SOFIA/GREAT [C II] observations in nearby clouds near the lines of sight towards B0355+508 and B0212+735[★]

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ABSTRACT

We present SOFIA/GREAT [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ (1.9005369 THz) observations of nearby clouds near the lines of sight towards the quasars B0355+508 and B0212+735. These clouds have previously been identified as warm non-LTE diffuse clouds with a temperature of $T \gtrsim 30$ K and sub-thermally excited CO lines. They are highly structured in CO with small-scale bright spots ($I(\text{CO } J = 1-0) \sim 5\text{--}20$ K km s^{−1}), both spectrally and spatially. This small-scale structure has been interpreted as small-scale variations in the chemistry, not as density and column-density structure. We did not detect [C II] 158 μm emission within the rms noise of $\sim 0.1\text{--}0.3$ K. Our non-detection in [C II] contradicts the above scenario. In diffuse clouds, the efficiency of photo-electric heating is highest. Under the assumption that [C II] is the dominant coolant in diffuse clouds, we can calculate the predicted [C II] emission arising from these clouds. Based on the derived hydrogen column densities for the diffuse clouds, a line width in [C II] of similar order to that of CO, and when at least the minimum amount of heating in the clouds is due to cosmic-ray heating, [C II] line intensities $\gtrsim 1.5$ to 5 K km s^{−1} are expected, which is a factor ~ 3 to 15 above the upper limits of the observations. The upper limits of the [C II] and the observed CO line intensities are, however, consistent with the intensities predicted for photon-dominated region (PDR) surfaces on regular cold ($T \sim 15$ K) low-density cloud fragments. Lower temperatures lead to less excited [C II]. The assumption of lower densities, which would equally lower the [C II] excitation, contradicts the observed cloud sizes and column densities. The CO(2–1)/CO(1–0) line ratios observed in these clouds are consistent with cloud temperatures of $T \sim 15$ K. The KOSMA- τ PDR-model of a cold moderate-density clump or an ensemble of such clumps with a canonical mass-size relation and mass spectrum, consistent with the total column densities derived for low density, shows that cold PDRs can reproduce the observed CO intensities, the observed CO(1–0) and CO(2–1) ratio, and the observed upper limits for [C II].

Key words. ISM: clouds – photon-dominated region (PDR) – ISM: structure

1. Introduction

1.1. Conditions in diffuse clouds

Interstellar clouds are in general classified as diffuse, dense, or translucent (e.g. [Snow & McCall 2006](#)). Diffuse clouds have a typical column density of $N(\text{H}) < 2 \times 10^{21}$ cm^{−2} ($A_v < 1$ mag), dense (and dark) clouds have a typical column density of $N(\text{H}) \sim 10^{22}$ cm^{−2} ($A_v > 4$ mag), and the column densities of translucent clouds falls somewhere in between.

Diffuse and translucent clouds have been identified mainly by means of their absorption spectra against bright mm-wave or optical background sources ([Sonnentrucker et al. 2007](#); [Burgh et al. 2007](#); [Sheffer et al. 2007, 2008](#)) and by optical extinction mapping ([Savage et al. 1977](#)).

[Liszt & Lucas \(1998\)](#) succeeded in detecting CO($J = 1-0$) and CO($J = 2-1$) emission, identified to be associated with presumably diffuse clouds because of their matching velocity characteristics with mm-wave absorption spectra, in a representative sample of mm-wave absorption lines-of-sight against background quasar sources. [Liszt & Pety \(2012\)](#) were able to map the CO (1–0) emission with a few arcmin extent around these

positions. The typical total hydrogen column density $N(\text{H}) = N(\text{H I}) + 2N(\text{H}_2)$ in these clouds was derived to be a few times 10^{21} cm^{−2} with a typical H₂ fraction of $\lesssim 1/3$ ([Liszt et al. 2010](#); [Liszt & Pety 2012](#)).

The observations show that the clouds in the sample of [Liszt & Pety \(2012\)](#), presumably located near the edge of the Local Bubble at distances of about 150 pc from the Sun ([Liszt & Pety 2012](#)), are surprisingly highly structured with small-scale bright spots in CO, localised both spatially ($\lesssim 1 \times 10^{-2}$ pc) and spectrally ($\Delta v \sim 1\text{--}2$ km s^{−1}).

Small-scale CO variations were interpreted as variations in the chemistry and not the density, or column-density variations in the clouds ([Pety et al. 2011](#)). The observed high line intensities of CO ($J = 1-0$), typically $I(\text{CO}) \sim 5\text{--}20$ K km s^{−1}, together with the observed almost uniform CO ($J = 2-1$)/($J = 1-0$) integrated intensity ratio of around 0.725 ([Liszt & Lucas 1998](#); [Pety et al. 2008](#)), were explained as sub-thermal excitation in a diffuse cloud ([Goldreich & Kwan 1974](#); [Pety et al. 2008](#)) with kinetic temperatures above 30 K, typically $T \approx 40\text{--}80$ K ([Pety et al. 2008](#)). We note here that the CO ($J = 2-1$) vs. ($J = 1-0$) line ratios observed in the clouds towards B0355+508 by [Pety et al. \(2008\)](#), however, are also consistent with the ratio expected in cold ($T \approx 14$ K) dense gas ([Pety et al. 2008](#)). The CO spectra shown in [Liszt & Lucas \(1998\)](#) imply a similar CO ($J = 2-1$)/($J = 1-0$) ratio for the

[★] The reduced spectra (FITS files) are available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/600/A94>

Table 1. Position of the [C II] observations.

Source	(1) Centre position		(2) CO-peak rel. offsets		(3) CO-void rel. offsets		(4) Off-position rel. offsets	
	RA	Dec	RA (")	Dec (")	RA (")	Dec (")	RA (")	Dec (")
	(J2000)	(J2000)						
B0355+508	03:59:29.73	50:57:50.1	−7	−6	−57	+38	+190	+430
B0212+735	02:17:30.81	73:49:32.6	+47	−64	−187	+86	+607	+33

Notes. Coordinates (J2000) of B0355+508 and B0212+735 (1). Rows (2) and (3) show the relative offsets to the CO-peak and CO-void. The relative offsets of the off-positions are listed in row (4). Images of the integrated CO emission of the sources are shown in Fig. 1.

clouds towards B0212+735 and B0355+508. The clouds furthermore show a mean $^{12}\text{CO}/^{13}\text{CO}$ brightness temperature ratio of $T(^{12}\text{CO})/T(^{13}\text{CO}) \sim 10$ to 15 (e.g. Pety et al. 2011). The ratio was explained by chemical fractionation of $^{12}/^{13}\text{CO}$ and $^{12}/^{13}\text{C}^+$ in diffuse clouds (Pety et al. 2008, 2011; Liszt et al. 2010). In the diffuse-cloud scenario the typical CO column densities are a few times 10^{16} cm^2 . The derived hydrogen column densities $N(\text{H})$ in diffuse clouds of a few times 10^{21} cm^2 (cf. Sect. 4) imply that only about $\sim 4\text{--}7\%$ of the carbon in diffuse clouds is in the form of CO (Sofia et al. 2004; Pety et al. 2011). The majority of carbon ($\sim 90\%$) therefore must exist in another form, presumably ionised carbon [C II] (Sofia et al. 2004; Liszt & Lucas 2000). Thus, the [C II] $^2\text{P}_{3/2} \rightarrow ^2\text{P}_{1/2}$ fine-structure transition at 1.9005369 THz is the main cooling line in the diffuse intrastellar medium (ISM) (Dalgarno & McCray 1972; Tielens & Hollenbach 1985a). For the translucent regime the neutral carbon hyperfine transitions ($^3\text{P}_1 \rightarrow ^3\text{P}_0$ and $^3\text{P}_2 \rightarrow ^3\text{P}_1$) are expected to contribute up to $\sim 30\%$ of the [C II] cooling amount of the cloud cooling (Juvela et al. 2003).

These predictions provided the motivation to search for the [C II] emission from these clouds using SOFIA/GREAT¹.

2. Observations and data processing

In November 2013 and February 2014 we performed [C II] observations of the interstellar clouds near the lines of sight towards B0355+508 and B0212+735 (cf. Table 1 and Fig. 1) using the dual-channel single-pixel German REceiver for Astronomy at Terahertz frequencies (GREAT; Graf et al. 2006; Heyminck et al. 2012) on-board the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA; Stutzki 2006; Becklin et al. 2007; Gehr et al. 2009; Young et al. 2012). A Fourier transform spectrometer (FFTS) with 8192 channels and a bandwidth of 1.5 GHz was used, providing a native resolution of $\sim 0.03 \text{ km s}^{-1}$. The observations were performed in single-point total power mode.

Out of a sample of five sources, selected for their expected high [C II] brightness from the CO maps by Liszt & Pety (2012), B0355+508 and B0212+735 were selected because they matched the flight plan of SOFIA.

In each individual source we observed two positions. One position was centred on the brightest CO emission (CO-peak). The second position was pointed towards a region with faint but clearly detectable CO emission (CO-void). These positions are marked in Fig. 1, and their coordinates are given in Table 1. This observation strategy was designed to collect information about the C^+ abundance and [C II] cooling in these clouds.

The off-source positions for B0355+508 and B0212+735 (coordinates see Table 1) were selected at regions with minimal $100 \mu\text{m}$ emission (IRAS, Neugebauer et al. 1984) and a minimal A_V (from E_{B-V} FIRAS/COBE measurements, Schlegel et al. 1998). Owing to their expected low column and volume densities, these positions are hence likely to be free of detectable [C II]-emission. Additional CO(1–0) data of the B0212+735 off-position (Pety, priv. comm.) show these positions to be free of CO emission.

2.1. GREAT data processing

The calibration of the data was performed with the standard pipeline for GREAT data (Guan et al. 2012). All spectra were converted into a main-beam brightness temperature scale using $T_{\text{mb}} = T_{\text{A}}^*/\eta_{\text{mb}}$, with a main beam efficiency $\eta_{\text{mb}} = 0.67$ (Heyminck et al. 2012).

The [C II] data were processed with the software package CLASS, version: jan14a².

A fifth-order baseline was subtracted from all spectra. In spectra that showed sinusoidal standing wave patterns, sinusoidal baselines with standing wave periods between 8 and 27 km s^{-1} were fitted to the spectra. If the fit improved the rms by more than 20% compared to a linear baseline fit, the fitted sinusoidal pattern was subtracted from the spectrum.

The data for B0212+735 and B0355+508 were smoothed to 0.4 km s^{-1} and 0.8 km s^{-1} , respectively, which is a factor ~ 3 below the CO line widths, for a better comparison.

2.2. Observational results

– B0355+508

Sixteen minutes of integration time were spent on the CO-peak, and we achieved an rms of 0.09 K in a velocity bin of 0.8 km s^{-1} , corresponding to one-third of the line width of the brightest CO line. Two minutes of integration time were spent on the CO-void, from which we achieved an rms of 0.17 K . In neither position did we detect [C II] emission. The 3σ upper limit for [C II] lines with widths corresponding to those of the CO lines thus are $\leq 0.37 \text{ K km s}^{-1}$ for the CO-peak and $\leq 0.71 \text{ K km s}^{-1}$ for the CO-void.

– B0212+735

About ten minutes integration time were spent on each position in B0212+735. We reached an rms of $\approx 0.21 \text{ K}$ in the CO-peak and $\approx 0.22 \text{ K}$ in the CO-void in a velocity bin of 0.4 km s^{-1} , corresponding to one-third of the line width of the CO line of $\sim 1.5 \text{ km s}^{-1}$. No line could be detected within the rms. The 3σ upper limit for the [C II] line thus is $\leq 0.45 \text{ K km s}^{-1}$ at both positions.

¹ GREAT is a development by the MPI für Radioastronomie and the KOSMA/Universität zu Köln, in cooperation with the MPI für Sonnensystemforschung and the DLR Institut für Planetenforschung.

² Available at <http://www.iram.fr/IRAMFR/GILDAS>

Fig. 1. Integrated CO ($J = 1-0$) emission around B0355+508 (Liszt & Pety 2012) and B0212+735 (Pety & Liszt, in prep.). Small crosses mark the positions observed in [C II]. The large cross in the middle marks the lines of sight towards B0355+508 and B0212+735. The length of the white bar corresponds to 0.05 pc in B0355+508 and 0.1 pc in B0212+735 for an assumed source distances of 150 pc (Liszt & Pety 2012).

The listed 3σ limits are upper limits to the integrated [C II]-line intensities, derived from the rms of the velocity bins given. Additional smoothing of the data shows no signs of [C II] lines broader than the CO lines.

2.3. Complementary observations

In the following sections we discuss three positions for each cloud, the CO-peak (marked P), CO-void (V), and the line of sight (Q) towards the quasar. CO(1–0) emission spectra are available for all positions. HCO⁺ and H I absorption spectra are only available for the LOS towards the quasars.

The CO(2–1) and CO(1–0) emission spectra along the LOS towards the quasars have been observed by Liszt & Lucas (1998) and Liszt & Pety (2012). The CO(1–0) emission spectra towards the CO-peak and -void positions were extracted from maps with a few arcmin extent around the quasars observed by Liszt & Pety (2012) and Pety & Liszt (in prep.). As errors for the CO data we assumed standard calibration uncertainties of 15%.

HCO⁺ absorption along the line of sight towards the quasars B0355+508 and B0212+735 have been observed with the Plateau de Bure Interferometer by Lucas & Liszt (1996) and Liszt & Lucas (2000). Complementary H I 21 cm absorption spectra towards the quasars are available from Dickey et al. (1983).

3. CO, HCO⁺, and H I in B0355+508 and B0212+735

In the following we describe the individual velocity components seen in emission and absorption along the line of sight towards the quasars (Sects. 3.1 and 3.2). The association of these absorption components with corresponding CO emission components at the CO-peak and CO-void is discussed in Sects. 3.3 and 3.4.

3.1. Line of sight towards B0355+508

B0355+508 is located at a Galactic latitude of $b = -1.6^\circ$. This low Galactic latitude implies that several diffuse clouds are observed simultaneously along the line of sight.

The H I absorption features in the spectra are very broad. The line width is $\sim 55 \text{ km s}^{-1}$ and the absorption is located between

Table 2. Upper limits for the intensity compared to CO lines intensities of separated CO velocity components at the observed positions of the CO-peak and CO-void in B0355+508 and B0212+735.

(1)	(2)	(3)	(4)	(5)
	$v_{\text{LSR CO}}$ [km s ⁻¹]	Δv_{CO} [km s ⁻¹]	$I(\text{CO})_{\text{P/V}}$ [K km s ⁻¹]	$I([\text{C II}])$ [K km s ⁻¹]
B0355+508				
CO-peak				
A_P	-16.9 ± 0.1	2.4 ± 0.1	6.4 ± 0.7	<0.3
B_P	-13.8 ± 0.1	1.2 ± 0.4	1.1 ± 0.8	<0.3
C_P	-9.8 ± 0.1	1.2 ± 0.1	20.0 ± 2.0	<0.4
CO-void				
A_V	-17.6 ± 0.1	1.1 ± 0.1	5.2 ± 0.6	<0.5
B_V	-13.8 ± 0.1	1.1 ± 0.1	1.8 ± 0.3	<0.5
C_V	-8.9 ± 0.1	1.9 ± 0.1	4.9 ± 0.5	<0.6
B0212+735				
CO-peak				
G_P	3.5 ± 0.1	1.4 ± 0.1	8.4 ± 0.9	<0.5
CO-void				
G_V	2.3 ± 0.1	1.8 ± 0.1	5.5 ± 0.6	<0.4

Notes. (1) Designation of the individual velocity components. The CO-peak and -void positions are marked by the subscripts P and V, respectively. (2) v_{LSR} of the CO component(s) in the sources. (3) Width of the CO line. (4) Integrated CO line intensity in the positions CO-peak and CO-void, labelled by the footnotes P and V. (5) Upper limits for the observed integrated [C II] intensity $I([\text{C II}])$. To estimate the upper limit of $I([\text{C II}])$ we assumed that the [C II] line is located at the same v_{LSR} as CO and that the [C II] line width is equal to Δv_{CO} .

$v_{\text{LSR}} \approx -40 \text{ km s}^{-1}$ and $+10 \text{ km s}^{-1}$. Except for the molecular absorption features at $v_{\text{LSR}} = -10 \text{ km s}^{-1}$ and $v_{\text{LSR}} = -8 \text{ km s}^{-1}$ (velocity components C and D in Table 3), the H I absorption spectra show no direct correspondence to the molecular lines (cf. Liszt & Pety 2012). This implies that a large amount of H I is in the foreground and background of the source.

Fig. 2. [C II] (black) and CO (red; Liszt & Pety 2012) spectra at the positions CO-peak and CO-void in B0355+508 (left) and B0212+735 (right). The spectra of B0355+508 are smoothed to a velocity resolution of $\Delta v = 0.8 \text{ km s}^{-1}$; B0212+735 spectra are smoothed to $\Delta v = 0.4 \text{ km s}^{-1}$. The blue dashed line shows the HCO^+ absorption spectra along the lines of sight towards the quasars B0355+508 and 0212+735 (Liszt & Lucas 1996, 2000). The red letters mark CO velocity components in the CO-peak and the CO-void, blue letters mark HCO^+ absorption components along the line of sight towards the quasar. Identical capital letters mark related velocity components in the three positions. For better clarity we do not show the identified HCO^+ absorption component F_Q at $v_{\text{LSR}} = 2.5 \text{ km s}^{-1}$ in B0212+735 (cf. Table 3) reported by Lucas & Liszt (1996).

The molecular absorption line profiles of CO(1–0) and HCO^+ show a complex structure along the line of sight towards B0355+508 (cf. Liszt & Pety 2012). Five individual HCO^+ components can be distinguished between $v_{\text{LSR}} \approx -17 \text{ km s}^{-1}$ and $v_{\text{LSR}} \approx -5 \text{ km s}^{-1}$. Two CO emission components at $v_{\text{LSR}} \approx -17.2 \text{ km s}^{-1}$ and -10.3 km s^{-1} can be observed. They are associated with the two HCO^+ absorption velocity components A_Q and C_Q (Table 3).

3.2. Line of sight towards B0212+735

B0212+735 is located at Galactic latitude $b \sim 12^\circ$. Two prominent H I absorption features can be observed in B0212+735 (cf. Liszt & Pety 2012). The largest amount ($\sim 80\%$) of H I absorption arises from a broad deep feature at a centre velocity of $v_{\text{LSR}} \sim -12 \text{ km s}^{-1}$ (cf. Liszt & Pety 2012). Roughly 20% of the total H I absorption arises from a fainter H I absorption component, located at $\sim +4 \text{ km s}^{-1}$. Interestingly, all molecular absorption lines and the CO emission line are located in the velocity range of the fainter H I absorption component. No molecular absorption line lies within the strong H I absorption feature. Lucas & Liszt (1996) identified two close-by narrow HCO^+ absorption lines at $v_{\text{LSR}} = 2.5$ and 3.5 km s^{-1} by using a Gaussian decomposition of the line profile (components F_Q and G_Q in Table 3), whereby the majority of the absorption arises from the component G_Q . Because of similar velocities, the CO emission component at this position (Liszt & Lucas 1998) can be associated with the HCO^+ absorption component G_Q at 3.5 km s^{-1} .

3.3. CO-peak and CO-void of B0355+508

At the CO-peak of B0355+508 two bright spectral components can be observed in CO (components A_P and C_P ; cf. Fig. 2 and Table 2). These components are associated with the components A_Q and C_Q along the line of sight towards B0355+508 (Table 3). A possible third faint CO component (B_P) may be associated with the HCO^+ absorption component B_Q (cf. Fig. 2 and Table 2).

Similar to the CO-peak, three spectral CO-components can be resolved at the CO-void, A_V , B_V and C_V , which are associated with the CO and HCO^+ components along the line of sight towards the quasar analogous to their counterparts at the CO-peak. (cf. Tables 2 and 3 and Fig. 2).

3.4. CO-peak and CO-void of B0212+735

The CO-peak position shows one prominent CO component (G_P), at $v_{\text{LSR}} = 3.5 \text{ km s}^{-1}$ with a width of $\Delta v \approx 1.4 \text{ km s}^{-1}$. It is located within the HCO^+ absorption features. The same component appears in the CO-void (G_V), although at a slightly lower velocity of $v_{\text{LSR}} = 2.3 \text{ km s}^{-1}$.

In conclusion, all CO emission spectra at the observed positions are associated with HCO^+ absorptions along the lines of sight towards the quasars, while not all HCO^+ absorptions are associated with CO emission velocity components. Liszt & Pety (2012) took this discrepancy as an indication that the $^{12}\text{CO}(1-0)$ spatial distribution maps chemical fluctuations and not the cloud density.

Table 3. HCO⁺ absorption and CO emission along the line of sight towards B0355+508 and B0212+735.

(1) Cloud component	(2) v_{LSR} km s ⁻¹	(3) Δv km s ⁻¹	(4) $\int \tau(\text{HCO}^+) dv$ K km s ⁻¹	(5) $I(\text{CO})_Q$ K km s ⁻¹
LOS towards quasar				
B0355+508				
A_Q	-17.4	0.8	1.2 ± 0.1	5.1 ± 0.5
B_Q	-13.9	1.6	1.3 ± 0.1	$<0.2 \pm 0.1$
C_Q	-10.4	0.6	1.3 ± 0.1	15.3 ± 1.5
D_Q	-8.5	1.2	1.1 ± 0.1	$<0.3 \pm 0.1$
E_Q	-4.1	2.1	1.2 ± 0.1	$<0.4 \pm 0.1$
B0212+735				
F_Q	2.5	1.0	0.7 ± 0.1	–
G_Q	3.5	0.9	3.0 ± 0.4	11.0 ± 2.4

Notes. (1) Designation of the velocity components. (2) Centre velocities of the HCO⁺ absorption. For B0355+508 from Liszt & Lucas (2000). For B0212+735 from Lucas & Liszt (1996). (3) FWHM of the HCO⁺ absorption. From Lucas & Liszt (1996). (4) For B0212+735 from Lucas & Liszt (1996). Some $\int \tau(\text{HCO}^+)$ for B0355+508 from Lucas & Liszt (1996) had slightly changed in Liszt & Lucas (2000). We listed the updated values from Liszt & Lucas (2000). (5) B0355+508 data from Liszt & Pety (2012). B0212+735 data from Liszt & Lucas (1998).

4. Hydrogen densities

In the following we discuss the amount of molecular, neutral, and total hydrogen in the observed clouds. The calculations of the molecular hydrogen column densities $N(\text{H}_2)$ from the HCO⁺ absorption and CO emission are based on two different approaches.

- In the interpretation of Liszt & Lucas (2000) the molecular hydrogen densities derived from the HCO⁺ absorptions are representative of the densities of the whole cloud. The CO intensity fluctuations in the specific CO-maps were interpreted as local variations in the cloud chemistry, induced by local changes of the ambient physical circumstances, for instance temporary dissipation of turbulent energy, not as variations of the cloud density (Liszt & Lucas 2000; Liszt & Pety 2012). As a consequence, regions with a low CO abundance should have a higher C⁺ abundance than regions with a high CO abundance (Liszt & Lucas 2000, cf. Sect. 5).
- Alternatively, deriving the molecular hydrogen column $N(\text{H}_2)$ from the CO line-integrated emission is based on the assumption that the CO-maps trace the intrinsic density structure of the source. In this case the position with a high CO emission would have a high column density as well. In consequence, also the [C II] emission would be higher in these positions, as $I([\text{C II}])$ is proportional to the $N(\text{H})$ (cf. Sects. 5 and 6).

In the following we estimate the integrated [C II] intensities that are expected in these two scenarios and discuss alternatives to explain the non-detection of [C II] reported here. We first review the different ways that were previously used to estimate the amount of molecular hydrogen in these clouds from HCO⁺ absorption and CO emission (Sect. 4.1). Section 4.2 discusses

the estimated molecular and total hydrogen column densities in the positions. Section 5 tests and discusses these two approaches by estimating the expected integrated [C II] intensities. Finally, Sect. 6 proposes an alternative scenario to explain the observations.

4.1. Calculating molecular hydrogen density

A detailed derivation and description of the $N(\text{H}_2)$ estimation based on HCO⁺ absorptions can be found in Liszt & Lucas (1996) and Liszt et al. (2010). The latter derive an H_2 fraction of typically $f(\text{H}_2) = 2N(\text{H}_2)/(2N(\text{H}_2) + N(\text{C}^+)) = 0.35$. The molecular hydrogen column density $N(\text{H}_2)$ in diffuse clouds can then be determined through

$$N(\text{H}_2)_{\text{HCO}^+} \approx \frac{N(\text{HCO}^+)}{8 \times 10^{-10} \left(2 + \frac{1-f(\text{H}_2)}{f(\text{H}_2)}\right)} = \frac{N(\text{HCO}^+)}{3.1 \times 10^{-9}}. \quad (1)$$

The last equation refers to an assumed H_2 fraction of $f(\text{H}_2) = 0.35$. The HCO⁺ column density can be calculated from the optical depth; $N(\text{HCO}^+) = 1.12 \times 10^{12} \text{ cm}^{-2} \int \tau(\text{HCO}^+) dv$ (cf. Table 3; Liszt et al. 2010; Liszt & Pety 2012).

Alternatively, the molecular hydrogen column density in diffuse clouds can be estimated from the integrated CO(1–0) line intensity by use of a CO- H_2 conversion factor X_{CO}

$$N(\text{H}_2)_{\text{CO}} = X_{\text{CO}} \times I(\text{CO}). \quad (2)$$

Liszt et al. (2010) derived a $X_{\text{CO}} = 2.04 \times 10^{20} \text{ cm}^{-2}$ for diffuse clouds. We note that this value is coincidentally equal to the mean CO- H_2 conversion factor measured in the Milky Way (Bolatto et al. 2013), as is discussed in Pety et al. (2011).

4.2. Neutral, molecular, and total hydrogen densities in B0355+508 and B0212+735

Table 4 summarises the molecular hydrogen column densities for the individual velocity components derived with Eqs. (1) and (2). For almost all CO velocity components in all discussed positions the derived $N(\text{H}_2)_{\text{CO}}$ exceeds the $N(\text{H}_2)_{\text{HCO}^+}$ of their counterparts along the line of sight to the quasar derived from the HCO⁺ absorptions. If the densities in the observed clouds are roughly constant, the CO velocity components would overestimate the expected amount of molecular hydrogen by up to a factor of ~ 10 (e.g. velocity component C in B0355+508). On the other hand, CO would significantly underestimate the amount of molecular hydrogen for HCO⁺ velocity components that have no or only faint corresponding counterparts in CO. In this case we would expect, especially for the velocity components B_P , B_V , E_P , E_V , and G_V , a relatively bright [C II] emission because they show relatively faint CO emissions combined with strong HCO⁺ absorptions.

If the CO emission traces the intrinsic density structure of the source, then the [C II] emission should have a distribution similar to the CO emission.

The total amount of H I in the cold interstellar gas along the lines of sight towards the quasars is listed in Table 4 (Dickey et al. 1983). The total amount of hydrogen for the individual velocity components identified is hard to determine as there are no H I absorption measurements available at the CO-peak and CO-void. In addition, the H I absorptions lines towards the line of sight to the quasars are relatively broad ($\Delta v(\text{H I}) \gg \Delta v(\text{HCO}^+)$), so that the fractional amount of neutral

Table 4. Molecular, neutral, and total hydrogen column densities and volume densities in the positions CO-peak, CO-void, and the LOS towards the quasars.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	$N(\text{H}_2)_{\text{CO}_0}$	$N(\text{H}_2)_{\text{HCO}^+}$	$N(\text{H})_{\text{HCO}^+}$	$n(\text{H})_{\text{HCO}^+}$	$N(\text{H}_2)_{\text{CO}_p}$	$N(\text{H})_{\text{CO}_p}$	$n(\text{H})_{\text{CO}_p}$	$N(\text{H}_2)_{\text{CO}_v}$	$N(\text{H})_{\text{CO}_v}$	$n(\text{H})_{\text{CO}_v}$	$N(\text{HI})_{\text{tot}}$
	$\text{cm}^{-2} 10^{20}$	$\text{cm}^{-2} 10^{20}$	$\text{cm}^{-2} 10^{21}$	$\text{cm}^{-3} 10^3$	$\text{cm}^{-2} 10^{20}$	$\text{cm}^{-2} 10^{21}$	$\text{cm}^{-3} 10^3$	$\text{cm}^{-2} 10^{20}$	$\text{cm}^{-2} 10^{21}$	$\text{cm}^{-3} 10^3$	$\text{cm}^{-2} 10^{20}$
LOS toward quasar											
CO-peak											
CO-void											
B0355+508											
A	10.4 ± 1.1	4.3 ± 0.7	2.5 ± 0.4	5.3 ± 0.9	13.1 ± 1.4	2.6 ± 0.3	5.7 ± 0.6	10.6 ± 1.1	2.1 ± 0.5	4.6 ± 0.6	62.8
B	$<0.4 \pm 0.1$	4.7 ± 0.7	2.7 ± 0.4	5.8 ± 0.9	2.2 ± 1.6	0.4 ± 0.3	1.0 ± 0.7	3.7 ± 0.5	0.7 ± 0.2	1.6 ± 0.4	
C	31.2 ± 3.1	4.7 ± 0.7	2.7 ± 0.4	5.8 ± 0.9	40.8 ± 4.1	8.2 ± 0.8	17.5 ± 1.8	10.0 ± 1.1	2.0 ± 0.5	4.3 ± 0.4	
D	$<0.6 \pm 0.1$	4.0 ± 0.7	2.3 ± 0.4	4.9 ± 0.9	—	—	—	—	—	—	
E	$<0.8 \pm 0.1$	4.3 ± 0.7	2.5 ± 0.4	5.3 ± 0.9	—	—	—	—	—	—	
B0212+735											
F	—	2.4 ± 0.4	1.4 ± 0.2	1.5 ± 0.2	—	—	—	—	—	—	16.8
G	22.5 ± 4.8	10.8 ± 1.4	6.2 ± 0.8	6.7 ± 0.9	17.1 ± 1.8	3.4 ± 0.4	3.7 ± 0.4	11.2 ± 1.3	2.2 ± 0.2	2.4 ± 0.3	

Notes. Estimated molecular and total hydrogen column densities and volume densities along the line of sight towards the quasars and in the positions CO-peak and CO-void. The footnotes CO and HCO⁺ note the underlying method used to derive these values. The CO-footnotes Q, P, V represent the positions LOS towards the quasar, CO-peak and CO-void. (1) Designation of the assigned velocity components. (2), (6), and (9) Molecular hydrogen column density derived from the CO emission by the use of Eq. (2). Liszt et al. (2010) give a $N(\text{H}_2)_{\text{CO}} \approx 35 \times 10^{20} \text{ cm}^{-2}$ for the LOS towards B0355+508. This value corresponds to the $N(\text{H}_2)_{\text{CO}}$ derived for component C along the line of sight towards B0355+508. (3) Molecular hydrogen column density derived from the HCO⁺ absorption along the line toward the quasar by the use of Eq. (1). The here calculated $N(\text{H}_2)_{\text{HCO}^+}$ for the components towards B0355+508 are consistent with the $N(\text{H}_2)_{\text{HCO}^+}$ given by Liszt et al. (2010) of $N(\text{H}_2)_{\text{HCO}^+} \approx 4.5 \times 10^{20} \text{ cm}^{-2}$. (4) Total hydrogen column density derived from $N(\text{H}_2)_{\text{HCO}^+}$ and an assumed H_2 fraction of 35%; $N(\text{H})_{\text{HCO}^+} = 5.7 \times N(\text{H}_2)_{\text{HCO}^+}$. (7) and (10) Lower limits of the total hydrogen column density derived from the CO emission; $N(\text{H})_{\text{CO}_P/V} = 2 \times N(\text{H}_2)_{\text{CO}_P/V}$. The (unknown) contribution of H I to the total amount of hydrogen is not considered. (5), (8), and (11) Volume hydrogen densities, derived by dividing $N(\text{H})$ by the assumed cloud diameter d_C for an assumed cloud distance of 150 pc ($d_C(\text{B0355+508}) = 0.15 \text{ pc}$, $d_C(\text{B0212+735}) = 0.3 \text{ pc}$; $n(\text{H}) = N(\text{H})/d_C$. (12) Total H I column density of the cold interstellar gas along the lines of sight towards the quasars. From Dickey et al. (1983).

hydrogen associated with the individual HCO^+ absorption features cannot be easily determined. As the $N(\text{H}_2)_{\text{HCO}^+}$ calculations are based on an H_2 fraction of 35%, resulting in $N(\text{H I}) \approx 3.7 N(\text{H}_2)$, we therefore assume in the following a total hydrogen column densities of $N(\text{H})_{\text{HCO}^+} = 2 \times N(\text{H}_2)_{\text{HCO}^+} + N(\text{H I}) = 5.7 \times N(\text{H}_2)_{\text{HCO}^+}$ based on the HCO^+ absorptions. As a lower limit for the total hydrogen based on the CO emission, we assume that all hydrogen is in molecular form; $N(\text{H})_{\text{CO}} = 2 \times N(\text{H}_2)_{\text{CO}}$. The total hydrogen column densities derived in this way for the individual velocity components are listed in Table 4. We note that these total hydrogen column densities for the majority of the velocity components are $\geq 2 \times 10^{21} \text{ cm}^{-2}$; corresponding to an $A_V \geq 1$ mag. These A_V classify the majority of the clouds at the upper limit of the diffuse regime or even in the translucent regime.

With the assumption that the cloud diameter d_C is equal to the depth of the cloud, it is possible to estimate the volume hydrogen density $n(\text{H})$ in the individual clouds with $n(\text{H}) = N(\text{H})/d_C$. Based on the typical size of the structural features in the CO(1–0)-maps (Fig. 1), we estimated a cloud diameter of 0.15 pc (200'') for B0355+508 and 0.3 pc (400'') for B0212+735 based on assumed cloud distances of 150 pc (Liszt & Pety 2012). The cloud diameter (in parsec) is given by $d_C[\text{pc}] \approx 4.85 \times 10^{-6} \rho[l'] d[\text{pc}]$, where $\rho[l']$ is the diameter of the cloud in arcsec and $d[\text{pc}]$ the cloud distance in parsec. The $n(\text{H})$ derived in this way for the individual velocity components are listed in Table 4. The densities derived from $N(\text{H})_{\text{HCO}^+}$ span between ~ 4000 to 7000 cm^{-3} and between ~ 2400 to 17000 cm^{-3} derived from $N(\text{H})_{\text{CO}}$. These densities are unusually high for diffuse clouds. Diffuse clouds are typically associated with a $n(\text{H}) \sim 100 \text{ cm}^{-3}$ (cf. Tielens 2010), roughly 20–100 times lower than the derived values. These densities are commonly found in translucent and dense molecular clouds, respectively.

5. Expected diffuse cloud [C II] intensities

We now discuss the heating (Sect. 5.1) and cooling (Sect. 5.2) in diffuse clouds. With the assumption that the cooling of diffuse clouds is dominated by [C II], we calculated the expected lower limit of the integrated [C II] intensity, $I([\text{C II}])$, emitting from the observed positions (Sect. 5.2).

5.1. Heating in diffuse clouds

In diffuse clouds with a visual extinction of about unity and an ambient interstellar radiation field of $G_0 = 1$ (Habing 1968), photo-electric heating is expected to be the main heating source. For low-density clouds with a density $\lesssim 3 \times 10^3 \text{ cm}^{-3}$ and a temperature $T \lesssim 100 \text{ K}$, the efficiency of photo-electric heating is highest (Tielens 2010), and the heating amounts to about $\Gamma \approx 5 \times 10^{-26} G_0 \text{ erg (H-Atom)}^{-1} \text{ s}^{-1}$ (Bakes & Tielens 1994; Tielens 2010), about 17 times stronger than the penetrating cosmic-ray heating of $\sim 3 \times 10^{-27} \text{ erg (H-Atom)}^{-1} \text{ s}^{-1}$ (Tielens 2010). Additional heating may be due to turbulent dissipation, resulting in local hot spots, a mechanism favoured to explain the unexpectedly high abundance of some species in diffuse clouds, in particular CH^+ (Falgarone et al. 2010a,b; Godard et al. 2010). In addition, the formation of H_2 may contribute some heating to the clouds (Liszt & Lucas 1996). Hence photoelectric heating alone provides a lower limit to the heating. Further heating of the diffuse clouds may be induced by magnetohydrodynamic shocks and C-shocks (Pineau des Forets et al. 1986; Draine & Katz 1986; Gusdorf et al. 2008). Chemical reactions

induced by these shocks would significantly increase the C^+ column densities in diffuse gas and could explain the detected HCO^+ (Draine & Katz 1986).

5.2. Cooling of diffuse clouds; expected $I([\text{C II}])$ in diffuse clouds

The [C II] 158 μm fine structure line is expected to be the dominant coolant in diffuse clouds (Hollenbach & Tielens 1999). Owing to its relatively low critical density ($\sim 3 \times 10^3 \text{ cm}^{-3}$) (Goldsmith et al. 2012), [C II] is easily excited in diffuse clouds. Oxygen is neutral in diffuse gas, but the [OI] 63 μm ground-state fine structure line has a much too high critical density to be significantly excited (Tielens & Hollenbach 1985b; Wolfire et al. 1990); nitrogen will be neutral and hence cannot radiate. Where the carbon is in molecular form (CO), carbon monoxide rotational line cooling should dominate. This line of reasoning allows us to estimate an expected [C II] brightness of the CO-clouds near the lines of sight towards B0355+508 and B0212+735, assuming they are indeed diffuse clouds.

The contribution of [C I] cooling does not exceed $\sim 30\%$ of the [C II] cooling (Juvela et al. 2003). Therefore it is not considered in the following.

In thermal equilibrium the cloud heating is in balance with the cooling. The expected integrated [C II] line intensity can be estimated by equating the photoelectric heating at a given G_0 with the [C II] cooling function,

$$I([\text{C II}]) \left[\frac{\text{K}}{\text{km s}} \right] = \frac{1}{4\pi} \frac{c^3}{2k_B \nu^3} 10^{-5} \Gamma G_0 N(\text{H}) \\ = 1.1 \times 10^4 \Gamma G_0 N(\text{H}). \quad (3)$$

For an assumed photo-electric heating rate of $\Gamma \approx 5 \times 10^{-26} \text{ erg (H-Atom)}^{-1} \text{ s}^{-1}$ and an ambient interstellar field of $G_0 = 1$, Eq. (3) gives an expected integrated [C II] line intensity $I([\text{C II}])$ of

$$I([\text{C II}]) \left[\frac{\text{K}}{\text{km s}} \right] = 5.7 \times 10^{-22} N(\text{H}) \left[\frac{\text{K}}{\text{km s}} \right]. \quad (4)$$

The expected $I([\text{C II}])$ for the total hydrogen column densities (cf. Table 4) of the individual velocity components derived with Eq. (4) are listed in Table 5.

- In the scenario where the spatial variations in the CO-maps are indeed induced by chemical and not by density variations, the expected $I([\text{C II}])$ is based on the total hydrogen column density derived from the HCO^+ absorption, $N(\text{H})_{\text{HCO}^+}$. The resulting intensities range from $I([\text{C II}]) = 1.3 \text{ K km s}^{-1}$ to 3.5 K km s^{-1} , a factor ~ 3 to 7 above the upper limits for a 3σ [C II] detection in the observed positions. We note that these intensities are based on an assumed H_2 fraction of 35%. Neglecting the additional hydrogen column in H I would still lead to an expected $I([\text{C II}]) \approx 0.5 \text{ K km s}^{-1}$ in B0355+508 and 1.2 K km s^{-1} in B0212+735. Even in this case, [C II] lines $>3\sigma$ should have been observed for almost all velocity components.
- In the scenario where the CO emission traces the density and not chemical variations, the derived lower limits of the [C II] emission are a factor ~ 3 to 15 above the upper limits for a 3σ [C II] detection for the majority of the velocity components. The expected $I([\text{C II}])$ spans from $\sim 0.3 (B_p)$ to $4.7 \text{ K km s}^{-1} (C_p)$, where the majority of the components have an expected $I([\text{C II}])$ of $1\text{--}2 \text{ K km s}^{-1}$. We note that these densities are

Table 5. Lower limits for the expected $I([\text{C II}])$ in diffuse clouds derived from the photo electric heating rate following Eq. (4).

(1)	(2)	(3)	(4)
	$I([\text{C II}])_{\text{HCO}^+}$ K km s ⁻¹	$I([\text{C II}])_{\text{CO}_p}$ K km s ⁻¹	$I([\text{C II}])_{\text{CO}_v}$ K km s ⁻¹
LOS towards quasar		CO-peak	CO-void
B0355+508			
A	1.4 ± 0.2	1.5 ± 0.2	1.2 ± 0.1
B	1.5 ± 0.2	0.3 ± 0.2	0.4 ± 0.1
C	1.5 ± 0.2	4.7 ± 0.5	1.1 ± 0.1
D	1.3 ± 0.2	–	–
E	1.4 ± 0.2	–	–
B0212+735			
F	0.8 ± 0.1	–	–
G	3.5 ± 0.5	1.9 ± 0.2	1.3 ± 0.1

Notes. (1) Designation of the assigned velocity components. (2) Expected integrated $[\text{C II}]$ intensity based on the total hydrogen column $N(\text{H})_{\text{HCO}^+}$ derived from the HCO^+ absorptions and an H_2 fraction of 35%; (3) and (4) Expected integrated $[\text{C II}]$ intensities in the positions CO-peak ($I([\text{C II}])_{\text{CO}_p}$) and CO-void ($I([\text{C II}])_{\text{CO}_v}$) based on molecular hydrogen column densities derived from the CO CO column density. The contribution of H I to the total amount of hydrogen is not considered.

lower limits; adding the additional (but unknown) H I -column density in these positions would increase the total.

The fraction of neutral carbon is undetermined in these clouds. It cannot be excluded that a fraction of the cloud cooling occurs by the C^0 hyperfine transitions, thus leading to fainter $[\text{C II}]$ emission lines. Using the upper limit for C^0 -cooling of $\sim 30\%$ estimated by Juvela et al. (2003), the emission should still have been detected.

In summary, the balance between heating and cooling calculated for the diffuse cloud case predicts that the integrated $[\text{C II}]$ intensity would be roughly a factor ~ 3 up to a factor 15 above the 3σ detection limit for the cloud components identified in CO. This indicates that the underlying assumption of the clouds being diffuse and warm is not adequate: there is no way to hide the $[\text{C II}]$ column that complements the detected CO, unless the $[\text{C II}]$ is less excited. This can be the case either with lower densities, resulting in a conflict with the sizes and column densities of the clouds, or with lower temperature, as discussed below.

6. $[\text{C II}]$ and CO emission from cold dense clouds

In the following we show that observed low- J CO line intensities and the upper limits on the integrated $[\text{C II}]$ intensities are consistent with the scenario of photon-dominated region (PDR) layers on cold and dense cloud fragments.

We note that the scenario of dense clouds is supported by the derived high molecular hydrogen volume and column densities of the individual velocity components (cf. Table 4). As described in Sect. 4.2, the derived $N(\text{H})$ correspond to optical extinction of $A_v \approx 1\text{--}4$ mag. These A_v classify them as translucent and as dense molecular clouds, respectively, which is also consistent with the derived $n(\text{H})$ density of a few times 10^3 cm^{-3} . In translucent clouds the photoelectric heating is less efficient, thus the clouds would be colder and $[\text{C II}]$ would be less excited. In such clouds ($n \sim \text{few } 10^3 \text{ cm}^{-3}$; $T < 20 \text{ K}$) bright CO lines in

the absence of $[\text{C II}]$ are expected and observed (e.g. Pineda et al. 2013), as only molecules with a low excitation energy, such as the low- J CO lines, are excited.

We first show that a cold cloud, with a temperature consistent with the low- J CO intensity ratio in the thermalized limit, which hypothetically has all its carbon in the form of C^+ , by itself has a sufficiently low $[\text{C II}]$ intensity consistent with the upper limits of the observations. We then show by applying PDR-modelling that the predicted $[\text{C II}]$ intensity stays below the upper limit for the observed intensity even if a PDR layer is included in such a dense cold cloud fragment.

6.1. Temperature dependency of $I([\text{C II}])$

Observations by Liszt & Lucas (1998) and Pety et al. (2008) found an almost uniform $\text{CO}(2\text{--}1)/\text{CO}(1\text{--}0)$ ratio of ≈ 0.725 in the observed clouds. This would indicate a gas temperature of 14 K for a cloud in local thermal equilibrium (LTE). Pety et al. (2008) rejected such an LTE solution in favour of a non-LTE explanation with sub-thermally excited CO lines (Goldreich & Kwan 1974; Pety et al. 2008) with cloud temperatures above 30 K, typically $T \approx 40$ to 80 K (Pety et al. 2008).

As we have shown in the previous section, the $[\text{C II}]$ intensity expected from such a warm low-density cloud would be well above the observed upper limit. We now show that for the observed column densities, a cold dense cloud would have $[\text{C II}]$ intensities well below the observed upper limit, even if the full column density has all carbon in the form of C^+ .

By adapting formula A3 in Crawford et al. (1985), the $[\text{C II}]$ emission for a low-density cloud is given by

$$I([\text{C II}]) = 1.3 \times 10^{-3} e^{-91/T} X_{\text{C}^+} n(\text{H}) N(\text{H})_{21} \Phi_b \left[\frac{\text{ergs}}{\text{s cm}^2 \text{ sr}} \right] \\ \approx 185 e^{-91/T} X_{\text{C}^+} n(\text{H}) N(\text{H})_{21} \Phi_b \left[\text{K } \frac{\text{km}}{\text{s}} \right], \quad (5)$$

where $N(\text{H})_{21}$ is the total hydrogen column density in units of 10^{21} cm^{-2} and $n(\text{H})$ the volume hydrogen density in cm^{-3} . The following calculations use a C^+ abundance of $X_{\text{C}^+} = 1.4 \times 10^{-4}$ (cf. Langer et al. 2014). As the spatial extent of the clouds exceeds the beam of SOFIA and to take the clumpy structure of clouds into account, we assumed a beam filling factor of $\Phi_b = 0.5$ for a conservative estimate.

Figure 3 illustrates the expected $I([\text{C II}])$ for gas temperatures of $T = 14 \text{ K}$ and 30 K and typical column and volume densities as found in the observed clouds. As an example, for a $T = 14 \text{ K}$ and typical densities of $n(\text{H}) = 4500 \text{ cm}^{-3}$ and $N(\text{H}) = 2 \times 10^{21} \text{ cm}^{-2}$, Eq. (5) gives an $I([\text{C II}]) \approx 0.17 \text{ K km s}^{-1}$. That is well below the 3σ detection limit for the $[\text{C II}]$ observations.

On the other hand, in the scenario of warm clouds with temperatures of $T \gtrsim 30 \text{ K}$ this simple analysis confirms that the $[\text{C II}]$ line should have been detectable for all velocity components, except for the lowest total hydrogen column densities. Even for a low beam filling factor of $\Phi_b = 0.1$, $[\text{C II}]$ line detections would have been expected for the two volume densities we discussed here (cf. Fig. 3).

Low temperatures imply shielding of the clouds from the ambient radiation field. This can be realised by cloud cores embedded within large H I -clouds, which absorb the majority of the incoming radiation. The observed wide H I absorption lines embedding the narrow HCO^+ and CO velocity components (Sect. 3) can be interpreted this way. Effectively, such a shielding layer is a photon-dominated surface layer with carbon being atomic and ionised. Hence we investigate in the following

Fig. 3. Expected $I([\text{C II}])$ for $n(\text{H}) = 4500 \text{ cm}^{-3}$ (left) and $n(\text{H}) = 2300 \text{ cm}^{-3}$ (right) at different total hydrogen column densities $N(\text{H})$ and temperatures calculated from Eq. (5). The filled grey areas show the expected $I([\text{C II}])$ for a $T = 30 \text{ K}$. The blue areas show the expected $I([\text{C II}])$ for a cold cloud with a kinetic gas temperature of 14 K , as indicated by the $\text{CO}(2-1)/\text{CO}(1-0)$ ratio. The dashed lines (---) represent the $I([\text{C II}])$ for a beam filling factor of $\Phi_b = 0.5$. The upper and lower edge of the grey and blue filled areas shows the $I([\text{C II}])$ for a beam filling factor of $\Phi_b = 1$ and $\Phi_b = 0.1$, respectively. The red areas mark the upper limits of the [C II] observations.

whether the observed intensities are consistent with such a PDR scenario.

6.2. PDR modelling of the observations

The PDR modelling can reproduce the observed CO intensities and the observed upper limits for [C II], as we show below.

We modelled the observations with the stationary KOSMA- τ PDR-model (Röllig et al. 2006, 2013; Röllig & Ossenkopf 2013; Andree-Labsch et al. 2017). The numerical KOSMA- τ code simultaneously solves the energy balance, chemical equilibrium, and radiative transfer of spherical clumps. The chemical fraction of carbon in PDRs is also included (Röllig & Ossenkopf 2013). The clumps are characterised by their total hydrogen mass, the surface hydrogen volume density, the strengths of the incident FUV field, and the metallicity. We only consider solar metallicities in the following. Pre-shielding of the penetrating FUV radiation by a HI envelope is not considered. The code is applicable for a single clump as well as for an ensemble of clumps. We handle both in the following. The radial volume density of the clump(s) is determined by a power-law function of the clump radius and the individual surface hydrogen volume density (e.g. Stoerzer et al. 1996; Cubick et al. 2008). We note that the KOSMA- τ code is a stationary PDR-model. The initial conditions of the cloud formation are not considered.

We modelled single clumps and ensembles of clumps with total masses in the range of $M = 1\text{--}10 M_\odot$, embedded in the standard Draine field of $\chi = 1$. The calculations for the single clump refer to a beam filling factor of $\Phi_b = 0.5$.

Figure 4 shows that the upper intensity limits for [C II], the observed absolute CO intensities, and the observed $\text{CO}(2-1)/\text{CO}(1-0)$ ratio of $\approx 0.73 \pm 0.16$ can be reproduced by PDR modelling. The model gives integrated line intensities in the order of $I(\text{CO}(1-0)) \approx 10 \text{ K km s}^{-1}$ and $I([\text{C II}]) \lesssim 0.3 \text{ K km s}^{-1}$ for cloud volume hydrogen densities of $n(\text{H}) \approx 10^{3.5}$ to 10^4 cm^{-3} for all the studied cases. The simulations also yield a $^{12}\text{CO}/^{13}\text{CO}$

ratio of ~ 11 for a $n(\text{H}) \sim 10^3 \text{ cm}^{-3}$ and ~ 5 for a $n(\text{H}) \sim 10^4 \text{ cm}^{-3}$. The ratio therefore roughly agrees with the observations. The $^{12}\text{CO}/^{13}\text{CO}$ ratio is affected by the density of the clumps. ^{12}CO is less self-absorbed in clumps with a lower density so that the $^{12}\text{CO}/^{13}\text{CO}$ ratio is increased compared to denser clumps. A higher $^{12}\text{CO}/^{13}\text{CO}$ ratio can therefore be explained by a halo of smaller clouds around an ensemble of clumps with higher densities. Hence the clouds do not have to be diffuse to produce the observed $^{12}\text{CO}/^{13}\text{CO}$ ratio.

We note that the assumed cloud masses in the PDR model are consistent with the anticipated cloud diameters of the clouds. A cloud mass of $10 M_\odot$ and a density of $n(\text{H}) = 5000 \text{ cm}^{-3}$ corresponds to a diameter of $d_c \approx 0.4 \text{ pc}$; $1 M_\odot$ is equal to $d_c \approx 0.2 \text{ pc}$.

The modelled chemical profiles meet the expectations of a standard PDR. The carbon towards the PDR-surface is dominated by C^+ , while the inner region of the PDR is dominated by CO. The transition zone between $\text{C}^+/\text{C}^0/\text{CO}$ is located at an $A_V \sim 0.5 \text{ mag}$. C^+ is associated with kinetic gas temperatures of $T \sim 30 \text{ K}$ to 20 K , while CO is associated with $T \sim 15 \text{ K}$ gas. The hydrogen is predominantly in molecular form throughout the simulated clumps. HCO^+ has a similar distribution as CO in all simulated cases. The fraction of HCO^+ increases beyond the $\text{C}^+/\text{C}^0/\text{CO}$ transition zone. HCO^+ is formed at slightly higher A_V than CO ($\sim 0.7 \text{ mag}$ compared to $\sim 0.5 \text{ mag}$). The $^{12}/^{13}\text{CO}/\text{HCO}^+$ ratio is thus highest near the $\text{C}^+/\text{C}^0/\text{CO}$ transition zone ($^{12}\text{CO}/\text{HCO}^+ \approx 1 \times 10^7$) and decreases towards the centre of the clumps ($^{12}\text{CO}/\text{HCO}^+ \approx 0.5 \times 10^7$). The simulations show no significant variations of the ratio in clumps with $n(\text{H}) = 10^3 \text{ cm}^{-3}$ and $n(\text{H}) = 10^4 \text{ cm}^{-3}$. The detailed chemical profile and the temperature profile are shown as an example in Fig. 5.

However, a $^{12}\text{CO}/^{13}\text{CO}$ ratio higher than ~ 5 requires clumps with masses significantly lower than $1 M_\odot$ because both CO lines tend to become optically thick, pushing the line ratio towards unity. Clumpy PDR ensembles do not suffer from this and are

Fig. 4. PDR modelling (KOMSA- τ model; Röllig et al. 2006) of clumps with masses of $M = 1$ and $10 M_{\odot}$ for surface volume hydrogen densities of $n(\text{H}) = 10^3$ to 10^5 cm^{-3} . The images on the *left* (A) and (C)) illustrate the modelling for an ensemble of clumps. The images on the *right* (B) and (D)) show the modelling for a single clump. For the single clump we anticipated a beam filling factor of $\Phi_b = 0.5$. The images at the *top* (A) and (B)) show the modelled [CII] and $^{12}\text{CO}(1-0)$ integrated line intensities. The black and grey lines show the modelled integrated line intensities of CO(1-0) and [CII]. The style of the line marks the anticipated clump mass. The grey areas show the rough lower and/or upper limits of the CO(1-0) and [CII] observations. The images at the *bottom* (C) and (D)) illustrate the modelled CO(2-1)/CO(1-0) ratio for clumps with $M = 1$ and $10 M_{\odot}$. The range of the observed CO(2-1)/CO(1-0) ratio ($\approx 0.73 \pm 0.16$) is marked by the grey area.

able to reproduce ratios $^{12}\text{CO}/^{13}\text{CO} > 10$ for higher masses as well.

The observations can therefore be explained as emission from PDRs. An ensemble of cold dense clumps, with $n(\text{H}) \sim 3000$ to $10\,000 \text{ cm}^{-3}$ penetrated by a Draine field of $\chi = 1$, reproduces the observed CO intensities, the upper limits for [CII], the $^{12}\text{CO}/^{13}\text{CO}$ line ratio, and clump sizes. We note that the hydrogen volume densities are also fully consistent with those calculated in Sect. 4.2.

7. Summary and conclusion

We observed the [CII] $^2\text{P}_{3/2} \rightarrow ^2\text{P}_{1/2}$ transition in two nearby molecular clouds near the lines of sight towards the quasars B0355+508 and B0212+735. No [CII] line was detected within the rms of ~ 0.1 – 0.3 K in either of the positions.

The observed upper [CII] intensity limits of $I([\text{CII}]) \lesssim 0.5 \text{ K km s}^{-1}$ contradict with the scenario proposed by Pety et al. (2008) and Liszt & Pety (2012) of warm non-LTE diffuse clouds ($T \gtrsim 30 \text{ K}$) with sub-thermally excited CO bright lines. In diffuse clouds the photo-electric heating rate is highest and the cooling is dominated by [CII]. We estimated the upper [CII] intensity limits in the observed cloud by balancing the heating with the cooling. If the observed clouds were indeed diffuse, the expected integrated [CII] intensities should be a factor ~ 3 up to 15 above the 3σ detection limit for the cloud components identified in CO emissions.

Fig. 5. Chemical profile of a clump with a surface volume hydrogen densities of $n(\text{H}) = 10^3 \text{ cm}^{-3}$ and a mass of $10 M_{\odot}$ penetrated by a standard Draine field of $\chi = 1$. The relative densities of H^0 , H_2 , C^+ , C^0 , $^{12}/^{13}\text{CO}$, and HCO^+ as function of A_V are shown by the black/grey lines (left axis). The temperature profile within the clump is shown by the red line (right axis).

The [CII] non-detection implies that C^+ is less excited than expected for diffuse clouds. As lower densities contradict the cloud sizes and column densities, the gas must therefore be colder. Cloud temperatures of $\sim 15 \text{ K}$ are supported by the observed CO(2-1)/CO(1-0) ratios. In addition, the total hydrogen column density in the clouds corresponds to an $A_V \sim 1$ to 4 mag, and their volume density is typically $n(\text{H}) \sim 5000 \text{ cm}^{-3}$, which is hard to reconcile with clouds being diffuse. These densities

classify the clouds as being in the translucent regime, or even as moderately dense molecular clouds.

The observed low- J CO absolute line intensities and their ratio, the non-detection of [C II] 158 μm within the observed upper limits, and the observed $^{12}\text{CO}/^{13}\text{CO}$ ratio are consistent with a PDR scenario (using the KOSMA- τ PDR model) where the PDR clump densities agree with our derived column and volume densities. The observations, the derived column and volume densities, and the size of the cloud are thus consistent with an ensemble of cold dense clumps.

In summary, the observations, calculations, and simulations indicate that the clouds along the line of sight towards B0355+508 and B0212+735 consist of an ensemble of cold dense clumps, with volume densities of $n(\text{H}) \sim 10^{3.5} \text{ cm}^{-3}$ to 10^4 cm^{-3} and core temperatures of $T \sim 15 \text{ K}$. The observations are not compatible with the scenario of warm diffuse clouds.

The study is based on a small sample of positions and relatively short integration times. Further mapping would significantly increase the statistical representativeness of this study. It would be worthwhile to investigate whether the emission from other clouds that have been identified as being diffuse are also consistent with a cold and dense clump scenario when the [C II] intensity is observed and taken into account

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