TENTATIVE DETECTION OF DEUTERATED METHANE TOWARD THE LOW-MASS PROTOSTAR IRAS 04368+2557 IN L1527

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ABSTRACT

The millimeter-wave rotational transition line \((J_K = 1_0-0_0)\) of deuterated methane CH₃D has tentatively been detected toward the low-mass Class 0 protostar IRAS 04368+2557 in L1527 with the Heinrich Hertz Submillimeter Telescope. This is the first detection of CH₃D in interstellar clouds, if confirmed. The column density and fractional abundance of CH₃D are determined to be \((9.1 \pm 3.4) \times 10^{19} \text{ cm}^{-2}\) and \((3.0 \pm 1.1) \times 10^{-7}\), respectively, where we assume the rotational temperature of 25 K. The column density and fractional abundance of the gaseous CH₄ are estimated to be \((1.3-4.6) \times 10^{17} \text{ cm}^{-2}\) and \((4.3-15.2) \times 10^{-6}\), respectively, by adopting the molecular D/H ratios of 2%–7% reported for various molecules in L1527. The fractional abundance of CH₄ is higher than or comparable to that found in high-mass star-forming cores by infrared observations. It is sufficiently high to trigger the efficient production of various carbon-chain molecules in a lukewarm region near the protostar, which supports the scenario of warm carbon-chain chemistry.

Key words: ISM: individual objects (L1527) – ISM: molecules

1. INTRODUCTION

Methane (CH₄) is the most fundamental hydrocarbon molecule in space, and is thought to play an important role in interstellar chemistry and planetary chemistry. The gas phase CH₄ has been identified toward bright infrared sources in interstellar chemistry and planetary chemistry. The gas molecule in space, and is thought to play an important role because of its relatively low column density in comparison with high-mass star-forming regions.

Recently, it was recognized that CH₄ plays a crucial role in chemical processes occurring in low-mass star-forming regions. Sakai et al. (2008, 2009a) found low-mass star-forming regions which harbor extremely rich carbon-chain molecules. They are L1527 in Taurus and IRAS15398–3359 in Lupus. According to the interferometric observation toward L1527, carbon-chain molecules and their related species show a steep increase in abundance inward of 500–1000 AU (Sakai et al. 2010), where the gas kinetic temperature is higher than 20 K (Shirley et al. 2002; Jørgensen et al. 2002). Furthermore, they reside even in the gas infalling to the protostar. In order to explain the observational results, it is proposed that carbon-chain molecules are regenerated near the protostar triggered by evaporation of the solid CH₄ on dust grains (Warm Carbon Chain Chemistry, WCCC; Sakai et al. 2008). The desorption temperature of CH₄ is about 25 K (Collings et al. 2004), which is lower than that of H₂O (~100 K). Hence CH₄ can be evaporated in a lukewarm region (20–30 K) around a newly born protostar. The CH₄ evaporated from dust grains reacts with C⁺ to form C₂H⁺, which gives C₂H₂ and C₂H by electron recombination reactions. Further reactions of C₂H₂ and C₂H with C⁺ produce longer carbon-chain molecules. A basic part of this scheme is confirmed by chemical model calculations (Aikawa et al. 2008; Hassel et al. 2008; Harada & Herbst 2008). The WCCC picture is consistent with the observed distribution of the carbon-chain molecules in L1527 (Sakai et al. 2010).

Because of a high expected abundance of CH₄, the WCCC sources would be a good target to search for the CH₃D line. The molecular D/H ratios are measured to be consistent for various molecules toward L1527 (Sakai et al. 2009b), and hence we can make a reasonable estimation for the abundance of gaseous CH₄ from the observation of CH₃D. The result will verify the WCCC mechanism and will lead us to a deeper understanding.
of a role of CH$_4$ in interstellar chemistry. With this motivation, we conducted a sensitive observation of the CH$_3$D line toward L1527.

2. OBSERVATIONS

We first observed the $J_K = 1_0 - 0_0$ line (232.644301 GHz) of CH$_3$D toward the low-mass protostar, IRAS 04368+2557 in L1527 with the IRAM 30 m telescope in 2008 April. The observed position was (α$_{2000}$, δ$_{2000}$) = (0h43m53.8s, 26°05′09.7″). We employed the A230/B230 receiver as a front end. The beam size is 10.6″. In this observation, we found a hint of the CH$_3$D line at the right $V_{LSR}$ velocity with the intensity of 20 mK ($T_{MB}$), although the confidence level is only 2.3σ.

Encouraged by this result, we then conducted a long integration observation of this line toward the same position with Heinrich Hertz Submillimeter Telescope (HHT)$^6$ in 2011 January and 2012 February. The ALMA Band 6 (1.3–1.1 mm) prototype receiver was used as a front end in the 4 IF dual polarization mode, whose system noise temperatures ranged from 180 K to 250 K. In the observation in 2011, the CH$_3$D $J_K = 1_0 - 0_0$ line was placed in the lower sideband with the CS $J = 3$–1 line (244.935565 GHz) in the upper sideband. The sideband rejection was about −13 dB. The beam size and the main beam efficiency of the telescope are listed in Table 1. In the observation in 2012, the CH$_3$D $J_K = 1_0 - 0_0$ line was placed in the upper sideband with the C$^{18}$O $J = 2$–1 line (219.5603541 GHz) in the lower sideband. The telescope pointing was checked every 1.5 hr by observing the continuum emission of Jupiter, or the CS($J = 5$–4) emission of S231 and IRC +10216, and was maintained to be better than 10″. A small daily variation of the intensity was calibrated by using the CS or C$^{18}$O line. The back end used was a filter bank whose bandwidth and resolution are 64 MHz and 250 kHz, respectively. The frequency resolution corresponds to the velocity resolution of 0.32 km s$^{-1}$, which is comparable to or slightly smaller than the line width in this source (0.3–0.6 km s$^{-1}$; Sakai et al. 2008, 2009b). The observation was made in position-switching mode with the off-position of Δα = 20 arcmin. The final spectrum was placed on the $T_{MB}$ scale using observations of Jupiter.

In the 2011 observation with HHT, we tentatively detected the $J_K = 1_0 - 0_0$ line of CH$_3$D toward the low-mass protostar IRAS 04368+2557 in L1527, as shown in Figure 1. The line can be recognized in both (H and V) polarization data, although it is marginally seen in the V-polarization data due to a larger noise level. The line is not well resolved due to a limited frequency resolution of the back end employed. In preparation of the spectra, each 5 minute integration scan was carefully checked to eliminate the bad-scan data with a heavy baseline distortion and/or apparent strong noise spikes. Note that no apparent spikes appear at the line channel. The on-source integration time for the H and V spectra are 25 and 13 hr, respectively. The vertical dotted line shows the averaged $V_{LSR}$ value reported for deuterated species in this source (5.9 km s$^{-1}$; Sakai et al. 2009b).

3. RESULTS

In the 2011 observation with HHT, we tentatively detected the $J_K = 1_0 - 0_0$ line of CH$_3$D toward the low-mass protostar IRAS 04368+2557 in L1527, as shown in Figure 1. The line can be recognized in both (H and V) polarization data, although it is marginally seen in the V-polarization data due to a larger noise level. The line is not well resolved due to a limited frequency resolution of the back end employed. In preparation of the spectra, each 5 minute integration scan was carefully checked to eliminate the bad-scan data with a heavy baseline distortion and/or apparent strong noise spikes, as a usual data reduction process. Note that no apparent spikes appear at the line channel. For the total spectrum, the confidence level of the detection is 7.9σ in the integrated intensity and 5.2σ in the peak intensity. This line shows the strongest intensity in the observed band (128 spectral channels), and the noise reveals a Gaussian distribution, as shown in Figure 2. Hence, the line is significantly detected in the total spectrum. The noise distributions of the H- and V-polarization spectra are also shown in Figures 2(b) and (c), respectively. They show the Gaussian form, although the V-polarization data have a slightly poor shape.

Table 1

| Parameter | Value |
|-----------|-------|
| Telescope | HHT   |
| $\theta_{MB}$ | 0.75  |
| HPBW      | 32 (arcsec) |
| Rest Frequency$^a$ | 232644.301 ± 0.075 (MHz) |
| $T_{MB}^b$ | 12 ± 2 (mK) |
| $\int S_{50}d\nu (3\sigma)$ | 7.4 ± 2.8 (mK km s$^{-1}$) |
| $V_{LSR}^c$ | 6.0 (km s$^{-1}$) |
| rms        | 2.2 (mK) |

Notes.

$^a$ The rest frequency is taken from CDMS (Müller et al. 2005). The uncertainty represents one standard deviation.

$^b$ Obtained by a Gaussian fit. In this fit, $dv$ is calculated to be (0.5 ± 0.1) km s$^{-1}$, but it is affected by the back-end resolution (0.32 km s$^{-1}$). The uncertainty represents one standard deviation of the fit.

$^c$ The rest frequency error (~0.1 km s$^{-1}$) and the channel spacing of the back end (0.32 km s$^{-1}$) are larger than the Gaussian fitting error.

$^6$ The HHT is operated by the Arizona Radio Observatory (ARO), Steward Observatory, University of Arizona.
To confirm the line, we also carried out the observation with a different frequency setting in 2012, where the CH$_3$D line is set in the upper sideband, and marginally confirmed the line with the 3.6σ confidence level. However, we unfortunately suffered from serious spurious signals probably due to instability of the receiver and the back end in the 2012 observation in contrast to the 2011 observation, and hence we did not use the 2012 data for the final spectrum.

The line width and the LSR velocity are consistent with those of other carbon-chain molecules observed in this source (e.g., Sakai et al. 2008, 2009b). We carefully checked the molecular line databases such as CDMS (Müller et al. 2005), JPL Catalog (Pickett et al. 1998), and confirmed that no appropriate line exists at the frequency of ±0.5 km s$^{-1}$ except for the CH$_3$D line. We also confirmed no strong line in the image band. The lines of saturated complex organic molecules such as HCOOCH$_3$, C$_2$H$_5$CN, and (CH$_3$)$_2$O, which give congested spectra, are not detected in L1527 even with a very sensitive observation (Sakai et al. 2007). This is in contrast to the high-mass star-forming regions like Orion KL, and also to the low-mass star-forming regions with the hot corino activity (e.g., IRAS16293–2422: Cazaux et al. 2003). Furthermore, the line width in L1527 is narrower than those in Orion KL (~5 km s$^{-1}$) and IRAS16293–2422 (~2 km s$^{-1}$). Although L1527 harbors various long carbon-chain molecules and their isomers, their rotational transitions in the 200 GHz region generally have very high upper state energies (>100 cm$^{-1}$, for carbon chains with four or more carbon atoms) and are difficult to be excited in L1527. Therefore, an accidental matching of other lines would be unlikely, and our identification of this line to CH$_3$D is the most reasonable.

The column density of CH$_3$D is estimated to be $(9.1 \pm 3.4) \times 10^{15}$ cm$^{-2}$ from the integrated intensity by assuming the local thermodynamic equilibrium (LTE) condition with the excitation temperature of 25 K, which corresponds to the evaporation temperature of CH$_4$ from dust grains. The source size is assumed to be 20″ (Sakai et al. 2010). Here the error is calculated from three times the standard deviation of the integrated intensities.

The fractional abundance of CH$_3$D in L1527 is approximately 2%–7% by referring the ratios observed in L1527 are within the above range regardless of the number of equivalent hydrogen atoms in CH$_4$ because the deuterium fractionation ratio of 2%–7% by referring the ratios observed in L1527 are within the above range regardless of (Womack et al. 1996). When we assume the deuterium fractionation ratio of 2%–7% by referring the ratios observed in L1527 are within the above range regardless of magnitude (Womack et al. 1996). When we assume the deuterium fractionation ratio of 2%–7% by referring the ratios observed in L1527 are within the above range regardless of CH$_4$/CH$_3$D fractionation ratio of 2%–7% by referring the ratios observed in L1527 are within the above range regardless of C$_2$H$_4$/C$_2$D fractionation ratio of 2%–7% by referring the ratios observed in L1527 are within the above range regardless of CH$_3$D/CH$_4$ ratios observed in L1527 (Cazaux et al. 2003). Furthermore, the line width and the LSR velocity are consistent with those of other carbon-chain molecules observed in this source (e.g., Sakai et al. 2008, 2009b). We carefully checked the molecular line databases such as CDMS (Müller et al. 2005), JPL Catalog (Pickett et al. 1998), and confirmed that no appropriate line exists at the frequency of ±0.5 km s$^{-1}$ except for the CH$_3$D line. We also confirmed no strong line in the image band. The lines of saturated complex organic molecules such as HCOOCH$_3$, C$_2$H$_5$CN, and (CH$_3$)$_2$O, which give congested spectra, are not detected in L1527 even with a very sensitive observation (Sakai et al. 2007). This is in contrast to the high-mass star-forming regions like Orion KL, and also to the low-mass star-forming regions with the hot corino activity (e.g., IRAS16293–2422: Cazaux et al. 2003). Furthermore, the line width in L1527 is narrower than those in Orion KL (~5 km s$^{-1}$) and IRAS16293–2422 (~2 km s$^{-1}$). Although L1527 harbors various long carbon-chain molecules and their isomers, their rotational transitions in the 200 GHz region generally have very high upper state energies (>100 cm$^{-1}$, for carbon chains with four or more carbon atoms) and are difficult to be excited in L1527. Therefore, an accidental matching of other lines would be unlikely, and our identification of this line to CH$_3$D is the most reasonable.

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4. DISCUSSIONS

In this study, we tentatively detected the rotational spectral line of CH$_3$D in interstellar space for the first time. Although no cataloged lines do match to the observed line, it might be a line...
of unknown species. To rule out this possibility completely, we need to observe the other rotational transitions. The intensities of the \( J_K = 2_0 - 1_0 \) (465 GHz; \( E_a = 33 \) K) and \( 3_0 - 2_0 \) (698 GHz; \( E_a = 67 \) K) lines are predicted to be 21 mK and 12 mK by assuming the excitation temperature of 25 K and the line width of 0.5 km s\(^{-1}\). However, their sensitive observations are difficult because of the relatively heavy atmospheric absorption at these frequencies. We have therefore decided to publish the present result as a tentative detection of \( \text{CH}_3\text{D} \), considering its importance in astrochemistry.

The gas-phase \( \text{CH}_4 \) abundance has been reported for a few high-mass star-forming regions by observing the infrared absorption lines. Lacy et al. (1991) found that the gas-phase \( \text{CH}_4 \) abundance is typically \( 10^{-3} \times \) times the CO abundance. If we assume the fractional abundance of CO to be \( 10^{-4} \), this corresponds to the fractional abundance of \( 10^{-7} \). This value is lower than that observed in the present study by an order of magnitude. On the other hand, Boogert et al. (2004) reported the gas-phase \( \text{CH}_4 \) abundance to be higher than \( 3 \times 10^{-6} \) toward the core of NGC 7538 IRS9, and Knez et al. (2009) recently reported it to be \( 4.8 \times 10^{-6} \) toward NGC 7538 IRS1. These abundances are comparable to our result, although their observation traces much hotter region (\( T_{\text{ex}} = 55–674 \) K) than our present observation.

According to the chemical model calculation of dynamically evolving cores by Aikawa et al. (2008), \( \text{CH}_4 \) is mainly produced in grain mantles and is evaporated in a lukewarm region near the protostar. The gas-phase \( \text{CH}_4 \) abundance in L1527 is comparable to or slightly lower than that expected from their chemical model calculation (\( 10^{-3} \)). It should be noted that the fractional abundance of \( \text{CH}_3\text{D} \) is also comparable to or slightly lower than the result of their new chemical model calculation involving the deuterated species (\( \sim 3.6 \times 10^{-7} \); Aikawa et al. 2012). If the emitting region of the \( \text{CH}_3\text{D} \) line is smaller than \( 20'' \), the abundance of \( \text{CH}_3\text{D} \) becomes higher, giving a better agreement with the model result.

In this relation, it is interesting to compare our result with the solid \( \text{CH}_4 \) abundance. The infrared absorption spectrum of solid \( \text{CH}_4 \) is not available for L1527 because the protostar is heavily obscured even in the mid-infrared region. However, it is detected in another WCCC source, IRAS15398−3359 (Öberg et al. 2008; Sakai et al. 2009a). The abundance of the solid \( \text{CH}_4 \) relative to the \( \text{H}_2\text{O} \) ice is reported to be 0.06. When we assume the fractional abundance of the \( \text{H}_2\text{O} \) ice relative to the gas-phase \( \text{H}_2 \) to be \( 10^{-4} \), the fractional abundance of the solid \( \text{CH}_4 \) is estimated to be \( 6 \times 10^{-6} \). This is almost comparable to the gas-phase \( \text{CH}_4 \) abundance found in L1527.

Recent observational studies of low-mass star-forming regions reveal a significant chemical diversity among the low-mass Class 0 protostars. Two distinct cases are hot corinos and the WCCC sources. The hot corino chemistry is characterized by rich saturated organic molecules such as HCOOCH\(_3\) and \( \text{CH}_3\text{CH}_2\text{CN} \), which are evaporated from grain mantles. The representative sources are IRAS 16293−2422 and NGC 1333 IRAS4A/B (e.g., Cazaux et al. 2003; Bottinelli et al. 2004; Sakai et al. 2006). In these sources, carbon-chain molecules are generally deficient. In contrast, the saturated organic molecules have not been detected so far in the WCCC sources in spite of very sensitive single-dish observations (e.g., Sakai et al. 2007). Such a chemical variation originates from the difference in the evaporated species, and thereby in chemical composition of grain mantles. In the WCCC mechanism, the abundances of carbon-chain molecules critically depend on the amount of \( \text{CH}_4 \) evaporated from grain mantles. If the gas-phase \( \text{CH}_4 \) abundance is higher than the abundance of \( \text{OH} \) (typically \( 10^{-7} \); e.g., Herbst & Leung 1989), \( \text{CH}_4 \) can be a major destructor of \( \text{C}^+ \) instead of \( \text{OH} \) in a lukewarm region where \( \text{H}_2\text{O} \) is still frozen out. Then, the WCCC occurs when the \( \text{CH}_4 \) abundance exceeds this level. The \( \text{CH}_4 \) abundance derived for L1527 certainly fulfills this requirement, which further strengthens the WCCC picture in L1527.

In order to verify a role of \( \text{CH}_4 \) in the observed chemical diversity, it is important to measure the \( \text{CH}_4 \) abundances in various low-mass star-forming regions. As demonstrated in this study, observations of \( \text{CH}_3\text{D} \) can be a useful method for this purpose.

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