THE ASTROPHYSICAL JOURNAL, 209:L143–L147, 1976 November 1

EVIDENCE FOR WEAK MASER ACTION IN INTERSTELLAR CYANODIACETYLENE

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Received 1976 June 3; revised 1976 August 2

ABSTRACT

The $J = 1 \rightarrow 0$ and $J = 8 \rightarrow 7$ rotational transitions of interstellar cyanodiacetylene have been observed in Sgr B2. These observations confirm the earlier detection of this heavy molecule, and provide further information on its excitation. The $J = 8 \rightarrow 7$ line and the previously observed $J = 4 \rightarrow 3$ line can be fitted to a thermal equilibrium model and give a total column density of 1.5×10^{14} cm^{-2}. The $J = 1 \rightarrow 0$ transition is much stronger than expected from thermal equilibrium, and suggests maser action.

Subject headings: interstellar: molecules — masers

I. INTRODUCTION

Avery *et al.* (1976) have recently detected the $J = 4 \rightarrow 3$ rotational transition of the linear molecule cyanodiacetylene (HC_5N) at 10.65 GHz in Sgr B2. The small value of the rotational constant, B, of this molecule (1.3 GHz) results in a large number of lines in the radio spectrum. This provides a good opportunity to study the molecular excitation. We now report observations of two additional lines, the $J = 1 \rightarrow 0$ and the $J = 8 \rightarrow 7$ rotational transitions at 2.663 GHz and 21.301 GHz, respectively. The resolved hyperfine splitting of the $J = 1 \rightarrow 0$ transition provides a value for the HC_5N quadrupole coupling constant.

II. OBSERVATIONS OF THE $J = 1 \rightarrow 0$ TRANSITION

Since the structure of HC_5N is similar to that of HC_3N, we estimated the hyperfine splitting of the $J = 1 \rightarrow 0$ transition by using a value for the quadrupole coupling constant $eqQ = -4.2$ MHz, as determined for HC_3N by Westenberg and Wilson (1950). This resulted in predicted frequencies for the three hyperfine lines of: $F = 1 \rightarrow 1$ at 2661.61 MHz, $F = 2 \rightarrow 1$ at 2662.87 MHz, and $F = 0 \rightarrow 1$ at 2664.76 MHz. Lines very close to these frequencies were detected in the source Sgr B2 on 1976 February 7–8 with the Parkes 64 meter telescope.

The average system temperature of the dual channel receiver was 160 K for line operation (Batchelor, Brooks, and Cooper 1968). The telescope had a half-power beamwidth of 8'.2 with an aperture efficiency of 0.48 and a beam efficiency of 0.80. Hydra A, which was used for calibration, was assumed to have a flux density of 23.5 Jy at 2.7 GHz. The spectral information was obtained with a 512 channel digital correlator (Ables *et al.* 1975) operating at a bandwidth of 19.5 kHz per channel.

The observed spectrum in the direction of the continuum peak of Sgr B2 is shown in Figure 1. The spectrum covers a frequency range of 6 MHz near 2.663 GHz, and has an rms noise level of 0.007 K in antenna temperature. The smooth line is that of three best-fit Gaussians through the points. From the observed separations of the hyperfine lines a value of -4.12 ± 0.07 MHz is obtained for eqQ. Results are given in Table 1.

III. OBSERVATIONS OF THE $J = 8 \rightarrow 7$ TRANSITION

The observations of the $J = 8 \rightarrow 7$ transition at 21301.247 MHz were made during the period 1976 February 13–17 and 1976 April 27–May 2, with the 46 m telescope of the Algonquin Radio Observatory.[1] The observing procedure was essentially that described by Avery *et al.* (1976). The half-power beamwidth was 1'.4 and the system temperature 300 K. The spectrometer, which was used in the total power mode, employs a dual bank of filters (McLeish 1973). For these observations resolutions of 100 kHz and 300 kHz were used.

The spectrum of the $J = 8 \rightarrow 7$ emission line in the direction of the 1.4 cm continuum peak of Sgr B2, observed with a resolution of 100 kHz, is shown in Figure 2. The smooth curve is a least-squares fit to the data of a Gaussian profile and a baseline composed of a straight line plus a sine wave. Observational results are given in Table 1. The line brightness temperature ΔT_J at 21.3 GHz was calculated by dividing the observed antenna temperature by the estimated atmospheric transmission coefficient, $\alpha = 0.82 \pm 0.08$ (at 77° zenith angle) and the beam efficiency, $\eta_B = 0.23$.

Limited observations at 2.8 cm (Avery, Broten, and MacLeod, unpublished) indicate that the HC_5N cloud in Sgr B2 has a diameter of about 6'. A beam dilution

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[1] The Algonquin Radio Observatory is operated by the National Research Council of Canada as a national radio astronomy facility.

factor[2] $F(\theta_b,\theta_c)$ has been applied to the line temperatures in Table 1, where the corrected brightness temperatures are listed as ΔT_J.

IV. DISCUSSION

a) Thermal Equilibrium Model

We assume thermal equilibrium of the molecules at an excitation temperature much greater than the temperature of the background ($T_{\rm ex} \gg T_{\rm bg}$), and optical depth $\tau \ll 1$. Then the total column density, a function of the brightness temperature $\Delta T_J(\nu)$ of the $J \rightarrow J-1$ transition, can be expressed as

$$NL = \frac{3ck^2T_{\rm ex}^2 \int \Delta T_J(\nu)d\nu}{8\pi^3 hB(T_{\rm ex} - T_{\rm bg})\nu_J^2(2J+1)|\mu_{J,J-1}|^2} \times \exp\left[\frac{hBJ(J+1)}{kT_{\rm ex}}\right]. \tag{1}$$

From the intensities of the observed $J = 4 \rightarrow 3$ and $J = 8 \rightarrow 7$ transitions, and assuming $T_{\rm ex} = 30$ K, we

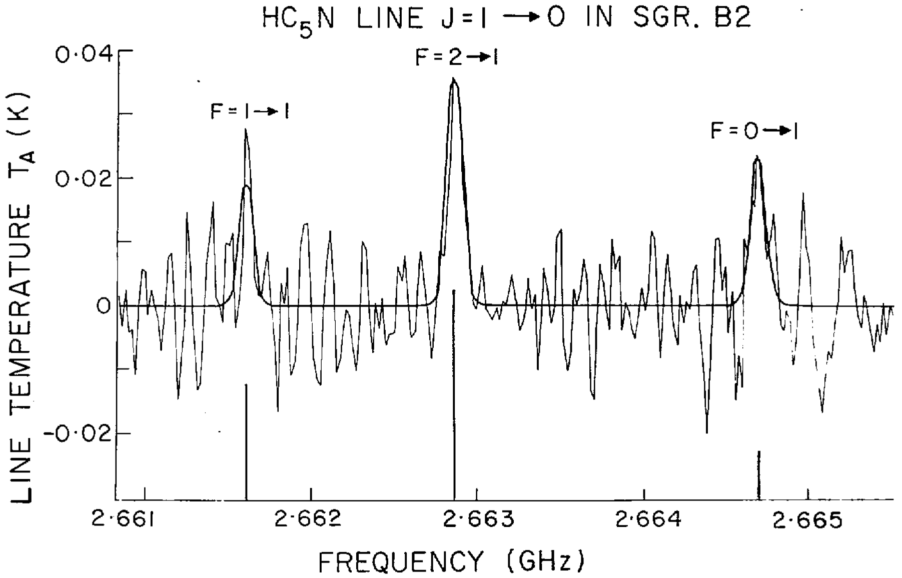

FIG. 1.—The spectrum of the interstellar $J = 1 \rightarrow 0$ HC$_5$N line in the direction of Sgr B2 observed with frequency resolution 19.5 kHz. The abscissa shows rest frequencies for a radial velocity $V_{\rm LSR}$ of +65.0 km s^{-1} (chosen so that the median position of the $F = 2 \rightarrow 1$ line falls at its rest frequency of 2662.87 MHz). The smooth line represents the best-fit Gaussians. The rms noise level in antenna temperature is 0.007 K. The theoretical hyperfine pattern is shown by vertical lines below the spectrum.

TABLE 1

HC$_5$N LINE PARAMETERS IN SAGITTARIUS B2

PARAMETER	$J = 1 \rightarrow 0$ $F = 1 \rightarrow 1$	$J = 1 \rightarrow 0$ $F = 2 \rightarrow 1$	$J = 1 \rightarrow 0$ $F = 0 \rightarrow 1$	$J = 8 \rightarrow 7$
Frequency (GHz)	2.66161	2.66287	2.66476	21.301247
Observed separation of hfs components (MHz)	−1.256±0.01	0	+1.823±0.01	
Line antenna temperature T_A (K)	0.020±0.007	0.036±0.007	0.023±0.007	0.031±0.006
Correction for beam dilution, $F(\theta_b,\theta_c)$*	0.4	0.4	0.4	0.9
Corrected line brightness temperature, ΔT_J (K)	0.06	0.11	0.06	0.190
Line intensity ratios:				
Theoretical	0.5	1	0.2	
Observed	0.5	1	0.5	
Line width (kHz)†	101 ±9	97 ±9	110 ±9	1670±350
Line width (km s^{-1})†	11.4±1	10.9±1	12.4±1	23.5±4.9
$V_{\rm LSR}$ (km s^{-1})	...	+64.5±1.0	...	+65.1±1.4
Continuum T_b (K)		32.9		3.8

* For λ = 2.8 cm, $F(\theta_b,\theta_c) = 0.8$, $\Delta T_J = 0.086$ K.

† Full width to half-power.

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[2] $F(\theta_b, \theta_c) = [1 + \theta_b^2/\theta_c^2]^{-1}$, where θ_b is the full beamwidth at half-power and θ_c is the cloud diameter to half-power. θ_c was taken as 6′.

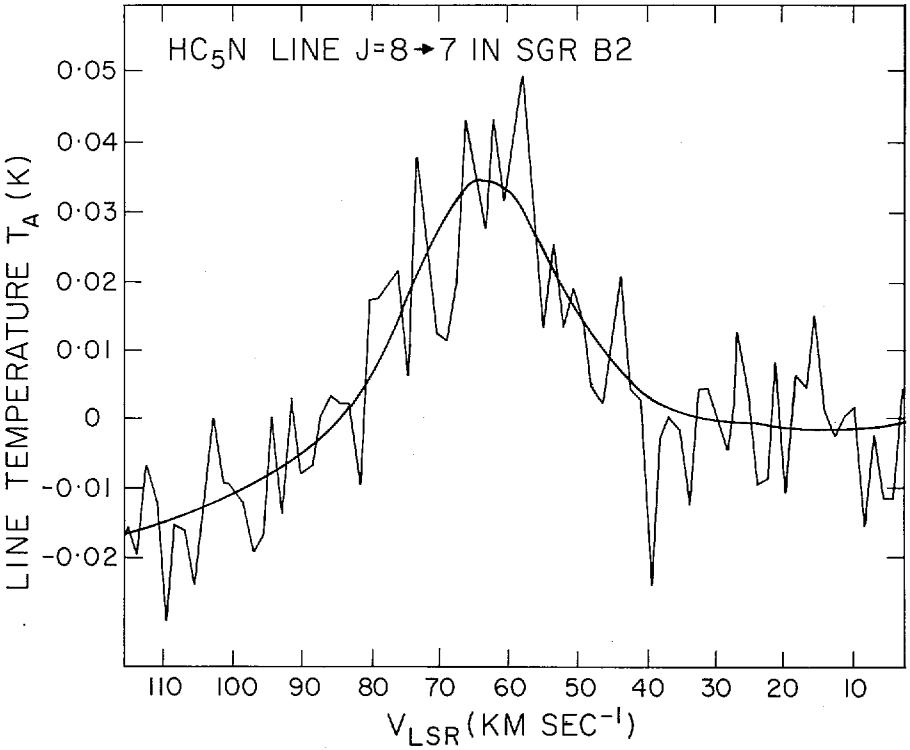

FIG. 2.—The observed spectrum of the interstellar $J = 8 \rightarrow 7$ line of cyanodiacetylene in the direction of Sgr B2, at a resolution of 100 kHz. The smooth line is a simultaneous least-squares fit of a Gaussian line profile and a composite baseline consisting of a straight line plus a sine wave. The period of the sine wave is that of the ripple caused by multiple reflections. The rms noise in the spectrum is $\Delta T_A = 0.008$ K. Total on-source integration time was 5 hours. Hyperfine splitting for this transition is less than 15 kHz for the stronger components, and is not resolved.

obtain the following total column densities:

$$\text{for } J = 4 \rightarrow 3\,, \quad NL = 1.8 \times 10^{14}\ \text{cm}^{-2}$$

and

$$\text{for } J = 8 \rightarrow 7\,, \quad NL = 1.5 \times 10^{14}\ \text{cm}^{-2}\,.$$

The similarity of these values does not depend strongly upon the choice of T_{ex} and indicates that a thermal model may in fact be a good approximation for J values from 4 to 8.

Equation (1) can be inverted to give the peak brightness temperature ΔT_J as a function of J,

$$\Delta T_J = \frac{155hB^2\mu^2NL(T_{ex} - T_{bg})J^2}{k^2T^2_{ex}\Delta V_J} \times \exp\left[\frac{-BhJ(J+1)}{kT_{ex}}\right], \qquad (2)$$

where ΔV_J is the full width at half-maximum of the spectral line in km s^{-1}. A Gaussian line shape has been assumed.

Figure 3*a* shows equation (2) plotted for HC$_5$N for various excitation temperatures. In this figure the total column density NL is adjusted such that the brightness temperature of the $J = 8 \rightarrow 7$ transition is normalized to the observed value. Since we assume $T_{ex} \gg T_{bg}$, NL is approximately proportional to T_{ex}. Figure 3*b* shows similar plots for HC$_3$N in the same source with ΔT_J normalized to the $J = 10 \rightarrow 9$ transition. In both figures ΔV_J is assumed to be independent of J. The observed HC$_5$N brightness temperatures for $J = 8$ and $J = 4$ in Figure 3*a* can be fitted by a large range of temperatures. However, the values of HC$_3$N in Figure 3*b* indicate $T_{ex} \sim 30$ K for high J levels in agreement with the more detailed discussions of Morris *et al.* (1976). It is because of the similarity between HC$_5$N and HC$_3$N that we have adopted $T_{ex} = 30$ K for our calculations of the HC$_5$N column densities.

Figure 3 indicates the nonthermal behavior of the $J = 1 \rightarrow 0$ transition in both HC$_3$N and HC$_5$N. Column densities calculated from this transition are roughly two orders of magnitude larger than those obtained from higher J lines (Turner 1971; McGee *et al.* 1973; Morris *et al.* 1976). Figure 3*b* indicates that the $J = 2 \rightarrow 1$ transition (Dickinson 1972; Balister and McGee 1976) also has an intensity well above the thermal value. Morris *et al.* (1976) have discussed the possibility of maser action in HC$_3$N.

b) Maser Action for the $J = 1 \rightarrow 0$ Line of HC$_5$N

The anomalously large intensity of the $J = 1 \rightarrow 0$ transition in HC$_5$N suggests maser action in this molecule as well. An additional observation which is consistent with this hypothesis is that the observed width of the $J = 1 \rightarrow 0$ line (10.9 ± 1 km s^{-1}) is appreciably

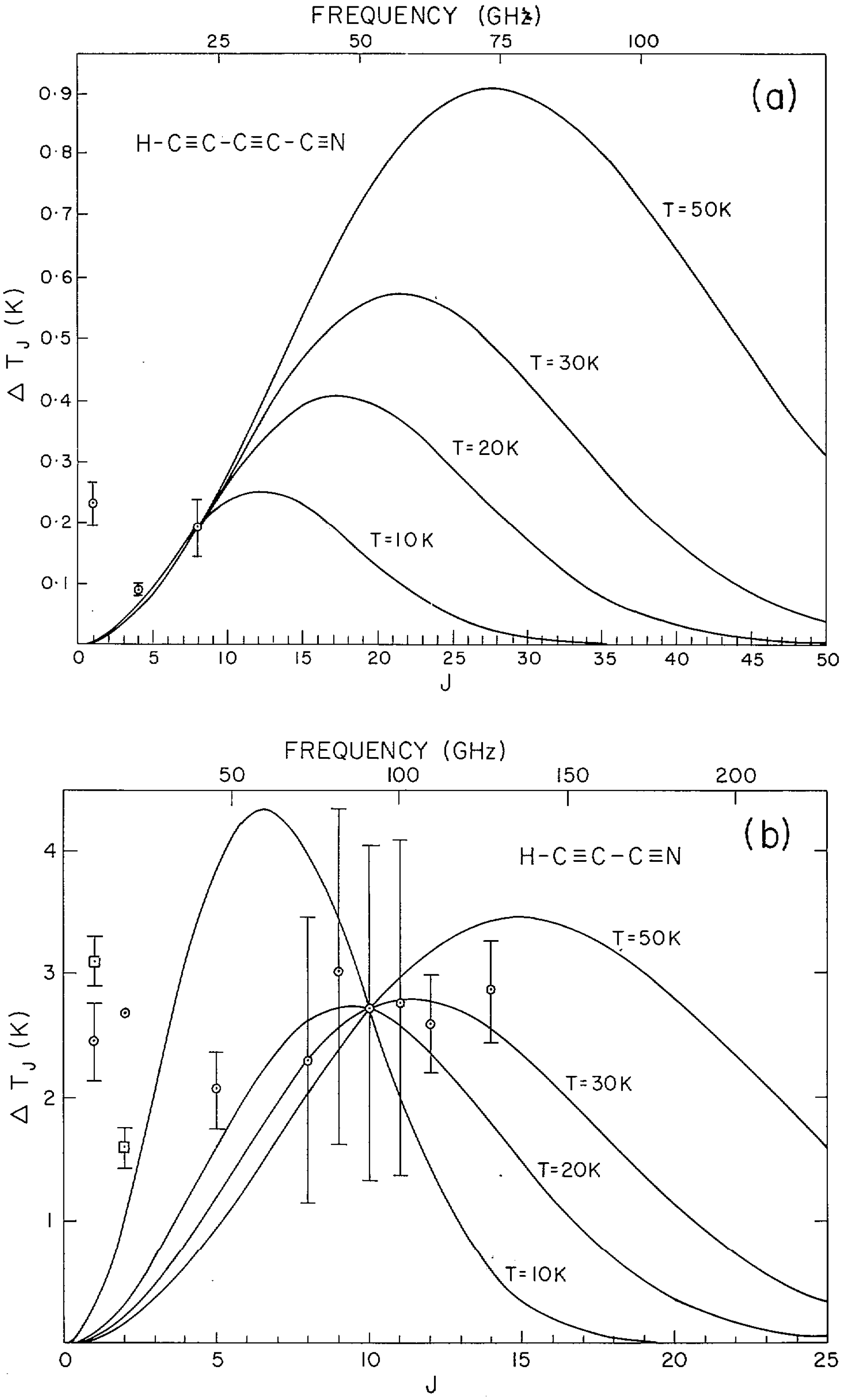

FIG. 3.—Expected brightness temperature ΔT_J as a function of J, assuming thermal equilibrium at temperature T. For cyanodiacetylene (*a*) the curves are normalized to the observed ΔT_J at $J = 8 \rightarrow 7$. For cyanoacetylene (*b*) the data plotted as circles are taken from Morris *et al.* (1976), and the data plotted as squares are from Balister and McGee (1976) ($J = 2 \rightarrow 1$) and from McGee *et al.* (1975) ($J = 1 \rightarrow 0$). The HC_3N curves are normalized to the observed ΔT_J at $J = 10 \rightarrow 9$.

narrower than that of both the $J = 4 \rightarrow 3$ line (19.4 ± 1.5 km s^{-1}) and the $J = 8 \rightarrow 7$ line (23.5 ± 4.9 km s^{-1}). Such nonthermal effects result when the radiative and kinetic temperatures are very different and the radiative and collisional rates are similar.

Goldsmith (1972) has calculated collisional and radiative processes in CO molecules. He has shown that a negative excitation temperature for the $J = 1 \rightarrow 0$ transition can occur for a reasonably wide range of physical conditions in a CO cloud. This is mainly because of the strong J-dependence of the spontaneous emission rate A_J for linear molecules:

$$A_J = \frac{64\pi^4 \nu_J{}^3 |\mu_{J,J-1}|^2}{3hc^3}$$

$$\propto \frac{J^4}{2J+1} B^3 \mu^2 . \qquad (3)$$

The spontaneous emission rate of the $J = 2$ level is about 10 times that of $J = 1$. This causes overpopulation in $J = 1$ with respect to $J = 0$ in certain ranges of density, kinetic temperature, and radiation field density. A more restricted range of physical conditions is required to produce negative excitation temperatures for higher J values because the J-dependence becomes less pronounced.

Goldsmith's calculation can be applied to HC_5N except that in this case the radiative processes induced by the 2.7 K blackbody radiation play a more important role than the spontaneous emission. The ratio of the induced emission rate to the spontaneous emission rate, $[\exp(h\nu/kT) - 1]^{-1} \sim kT/h\nu$, reduces the J dependence of the radiative rate R_J to

$$R_J \propto \frac{J^3}{2J+1} B^2 \mu^2 .$$

However, a negative T_{ex} can still result for a reasonable range of cloud conditions. It may be noted that the large dipole moment of HC_5N (4.33 debyes), as compared to that of CO (0.1 debyes), compensates for the smaller rotational constant, so the values of $B^2\mu^2$ are nearly equal for the two molecules.

In summary, we believe that there is observational evidence and theoretical support for weak maser action in the $J = 1 \rightarrow 0$ line of HC_5N.

REFERENCES

Ables, J. G., Cooper, B. F. C., Hunt, A. J., Moorey, G. G., and Brooks, J. W. 1975, *Rev. Sci. Instr.*, **46**, 284.
Avery, L. W., Broten, N. W., MacLeod, J. M., Oka, T., and Kroto, H. W. 1976, *Ap. J. (Letters)*, in press.
Balister, M., and McGee, R. X. 1976, private communication.
Batchelor, R. A., Brooks, J. W., and Cooper, B. F. C. 1968, *IEEE Trans. AP*, **16**, 228.
Dickinson, D. F. 1972, *Ap. Letters*, **12**, 235.
Goldsmith, P. F. 1972, *Ap. J.*, **176**, 597.
McGee, R. X., Newton, Lynette, M., Batchelor, R. A., and Kerr, A. R. 1973, *Ap. Letters*, **13**, 25.
McGee, R. X., Newton, L. M., and Butler, P. W. 1975, *Ap. J.*, **202**, 76.
McLeish, W. C. 1973, *IEEE Trans., IM*, **26**, 279.
Morris, M., Turner, B. E., Palmer, P., and Zuckerman, B. 1976, *Ap. J.*, **205**, 82.
Turner, B. E. 1971, *Ap. J. (Letters)*, **163**, L35.
Westenberg, A. A., and Wilson, E. B., Jr. 1950, *J. Am. Chem. Soc.*, **72**, 199.

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