CH radio emission from Heiles Cloud 2 as a tracer of molecular cloud evolution*

N. Sakai¹, H. Maezawa², T. Sakai³, K. M. Menten⁴, and S. Yamamoto¹

¹ Department of Physics and Research Center for the Early Universe, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
e-mail: nami@taurus.phys.s.u-tokyo.ac.jp
² Physical Science, Osaka Prefecture University, Gakuen-cho, Naka-ku, Sakai-shi, 599-8531, Japan
³ Institute of Astronomy, The University of Tokyo, Osawa, Mitaka, Tokyo, 181-8588, Japan
⁴ Max-Planck-Institut fuer Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

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ABSTRACT

Aims. A mapping observation of the J = 1/2 A-type doubling transition (3.3 GHz) of CH has been conducted toward Heiles Cloud 2 (HCL2) in the Taurus molecular cloud complex to reveal its molecular cloud-scale distribution.

Methods. The observations were carried out with the Effelsberg 100 m telescope.

Results. The CH emission is found to be extended over the whole region of HCL2. It is brighter in the southeastern part, which encloses the TMC-1 cyanopolyne peak than in the northwestern part. Its distribution extends continuously from the peak of the neutral carbon emission (CI peak) to the TMC-1 ridge, as if it were connecting the distributions of the [CI] and C¹8O emissions. Since CH is an intermediate in gas-phase chemical reactions from C to CO, its emission should trace the transition region. The above distribution of the CH emission is consistent with this chemical behavior. Since the CH abundance is subject to the chemical evolutionary effect, the CH column density in HCL2 no longer follows a linear correlation with the H² column density reported for diffuse and translucent clouds. More importantly, the CH line profile is found to be composed of the narrow and broad components. Although the broad component is dominant around the CI peak, the narrow component appears in the TMC-1 ridge and dense core regions such as L1527 and TMC-1A. This trend seems to reflect a narrowing of the line width during the formation of dense cores. These results suggest that the 3.3 GHz CH line is a useful tool for tracing the chemical and physical evolution of molecular clouds.

Key words. astrochemistry – ISM: individual objects: HCL2 – ISM: individual objects: Taurus – ISM: individual objects: TMC-1 – ISM: molecules

1. Introduction

It is widely recognized that chemical abundances show significant variations within a molecular cloud as well as between one cloud and another. Understanding this differentiation is an important topic of astrochemistry and astrophysics. A most famous and well-studied case is the TMC-1 ridge, which is a part of Heiles Cloud 2 (HCL2) in the Taurus molecular cloud complex. Carbon-chain molecules such as CCS and HC₃N are abundant in its southeastern part (“cyanopolyne peak”; referred to hereafter as TMC-1(CP)), whereas NH₃ and N₂H⁺ are abundant in the northwestern part (“ammonia peak”; referred to hereafter as TMC-1(NH₃)) (e.g. Little et al. 1979; Hirahara et al. 1992; Olano et al. 1988; Pratap et al. 1997). This chemical differentiation is most naturally interpreted in terms of an evolutionary effect (e.g. Hirahara et al. 1992), although other possibilities have also been proposed (e.g. Markwick et al. 2000; Garrod et al. 2007). Carbon-chain molecules are generally abundant in early stages of the chemical evolution before C is not completely locked up in CO, while they become deficient in more advanced stages due to gas-phase destruction and depletion onto dust grains (Suzuki et al. 1992; Benson et al. 1998; Aikawa et al. 2003). In contrast, NH₃ and N₂H⁺ appear in advanced stages because of their slow formation (Suzuki et al. 1992; Benson et al. 1998). In fact, the protostar IRAS 04381+2540 has been found near the ammonia peak of the TMC-1 ridge (Terebey et al. 1989), testifying that this peak is, indeed, more chemically evolved than the cyanopolyne peak. All these results suggest that along the TMC-1 ridge we are observing an evolutionary trend from less advanced in its southeastern part to more advanced in the northwestern part.

This evolutionary scenario is supported by observations of the 492 GHz atomic carbon [CI] P₁₋₁ – P₀ fine structure line with the Mount Fuji Submillimeter-Wave Telescope, see Maezawa et al. (1999). These authors conducted a large-scale survey of the [CI] line covering the whole region of HCL2, and found that the [CI] emission is more intense in the southeastern part of HCL2 than in the northwestern part by a factor of 2. On the other hand, the C¹8O line is generally intense in the northwestern part. Because the major form of carbon in the gas phase changes from CCO to CO, the direction of chemical evolution from less to more developed is again from the southeast to the northwest. This is nicely consistent with the CCS and NH₃ observations of the TMC-1 ridge, and important for our understanding of the formation of molecular cloud cores. A similar behavior of C, CO, and CCS on a much larger scale is observed in the AFGL333 region of the W3 giant molecular cloud by Sakai et al. (2006).

To examine the above formation process of HCL2 in more detail, we focus on observations of the CH emission (3.3 GHz). CH is the first and simplest neutral molecule formed from C and/or C⁺ in the gas phase and an important chemical intermediate in the production pathway of CO from C and C⁺. It is also suggested to be a key reactant in the production of

* The data cube (in FITS format) is only 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/546/A103
carbon-chain molecules at early evolutionary stages (Sakai et al. 2007a). Observations of the CH line toward the HCL2 region were first reported by Rydbeck et al. (1976), although only toward two positions in HCL2 were observed with the 15″ beam. Very recently, Suutarinen et al. (2011) reported observations of the CH line along the TMC-1 with the MIRIR 100 m telescope. They found that the abundance of CH has a peak toward TMC-1(CP) on the basis of a strip map along the ridge. However, these authors only focused on the TMC-1 ridge, leaving the overall distribution of CH in HCL2 unexplored.

The CH emission (3.3 GHz) has extensively been observed for diffuse clouds, translucent clouds, bright limbed clouds, outflows, and dark clouds (e.g. Lang & Willson 1978; Sandell et al. 1980, 1981; Mattila 1986; Jacq et al. 1987; Sandell et al. 1988; Magnani et al. 1992; Magnani & Onello 1993). Many of these previous efforts focused on the correlation between the CH column density and the optical extinction. With the aid of the optical data, the CH column density is recognized as a good tracer of the H2 column density in diffuse and translucent clouds (e.g. Federman 1982; Danks et al. 1984; Mattila 1986; Sheffer et al. 2008). Recently, Chastain et al. (2010) conducted the high spatial resolution observation of the high-latitude translucent clouds MBM 3 and MBM 40 with the NAIC 305 m telescope at Arecibo, and found a slight difference between the distribution of CH and that of CO. This may suggest that the CH column density does not always correlate to the H2 column density, and that we have to consider chemical evolutionary effects on the CH abundance. With these in mind, we have explored the distribution of the CH line in a whole region of HCL2.

2. Observations

Observations were carried out with the MPIfR 100 m telescope at Effelsberg in August 2007, September 2008, and September 2009. We observed two hyperfine components of the J = 1/2 A-type doubling transition of CH (F = 1−1; ν = 3.335482(1) GHz; Sμ = 1.4205 Debye2 F = 0−1; ν = 3.349193(3) GHz; Sμ = 0.7105 Debye2) (McCarthy et al. 2006; Müller et al. 2005 (CDMS)) toward HCL2. Here, the numbers in parentheses represent the 1σ error in units of the last significant digits. We did not observe the F = 1−0 line (ν = 3.263795(3) GHz) because of the limitation of the backend. We used the 9 cm receiver as a frontend, whose system noise temperature was about 35 K. The beam size and the main beam efficiency of the telescope are 3.8 and 0.73, respectively. The telescope pointing was checked every three hours by observing nearby continuum sources, and was maintained to be better than 20″. A small daily variation of the intensity was calibrated by repeatedly observing the F = 1−1 main line toward TMC-1(CP). Our backend was the fast Fourier transform spectrometer, FFTS, with a bandwidth and resolution of 20 MHz and 1.2 kHz, respectively. This frequency resolution corresponds to a velocity resolution of 0.1 km s−1. The observations were carried out in the frequency-switching mode with a frequency offset of 0.2 MHz. The whole HCL2 region was mapped in the F = 1−1 main line. Toward a few selected positions, we observed the F = 1−1 main line and the F = 0−1 satellite line with a higher signal to noise (S/N) ratio to investigate the line profile.

3. Results

3.1. Line profile

Our first CH observation toward TMC-1(CP) was conducted in 2007. After a long on-source integration of 25 h for a search for 13CH, the CH lines were detected with a high S/N ratio, as shown in Fig. 1. In addition to the main line (F = 1−1), the satellite line (F = 0−1) was also detected. The intensity ratio between the main and satellite lines is close to the intrinsic intensity ratio of 2, indicating that the lines are optically thin. As seen in Fig. 1, the line profile apparently consists of narrow and broad components both for the main and the satellite lines. The two components can be separated by fitting two Gaussian profiles, as shown in Fig. 2. The derived parameters are given in Table 1.

The narrow component of the main line has an LSR velocity, \( V_{\text{LSR}} \), of 5.916(3) km s\(^{-1}\) and a line width, \( \Delta V \), of 0.26(1) km s\(^{-1}\), where the numbers in parentheses represent the fitting error in units of the last significant digits. This \( V_{\text{LSR}} \) value is close to the velocities observed in various molecular lines toward this position (e.g. Dickens et al. 2001; Kaifu et al. 2004; Sakai et al. 2008), whereas the line is slightly narrower than those of
For the frequency of the F1 component. See text for details.

Table 1. Line parameters of the CH emission observed toward several cores.

| Source          | Transition | $T_{mb}$  | $\Delta V$  | $V_{lsr}$  | $\int T_{mb} dv$ |
|-----------------|------------|-----------|-------------|-------------|-----------------|
|                  | F = 1–1 narrow | 0.536(12) | 0.26(1)     | 5.916(3)   | 0.787(3) |
| TMC-1(CP)       | F = 1–1 broad | 0.429(8)  | 1.28(2)     | 6.123(8)   | –               |
| (04h41m42.8′, 25°41′27.0′) | F = 0–0 narrow | 0.237(8)  | 0.27(1)     | 5.693(4)   | 0.333(3) |
|                 | F = 0–0 broad | 0.181(5)  | 1.29(3)     | 5.892(13)  | –               |
| TMC-1(NH$_3$)   | F = 1–1, 1′  | 0.445(22) | 1.40(8)     | 5.97(3)    | 0.665(22) |
| (04h41m′18.50, 25°48′13′6′) | F = 0–1 narrow | 0.205(21) | 1.44(17)    | 5.81(7)    | 0.349(21) |
| CI peak         | F = 1–1     | 0.407(21) | 1.60(9)     | 5.97(4)    | 0.759(23) |
| L1527           | F = 1–1 narrow | 0.333(58) | 0.22(5)     | 6.26(2)    | 0.607(22) |
| (04h39m′53.8′, 26°03′11′0′) | F = 1–1 broad | 0.310(30) | 1.57(14)    | 6.34(5)    | –               |
|                 | F = 0–0 narrow | 0.204(64) | 0.31(11)    | 6.02(3)    | 0.179(17) |
|                 | F = 0–0 broad | 0.089(57) | 1.13(46)    | 6.12(16)   | –               |

Notes. $T_{mb}$, $\Delta V$, and $V_{lsr}$ are obtained by a Gaussian fit. The error in the parentheses denotes one standard deviation in units of the last significant digits. The $V_{lsr}$ values refer to the rest frequencies given in Sect. 2, and the error of $V_{lsr}$ does not include the uncertainty of the rest frequency. A slight difference of the $V_{lsr}$ values between the $F = 1–1$ (main) and $F = 0–1$ (satellite) component likely originates from the error of the rest frequency of the $F = 0–1$ component. See text for details.

Table 2. Column densities of CH.

| Sources          | N(CH) [cm$^{-2}$] |
|-----------------|------------------|
| TMC-1(CP)       | 0.41 $\pm$ 0.05 $\times 10^{14}$ |
| TMC-1(NH$_3$)   | 1.79 $\pm$ 0.42 $\times 10^{14}$ |
| CI peak         | 1.88 $\pm$ 0.45 $\times 10^{14}$ |
| L1527           | 0.21 $\pm$ 0.18 $\times 10^{14}$ |
|                 | 1.39 $\pm$ 0.57 $\times 10^{14}$ |

Notes. The error is evaluated from three times the standard deviation of the line parameters. $T_{ex}$ is assumed to be $\approx 60$ K. See text.

3.2. Column densities

The column density of CH is evaluated by assuming optically thin emission. This is justified, because the intensity ratio between the main and satellite hyperfine components is close to the ratio of their intrinsic intensities, as mentioned before. HCL2 is a quiescent cloud not influenced by high-mass star formation activities, although several low-mass protostars such as IRAS 04381+2540 and IRAS 04368+2557 are associated with it. Therefore, the gas kinetic temperature is as low as 10 K in its dense parts. This means that almost all the CH molecules are populated in the $J = 1/2$ A-type doubling levels, and the populations of the higher $J$ levels are negligible. In the cloud peripheries, the temperature would be higher than 10 K due to photoelectric heating by interstellar UV radiation. In this case, the density is too low to excite CH even to the first rotationally excited state ($J = 3/2$), because the critical density required for the excitation of the lowest rotational transition ($J = 3/2$–$1/2$; 530 GHz) is as high as $10^6$ cm$^{-3}$. Hence, practically all CH molecules are in the $J = 1/2$ levels. For this reason, we only considered the $J = 1/2$ levels for calculations of the partition function in the evaluation of the column density.

It is well known that the populations of the $J = 1/2$ A-type doubling levels are inverted over a wide range of physical conditions (Genzel et al. 1979; Bujarrabal et al. 1984; Sandell et al. 1988; Liszt & Lucas 2002). Hence, the excitation temperatures are usually negative for the $F = 1–1$, 1–0, and 0–1 lines. In particular, a strong excitation anomaly occurs for the $F = 0–0$ line, which sometimes appears as an absorption against the background continuum sources (e.g. Genzel et al. 1979). In contrast, the $F = 1–1$ main line behaves quite normally. Under the assumption of optically thin emission, the column density of CH, $N(CH)$, can be related to the integrated intensity ($W$ in K km s$^{-1}$) of the $F = 1–1$ line as

$$N(CH) = 2.82 \times 10^{14} \frac{T_{ex}}{(T_{ex} - T_b)} \text{ W cm}^{-2},$$

where $T_{ex}$ and $T_b$ represent the excitation temperature and the cosmic microwave background temperature, respectively (e.g. Sandell et al. 1988). Assuming an effective excitation temperature of $\approx 60$ K reported for dark clouds (Genzel et al. 1979), we calculated the column densities, as summarized in Table 2. As expected from Eq. (1), the uncertainty of the excitation temperature does not contribute to the error of the column density very much, unless $T_{ex}$ is as low as $T_b$. Even if we change the
Fig. 3. Profile map of the CH ($F = 1-1$) main line. The spacing of the spectra is 4' in each direction. Approximate positions of the CI peak, TMC-1(CP), TMC-1(NH$_3$), L1527, TMC-1C, and TMC-1A are given. The typical rms noise level is about 0.1 K.

excitation temperature by ±30 K, the column density varies only within 5%.

3.3. Distribution

To explore the distribution of the CH emission and the origin of the line shape variation, we then conducted mapping observations of the whole HCL2 region. To do this within the limited observation time, we employed a roughly FWHM-sized grid spacing of 4'. Therefore, the map is undersampled. The integration time for each position was typically 10 min. Figure 3 shows a profile map of the CH main line, and Fig. 4a shows the corresponding integrated intensity map. The CH emission is distributed throughout the HCL2 region. The ring structure of HCL2 can be seen, and the TMC-1 ridge structure is also evident. In addition to these, the CH emission is observed with moderate intensities around the CI peak. It is generally brighter in the southeastern part, which includes TMC-1(CP), than in the northern part. Figures 5a and 5b show the integrated intensity map of CH overlaid on the images of the [C I] and C$^{18}$O ($J = 1-0$) emission, respectively. The distribution of CH looks continuous from the CI peak to the TMC-1 ridge, as if it connected the distributions of [C I] and C$^{18}$O.

Next, we focused on the line profile. As shown in Fig. 3, the line profile systematically changes from the CI peak to the TMC-1 ridge. The CH line is quite broad (typically 3 km s$^{-1}$)
Fig. 4. a) Integrated intensity map of the CH emission from 5.0 to 7.2 km s\(^{-1}\). Contours show every 0.1 K km s\(^{-1}\) from 0.1 K km s\(^{-1}\). b) Integrated intensity map of the broad component of the CH emission (4.7–5.8 and 6.6–7.2 km s\(^{-1}\)). Contours show every 0.1 K km s\(^{-1}\) from 0.2 K km s\(^{-1}\). c) Integrated intensity map of the narrow component of the CH emission. Since the narrow component velocity slightly changes in a large scale, the 0.2 km s\(^{-1}\) span centered at the peak velocity is integrated to extract the narrow component. Hence, it should be noted that a part of the broad component is contaminated. Contours show every 0.05 K km s\(^{-1}\) from 0.1 K km s\(^{-1}\). Filled circle, filled square, open square, star, cross mark, and x symbols correspond to the position of the CI peak, TMC-1(CP), TMC-1(NH\(_3\)), L1527, TMC-1C, and TMC-1A, respectively, as shown in c).

Fig. 5. a) Contours show the integrated intensity map of CH overlaid on the color image of the \([\text{C I}] (^3P_1 - ^3P_0: 492 \text{ GHz})\) distribution taken with the Mount Fuji Submillimeter-Wave Telescope (Maezawa et al. 1999). The velocity range of the integration for the CH line is from 5.0 to 7.2 km s\(^{-1}\). The lowest contour and the contour interval is 0.1 K km s\(^{-1}\). b) Contours show the integrated intensity map of CH overlaid on the color image of the \(^{18}\text{O} (J = 1–0)\) distribution taken with the Nobeyama 45 m telescope (archival data). The velocity range of the integration of the \(^{18}\text{O}\) line is from 5.0 to 7.2 km s\(^{-1}\).

4. Discussion

4.1. Abundance of CH

The column densities of CH toward TMC-1(CP) are evaluated to be \((0.41 \pm 0.05) \times 10^{14}\) and \((1.57 \pm 0.12) \times 10^{14}\) cm\(^{-2}\) for the narrow and broad components, respectively. The error denotes three times the standard deviation. The total column density is \((1.98 \pm 0.17) \times 10^{14}\) cm\(^{-2}\). Rydbeck et al. (1976) reported the column density of CH toward TMC-1 to be \(3 \times 10^{14}\) cm\(^{-2}\) with
the 15′ beam, assuming a beam dilution factor of 2. The total column density derived in our study is consistent with theirs. Furthermore, our column density toward TMC-1(CP) is also consistent with that reported by Suutarinen et al. (2011).

If we assume an H2 column density of $1.5 \times 10^{22}$ cm$^{-2}$ for the narrow component (Maezawa et al. 1999), we calculate a fractional abundance of CH of $2.7 \times 10^{-8}$. The H2 column density of the broad component is uncertain. Obviously, its upper limit would be the H2 column density of the narrow component. Then, the fractional abundance of the broad component is higher than $1.0 \times 10^{-5}$. This indicates that the CH abundance is higher in the less dense component. In dense core regions, the reaction of CH with O proceeds rapidly to produce CO, and hence, the CH abundance becomes relatively low, particularly in the late stages of chemical evolution (e.g. Herbst & Leung 1989). A similar trend can also be seen for the column densities of the narrow and broad components in L1527, as shown in Table 2. Note that the narrow component emission may be diluted by the telescope beam (3′/8), since the dense core of L1527 is as small as 2′ (Benson & Myers 1989).

On the other hand, the CH column density toward the CI peak is evaluated to be $(1.88 \pm 0.45) \times 10^{14}$ cm$^{-2}$. Since the H2 column density toward this position is reported to be $6 \times 10^{21}$ cm$^{-2}$ or higher (Maezawa et al. 1999), the fractional abundance of CH is evaluated to be about $3 \times 10^{-8}$. The column density and the fractional abundance of CH are close to those found in the broad component toward TMC-1(CP). Furthermore, they are almost comparable to the CH abundance in diffuse clouds ($4.3 \pm 1.9 \times 10^{-8}$; Liszt & Lucas 2002; $3.5^{+2.2}_{-1.1} \times 10^{-8}$; Sheffer et al. 2008). The high abundance of CH is consistent with our interpretation that the broad component traces less-dense envelopes.

4.2. Distribution of CH

In the present study, we mapped the $0.8 \times 1.0$ deg$^2$ region of HCL2 in the $J = 1/2$ A-type doubling transition of CH. We here compare the distribution of CH with those of C$^{18}$O ($J = 1-0$) and [C I]. As seen in Fig. 5b, the C$^{18}$O distribution traces the TMC-1 ridge well and also several low-mass star-forming cores such as L1527 and TMC-1A. On the other hand, the [C I] emission shows a much more extended distribution (Fig. 5a). In particular, the [C I] emission is extended to the southern part of HCL2, where the C$^{18}$O emission is fairly faint. Hence, the distributions of C$^{18}$O and [C I] are anticorrelated to each other, as suggested by Maezawa et al. (1999). They suggest that the anticorrelation represents a chemical evolutionary sequence from C to CO. However, the [C I] and C$^{18}$O distributions are very different, and their mutual relationship is not very clear. When we focus on the TMC-1 ridge traced by C$^{18}$O, for instance, its distribution is suddenly disrupted at its southern end, and there seems to exist a certain gap between the ridge and the CI peak. Now, we find that the CH emission is distributed as if it continuously bridged the CI peak and the TMC-1 ridge. Therefore, it is likely that the CI peak and the TMC-1 ridge are physically related to each other.

This argument can be supported from the chemical point of view. Figure 6 shows a schematic diagram of the basic hydrocarbon chemistry and its connection to the production of CO. CH is one of the simplest neutral species first produced from C$^+$ or C in molecular clouds. The reaction of CH with O is an important route to produce CO, although there are other pathways producing CO, such as C + OH. Hence, CH can be regarded as an intermediate species between C and CO. The distribution of CH bridging the spatial gap between those of C$^{18}$O and [C I] seems to be a natural consequence of this chemical characteristic of CH, giving a yet another verification of the evolutionary picture in HCL2.

Furthermore, the distribution of the narrow component of CH in the TMC-1 ridge has a maximum at the cyanopolyne peak. The narrow component becomes weaker in the northern part of the ridge around the ammonia peak, just as in the case of carbon-chain molecules (e.g. Little et al. 1979; Hirahara et al. 1992; Olano et al. 1988). Since CH is converted to CO rapidly in dense cores (e.g. Herbst & Leung 1989), it is abundant in the young stage. This is consistent with the chemical youth of TMC-1(CP) in comparison with TMC-1(NH$_3$) (Hirahara et al. 1992).

It is known that the CH column density shows a good correlation with the H2 column density in diffuse and translucent clouds with $A_v < 3$ (e.g. Mattila 1986; Danks et al. 1984; Federman 1982; Sheffer et al. 2008). At the same time, a hint of the turnover for higher $A_v$ region is suggested in the observation toward the dark cloud L134N (Mattila 1986). To explore the $N$(CH)$-N$(H$_2$) relation in HCL2, we prepared the correlation diagram (Fig. 7). Since $N$(H$_2$) is known to be proportional
to \( E(B-V) \), we employed the \( E(B-V) \) data reported by Schlegel et al. (1998) to evaluate \( N(H_2) \). For comparison, our CH data is smoothed to the 6.1' resolution, which is the resolution of the \( E(B-V) \) data. The range of \( E(B-V) \) of our observed positions is from 1.4 to 3.2, which corresponds to the range of \( N(H_2) \) from \( 4.1 \times 10^{21} \) to \( 9.3 \times 10^{21} \) cm\(^{-2}\). Our CH data are not smoothly connected with the CH data taken toward the diffuse and translucent clouds. The CH column density in the higher \( N(H_2) \) region is much larger than that expected from the correlation found in the lower \( N(H_2) \) region, for instance.

Such a break, although maybe at even lower H\(_2\) column densities (of order 10\(^{21}\) cm\(^{-2}\)), was also noted by Qin et al. (2010). These authors used the Heterodyne Instrument for the Far-Infrared (HIFI) aboard Herschel to observe the 533 and 537 GHz fundamental spin-rotational transitions of CH in absorption toward the strong submillimeter continuum emission from the star-forming region Sgr B2(M) near the Galactic center. In addition to absorption from the Sgr B2(M) itself, absorption is also detected over a wide LSR velocity range toward Galactic center gas as well as a series of diffuse and translucent clouds in intervening spiral arms that have H\(_2\) column densities between \( 8 \times 10^{20} \) and \( 6 \times 10^{21} \) cm\(^{-2}\). The data point for Sgr B2(M) itself, which, compared to the other absorbing clouds has a much greater \( N(H_2) \) of \( 5.4 \times 10^{22} \) cm\(^{-2}\), but a significantly (3.3–56 times) lower CH abundance, falls on the trend established by these \( N(H_2) > 10^{21} \) cm\(^{-2}\) absorbers.

4.3. CH as a tracer of cloud evolution

The most puzzling question of our study is the origin of the broad component. So far, the broad component (or “pedestal” component) has not been recognized in the HCL2 region. In fact, it is not a component. So far, the broad component (or “pedestal” component) has not been recognized in the HCL2 region. In fact, it is not a component. So far, the broad component (or “pedestal” component) has not been recognized in the HCL2 region. In fact, it is not a component. So far, the broad component (or “pedestal” component) has not been recognized in the HCL2 region. In fact, it is not a component.

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chemistry (WCCC) exists in its northern part (e.g. Sakai et al. 2007b, 2008). An origin of the richness of carbon-chain molecules in these two sources might be related to the formation process of HCL2 (Sakai et al. 2009). In this relation, it seems interesting to observe the Lupus-1 cloud with the CHΛ-type doubling transition lines. The Lupus-1 cloud contains a young starless core, Lupus-1A, with abundant carbon-chain molecules like TMC-1(CP) (Sakai et al. 2010). Indeed, the abundances of carbon-chain molecules are comparable to those in TMC-1(CP). In addition, the WCCC source IRAS15398-3359 is also associated in this region (Sakai et al. 2009). A similarity of the Lupus-1 cloud and HCL2 would be related to a similarity of the formation process of dense cores, which can be explored by the large-scale distributions of the [CI], CH, and C18O lines.

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