wright et al. 1991). At low kinetic temperatures the [C I] 492 GHz line is expected to be the dominant coolant in diffuse clouds as long as carbon is still mostly in atomic form, because the upper level of the [C II] 158 μm line lies at 92 K. The total hydrogen column density in the direction of the star HD 210121 is $N_{\rm H} = (2 \pm 0.5)10^{21}$ cm^{-2} (de Vries & van Dishoeck 1988). The total cooling rate per hydrogen atom for the [C I] 492 GHz line in this direction is therefore $< 1 \times 10^{-27}$ erg s^{-1} per H nucleus. If the total hydrogen column density is constant over the whole cloud (Stark 1993), the maximum cooling rate of the [C I] 492 GHz line would be about 2×10^{-27} erg s^{-1} per H nucleus toward ($-28.75, 4.0$), and $\sim 9 \times 10^{-27}$ erg s^{-1} per H nucleus if both [C I] lines are considered. These values are lower than the global cooling rate of the [C II] 158 μm line, which has been measured to be $\sim 2.6 \times 10^{-26}$ erg s^{-1} per H nucleus for clouds at high latitudes from rocket-borne (Bock et al. 1993) and *COBE* data (Bennett et al. 1994), and inferred to be $10^{-26} - 10^{-25}$ erg s^{-1} per H nucleus from ultraviolet absorption line data of diffuse clouds such as that toward ζ Oph (Gry et al. 1992; Savage et al. 1993; Black 1994). However, both these data sets are biased toward the warmer clouds, whereas the [C II] line is expected to decrease significantly for colder clouds at higher latitudes. Indeed, the same models discussed above give a [C II] cooling rate less than 10^{-26} erg s^{-1} per H nucleus for $T_{\rm K} <$20 K. Thus, the [C I] 492 GHz line may be comparable to the [C II] line within a factor of a few within this cloud.

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