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THE NEW OBSERVATION OF $C^{18}O(J = 1–0)$ MOLECULAR EMISSION IN THE CEPHEUS OB3 MOLECULAR CLOUD

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ABSTRACT

We present the $C^{18}O(J = 1–0)$ observation of the Cep OB3 molecular cloud. The observation was made for a week in 1993 December with the new 4 m millimeter telescope at Nagoya University. The extent of the $C^{18}O(J = 1–0)$ emission indicates that total area coverage of the map is substantially less than 2°.8 × 1°.4 structure. A portion of the Cep OB3 molecular cloud has been mapped in the $C^{18}O(J = 1–0)$ line on a completely sampled grid with a 2'.0 spacing. The physical parameters of the $C^{18}O(J = 1–0)$ core are derived. The $C^{18}O(J = 1–0)$ emission is also tracing the dense gas in the core. The large dense core appears to have been disturbed significantly by the star formation activity within it.

Subject headings: ISM: clouds — ISM: individual (Cepheus OB3 cloud) — ISM: molecules — ISM: structure

1. INTRODUCTION

The giant molecular complexes (GMCs) in our Galaxy, for example the Cep OB3 molecular cloud, show a clumpy appearance when mapped in radio lines of interstellar molecules (Blitz 1980). The typical complex is a conglomerate of a large number of individual clouds of various sizes and masses adding up to a total mass $10^4\ M_\odot$ or greater. The average volume density for the complexes as determined from the observed mass and size is quite low, $\sim 50\ cm^{-3}$ (Blitz 1980), implying a small volume filling factor for the gas. The structure in GMCs is possibly hierarchical in nature, where higher density regions occupy a small volume fraction of lower density regions. The characteristics of the structure and the properties of how the gas is clumped depend presumably upon the process that control the formation and evolution of the complexes. A better understanding of the gas distribution and kinematics within molecular complexes is a necessary step toward better theories on the origin and evolution of GMCs.

The work presented in this paper is an attempt to study the structure of the molecular gas in a giant molecular complex. The $C^{18}O(J = 1–0)$ emission at 109 GHz is used to trace mass distribution in such dense regions having average density of $\sim 10^4\ cm^{-3}$. These $C^{18}O(J = 1–0)$ observations form the basis for an interesting study on the cloud cores and star formation activity in the cores of the Cepheus OB3 molecular cloud. A completely sampled observation in the $C^{18}O(J = 1–0)$ line was made over a portion of the Cep OB3 molecular cloud. This large molecular cloud is associated with the Cep OB3 association and was mapped in CO by Sargent (1977, 1979). The Cep A–F nomenclature was also created by him (Sargent 1977, 1979). Strömgren photometry was presented for 45 stars in the region of Cep OB3, and their relationship to the association was analyzed (Jordi et al. 1992). Harju, Walmsley, & Wouterloot (1991) presented statistics of clump properties in the Cepheus cloud complex based on ammonia mapping observations. Their main interest has been determining the clump sizes and masses on the basis of the ammonia column density distribution, which together with the observed velocity dispersion leads to a rough estimate of the dynamical state. They have studied the star clump separations, which should give us estimates of the same ages. Cardelli & Smith (1988) revealed the optical atomic and molecular absorption toward the Cepheus OB3 molecular cloud. Strip maps of ^{12}CO, ^{13}CO, and $C^{18}O$ emission from the Cep C dense core have been obtained to determine its density distribution and kinematic properties (Heyer & Ladd 1995). By comparing the CO data with associated *IRAS* point sources, Sugitani & Fukui (1988) suggested that the Cepheus region was a very active site of relatively massive star formation. Carr (1987) mapped a portion of the Cepheus OB3 molecular cloud in the ^{13}CO line on a completely sampled grid with a 1'.5 spacing. At a distance of 730 pc, the molecular cloud complex is $\sim 20 \times 60$ pc in size and is elongated parallel to the Galactic plane. The mass given by Sargent for the complex is $5 \times 10^3\ M_\odot$. We present the observation in § 2, the results in § 3, and the discussion in § 4.

2. OBSERVATION

The observation was made for a week in 1993 December with the new 4 m telescope at Nagoya University to delineate the detailed distribution of the molecular gas in the Cep OB3 cloud. Its half-power beamwidth was 2'.7 with a main beam efficiency of 0.7 at 110 GHz. The 4 K cooled Nb SIS mixer receiver provided a typical single-sideband system temperature of 300 K, including the atmosphere for the molecule (Kawabata et al. 1985). The spectrometer was an acousto-optical spectrometer (AOS). The beamwidth of AOS is 40 MHz divided into 1024 channels, and effective frequency resolution was 40 kHz, equivalent to a velocity coverage of 100 km s^{-1} and velocity resolution of 0.1 km s^{-1}, respectively (Nozawa et al. 1991). Frequency-switching technique with a frequency interval of 13 MHz corresponding to ~ 35 km s^{-1} at 110 GHz was used to obtain the data. An ambient-temperature chopper wheel was used to determine the antenna temperature scale. S140 was observed every 2 hr to check the receiver stability. The rms noise fluctuations of the obtained spectra are ~ 0.1 K for 0.1 km s^{-1} resolution. The integration time is 4 or 5 minutes. The observed properties of $C^{18}O$ peak emission in the Cep OB3 molecular cloud are in Table 1. The peak temperature T_R^*,

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TABLE 1

OBSERVED PROPERTIES OF CLOUD CORE IN CEPHEUS OB3

	POSITION				$C^{18}O(J = 1\text{–}0)$			
CLUMP	α(1950)	δ(1950)	*l* (deg)	*b* (deg)	*I* (K km s^{-1})	*T* (K)	Δ*V* (km s^{-1})	V_{LSR} (km s^{-1})
L1211..........	22 45 00.4	61 52 27.5	108.93	2.70	2.15	1.30	1.6	−10.1
Cep A	22 54 20.2	61 44 53.8	109.87	2.10	3.14	1.00	3.2	−10.6
Cep F..........	22 51 05.6	62 04 58.5	109.67	2.57	1.74	1.01	1.3	−8.4
Cep B..........	22 55 51.5	62 18 36.4	110.27	2.53	1.08	0.74	1.5	−12.2
Cep E..........	23 01 02.9	61 31 31.7	110.50	1.57	1.50	0.85	1.6	−10.2
Cep C (a)......	23 01 42.2	62 10 41.4	110.83	2.13	1.17	0.49	2.3	−10.5
Cep C (b)......	23 04 01.8	62 13 22.1	111.10	2.07	3.17	1.28	2.3	−10.6
Cep C (c)......	23 05 56.6	62 12 30.5	111.30	1.97	2.55	1.16	2.1	−10.2

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

line width at half-maximum Δ*V*, and LSR velocity V_{LSR} were estimated by fitting a single Gaussian curve.

3. RESULTS

We mapped a total area of 474 positions in the $C^{18}O(J = 1\text{–}0)$ emission, covering the total area in less than $\sim 2°8 \times 1°4$. The map covers only a portion of the complex found by Sargent (1977). The observation is on a grid in Galactic coordinates with a 2′0 spacing. Figure 1 shows our maps of integrated intensity of the $C^{18}O(J = 1\text{–}0)$ emission observed with the Nagoya 4 m telescope in Galactic coordinates. Contours start from 0.48 K km s^{-1}, with increments of 0.16 K km s^{-1}. The large-scale pattern of the emission is similar to that seen in ^{12}CO, but the $C^{18}O(J = 1\text{–}0)$ map shows smaller scale structure, including regions A, B, C, E, F, and L1221. This is partly due to the large $\sim 2°8 \times 1°4$ spacing in Sargent's ^{12}CO map.

Figure 2 shows the broader wings extending to about 3 km s^{-1} and 2 km s^{-1} from the line center at the 3 σ level to both the blueshifted and redshifted, respectively. These $C^{18}O(J = 1\text{–}0)$ spectra with single-peaked profiles indicate the velocity of the quiescent cloud. The profiles are most symmetric and do not show prominent wing emission more blueshifted than −13 km s^{-1} or more redshifted than −8 km s^{-1}.

We have listed the physical parameters of the $C^{18}O(J = 1\text{–}0)$ core that are well defined by the $C^{18}O(J = 1\text{–}0)$ emission in a total intensity map (Fig. 1). The physical parameters of the $C^{18}O(J = 1\text{–}0)$ cores were estimated in the following manner (Sato et al. 1994):

1. The excitation temperature, T_{ex}, was assumed to be equal for the three CO isotopes. It was estimated from the peak intensity of the $^{12}CO(J = 1\text{–}0)$ emission, $T_R^*(^{12}CO)$ (Sargent 1977), by the following equation:

$$T_{ex} = 5.53/\ln\{1 + 5.53/[T_R^*(^{12}CO) + 0.819]\} .$$

2. As a measure of the velocity dispersion of the gas within a clump, composite profiles were formed by adding

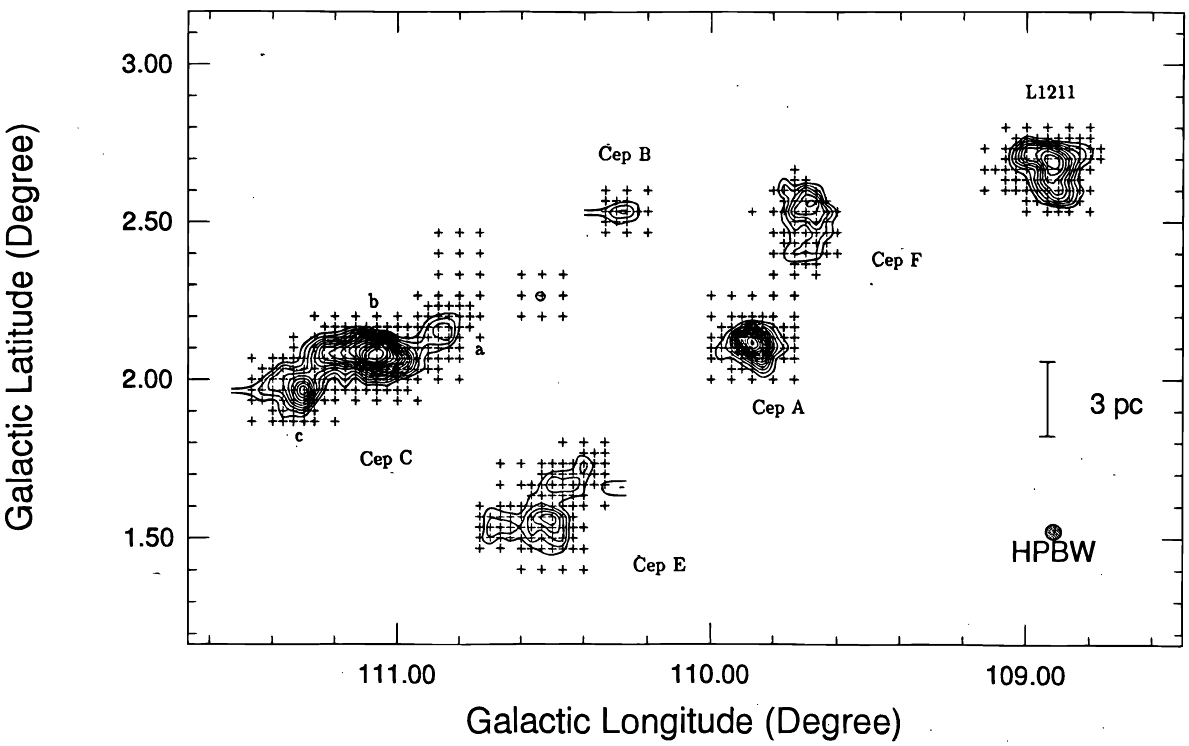

FIG. 1.—An integrated intensity map of $C^{18}O(J = 1\text{–}0)$ in Galactic coordinates. Contours start from 0.48 K km s^{-1} with increments of 0.16 K km s^{-1}.

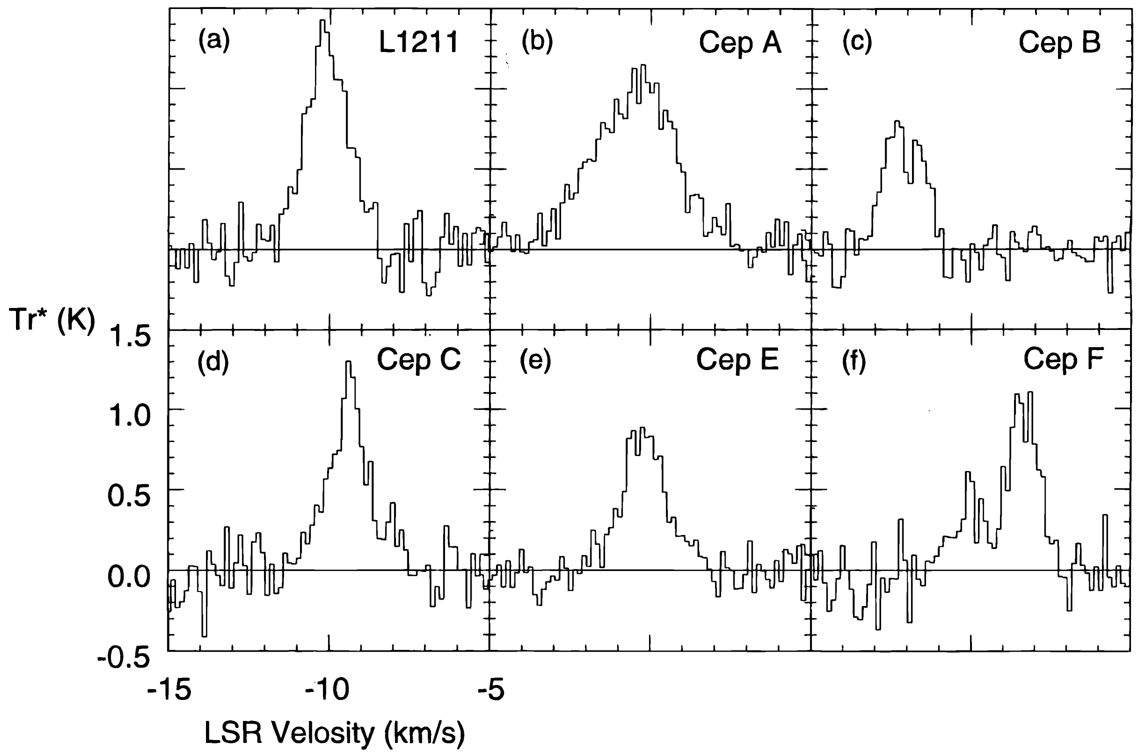

FIG. 2.—Profiles of $C^{18}O(J = 1\text{–}0)$ emission. (*a*) L1211; (*b*) Cep A; (*c*) Cep B; (*d*) Cep C; (*e*) Cep E; (*f*) Cep F.

together all spectra associated with a given clump. From these composite spectra, the velocity width is defined as

$$\Delta V(C^{18}O) = \int T_A^* \, dv/(1.06 T_A^*) .$$

The small correction factor relates integrated area to peak intensity and FWHM line width for a Gaussian line profile.

3. Optical depths of $C^{18}O(J = 1\text{–}0)$ and column density of $C^{18}O(J = 1\text{–}0)$ were estimated with the following equations on the assumption that the cloud is in local thermodynamic equilibrium (LTE):

$$\tau(C^{18}O) = -\ln \| 1 - T_R^*(C^{18}O)/\{5.27[1/\langle \exp(5.27/T_{ex}) - 1 \rangle - 0.166]\} \| ,$$

$$N(C^{18}O) = 2.42 \times 10^{14} \tau(C^{18}O) \Delta V(C^{18}O) \times T_{ex}/[1 - \exp(-5.27/T_{ex})] .$$

4. The H_2 column density $N(H_2)$ was estimated from the column density of $C^{18}O(J = 1\text{–}0)$, assuming that the same fractional abundance of $C^{18}O/H_2 = 1.7 \times 10^{-7}$ derived for cloud interiors of ρ Oph and Taurus by Frerking, Langer, & Wilson (1982) is applicable also to the Cepheus OB3 molecular cloud. The H_2 number density $n(H_2)$ was calculated by $N(H_2)$/(size).

5. Size of the core was defined at the half-contour level of the intensity at the peak position, assuming that the $C^{18}O$ intensity profiles along the two axes are Gaussian.

6. The virial mass M(vir) was calculated by assuming that the core is spherical.

In Table 2, we have listed the physical parameters of the $C^{18}O(J = 1\text{–}0)$ cores that are well defined by the $C^{18}O(J = 1\text{–}0)$ emission in the total intensity map (Fig. 1).

4. DISCUSSION

4.1. *The Variations of the Line Width and the Velocity Centroid*

The velocity dispersion of the gas was estimated from composite spectra. The measured peak velocity difference between clumps is 4.0 km s^{-1} (Table 1). The velocity of Cep F and B is especially different from that of the rest of the clumps in Cepheus OB3. In addition, it is found from

TABLE 2

PHYSICAL PARAMETERS OF CLOUD CORES IN CEPHEUS OB3

Clump	Size (pc)	T_{ex} (K)	$\tau(C^{18}O)$	$N(C^{18}O)$ (10^{15} cm^{-2})	$N(H_2)$ (10^{22} cm^{-2})	$n(H_2)$ (10^3 cm^{-3})	M(LTE) ($M_\odot$)	M(vir) ($M_\odot$)
L1211	1.9	17	0.100	2.6	1.5	2.6	610	490
Cep A	1.2	22	0.055	4.6	2.7	7.6	410	1200
Cep F	1.4	12	0.124	1.4	0.8	1.9	180	240
Cep B	0.7	33	0.025	2.1	1.2	6.0	62	150
Cep E	1.5	17	0.064	1.7	1.0	2.1	250	390
Cep C (a)	1.2	17	0.037	1.4	0.8	2.2	120	610
Cep C (b)	1.9	17	0.099	3.6	2.1	3.8	820	970
Cep C (c)	1.0	17	0.089	3.0	1.8	6.1	180	430

Figure 1 and Table 2 that the cores of Cep F and B have different physical parameters and space range, respectively. It would be interesting to determine the relative contributions to the total velocity dispersion from the observed point-to-point variations in line width along the line of sight and the velocity centroid in a clump. From the composite spectra, it is found that the variations of the line width in a clump are small. The difference between the average line width and peak line width is $\sim$0.1–0.14 km s^{-1}. The relative value is $\sim$5%–7% in a clump. From the composite spectra, it is found also that the variations of the velocity centroid in a clump are smaller. The variations are $\sim$0.05–0.1 km s^{-1}. The relative value is $\sim$0.5%–1%. Although the clump-to-clump line width and velocity centroid are always changed, the point-to-point one in a clump is almost constant. On the contrary, the physical parameters in different clumps are very much different.

4.2. *Three Cores of* $C^{18}O(J = 1\text{–}0)$ *in Cep C*

It is found also from Figure 1 and Tables 1 and 2 that there are obviously three cores of $C^{18}O(J = 1\text{–}0)$ in Cep C. This is a new result. The reasons are as follows: (1) The system noisy temperature is different; (2) the optical depth of the three isotopic molecules of CO is different; (3) their distribution in space is different.

4.3. *Noncollimation of Molecular Flow of Cep E*

It is found from Figure 1 that the molecular flow of Cep E shows the noncollimation. The extension is along east and northwest. Maybe the reason is that media at east and west are different.

4.4. *The Clumps in Cep OB3 Close to Virial Equilibrium*

We derive a virial mass of 4480 $M_\odot$. This value is consistent with the 5000 $M_\odot$ given by Sargent (1979). Molecular clouds are often found to be close to virial equilibrium when cloud masses are compared with line width (Larson 1981). It is found from Table 2 that the virial masses are higher than the LTE masses in each of the cores. We believe that the differences are real because the physical parameters are determined by the models and observations. So we have reason to imply that the molecular clouds in Cep OB3 are close to virial equilibrium.

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