Detection of HCOOCH₃ toward a Low-Mass Protostar, NGC 1333 IRAS 4B

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Abstract

The rotational spectral lines of methylformate (HCOOCH₃) have been detected toward a low-mass protostar, NGC 1333 IRAS 4B, with the Nobeyama 45 m radio telescope. The column density is derived to be (7–37) × 10¹⁵ cm⁻², assuming a source size of 1″ and the range of the excitation temperature to be from 50 K to 200 K. The column density is almost comparable to those found in other low-mass star-forming regions, NGC 1333 IRAS 4A and IRAS 16293–2422. The line width of HCOOCH₃ is (1.0–1.2) km s⁻¹, which is narrower than that of the high-excitation line of CH₃OH (8–9). Since NGC 1333 IRAS 4B is likely to be a very young protostar, HCOOCH₃ appears even in the early stage of protostellar evolution. The spectral lines of HCOOCH₃ could be used as a novel tracer for detecting an onset of star formation.

Key words: ISM: abundances — ISM: individual (NGC 1333 IRAS 4B) — ISM: molecules — stars:formation

1. Introduction

Among more than 120 molecules found in interstellar space, large organic molecules, such as HCOOCH₃, (CH₃)₂O, and C₂H₅CN, have long been recognized as molecules that are characteristic to hot cores in massive star-forming regions, like Orion KL and Sgr B2 (e.g., Cummins et al. 1986; Blake et al. 1987; Friedel et al. 2004). In fact, these molecules have never been detected in a cold dark cloud, TMC-1 (Kaifu et al. 2004). Such highly saturated molecules are difficult to produce by gas-phase chemical reactions under low-temperature conditions, and hence the grain surface chemistry is thought to play an important role in their production (e.g., Brown et al. 1988; Charnley et al. 1992). When star formation takes place, the grain mantles are heated up by various activities of newly born stars, supplying parent molecules, like CH₃OH and H₂CO, into the gas phase by evaporation. Subsequent gas-phase processes under high-temperature, high-density conditions would produce large organic molecules.

Cazaux et al. (2003) succeeded to detect HCOOCH₃, (CH₃)₂O, and C₂H₅CN toward a low-mass protostar, IRAS 16293–2422. The abundances relative to H₂ were found to be 4.0 × 10⁻⁷, 2.4 × 10⁻⁷, and 1.2 × 10⁻⁸ for HCOOCH₃, (CH₃)₂O, and C₂H₅CN, respectively, which are by about an order of magnitude higher than the corresponding abundances found in the hot core of Orion KL. The derived rotation temperature ranges from 54 K to 67 K, indicating that the lines come from high-temperature regions. This observation clearly established the existence of “hot cores” even in a low-mass star-forming region. Subsequent imaging observations with the Submillimeter Array (SMA) and the IRAM Plateau de Bure (PdB) interferometers showed that these species are concentrated around two binary protostars, IRAS 16293–2422 A and B, and that the relative intensities toward two protostars are different from molecule to molecule (Kuan et al. 2004; Bottinelli et al. 2004b).

Very recently, Bottinelli et al. (2004a) reported the detection of HCOOCH₃ toward a class 0 protostar, NGC 1333 IRAS 4A. This is the second example where large organic molecules have been detected in a low-mass star-forming region. Bottinelli et al. (2004a) named the hot region emitting the HCOOCH₃ lines as a hot corino. The abundance of HCOOCH₃ is comparable to that in IRAS 16293–2422, whereas that of C₂H₅CN is significantly lower, probably reflecting the physical conditions and evolutionary stages of the hot cores.

So far, large organic molecules have been detected in class 0 protostars. This means that they can exist in the early stage of protostellar evolution. Therefore, it is important to understand when these species are first produced. In order to assess this, we focus on another class 0 protostar, NGC 1333 IRAS 4B (sometimes referred to as IRAS 4B1). This source is apart from IRAS 4A by about 30″, which corresponds to 0.03 pc at a distance of 220 pc (Černis 1990). According to the dynamical age of the molecular outflow, IRAS 4B is considered to be in a younger evolutionary stage than IRAS 4A (Choi 2001). Since the high-excitation lines of H₂CO as well as the CS J = 10–9 line were detected in IRAS 4B (Maret et al. 2004; Jørgensen et al. 2005), it seems probable that the hot cores are associated with IRAS 4B. In the present paper, we report on the detection of HCOOCH₃ toward NGC 1333 IRAS 4B, and discuss its implications.

2. Observations

The observations were carried out in 2005 April with the Nobeyama 45 m radio telescope. The observed position was α(2000.0) = 3²0²1²0” and δ(2000.0) = 31°13’09””, which coincides with the position of IRAS 4B. We observed the molecular lines in the 89 GHz region listed in table 1. Two SIS mixer receivers, S80 and S100, were used simultaneously.
By observing the orthogonal linear polarization with the two receivers, we intended to reduce the rms noise in order to detect any faint emissions of large organic molecules. The beam offset between these receivers was less than 2″. The pointing accuracy was better than 7″ (rms). The position-switching mode was employed for the observations, where the off position was taken at Δα = 15″, Δδ = 0″. The backend was a bank of acousto-optical radiospectrometers (AOSs). We used eight wide-band AOSs (AOS-W) with a bandwidth of 250 MHz each, and eight high-resolution AOSs (AOS-H) with a bandwidth of 40 MHz each. The velocity resolution of AOS-W is 0.84 km s⁻¹ at 89 GHz, whereas that of AOS-H is 0.12 km s⁻¹. The intensity scale was calibrated by the chopper wheel method.

3. Results and Discussion

3.1. Detection of HCOOCH₃

In the present observations, we succeeded to detect two lines of the 8₁₈−7₁₇ transition of HCOOCH₃, which are the A and E state lines split by the internal rotation of the methyl group. The spectral line profile is shown in figure 1, and the line parameters derived from the Gaussian fitting procedures are summarized in table 2. The on-source integration time was 18.5 hr. The peak main beam temperature is 22 ± 4 mK for the A state line, and 19 ± 4 mK for the E state line. Since the rms noise averaged over the line width is 3.6 mK, the lines are definitively detected. The line widths are as narrow as 1 km s⁻¹. The LSR velocity for the A state line (7.1 ± 0.1 km s⁻¹) agrees well with that of the E state line (7.2 ± 0.1 km s⁻¹). These Vₗₛₗ values are consistent with those reported for other molecules (e.g., 6.8 km s⁻¹ for C¹⁷O and 7.4 km s⁻¹ for C¹⁸O J = 2–1, 3–2) toward this source (Jørgensen et al. 2002). These results further support that the carrier of the lines is HCOOCH₃. Since the beam size is 18″, the contribution of the emission from IRAS 4A, which is apart from IRAS 4B by about 30″, would be negligible. It is known that IRAS 4B is close to the class I protostar IRAS 4BII, whose separation from IRAS 4B is 10″ (Looney et al. 2000). Since the C¹⁸O emission is not detected toward IRAS 4BII (Choi 2001), it seems reasonable to assume that the HCOOCH₃ emission comes from IRAS 4B. This is a novel detection of large organic molecules toward low-mass star-forming regions, after IRAS 16293−2422 (Cazaux et al. 2003) and NGC 1333 IRAS 4A (Bottinelli et al. 2004a).

The integrated intensities of the 8₁₈−7₁₇ transitions are 0.026 ± 0.005 K km s⁻¹ and 0.020 ± 0.007 K km s⁻¹ for the A and E states, respectively. These values are slightly lower than the integrated intensities of the 8₀₈−7₀₇ transitions observed toward IRAS 4A (0.041 K km s⁻¹). Note that the upper state energy and the line strength of the 8₀₈−7₀₇ transition are close to those of the 8₁₈−7₁₇ transition, and hence we can roughly compare the intensities of these two lines without any correction. Considering that the C¹⁸O emission is even weaker by a factor of 2.5 in IRAS 4B than in IRAS 4A (Choi 2001), the abundance of HCOOCH₃ in IRAS 4B might be comparable to that in IRAS 4A.

The column density of HCOOCH₃ is derived under the assumption of the LTE condition, where the effect of the optical depth is taken into account. In the present study, we detected

<table>
<thead>
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<th>Table 1. Molecular line parameters.</th>
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<tbody>
<tr>
<td><strong>Species</strong></td>
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<td>----------</td>
</tr>
<tr>
<td>HCOOCH₃</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>CH₃OCH₃</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>C₂H₃CN</td>
</tr>
<tr>
<td></td>
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<tr>
<td>CH₃OH</td>
</tr>
</tbody>
</table>

only one transition each for the A and E states, and hence the excitation temperature of HCOOCH3 cannot be determined observationally. Although the $|11,10\rangle$–$|11,11\rangle$ lines are involved in the observed frequency range, they were not detected due to their small intrinsic line strengths. For this reason, even the upper limit to the excitation temperature cannot be derived. Therefore, we assume the range for the excitation temperature to be from 50 K to 200 K according to the results for the other hot cores associated with the low-mass star-forming regions (Cazaux et al. 2003; Bottinelli et al. 2004a). The size of the region emitting the HCOOCH3 line constitutes another uncertain factor in calculations of the column density. Here, we assume the size to be 1″ according to the size of the hot core in IRAS 16293–2422, reported by interferometric observations (Kuan et al. 2004; Bottinelli et al. 2004b). This assumption of the source size is also consistent with the size of the high-temperature region with a dust temperature of $\geq$ 50 K in the model of IRAS 4B by Maret et al. (2004). Under these assumptions, the derived column densities of HCOOCH3 are given in Table 3 for excitation temperatures of 50 K, 100 K, and 200 K. The range of the column density is from $7 \times 10^{15}$ cm$^{-2}$ to $3.7 \times 10^{16}$ cm$^{-2}$, being comparable to that found in IRAS 16293–2422.

If the size of the emitting region is smaller than 1″, the column density would be higher. However, the radiation temperature becomes higher than 200 K if the source size is less than 0″23. In this case, the line becomes optically thick, even if the excitation temperature is as high as 200 K. Bottinelli et al. (2004b) pointed out that the HCOOCH3 line might be optically thick on the basis of the line profile, which is a characteristic of the self-absorption feature due to the infalling gas. In the present case, such a line profile is not seen, and it is unlikely that the observed line is optically thick. Therefore, the source size of the HCOOCH3 would have to be larger than 0″23, which corresponds to 51 AU.

It is difficult to derive the fractional abundance of HCOOCH3 relative to H$_2$. If we employ the column density of H$_2$ ($3 \times 10^{23}$ cm$^{-2}$) reported by Jørgensen, Schöier, and van Dishoeck (2002), the fractional abundance range in IRAS 4B is estimated to be from $2.2 \times 10^{-8}$ to $1.2 \times 10^{-7}$. This result is comparable to the abundance reported in IRAS 4A ($7 \times 10^{-8}$) by assuming a source size of 0″5. When we assume the same source size of 0″5 for IRAS 4B, the fractional abundance range is from $1.7 \times 10^{-7}$ to $5.4 \times 10^{-7}$, being higher than that in IRAS 4A.

### 3.2. Other Molecules

In addition to the lines of HCOOCH3, we also detected the $8\rightarrow 9_3$ line of CH$_3$OH, as shown in figure 2. The upper state of this transition is as high as 171 K, indicating that NGC 1333 IRAS 4B harbors a hot core around the protostar. The width of the CH$_3$OH line is $4.2 \pm 1.0$ km s$^{-1}$, which is about four times broader than that of HCOOCH3. The 2$_{1,1}$–2$_{1,2}$ transitions of (CH$_3$)$_2$O and the K structure lines of the $J = 10\rightarrow 9$ transition of C$_2$H$_5$CN fall in the observed frequency range. However, these lines were not detected in the present study. From the observed rms noise, we estimated the upper limits to the column densities for these two molecules. The results

### Table 2. Molecular lines detected toward NGC 1333 IRAS 4B. *

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>$T_{mb}$ [mK]</th>
<th>$V_{LSR}$ [km s$^{-1}$]</th>
<th>$\Delta V$ [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCOOCH$_3$</td>
<td>8$<em>{1,8}\rightarrow$7$</em>{1,7}$ E</td>
<td>19(4)</td>
<td>7.2(1)</td>
<td>1.0(3)</td>
</tr>
<tr>
<td></td>
<td>8$<em>{1,8}\rightarrow$7$</em>{1,7}$ A</td>
<td>22(4)</td>
<td>7.1(1)</td>
<td>1.2(2)</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>8$-4\rightarrow$9$-3$</td>
<td>10(2)</td>
<td>6.7(4)</td>
<td>4.2(10)</td>
</tr>
</tbody>
</table>

* The numbers in parentheses represent standard deviations in units of the last significant digits.

### Table 3. Column densities. *

<table>
<thead>
<tr>
<th></th>
<th>NGC 1333 IRAS 4B†</th>
<th>IRAS 16293–2422‡</th>
</tr>
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<tbody>
<tr>
<td>$N_{HCOOCH_3}$ E</td>
<td>3</td>
<td>9.8 ± 6.0</td>
</tr>
<tr>
<td>$N_{HCOOCH_3}$ A</td>
<td>4</td>
<td>12.8 ± 5.3</td>
</tr>
<tr>
<td>$N_{CH_3OCH_3}$</td>
<td>$\leq 7$</td>
<td>18.0 ± 27.8</td>
</tr>
<tr>
<td>$N_{C_2H_5CN}$</td>
<td>$\leq 0.1$</td>
<td>0.9 ± 0.3</td>
</tr>
</tbody>
</table>

* In units of $10^{15}$ cm$^{-2}$.
† The size of the region emitting the HCOOCH3 is assumed to be 1″.
‡ Cazaux et al. (2003). $T_{ex}$ is assumed to be $67 \pm 14$, $59 \pm 14$, $65 \pm 100$, and $54 \pm 11$ K for HCOOCH$_3$, HCOOCH$_3$ A, CH$_3$OCH$_3$, and C$_2$H$_5$CN, respectively.
are summarized in table 3. The upper limits are not so tight that these molecules may actually exist with column densities that are slightly lower than the upper limits. It should be noted that these two molecules were not detected either in IRAS 4A (Bottinelli et al. 2004a).

3.3. Astrochemical Implication

It is proposed that large organic molecules, including HCOOCH$_3$, are produced in the gas phase from the parent molecules, H$_2$CO and CH$_3$OH, evaporated from grain mantles. Chemical model calculations based on this scheme predict that the daughter molecules, like HCOOCH$_3$, have a peak at $10^4$ yr after injection of the parent molecules (Charnley et al. 1992, 2001; Nomura, Millar 2004). Bottinelli et al. (2004a) pointed out that the time scale of a free-falling gas passing through a hot core is only $10^2$ yr, being much shorter than the time scale for the gas-phase production. Therefore, the production mechanism of large organic molecules is still controversial.

According to interferometric observations of the HCN line by Choi (2001), molecular outflows are associated with IRAS 4A and IRAS 4B. The spatial extent of the molecular outflow in IRAS 4B is very compact, and its dynamical age is estimated to be 6500 yr. The present detection of HCOOCH$_3$ in IRAS 4B indicates that large organic molecules do exist, even in the very early stage of protostellar evolution.

The detection of HCOOCH$_3$ in a very young protostar, NGC 1333 IRAS 4B, may raise the possibility that HCOOCH$_3$ would be directly supplied from grain mantles. At the present stage, no direct evidence of HCOOCH$_3$ on grain mantles has been reported by infrared observations. However, this may be a result of its relatively small abundance. In the current chemical models, the production of HCOOCH$_3$ on grain mantles has not been considered seriously. Further theoretical and laboratory studies on such processes would be important to assess this possibility.

Another possibility to solve the time-scale problem is that HCOOCH$_3$ is produced in an even earlier stage of the star-formation process. According to star-formation theories (e.g., Larson 1969; Masunaga, Inutsuka 2000), the “first core” is formed after the isothermal contraction of a dense core. In the “first core” stage, the temperature raises up to 100 K, where ice mantles on dust grains can be evaporated. Large organic molecules, like HCOOCH$_3$, could start to be formed in this stage as parent or daughter molecules. If this is the case, HCOOCH$_3$ can be a potential tracer to diagnose an onset of star formation.

It is still important to make highly sensitive observations of large organic molecules toward various low-mass star-forming regions. Particularly, it seems essential to know when these molecules first appear to be observed during the star-formation process from dense cores to protostars. For this purpose, observations of starless cores with these molecular lines would be very interesting.

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References