

# Interstellar CH absorption in the diffuse interstellar medium along the sight-lines to G10.6–0.4 (W31C), W49N and W51 <sup>★</sup>

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## ABSTRACT

We report the detection of the ground state  $N, J = 1, 3/2 \rightarrow 1, 1/2$  doublet of the methylidyne radical CH at  $\sim 532$  GHz and  $\sim 536$  GHz with the *Herschel* HIFI instrument along the sight-line to the massive star forming regions G10.6–0.4 (W31C), W49N and W51. While the molecular cores associated with these massive star forming regions show *emission* lines, clouds in the diffuse interstellar medium are detected in *absorption* against the strong submillimeter background. The combination of hyperfine structure with emission and absorption results in complex profiles, with overlap of the different hyperfine components. The opacities of most of the CH absorption features are linearly correlated with those of CCH, CN and HCO<sup>+</sup> in the same velocity intervals. In specific narrow velocity intervals, the opacities of CN, HCO<sup>+</sup> deviate from the mean trends, giving rise to more opaque absorption features. We propose that CCH can be used as another tracer of the molecular gas in the absence of better tracers, with  $[CCH]/[H_2] \sim 3.2 \pm 1.1 \times 10^{-8}$ . The observed  $[CN]/[CH]$ ,  $[CCH]/[CH]$  abundance ratios suggest that the bulk of the diffuse matter along the lines of sight has gas densities  $n_H = n(H) + 2n(H_2)$  ranging between 100 and 1000 cm<sup>-3</sup>.

**Key words.** ISM: abundances - ISM: molecules - ISM : clouds : G10.6–0.4, W49N, W51

## 1. Introduction

The methylidyne radical was detected in the interstellar medium as early as 1937 (Swings and Rosenfeld 1937). Since then, it has remained one of the most studied interstellar molecules through its electronic transitions at 430 nm. CH is now established as a powerful tracer of molecular hydrogen, with a tight correlation over nearly two decades of column density  $[CH]/[H_2] = 3.5 \times 10^{-8}$  (Sheffer et al 2008). While optical spectroscopy can reach excellent spectral resolution, it is limited to relatively bright objects and cannot sample the full variety of interstellar environments. Radio observations are thus an interesting complement to optical spectroscopy. Qin et al. (2010) discuss the CH spectroscopy and the energy level diagram of CH is shown in Naylor et al. (2010). The lambda doubling transitions at 3 GHz are relatively easily detected at cm wavelengths but their quantitative interpretation is difficult because they show anomalous excitation (Liszt & Lucas 2002 and references therein). The CH rotational lines lie at submillimeter and far infrared wavelengths, with a characteristic doublet pattern. While the first observations were obtained with the *Kuiper Airborne Observatory* (KAO) by Stacey et al. (1987) towards the massive region Sgr B2 in the Galactic center, these transitions attracted little attention

until the 149  $\mu$ m CH doublet was identified in many *ISO-LWS* spectra (Goicoechea et al. 2004; Polehampton et al 2005).

In the framework of gas-phase molecule chemistry, the formation of CH is initiated by the slow radiative association between ionised carbon C<sup>+</sup> and molecular hydrogen H<sub>2</sub>, leading to CH<sub>2</sub><sup>+</sup>, because the direct reaction to form CH<sup>+</sup> faces an energy barrier of  $\sim 4640$  K (Black and Dalgarno 1973; Godard et al. 2009). In low density gas illuminated by ultraviolet radiation, the reaction of C<sup>+</sup> with vibrationally excited H<sub>2</sub> is not efficient enough to bypass the radiative association reaction (Agundez et al. 2010). Once formed, CH<sub>2</sub><sup>+</sup> rapidly reacts with H<sub>2</sub> to form CH<sub>3</sub><sup>+</sup>, a key precursor of many interstellar hydrocarbons. CH results from the dissociative recombination of both CH<sub>2</sub><sup>+</sup> and CH<sub>3</sub><sup>+</sup>. It is expected theoretically, and verified by the observations, that the CH column density will scale with the H<sub>2</sub> column density in regions where the chemistry is dominated by the ultraviolet radiation (Federman 1982; Sheffer et al 2008).

The chemistry of the diffuse interstellar medium cannot be entirely captured by the simple framework described above, as reactions on surfaces and transient processes may play important roles, too. For example, the energy release mediated by magnetic fields in the dissipation regions of strong interstellar turbulence may drive a “warm chemistry” where reactions that would otherwise be inhibited at low temperature become important (Godard et al. 2009). The methylidyne ion, CH<sup>+</sup>, is predicted to arise in such turbulent dissipation regions. There is already observational evidence that some fraction of the CH forms from CH<sup>+</sup>

<sup>★</sup> Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA

**Table 1.** CH spectroscopic parameters for the  $N = 1 \leftarrow 1$  transitions

Frequency MHz	transition $u \leftarrow \ell$ $J', F' \leftarrow J'', F''$	$A_{ul}$ $10^{-4} \text{ s}^{-1}$	$E_u/k$ K	$\int \tau dV/N^a$ $10^{-13} \text{ km s}^{-1} \text{ cm}^{-2}$	$V_{\text{off}}$ $\text{km s}^{-1}$
532721.68	$3/2, 1^+ \leftarrow 1/2, 1^-$	2.07	25.7	0.055	1.3
532723.93	$3/2, 2^+ \leftarrow 1/2, 1^-$	6.21	25.7	0.275	0.0
532793.31	$3/2, 1^+ \leftarrow 1/2, 0^-$	4.14	25.7	0.110	-39.0
536761.15	$3/2, 2^- \leftarrow 1/2, 1^+$	6.38	25.8	0.276	0.0
536781.95	$3/2, 1^- \leftarrow 1/2, 1^+$	2.13	25.8	0.055	-11.6
536795.68	$3/2, 1^- \leftarrow 1/2, 0^+$	4.25	25.8	0.111	-19.3

<sup>(a)</sup> Opacity integrated over the line profile per total CH column density, under the assumption that  $T_{\text{ex}} \ll E_u/k$ .

**Table 2.** Source parameters

Name	RA J2000	DEC J2000	$V_{\text{LSR}}$ $\text{km s}^{-1}$	$N_{\text{H}}^a$ $10^{22} \text{ cm}^{-2}$	$N(\text{H})$ $10^{22} \text{ cm}^{-2}$
W31C <sup>b</sup>	18:10:28.7	-19:55:50.0	-2	2.7	1.2
W49N	19:10:13.2	09:06:12	11	4.1	1.4
W51 <sup>c</sup>	19:23:43.9	14:30:30.5	57	2.5	0.8

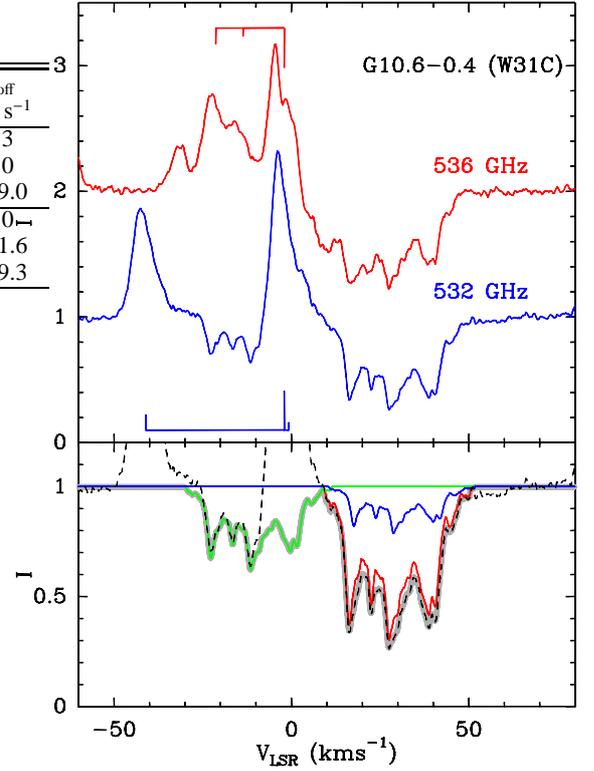
<sup>(a)</sup> Total hydrogen:  $N_{\text{H}} = 2N(\text{H}_2) + N(\text{H})$ , see text <sup>(b)</sup> Also known as G10.6-0.64 <sup>(c)</sup> W51-E4

(Pan et al. 2005), in addition to the quiescent, photon-dominated source discussed above. In this paper, we present a comparison of CH with other carbon species present in the diffuse interstellar medium,  $\text{HCO}^+$ , CN and CCH towards the targets, W31C, W51 and W49N (Table 2).

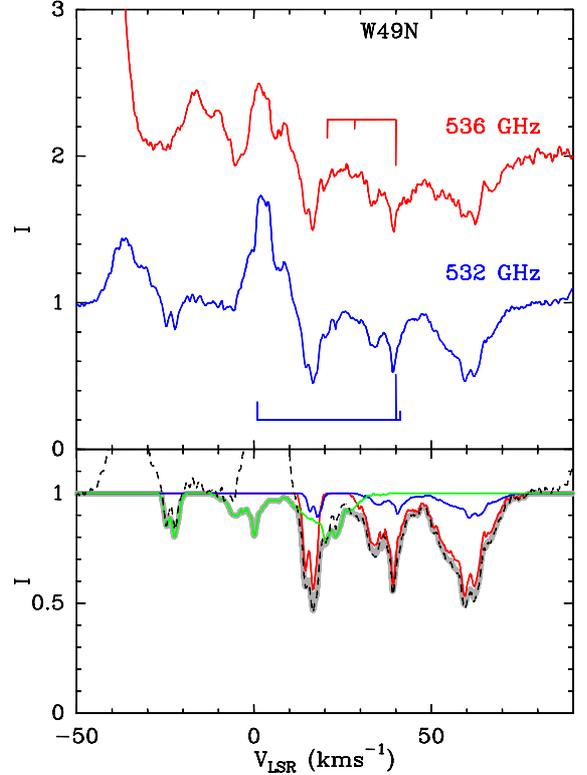
## 2. Observations

The observations were performed with the *Herschel* HIFI instrument (de Graauw et al. 2010) in 2010 March and April. The data were taken in Double Beam Switching (DBS) mode with a throw of 3 arc-minutes. To remove the ambiguity on the line frequency in observations performed with double side band mixers, each line was observed with three settings of the Local Oscillator (LO). We used the two HIFI spectrometers: the wide band spectrometer (WBS) that provides a total bandwidth of 4 GHz, with 1.1 MHz spectral resolution ( $0.56 \text{ km s}^{-1}$  at 532 GHz), and the high resolution spectrometer (HRS) with 0.12 MHz spectral resolution. The on source integration times have been set to reach a S/N ratio on the continuum of at least 50 for a velocity resolution of  $1 \text{ km s}^{-1}$ . This translates into observing times of 23, 7.5 and 11 minutes for G10.6 - 0.4, W49N and W51, respectively, for each CH line.

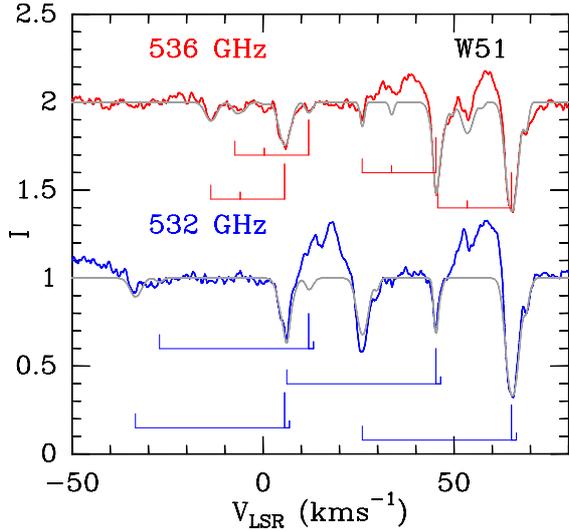
The spectra were calibrated with a hot and cold blackbody (Roelfsema et al 2010). As we are interested in the absorption, we have not corrected the data for the main beam efficiency. The data were first processed using HIPE (Ott et al. 2010), and subsequently exported to CLASS (Hily-Blant et al. 2005; Pety 2005). For each source, the data obtained with the three LO settings were in excellent agreement (better than 10%) and could be co-added. The spectra obtained from the H and V polarization mixers were also in good agreement. The continuum levels agree well for both polarizations but do not generally coincide. At 532 GHz, we obtained Double Side Band continuum  $T_c$  of  $0.94 \pm 0.03 \text{ K}$ ,  $1.5 \pm 0.5 \text{ K}$  and  $1.8 \pm 0.1 \text{ K}$  for G10.6-0.4, W49N and W51. We produced normalized spectra as  $I = 2(T - \frac{T_c}{2})/T_c$ , where  $T$  stands for the antenna temperature, and we assume that the relative gains of the lower and upper side bands are equal. The H and V normalized spectra were finally co-added to produce the spectra shown in Figures 1, 2 and 3.



**Fig. 1.** Top : Normalized spectra of the CH transitions at 532 GHz and 536 GHz towards G10.6 - 0.4. The 536 GHz spectrum has been shifted by 1 for clarity. Bottom : Decomposition of the 532 GHz line into three hyperfine components, the red line shows the main component, the blue and green lines the satellites, and the grey curve the sum of the three components. The data are shown with a black dashed line.



**Fig. 2.** Same as Fig 1 for W49N



**Fig. 3.** Normalized spectra of the CH transitions at 532 GHz and 536 GHz towards W51. The 536 GHz spectrum has been shifted for clarity. The grey lines show the model, the positions of the CH triplets for the four velocity components are indicated below each transition.

For both CH triplets, the line profiles are complex because the emission or absorption of each of the three hyperfine components overlaps partly with the signal from the other components. High spectral resolution data are therefore a prerequisite to properly derive the CH column densities in complex sources. To properly separate the foreground absorption and extract the velocity structure of the absorbing gas, we have taken advantage of the known frequency offsets of the hyperfine components to “deconvolve” the spectra from the hyperfine structure. We have written the normalized spectra as  $I = e^{-\sum_{i=1}^3 \tau_i}$ , hence  $-\ln(I) = \sum_{i=1}^3 \alpha_i \tau_m$ , where  $\tau_i = \alpha_i \tau_m$  stands for the opacity of the hyperfine component  $\#i$ , and  $\alpha_i$  is the intensity of this component relative to the main one. This formula uses the assumption that the ratios of the opacities of the CH hyperfine components follow the relative intensities, *i.e.*, there is no anomalous excitation of the hyperfine levels. In regions of the spectrum where the main hyperfine component is blended with satellite lines from another velocity component, its opacity can be deduced from the opacity of the satellite lines in “clean” spectral regions. The deconvolution method was performed on either the 532 GHz or the 536 GHz triplets depending on the source. We checked that the resulting velocity structure is in agreement with the observations of the other triplet. The bottom panels in Figures 1 and 2 show the absorption profiles for each hyperfine component overlaid on the data. For W51 (Figure 3), the overlap of the hyperfine components is not as severe as for the other sources, and we fitted the 532 GHz absorption profile with four Gaussian velocity components. We used the position and width as derived from the fit of the HF and HCO<sup>+</sup> spectra (Sonnentrucker et al. 2010; Godard et al. 2010).

### 3. Results

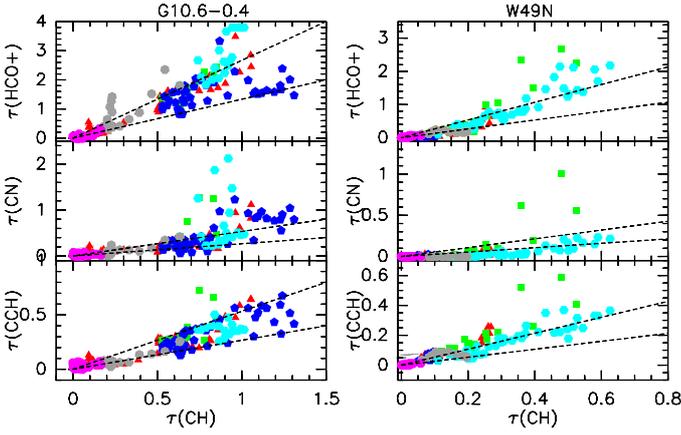
We used the profile of the main hyperfine component of CH to derive the properties of the absorbing material. At first sight, the CH profile is similar to those of ground state transitions of simple molecules like HF and H<sub>2</sub>O (Neufeld et al. 2010a; Sonnentrucker et al. 2010; Lis et al. 2010), HCO<sup>+</sup>, CN, CCH and *c*-C<sub>3</sub>H<sub>2</sub> (Godard et al. 2010; Gerin et al. 2010b), and OH<sup>+</sup> and CH<sup>+</sup> (Neufeld et al. 2010b; Gerin et al. 2010a;

Falgarone et al. 2010). To be more quantitative, we show in Figure 4 comparisons of the opacities of the main spin-rotation-hyperfine component of CH( $N = 1 \leftarrow 1$ ), CCH( $N = 1 \leftarrow 0$ , 87316.898 MHz), CN( $N = 1 \leftarrow 0$  113191.2787 MHz), and of the  $J=1-0$  line of HCO<sup>+</sup> in selected velocity intervals. Each point corresponds to one velocity channel in the spectra. We have arbitrarily set the maximum value of opacity of the HCO<sup>+</sup> data to 3.5 as the observations are not sensitive to opacities larger than  $\sim 3$ . For all lines of sight the plots present the same structure: a general linear trend and strong deviations in narrow velocity intervals where the CN and HCO<sup>+</sup>, and to a lesser extent CCH, opacities, get larger than the average for a given CH opacity. Since CH is expected to be linearly correlated with H<sub>2</sub>, an increase in the total column density cannot explain these sharp features. As discussed by Sheffer et al. (2008), it is more likely that the sharp features are associated with regions of higher-than-average density along the lines of sight. It is known that the CN abundance is sensitive to the gas density in diffuse clouds (Cardelli et al. 1991; Federman et al. 1994). The *Herschel* data nicely confirm the results of optical spectroscopy.

The linear trends in optical depth show that the ratios of molecular column densities stay in a narrow range for the three sources we have sampled. At the densities typical of diffuse gas,  $n(\text{H}_2) \lesssim 10^3 \text{ cm}^{-3}$ , the rotational excitation of CH is controlled mainly by radiative processes so that the excitation temperatures of the 532 and 536 GHz transitions are expected to be  $T_{\text{ex}} \approx 3.1$  K in the average Galactic background radiation. For these unsaturated submillimeter transitions  $T_{\text{ex}} \ll hv/k$  and almost all CH molecules are in the lowest rotational state; therefore, we expect a simple relationship between the integrated absorption  $\int \tau dV$  and the total column density of CH,  $N(\text{CH})$  (see Table 1). Low-lying excited states are populated in the heavier molecules CN, CCH, and HCO<sup>+</sup>, but the rotational excitation temperatures are expected to remain in the range 2.73 to 3.1 K, low enough that column densities are simply related to integrated absorption when the lines are unsaturated. These linear relations between opacity and column density have been tested by means of non-LTE excitation calculations that include collisions by neutrals and electrons as well as radiative excitation in the average Galactic background continuum (cf. van der Tak et al. 2007). We find ratios of column densities  $N(\text{CCH})/N(\text{CH}) = 0.6 - 1.2$  with values up to 1.8, and  $N(\text{CN})/N(\text{CH}) = 0.5 - 1$  with values up to 3. The HCO<sup>+</sup> spectra are more saturated, but follow the same trends. We find  $N(\text{HCO}^+)/N(\text{CH}) = 0.04 - 0.08$  with values up to at least 0.2. The [CN]/[CH] ratio lies at the upper end of the values derived from optical spectroscopy (Sheffer et al 2008; Weselak et al. 2008).

As further described in the appendix, we have used the Meudon-PDR code (Le Petit et al. 2006; Goicoechea & Le Bourlot 2007; Gonzalez Garcia et al. 2008) to study how these abundance ratios depend on the gas density. The [CN]/[CH] and [CCH]/[CH] abundance ratios are sensitive to the gas density as suggested by Cardelli et al. (1991). For the bulk of the diffuse matter producing the absorption features, the observations are consistent with gas densities between 100 and 1000  $\text{cm}^{-3}$ .

The CH column densities for selected velocity intervals are reported in Table A.1, together with the H<sub>2</sub> column densities, assuming the mean CH abundance  $[\text{CH}]/[\text{H}_2] = 3.5 \times 10^{-8}$  (Sheffer et al 2008). The deduced total H<sub>2</sub> column densities are  $N(\text{H}_2) = 1.6 \times 10^{22} \text{ cm}^{-2}$ ,  $1.1 \times 10^{22} \text{ cm}^{-2}$  and  $0.16 \times 10^{22} \text{ cm}^{-2}$  for G10.6–0.4, W49N and W51 respectively. The total hydrogen column can be estimated independently from the K-band extinction (Marshall et al 2006), and the atomic hy-



**Fig. 4.** Comparison of the opacity of the main CH hyperfine component with those of the CCH, CN and HCO<sup>+</sup> ground state millimeter-wave transitions. Each point corresponds to a 0.5 km s<sup>-1</sup> velocity channel. Dashed lines indicate the minimum and maximum ratios of the opacities in the linear trend. For G10.6-0.4, the velocity range 12 – 22 km s<sup>-1</sup> is shown in red, 22 – 25 km s<sup>-1</sup> in green, 25 – 38 km s<sup>-1</sup> in blue, 38 – 43 km s<sup>-1</sup> in cyan, 43 – 48 km s<sup>-1</sup> in grey and 48 – 60 km s<sup>-1</sup> in purple. For W49N, the velocity range 30 – 36 km s<sup>-1</sup> is shown in red, 36 – 43 km s<sup>-1</sup> in green, 43 – 50 km s<sup>-1</sup> in blue, 50 – 67 km s<sup>-1</sup> in cyan, 67 – 71 km s<sup>-1</sup> in grey and 71 – 78 km s<sup>-1</sup> in purple.

drogen column from H I 21 cm line data (Godard et al. 2010; Sonnentrucker et al. 2010), as listed in Table 2. This second method yields  $N(\text{H}_2) = 0.75 \times 10^{22} \text{ cm}^{-2}$ ,  $1.3 \times 10^{22} \text{ cm}^{-2}$  and  $0.85 \times 10^{22} \text{ cm}^{-2}$ . Given the scatter in the [CH]/[H<sub>2</sub>] relation (0.2 dex corresponding to a factor of 1.6) and the uncertainties in total extinction, the two methods are in good agreement for G10.6 – 0.4 and W49N. The total H column may be overestimated towards W51. A likely explanation is that the quoted figure includes extinction directly associated with the W51 molecular complex itself that could be related to the 65 km s<sup>-1</sup> velocity feature (Koo 1997). Our analysis of three sight-lines suggests that the abundance of CH relative to H<sub>2</sub> in the Galactic disk is similar to that in the Solar neighborhood.

CCH appears to be better correlated with CH than either CN or HCO<sup>+</sup>. Therefore we suggest that CCH can be used as another tracer of molecular hydrogen, that is easily observable from the ground and complements CH and HF. Assuming that the mean CH abundance relative to H<sub>2</sub> derived by Sheffer et al. (2008) holds in the Galactic plane, we derive  $[\text{CCH}]/[\text{H}_2] = (3.2 \pm 1.1) \times 10^{-8}$ , which is in excellent agreement with the abundance estimated by Lucas & Liszt (2000).

#### 4. Conclusion

Unlike lines of other hydrides, CH submillimeter absorption lines in the diffuse matter are not saturated, a feature already identified in the ISO-LWS spectra of the CH ground state transitions at 149  $\mu\text{m}$ . This makes CH a powerful tracer of the diffuse molecular gas along Galactic lines of sight, that complements HF (Neufeld et al. 2010a; Sonnentrucker et al. 2010). We show that the column densities of simple molecules (CN, CCH, HCO<sup>+</sup>) are well correlated with those of CH except in some narrow velocity ranges where significantly higher column densities than average are derived, especially for CN and HCO<sup>+</sup>. This behaviour may trace the densest regions along the line of sight. The bulk of the matter lies at  $n_{\text{H}} = 100 - 1000 \text{ cm}^{-3}$ . We propose that CCH can be used as a complementary tracer of H<sub>2</sub>, with  $[\text{CCH}]/[\text{H}_2] = (3.2 \pm 1.1) \times 10^{-8}$ .

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**Table A.1.** CH column densities

Name	$V_{\min}$ km s <sup>-1</sup>	$V_{\max}$ km s <sup>-1</sup>	$N(\text{CH})$ 10 <sup>13</sup> cm <sup>-2</sup>	$N(\text{H}_2)^a$ 10 <sup>21</sup> cm <sup>-2</sup>
G10.6-0.64 (W31C)	10	20	14 ± 1	3.9
	20	25	9.8 ± 1	2.7
	25	35	26 ± 1	7.3
	25	42	17 ± 1	4.8
W49N	42	47	3.3 ± 1	0.9
	30	50	13 ± 1	3.7
	50	78	24 ± 1	6.6
W51	67	71	1.5 ± 0.2	0.4
	3	10	3.7 ± 0.2	1.0
	10	15	0.5 ± 0.15	0.14
	42	47	1.8 ± 0.15	0.5

<sup>(a)</sup> Based on  $[\text{CH}]/[\text{H}_2] = 3.5 \times 10^{-8}$  (Sheffer et al 2008).

## Appendix A: CH column densities

### Appendix B: PDR models

Figure B.1 presents models produced using the Meudon PDR code, a steady-state, depth-dependent model of a plane-parallel cloud (Le Petit et al. 2006; Goicoechea & Le Bourlot 2007; Gonzalez Garcia et al. 2008). Our chemical network is based on a modified version of the Ohio State University (OSU) gas-phase network updated for photochemical studies. We have computed the thermal and chemical structure of diffuse clouds with  $A_V < 5$ ,  $n_H = 100\text{--}5000\text{ cm}^{-3}$ , cosmic ray ionization rates  $\zeta_H$  of  $10^{-17}\text{ s}^{-1}$ ,  $10^{-16}\text{ s}^{-1}$ , and  $10^{-15}\text{ s}^{-1}$ , and illuminated only at one side by a UV field,  $\chi$ , between 1 and 10 times the mean interstellar radiation field (in Draine units). The  $[\text{CN}]/[\text{CH}]$ ,  $[\text{HCO}^+]/[\text{CH}]$  and  $[\text{C}_2\text{H}]/[\text{CH}]$  ratios are sensitive to the gas density as suggested by Cardelli et al. (1991). For the bulk of the diffuse matter producing absorption features, the observations are consistent with gas densities between 100 and  $1000\text{ cm}^{-3}$ . Fig. A.1 also shows the predicted scaling between CH and H<sub>2</sub> column densities in the parameter space appropriate for diffuse clouds. An approximately similar trend is predicted for C<sub>2</sub>H when  $A_V > 0.01$ .

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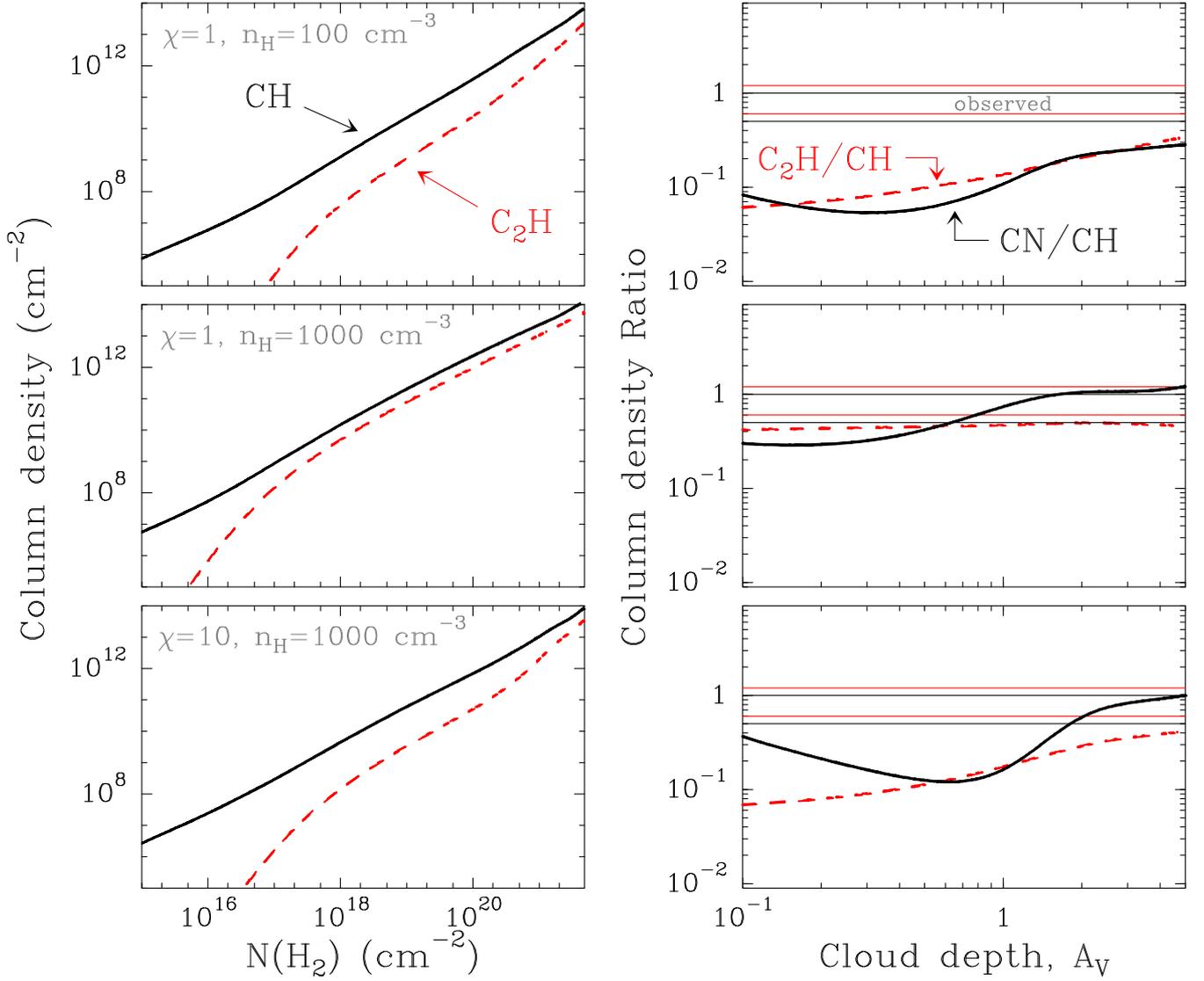
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**Fig. B.1.** Left: Predicted variation of the CH (black line) and CCH (red dashed line) column density as a function of the H<sub>2</sub> column density for three models, computed with  $\zeta_H = 10^{-16} \text{ s}^{-1}$ :  $\chi=1$  and  $n_H = 100 \text{ cm}^{-3}$  (top),  $\chi=1$  and  $n_H = 1000 \text{ cm}^{-3}$  (middle) and  $\chi=10$  and  $n_H = 1000 \text{ cm}^{-3}$  (bottom). Right: Variation of the CN/CH (black lines) and CCH/CH (red dashed lines) column density ratios for the same models. The gas density  $n_H$  is defined as  $n(H) + 2n(H_2)$ . The observed ranges are indicated. .