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LETTER

Observation of C_8H^- toward IRC +10216

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Abstract

Five rotational lines of the C_8H^- ion were observed in the circumstellar envelope of IRC +10216 with the Nobeyama 45 m telescope. An improved value of the column density of the C_8H radical yielded a $[C_8H^-]/[C_8H]$ ratio of 37% — nearly 4 times larger than the $[C_6H^-]/[C_6H]$ ratio (8.6%) and nearly 1500 times the $[C_4H^-]/[C_4H]$ ratio (0.024%), which may indicate more efficient formation of longer carbon chain anions. The excitation temperature of C_8H^- (16 ± 2 K) derived here is somewhat lower than that of the two smaller anions C_6H^- (32 K) and C_4H^- (23 K) in IRC +10216.

Key words: ISM: molecules — molecular processes — radio lines: stars — stars: circumstellar matter — stars: individual (IRC +10216)

1. Introduction

Recently, McCarthy et al. (2006) measured the millimeter-wave and Fourier transform microwave (FTM) spectra of the C_6H^- anion in the laboratory and established that this ion is the carrier of the series of lines with the rotational constant 1377 MHz first detected toward IRC +10216 in a spectral line survey with the Nobeyama 45 m telescope (Kawaguchi et al. 1995). On the basis of a theoretical calculation, Aoki (2000) first suggested that the carrier of this series might be C_6H^-, but this suggestion seemed implausible at the time owing to the very low abundance of the positive molecular ion HCO^+ in IRC +10216 (the column density $N = 1.5 \times 10^{11}\,\mathrm{cm}^{-2}$: Pulliam & Ziurys 2007), even though Millar, Herbst, and Bettens (2000) had predicted that the abundances of the C_nH^- ($n \geq 7$) anions might be fairly high in this source. Following the identification of C_6H^- in space, Gupta et al. (2007) observed the rotational spectra of C_4H^- and C_8H^- in the laboratory, and both anions have now been detected in space: C_4H^- in IRC +10216 with the IRAM 30 m telescope (Cernicharo et al. 2007), and C_8H^- in TMC-1 (Brünken et al. 2007) with the 100 m Green Bank Telescope (GBT). The ratio $[C_4H^-]/[C_4H]$ (0.024%) is much lower than that of $[C_6H^-]/[C_6H]$ (8.6%), and an even higher value is predicted for $[C_8H^-]/[C_8H]$ by Millar, Herbst, and Bettens (2000). The present paper reports the observation of five rotational lines of C_8H^- with the Nobeyama 45 m telescope toward IRC +10216. During the course of our observations, we learned that Remijan et al. (2007) had detected C_8H^- toward IRC +10216 from five lines found in the archival data taken with the GBT. Our observations confirm the detection of C_8H^- by Remijan et al. (2007), and yield an independent determination of the $[C_8H^-]/[C_8H]$ ratio in IRC +10216. These observations will help to clarify the role of negative ions in molecular sources.

2. Observations

The observations were carried out with the Nobeyama 45 m radio telescope during 2007 May–June. An SIS receiver with a single side-band filter was used for observations at 36, 39, and 44 GHz, and a HEMT amplifier was used at 28 and 29 GHz. The system temperatures were 130–200 K. The receiver back-end consisted of a bank of acousto-optical spectrometers with a resolution of 250 kHz. The main beam efficiencies were 0.79 at 28 GHz, 0.78 at 34 GHz, and 0.77 at 44 GHz. Observations were made toward the position $\alpha_{1950} = 9^{\mathrm{h}}45^{\mathrm{m}}15^{\mathrm{s}}$, $\delta_{1950} = 13°30'45''$ by position-switching. The pointing was checked every 2 hr with the SiO maser line from R Leo.

3. Results and Discussion

The observed lines of C_8H^- are shown in figure 1 and the frequencies and intensities are listed in table 1. The $J = 31$–30 and 38–37 lines are wider than the other three lines, owing to accidental blends with lines of other molecules. In the analysis of our data, we have adopted the local thermodynamic equilibrium (LTE) approximation and have used the following expression:

* Nobeyama Radio Observatory is a branch of the National Astronomical Observatory of Japan, National Institute of Natural Science.

Table 1. Observed transitions of C_8H^- in IRC +10216.

Transition J'-J''	ν (MHz)	$\int T_a^* dv^\dagger$ (K km s^{-1})	$\int T_B^* dv^\ddagger$ (K km s^{-1})	$\delta^\S$ (K km s^{-1})	weight
24–23	28000.1	0.167(25)	0.792	−0.011	1.0
25–24	29166.7	0.194(50)	0.867	0.065	0.31
31–30	36166.6	0.489(49)	1.680$^\|$	0.986	0.0
34–33	39666.5	0.171(38)	0.526	−0.073	0.43
38–37	44332.9	0.200(47)$^\#$	0.544	0.087	0.29

† Integrated line intensity. The 1σ uncertainties in parentheses are in units of the last significant digits.

‡ Integrated intensity corrected for beam efficiency and beam dilution, assuming a source diameter of 33″.

§ Observed minus calculated value of the integrated intensity $\int T_B^* dv$.

‖ This line is blended with an unidentified line and was not included in the least-squares fit.

\# Integrated intensity was evaluated in the velocity range of $v_{LSR} = -10 - -40$ km s^{-1}.

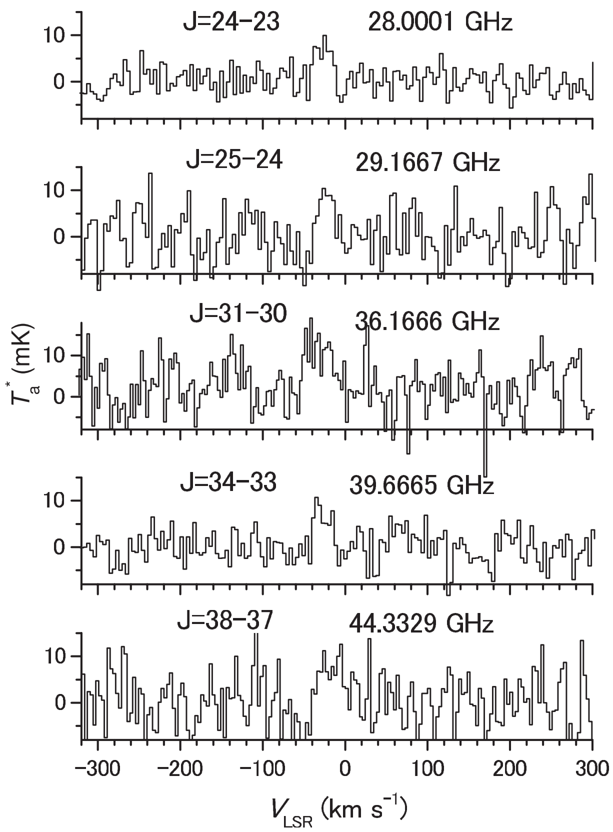

Fig. 1. Observed line profiles of C_8H^- in IRC +10216 with the Nobeyama 45 m telescope. The spectra were measured at a resolution of 250 kHz, and subsequently smoothed to 3 km s^{-1}. The 36.2 GHz and 44.4 GHz lines are broadened owing to blends with unknown lines.

$$T_B = [J(T_{ex}) - J(T_{bg})][1 - e^{-\tau}] \tag{1}$$

where $J(T) = h\nu/\{k[\exp(h\nu/kT) - 1]\}$, T_B is the brightness temperature, and T_{ex} and T_{bg} are the excitation temperature and the cosmic background temperature (2.7 K), respectively. The optical depth τ is related to the column density as follows:

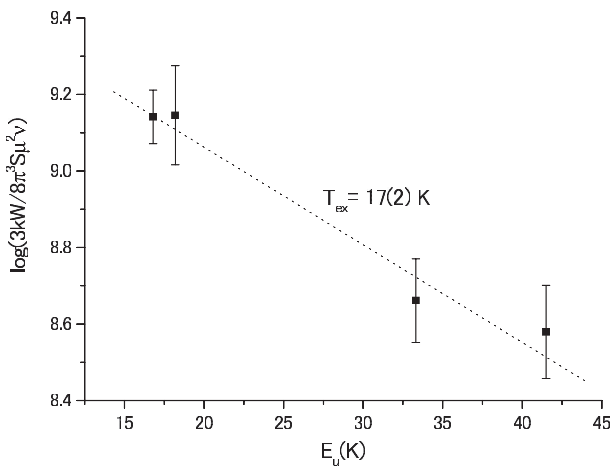

Fig. 2. Rotational temperature diagram of C_8H^- in IRC +10216. The line at 36.2 GHz was not included in the least squares analysis, because it is blended with another line.

$$\tau = \left(\frac{8\pi^3\mu^2 S g_I N}{3h\Delta v Q}\right)[\exp(h\nu/kT_{ex}) - 1]\exp(-E_u/kT_{ex}). \tag{2}$$

where μ is the dipole moment μ (11.9 D for C_8H^-: Gupta et al. 2007), S the line strength, N the column density, E_u the upper state energy of the transition, Δv the velocity width, and Q the rotational partition function. The observed antenna temperature (T_a^*) is related to the brightness temperature (T_B) of the molecular transition by:

$$T_a^* = T_B\ \eta\ \eta_{BD}, \tag{3}$$

where η is the main beam efficiency of the telescope, and η_{BD} is the beam dilution correction, given by

$$\eta_{BD} = \frac{\theta_S^2}{\theta_S^2 + \theta_B^2}, \tag{4}$$

where θ_B is the antenna beam width (FWHM) given by $\theta_B = 5.5667 \times \lambda$ [mm] arcsec and θ_S is the source diameter (Bell 1993).

Table 2. Observed transitions of C_8H in IRC +10216.

Transition $J' - J''$	ν (MHz)	$\int T_a^* dv$† (K km s^{-1})	$\int T_B^* dv$‡ (K km s^{-1})	δ§ (K km s^{-1})	weight
26.5–25.5	31093.2	0.134(37)	0.562	0.081	0.19
27.5–26.5	32266.4	0.104(16)	0.414	−0.082	1.
30.5–29.5	35786.4	0.151(32)	0.526	−0.005	0.25
31.5–30.5	36959.7	0.200(50)	0.669	0.131	0.1
34.5–33.5	40480.5	0.213(43)	0.640	0.089	0.14
35.5–34.5	41652.9	0.250(44)	0.728	0.176	0.14
42.5–41.5	49865.6	0.280(67)	0.716	0.207	0.06

† Integrated line intensity. The 1σ uncertainties in parentheses are in units of the last significant digits.
‡ Integrated intensity corrected for beam efficiency and beam dilution, assuming a source diameter of 33″.
§ Observed minus calculated value of the integrated intensity $\int T_B^* dv$, where the column density of 5.4×10^{11} cm^{-2} and the excitation temperature of 35 K were used for the calculation.

Recent calculations on the astronomical formation of hydrocarbon anions (Millar et al. 2007; Remijan et al. 2007) predict that C_8H^- and C_8H peak farther from the central star in IRC +10216 than those of C_6H and C_4H and their anions. Since acetylene plays an important role in carbon chain growth, the longer carbon chain radicals and anions tend to be produced farther from the central star than the shorter ones because the formation of longer chains requires more reaction steps. So we assumed a source diameter of 33″ ± 3″ which is 10% larger than that for C_6H^- (Kasai et al. 2007). Figure 2 shows the rotational temperature diagram of four of the five observed transitions of C_8H^- on the assumption of optically thin lines, where W denotes the integrated intensity $\int T_B^* dv$. Although an excitation temperature of 17 ± 2 K can be obtained simply from the slope of this diagram, a more rigorous nonlinear least-squares fit by using equation (1) for the four transitions in table 1 yields

$$N = (2.6 \pm 0.4) \times 10^{12}\ \mathrm{cm}^{-2}, \tag{5}$$

$$T_{\mathrm{ex}} = 16 \pm 2\ \mathrm{K}, \tag{6}$$

where the statistical weight of each line is 1/(rms)^2, the uncertainty in N corresponds to an assumed beam size tolerance of 3″, and the error in T_{ex} is one standard deviation. The low excitation temperature of C_8H^- relative to those for C_6H^- (32 K) and C_4H^- (24 K) may result from the very large dipole moment of C_8H^- (11.9 D) and from the greater distance of this ion from the central star.

From a rotational temperature analysis of five lines between 25 and 45 GHz obtained with the GBT, Remijan et al. (2007) obtained a C_8H^- column density of 2.1×10^{12} cm^{-2} by assuming $T_{\mathrm{ex}} = 34$ K and a source size of 30″. Although the column density derived here is comparable to theirs, the rotational temperature is lower.

Cernicharo and Guélin (1996) reported the first detection of the C_8H radical in IRC +10216 and determined the molecular constants B and D. McCarthy et al. (1996, 1999) measured the millimeter-wave and FT microwave spectra of C_8H in the laboratory. From an analysis of 3 lines observed with the IRAM (Institut de Radio Astronomie Millimétrique) 30 m and 7 lines with the NRO (Nobeyama Radio Observatory) 45 m telescopes, the column density and excitation temperature have been estimated to be 5.5×10^{12} cm^{-2} (for $^2\Pi_{3/2}$) and $T_{\mathrm{ex}} = 52$ K.

In the IRAM data for C_8H, two lines at 74.5 GHz and 83.9 GHz blend with other lines, and one line at 82.7 GHz is observed as an isolated line, although it is possible that this third line is also a blend with a ^{13}CCCCH line. Therefore, we performed a least-squares analysis by only including lines near 40 GHz as listed in table 2 and obtained N ($^2\Pi_{3/2}$) = $(5.4 \pm 1.2) \times 10^{12}$ cm^{-2} with an assumed source diameter of 33″; the excitation temperature was fixed to a value between 20–50 K. The column density shows a very weak dependence on the excitation temperature. When we consider the population in the $^2\Pi_{1/2}$ state of C_8H, which lies 19.33 cm^{-1} higher in energy than the ground state, we estimate a total column density of $(7 \pm 2) \times 10^{12}$ cm^{-2}. From the GBT data, Remijan et al. (2007) obtained $N = (8 \pm 3) \times 10^{12}$ cm^{-2} and $T_{\mathrm{ex}} = 13 \pm 2$ K. The column density agrees with the value derived here within the error limits. Thus, we obtain the ratio $[C_8H^-]/[C_8H] = 0.37$, which is somewhat larger than the value 0.26 obtained by Remijan et al. (2007).

Remijan et al. (2007) inferred that the C_8H^- ion may be somewhat closer to the central star in IRC +10216 than the C_8H radical, because of the difference in the rotational temperatures of the two molecules. Kasai, Kagi, and Kawaguchi (2007) noted a similar trend in the relative distribution of C_6H^- and C_6H from the observed line shapes. When we assume a larger source diameter, 36″ ± 3″ for C_8H, the column density becomes $4.7 \pm 1.2 \times 10^{12}$ cm^{-2}, which is within the errors of the value obtained with a source diameter of 33″ ± 3″.

In summary, the abundance of C_8H^- obtained here is consistent with the GBT result of Remijan et al. (2007), but our excitation temperature is lower than their value. Since the rotational dependence of line intensities is small, deep observations with higher signal-to-noise ratios are needed for a more precise determination of the excitation temperature. The large abundance ratio $[C_8H^-]/[C_8H]$ compared with those of C_6H^- and C_4H^- might indicate a higher efficiency of formation of longer carbon chain anions, as predicted by Millar, Herbst, and Bettens (2000) and Millar et al. (2007). However, the magnitudes of the predicted abundances do not agree with the observed values.

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