DETECTION OF C_6H\(^\text{−}\) TOWARD THE LOW-MASS PROTOSTAR IRAS 04368+2557 IN L1527

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ABSTRACT

We have detected the J = 7–6, 8–7, and 15–14 lines of C_6H\(^\text{−}\) toward a low-mass star-forming region of L1527. We have also detected the J = 15/2–13/2 and 33/2–31/2 lines of the corresponding neutral species, C_6H, and the 8J_3–7J_2 line of C_6H\(_2\) in L1527. This is the first detection of these three species in star-forming regions. The column density of C_6H\(^\text{−}\) is \((5.8 \pm 1.8) \times 10^{10} \text{cm}^{-2}\), which is comparable to that in TMC-1, although the column density of C_6H in L1527 is about 1/5 of that in TMC-1. Hence, the N(C_6H\(^\text{−}\))/N(C_6H) ratio is 0.093 \pm 0.029, which is higher than that in TMC-1 by a factor of 4. This high anion-to-neutral ratio is discussed in terms of a simplified chemical model.

Subject headings: ISM: individual (L1527) — ISM: molecules

1. INTRODUCTION

Recently, McCarthy et al. (2006) succeeded in observing rotational spectral lines of C_6H\(^\text{−}\) in the laboratory. Based on the result, they then detected the J = 4–3 and 5–4 lines of C_6H\(^\text{−}\) toward a cold starless core, TMC-1. Furthermore, they identified C_6H\(_2\)\(^\text{−}\) as the carrier of a series of unknown lines named “B1377” observed toward the envelope of the evolved star, IRC +10216 (Kawaguchi et al. 1995). These studies represented the first detection of a molecular anion in interstellar and circumstellar clouds. Surprisingly, the column density of C_6H\(^\text{−}\) in TMC-1 is as high as \(10^{11} \text{cm}^{-2}\), which is 2.5\% of that of C_6H. Kasai et al. (2007) reanalyzed the “B1377” lines of Kawaguchi et al. (1995), and reported that the column density of C_6H\(^\text{−}\) is 8.6\% that of C_6H in IRC +10216. These results clearly demonstrate the important role of molecular anions in interstellar chemistry as predicted by Herbst (1981). In particular, large molecular anions seem to carry a substantial fraction of the negative charges in dense clouds, which affects the recombination processes of positive ions and, ultimately, the formation of various neutral molecules. For a detailed understanding of the behavior of molecular anions in interstellar clouds, their observations toward various molecular clouds would be very important. However, long carbon-chain molecules like C_6H\(_2\) are scarcely detected in molecular clouds, with the exception of TMC-1 (Kaifu et al. 2004), and hence, it has been thought that a study of source-to-source variation of C_6H\(^\text{−}\) would be difficult to carry out.

We have recently found that various carbon-chain molecules are extraordinarily abundant in the low-mass star-forming region L1527 (Sakai et al. 2007a). Most interestingly, the high-excitation lines of various carbon-chains such as C_4H, C_5H, and CH_2CH, are observed with much higher intensities than in TMC-1. The detailed analysis indicates that these emissions come from a dense (\(<10^4 \text{cm}^{-3}\)) and warm (\(T_k = 13.9 \text{K}\)) part of the protostellar core. Toward this source, the spectral lines of C_6H\(_2\) (J = 33/2–31/2) are also detected with moderate intensities (\(T_{\text{MB}} = 55 \pm 17 \text{mK}\)) in our observations with the Nobeyama Radio Observatory (NRO) 45 m radio telescope,\(^4\) indicating that one might detect C_6H\(^\text{−}\) toward L1527. If C_6H\(_2\) were detected, we could obtain novel information on the abundance of this anion in a dense core of a star-forming region, which would be useful in understanding the role of molecular anions in star formation. With this motivation, we have carried out a sensitive observation of C_6H\(^\text{−}\) toward L1527.

2. OBSERVATIONS

Observations in the 20 GHz region were performed with the National Radio Astronomy Observatory\(^5\) in 2006 December (Sakai et al. 2007b). The observed position of L1527 was J2000.0 = (04h39m53.89s, 23°03′11.0′′). We also observed the lines of C_6H and C_6H\(_2\) in TMC-1 at J2000.0 = (04h41m42.88s, 25°41′27.0′′). The beam size of the telescope is 37″, and the main-beam efficiency is 0.88 at 20 GHz. The system temperature during the observations ranged from 20 to 50 K. The pointing of the telescope was checked by observing nearby continuum sources every hour and was maintained to be better than 7″. Frequency switching was employed for the observations, with a frequency offset of 3 MHz. We used the autocorrelators as back ends, whose individual bandwidths and resolutions are 50 MHz and 12 kHz, respectively. The resolution corresponds to 0.16 km s\(^{-1}\) at 22 GHz. The intensity calibration was done by noise injection. To obtain the final spectrum, we took the weighted average of the spectra of the right- and left-handed circular polarizations.

Observations in the 40 GHz region were conducted with the NRO 45 m from 2006 to 2007. The observed lines in both frequency regions are summarized in Table 1. At the NRO, the SIS mixer receiver, S40, was used as a front end, with typical system temperature of about 180 K. The main-beam efficiency and the beam size of the telescope are 0.77 and 38.8″, respectively, at 43 GHz. The telescope pointing was checked by observing the nearby SiO maser source, NML Tau, every hour. The pointing accuracy was better than 8″. Position switching was employed for the observations, with the off position at (Δα = 30″, Δδ = 30″). The back end was a bank of acousto-optical radio spectrometers (AOSs). We used eight high-resolution AOSs (AOS-H) with a bandwidth of 40 MHz.

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These are the first detections of C$_6$H in Figure 2, and the line parameters are summarized in Table 1. The column density of C$_6$H forming regions.

The column density of C$_6$H in L1527 were derived to be 12.0 $\pm$ 0.3 km $\cdot$ s$^{-1}$, respectively. The column density of C$_6$H in TMC-1 were determined to be 6.7 $\pm$ 0.5 K and (3.0 $\pm$ 0.3) $\times$ 10$^{-12}$ cm$^{-2}$, respectively. The J = 33/2–31/2 line of C$_6$H and the J = 8–7 line of C$_6$H$^+$ are assumed, respectively.

### TABLE 1

| Species | Transition | Frequency (GHz) | Telescope | $T_{MB}$ (mK) | $dv$ (km s$^{-1}$) | $V_{LSB}$ (km s$^{-1}$) | rms$^a$ (mK) | $\int T_{MB} dv$ (3 $\sigma^a$) (mK km s$^{-1}$) |
|---------|------------|-----------------|-----------|----------------|-------------------|------------------|-------------|---------------------------------|
| C$_4$H$^+$ | J = 7–6 | 19.276038 | GBT | 14(3) | 0.45(11) | 5.93(9) | 2.9 | 7(4) |
| C$_4$H$^+$ | J = 8–7 | 22.029740 | GBT | 26(4) | 0.49(10) | 5.89(3) | 3.1 | 18(5) |
| C$_4$H$^+$ | J = 15–14 | 41.305453 | NRO 45 m | 26(6) | 0.48(12) | 5.98(6) | 4.5 | 15(6) |
| C$_6$H, $^3$II$_{a2}$ | J = 15/2–13/2, J = 8–7 | 20.792872 | GBT | 23(6) | 0.66(21) | 5.85(9) | 2.5 | 14(5) |
| C$_6$H, $^3$II$_{a2}$ | J = 15/2–13/2, J = 8–7 | 20.792926 | GBT | 31(9) | 0.30(9) | 5.57(5) | 3.8 | 10(3) |
| C$_6$H, $^3$II$_{a2}$ | J = 15/2–13/2, J = 8–7 | 20.794439 | GBT | 26(8) | 0.43(15) | 5.88(7) | 3.4 | 12(4) |
| C$_6$H, $^3$II$_{a2}$ | J = 15/2–13/2, J = 8–7 | 20.794494 | GBT | 24(9) | 0.34(15) | 5.70(6) | 3.8 | 9(4) |
| C$_6$H | J = 15/2–13/2, J = 7–6 | 45.742533 | NRO 45 m | 55(17) | 0.62(22) | 6.13(10) | 11.4 | 39(21) |
| C$_6$H | J = 15/2–13/2, J = 7–6 | 45.750079 | NRO 45 m | ... | ... | 12.6 | $\leq$24 |
| C$_6$H$^+$ | $6_1^e$–$7_1^e$ | 21.488256 | GBT | 7(2) | 0.77(20) | 5.95(9) | 1.2 | 6(3) |
| C$_6$H$^+$ | J = 9–8 | 83.787263 | NRO 45 m | ... | ... | 12.8 | $\leq$19 |

**Note.** The numbers in parentheses represent the errors in units of the last significant digits.

$^a$ Obtained by the Gaussian fit.

The spectral line profiles of C$_6$H and C$_6$H$^+$ are shown in Figure 1. The line parameters derived Gaussian fitting are summarized in Table 1. These three lines are clearly detected with 5 $\sigma$, 11 $\sigma$, and 7 $\sigma$ confidence levels in $\int T_{MB} dv$, respectively. The $V_{LSB}$ and the width of each line are consistent with those of the carbon-chain molecules in TMC-1 (e.g., Sakai et al. 2007a) and TMC-1 (Sakai et al. 2007a) and TMC-1 (Sakai et al. 2007a).

We succeeded in detecting the J = 7–6 and 8–7 lines and the J = 15–14 line of C$_6$H$^+$ in L1527 with the GBT and NRO 45 m telescopes, respectively. Their spectral line profiles are shown in Figure 1. The line parameters derived from Gaussian fitting are summarized in Table 1. These three lines are clearly detected with 5 $\sigma$, 11 $\sigma$, and 7 $\sigma$ confidence levels in $\int T_{MB} dv$, respectively. The $V_{LSB}$ and the width of each line are consistent with those of the carbon-chain molecules in this region (Sakai et al. 2007a).

We assumed local thermodynamic equilibrium (LTE) and corrected for the optical depth. The 19–22 GHz observations with the GBT and the 41–45 GHz observations with the NRO 45 m have a similar beam size, and hence, we could determine the rotational temperature and the column density accurately without suffering from a difference in the beam dilution effect.

The rotational temperature and the column density of C$_6$H$^+$ were derived to be 9.5 $\pm$ 4.6 K and (5.8 $\pm$ 1.8) $\times$ 10$^{10}$ cm$^{-2}$, respectively.

The rotational temperature and the column density of C$_6$H$^+$ are roughly consistent with the value reported by Langer et al. (1997).

The column densities of C$_6$H$_2$ were found to be 1.5 $\times$ 10$^{11}$ and 1.8 $\times$ 10$^{11}$ cm$^{-2}$ for L1527 and TMC-1, respectively, assuming the rotational temperatures of C$_6$H$^+$ mentioned above, and an ortho-to-para ratio of 3. The column density for TMC-1 is comparable to that found by Bell et al. (1999; 4 $\times$ 10$^{12}$ cm$^{-2}$).

The rotational temperatures of C$_6$H$^+$ and C$_6$H in L1527 are significantly higher than those of C$_6$H$^+$ and other carbon-chain molecules in TMC-1 (e.g., Kawaguchi et al. 1991) and are consistent with those of other carbon-chain molecules in L1527 (Sakai et al. 2007a).

Therefore, C$_6$H$^+$ seems to exist in a dense part of the protostellar core of L1527.

The column density ratio N(C$_6$H$^+$)/N(C$_6$H) is calculated to be 9.3% $\pm$ 2.9% in L1527. This value is much higher than the corresponding ratio in TMC-1 (2.5%; McCarthy et al. 2006), implying that the negative ion species is relatively abundant in the dense part of the star-forming region.

### 4. DISCUSSION

Two possible formation routes of C$_6$H$^+$ are

$$C_6H + e \rightarrow C_6H^+ + h\nu.$$  \hspace{1cm} (1)

and

$$C_6H_2(\text{hexapentaenylidene}) + e \rightarrow C_6H^+ + H.$$  \hspace{1cm} (2)

The dissociative attachment reaction (2) is exothermic by 16 kJ mol$^{-1}$, according to our B3LYP/aug-cc-pVTZ calculations (Frisch et al. 1998), although the corresponding reaction
of C₆H₂ (triacetylene) is endothermic by 158 kJ mol⁻¹. The destruction processes for C₆H⁻ are

\[ \text{C}_6\text{H}^- + \text{M}^+ \rightarrow \text{C}_6\text{H} + \text{M}, \]  

\[ \text{C}_6\text{H}^- + \text{G} \rightarrow \text{C}_6\text{H} + \text{G}^-, \]

and

\[ \text{C}_6\text{H}^- + \text{H} \rightarrow \text{C}_6\text{H}_2\text{(triacetylene)} + e, \]

where \( \text{M}^+ \) can be any positive ion, and \( \text{G} \) represents large molecules or grains with an electron affinity larger than that of \( \text{C}_6\text{H}^- \). When we assume the steady state condition, the \([\text{C}_6\text{H}^-]/[\text{C}_6\text{H}] \) abundance ratio can be written as

\[ \frac{[\text{C}_6\text{H}^-]}{[\text{C}_6\text{H}]} = \frac{[e]}{k_i + k_2[\text{C}_6\text{H}_2]/[\text{C}_6\text{H}]} \times \frac{k_c}{k_c[\text{M}^+] + k_4[\text{G}] + k_4[\text{H}]}, \]

where \( k_i \) represents the rate coefficients for reactions (1)–(5).

First, we consider the destruction processes. We employ a rate coefficient \( k_i \), derived for the PAH⁻ + M⁺ reaction, of \( 1.3 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1} \) at 10 K. On the other hand, we assume the Langevin rate coefficient of \( 1 \times 10^{-6} \text{ cm}^3 \text{ s}^{-1} \) for reactions (4) and (5). According to the chemical models of Leung et al. (1984), \([e]/[\text{H}_2] \) is 3.5 \( \times 10^{-8} \) for \( n = 10^4 \text{ cm}^{-3} \), 1.4 \( \times 10^{-8} \) for \( n = 10^6 \text{ cm}^{-3} \), and 4.8 \( \times 10^{-8} \) for \( n = 10^8 \text{ cm}^{-3} \) at steady state, and is almost independent of time. The \([\text{H}] /[\text{H}_2] \) ratio is inversely proportional to the density, and is 1.1 \( \times 10^{-4} \) for \( n = 10^4 \text{ cm}^{-3} \), 1.1 \( \times 10^{-5} \) for \( n = 10^5 \text{ cm}^{-3} \), and 1.1 \( \times 10^{-6} \) for \( n = 10^6 \text{ cm}^{-3} \) at the steady state. These abundances are essentially similar to those in other models (Herbst & Leung 1989; Lee et al. 1996). Since \([\text{G}]/[\text{H}_2] \) is much lower than \( 10^{-5} \), reaction (4) can be excluded as the main destruction process. Under these conditions, reaction (5) becomes the most important destruction pathway of \( \text{C}_6\text{H}^- \) if \( n < 10^6 \text{ cm}^{-3} \). Here we assume that \([\text{M}^+] = [e] \). In this case, \([\text{C}_6\text{H}^-]/[\text{C}_6\text{H}] \) ratio can be represented as

\[ \frac{[\text{C}_6\text{H}^-]}{[\text{C}_6\text{H}]} \sim \frac{k_{\text{eff}}}{k_i}, \]

and the ratio is independent of density. Since the density of L1527 can be at least as high as \( 10^6 \text{ cm}^{-3} \) (Sakai et al. 2007a), the latter condition is fulfilled. From the observed ratio in L1527 (0.093), we can evaluate \( k_{\text{eff}} \) to be \( 4 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1} \). With this rate coefficient, the \([\text{C}_6\text{H}^-]/[\text{C}_6\text{H}] \) ratio is estimated to be 0.012 for \( n = 10^4 \text{ cm}^{-3} \) by using equation (7), which is roughly consistent with the ratio in TMC-1. Very recently, Cernicharo et al. (2007) estimated \( k_{\text{eff}} \) to be \( 5 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1} \), based on their observations of \( \text{C}_6\text{H}^- \) and \( \text{C}_6\text{H} \) toward IRC +10216. Our result is in good agreement with theirs.

The rate coefficient of reaction (1) is represented as \( k_i \), where \( k_i \) is the collisional rate coefficient and \( f \) is the efficiency of the radiative stabilization. The rate coefficient of reaction (2) is approximately equal to \( k_i \), so that \( k_{\text{eff}} = k_i + k_2[\text{C}_6\text{H}_2]/[\text{C}_6\text{H}] \). Referring to Petrie & Herbst (1997), \( k_i \) is assumed to be \( 6.8 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1} \) at 10 K. The \([\text{C}_6\text{H}_2]/[\text{C}_6\text{H}] \) ratio is 0.06 for TMC-1 and 0.24 for L1527, according to the present observation. Hence, \( k_{\text{eff}} \) would be at least a few times \( 10^{-6} \text{ cm}^3 \text{ s}^{-1} \), even if \( f \ll 0.1 \). If \( f \sim 0.1 \), both reactions (1) and (2) would contribute to the formation of the anion. This rough estimate of \( k_{\text{eff}} \) is consistent with the observational constraint mentioned above. It should be noted, however, that \( k_{\text{eff}} \) would become too large if \( f \sim 1 \).

We have attempted to find the \( J = 9 \rightarrow 8 \) line of \( \text{C}_6\text{H}^- \) (Gupta et al. 2007) toward L1527 with the NRO 45 m without success (Table 1). The upper limit to the \([\text{C}_6\text{H}^-]/[\text{C}_6\text{H}] \) ratio is estimated to be \( 1/4500 \), assuming a rotational temperature of 9.5 K. The ratio is much lower than that for \( \text{C}_6\text{H}^- \) and is almost comparable to the \([\text{C}_6\text{H}^-]/[\text{C}_6\text{H}] \) ratio observed toward IRC +10216 (1/4200; Cernicharo et al. 2007). The small value seems to originate from a smaller radiative attachment rate coefficient for \( \text{C}_6\text{H}^- + e \), and also the endothermicity of the \( \text{C}_6\text{H}_2\text{(butatrienylidene, diacetylene)} + e \rightarrow \text{C}_6\text{H}^- + \text{H}(-26.0 \text{ kJ mol}^{-1}, -194.7 \text{ kJ mol}^{-1}) \) reactions.

The present result demonstrates the importance of anion chemistry in a dense part of star-forming regions. A chemical simulation of the \([\text{C}_6\text{H}^-]/[\text{C}_6\text{H}] \) ratio in a gravitationally contracting cloud would be interesting. One particularly interesting
point is that the H abundance will be enhanced in the innermost region of the protostellar core, because the temperature there is well above the evaporation temperature of H ($\sim$15 K; e.g., Aikawa et al. 2007). In that case, anion abundances will be lowered. Observations with high spatial resolution would therefore be useful in exploring the anion abundance as a function of position.

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Note added in proof.—Very recently we have tentatively detected the $J = 9$–8 line of C$_5$H$^-$ in L1527. The line intensity is consistent with the upper limit given in this Letter.