OBSERVATION OF THE C i 3P2.3P1 LINE TOWARD THE ORION KLEINMANN-LOW REGION

OBSERVATION OF THE C I $^3P_2$–$^3P_1$ LINE TOWARD THE ORION KLEINMANN-LOW REGION

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ABSTRACT

The $^3P_2$–$^3P_1$ fine-structure line of the neutral carbon atom (809 GHz) has been observed toward the Orion Kleinmann-Low (KL) region with the Mount Fuji submillimeter-wave telescope. The $6' \times 6'$ area centered at Orion KL has been mapped with a grid spacing of 1'.5. The intensity distribution of the $^3P_2$–$^3P_1$ line is found to be similar to that of the $^3P_1$–$^3P_0$ line; these lines are rather weak toward Orion KL, while they are both bright at Orion KL's northern and southern positions. The excitation temperature determined from the intensity ratio between the $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$ lines ranges from 40 to 110 K. The excitation temperature is not enhanced toward Orion KL, whereas it tends to be high in the vicinity of θ^1 Orionis C. These results indicate that the C I emission arises from a photodissociation surface illuminated by strong UV radiation from θ^1 Ori C. The relative reduction in the C I intensities toward Orion KL is found to originate from a relatively low excitation temperature rather than from the depletion of the C I column density. The origin of the low-excitation temperature of C I toward Orion KL is discussed in terms of a radiative transfer effect.

Subject headings: ISM: atoms — ISM: clouds — ISM: individual (Orion Kleinmann-Low)

1. INTRODUCTION

The neutral carbon atom (C I) plays an important role in both the chemistry and the cooling processes of molecular clouds. It is thus important to explore its large area distribution over various clouds. By comparing the distribution of C I with that of CO, we would be able to obtain a lot of information on the detailed structure, formation processes, and thermal balance of molecular clouds. However, observations of the submillimeter-wave C I lines have been limited to relatively small regions around representative objects (e.g., Plume, Jaffe, & Keene 1994; Plume et al. 1999; Tatematsu et al. 1999). In order to change this situation, we have recently constructed the Mount Fuji submillimeter-wave telescope for the exclusive use of surveying the submillimeter-wave C I lines (Sekimoto et al. 2000). With this telescope, we have already mapped more than 35 deg^2 of the sky with the lowest transition ($^3P_1$–$^3P_0$ at 492 GHz) of C I (Maezawa et al. 1999; Ikeda et al. 1999).

In order to determine the physical conditions of the C I–emitting region, it is necessary to observe another transition of C I, the $^3P_2$–$^3P_1$ line at 809 GHz. This line was first observed by Jaffe et al. (1985) with the University of Hawaii 2.2 m telescope at Mauna Kea. After that, a few observations of this line were reported for several sources (e.g., Zmuidzinas, Betz, & Goldhaber 1986; Zmuidzinas et al. 1988; Genzel et al. 1988; Stutzki et al. 1997). However, the observations were carried out toward a very limited number of positions, so that no two-dimensional map has been prepared as far as we know. According to the far-infrared absolute spectrophotometer observation by the *COBE* satellite with its 7° beam (Wright et al. 1991), the $^3P_2$–$^3P_1$ line is generally bright in the Galactic plane. Therefore, it is interesting to clarify its detailed distribution in individual clouds.

The Orion Kleinmann-Low (KL) region is a famous massive star-forming region that is close to the Sun (450 pc; Genzel & Stutzki 1989). It is also known to contain a typical photodissociation region (e.g., Tielens & Hollenbach 1985). Extensive observations of the C I ($^3P_1$–$^3P_0$) line were reported toward this region (White & Padman 1991; White & Sandell 1995; Tatematsu et al. 1999; Ikeda et al. 1999; Plume et al. 2000). According to these results, the C I line intensity is weaker in the $2'$ region centered at Orion KL than in the northern and southern regions. Although it is important to observe the $^3P_2$–$^3P_1$ line for an understanding of the origin of the relative reduction in the C I intensity, such an observation was only carried out toward Orion KL (Zmuidzinas et al. 1988). Motivated by this, we have observed the $6' \times 6'$ region covering the above $2'$ region with the C I $^3P_2$–$^3P_1$ line.

2. OBSERVATIONS

Observations of the $^3P_2$–$^3P_1$ line (809.3432 GHz) were carried out with the Mount Fuji submillimeter-wave telescope in 1999 December. The diameter of the main reflector is 1.2 m, which gives a half-power beamwidth of 1'.4 at 809 GHz. The telescope is enclosed in a space frame radome with a GORE-TEX membrane. The Moon efficiency, including the radome loss, was 0.60 at 809 GHz. The pointing of the telescope was calibrated by the continuum observations of the Sun and the Moon at 345 GHz, and the pointing accuracy was maintained to be $20''$ (rms).

For observations of the $^3P_2$–$^3P_1$ line of C I, we developed a triple-band receiver, in which the SIS mixers for the 345, 492, and 809 GHz bands are installed. We employed the parallel-connected twin junction type SIS mixers for the 809 and 345 GHz bands, whereas we used a distribution junction type mixer for the 492 GHz band (Shi et al. 1999). All mixers are

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operated in the double sideband (DSB) mode. The noise temperature for the 809 GHz mixer was 600 K at the operation temperature of 3.9 K (Maezawa et al. 2000). The back end is the acousto-optical radio spectrometer with a total bandwidth of 700 MHz. The frequency resolution of the spectrometer is 1.6 MHz, which corresponds to the velocity resolution of 0.6 km s^{-1} at 809 GHz. During the observations, the zenith opacity was around 1.0, and a typical system noise temperature was 6500 K (DSB).

We observed the $6' \times 6'$ region centered at Orion KL [α(B1950) = $5^h32^m46\overset{s}{.}5$, δ(B1950) = $-5°24'28''$] with a grid spacing of $1\overset{'}{.}5$. In total, 25 positions were observed. Observations were carried out in a frequency-switching mode, in which the frequency offset is set to be 80 MHz. The observed spectrum was folded to improve the signal-to-noise ratio (S/N). Figure 1*a* shows the profile map of the $^3P_2$–$^3P_1$ line. The integration time for the central position, the surrounding eight positions, and the outer 16 positions was 20 minutes, 200 s, and 100 s, respectively. The rms noise was 1 K for the central position, while it was 2 K for the others. The intensity was calibrated by using the chopper-wheel method, in which the difference between the absorber and sky temperatures was taken into account. We also

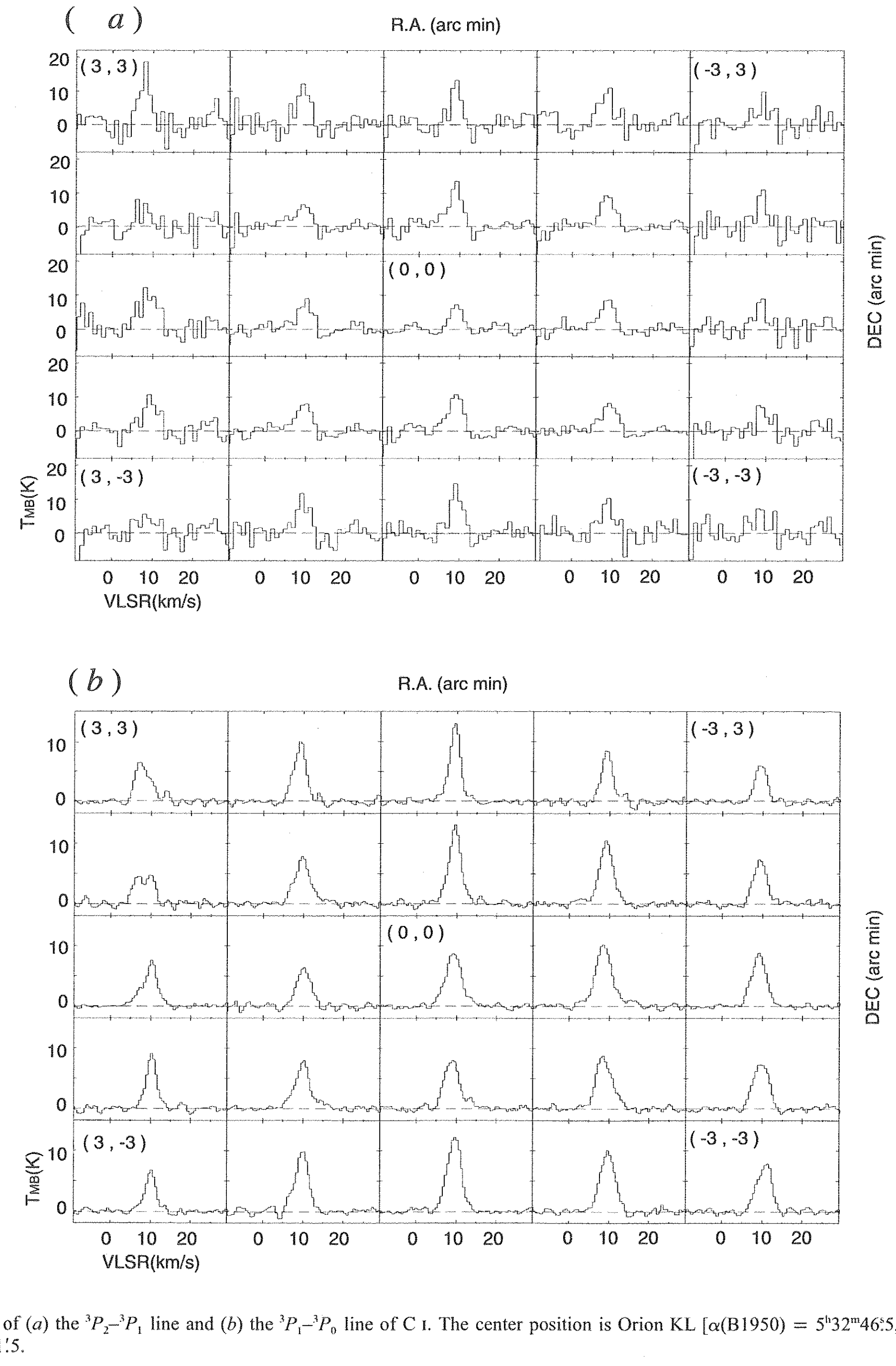

FIG. 1.—Profile maps of (*a*) the $^3P_2$–$^3P_1$ line and (*b*) the $^3P_1$–$^3P_0$ line of C I. The center position is Orion KL [α(B1950) = $5^h32^m46\overset{s}{.}5$, δ(B1950) = $-5°24'28''$], and the grid spacing is $1\overset{'}{.}5$.

TABLE 1

PARAMETERS FOR THE $^3P_2$–$^3P_1$ AND $^3P_1$–$^3P_0$ LINES OBSERVED IN THE ORION KL REGION[a]

POSITION OFFSET[b] ($\Delta\alpha$, $\Delta\delta$)	$^3P_2$–$^3P_1$ T_{mb} (K)	$^3P_2$–$^3P_1$ Δv (km s^{-1})	$^3P_2$–$^3P_1$ V_{LSR} (km s^{-1})	$^3P_1$–$^3P_0$ T_{mb} (K)	$^3P_1$–$^3P_0$ Δv (km s^{-1})	$^3P_1$–$^3P_0$ V_{LSR} (km s^{-1})	T_{ex} (K)	N(C I) ($\times 10^{17}$ cm^{-2})
(0, 0)	7.5(7)	3.4	9.1	8.7(1)	4.7	9.2	44(6)	6.4(2)
(−1.5, 0)	9.0(11)	4.1	8.6	10.0(2)	4.8	8.6	46(8)	7.7(2)
(−1.5, −1.5)	8.0(6)	4.9	9.2	8.6(2)	4.7	8.7	48(6)	6.2(2)
(0, −1.5)	11.5(11)	3.7	9.1	7.9(2)	4.5	8.9	110(40)	5.7(2)
(1.5, −1.5)	8.5(10)	4.1	9.6	7.2(2)	4.4	9.9	69(17)	4.9(2)
(1.5, 0)	8.6(9)	3.6	9.9	6.3(2)	4.1	10.1	93(30)	4.1(2)
(1.5, 1.5)	6.1(10)	5.1	9.0	7.3(2)	4.5	9.7	42(9)	5.0(2)
(0, 1.5)	12.7(14)	3.8	8.9	12.6(2)	3.6	9.6	55(10)	7.4(2)
(−1.5, 1.5)	9.5(11)	4.2	8.5	10.2(2)	4.0	9.2	49(8)	6.5(2)
(0, −3)	13.4(13)	3.4	9.3	12.3(2)	4.1	9.6	63(11)	8.2(1)
(0, 3)	13.4(16)	2.7	8.9	12.7(2)	3.2	9.4	59(12)	6.6(1)

[a] The numbers in parentheses represent standard deviations in units of the last significant digits.

[b] Offset from Orion KL in arcminutes.

observed the $^3P_1$–$^3P_0$ line toward these positions in a position-switching mode, as shown in Figure 1*b* (Ikeda et al. 1999). Line parameters for representative positions are listed in Table 1.

3. DISTRIBUTION OF C I AROUND ORION KL

The peak brightness temperature, the FWHM line width, and the LSR velocity of the C I $^3P_2$–$^3P_1$ line observed toward Orion KL are 7.5 K, 3.4 km s^{-1}, and 9.1 km s^{-1}, respectively. Zmuidzinas et al. (1988) reported a peak brightness temperature of 9.7 K, a line width of 4.3 km s^{-1}, and an LSR velocity of 9.6 km s^{-1} using the 80″ beam observations from the Kuiper Airborne Observatory. Our observational results are almost consistent with theirs.

Figure 2*a* shows the integrated intensity map of the $^3P_2$–$^3P_1$ line of C I. As shown in this map, and in the profile map of Figure 1*a* as well, the C I $^3P_2$–$^3P_1$ emission is stronger by a factor of 2 toward the 1′.5 north and 3′ south positions of Orion KL than toward the center position. This trend can also be seen in the distribution of the $^3P_1$–$^3P_0$ line emission. Figure 1*b* shows the profile map of the $^3P_1$–$^3P_0$ line observed with the Mount Fuji submillimeter-wave telescope. The $^3P_1$–$^3P_0$ emission is rather weak at Orion KL, whereas it is bright at the northern and southern positions, as in the case of the $^3P_2$–$^3P_1$ line. Such a trend in the C I $^3P_1$–$^3P_0$ line emission toward Orion KL was also reported by White & Sandell (1995) through high angular resolution observations (9″.8) using the James Clerk Maxwell Telescope. Our observation indicates that the intensity reduction is also seen in the $^3P_2$–$^3P_1$ line. In contrast, the CO line emission and the dust emission always have a peak toward Orion KL (White & Sandell 1995). Thus, the distribution of the C I emission is locally anticorrelated with those of the CO and dust emissions in the Orion KL region.

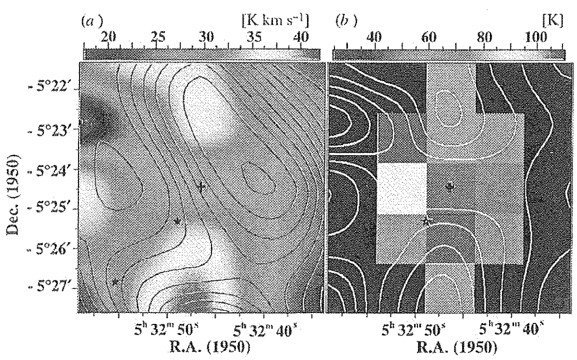

FIG. 2.—(*a*) Map of the integrated intensity of the $^3P_2$–$^3P_1$ line of C I (*color*) superposed on the integrated intensity map of the $^3P_1$–$^3P_0$ line (*contours*). The contours start from 25.5 to 49.5 K km s^{-1} with intervals of 3 K km s^{-1}. The cross indicates Orion KL. The upper star represents θ^1 Ori C, whereas the lower star denotes θ^2 Ori. (*b*) Map of the excitation temperature of C I superposed on the integrated intensity map of the $^3P_2$–$^3P_1$ line (*contour*). The contours start from 19.8 to 39.6 K km s^{-1} with intervals of 3.3 K km s^{-1}.

4. EXCITATION TEMPERATURE

By using equations (7) and (8) of Zmuidzinas et al. (1988), the excitation temperature of C I was evaluated from the observed intensities of the $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$ lines for 11 positions around Orion KL, where the $^3P_2$–$^3P_1$ spectrum was observed with a good S/N. The results are given in Table 1 and Figure 2*b*. In these calculations, we assumed that the excitation temperatures for the two transitions are equal to each other. We made no correction for the difference in the beam size of the two transitions. The excitation temperature ranges from 40 to 110 K, as shown in Table 1. It is determined to be 44 K toward Orion KL, where the optical depths of the $^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$ lines are 0.32 and 0.30, respectively. Zmuidzinas et al. (1988) derived the excitation temperature of C I to be 77 K. White & Sandell (1995) also reported the excitation temperature to be higher than 90 K by using the $^3P_2$–$^3P_1$ intensity measured by Zmuidzinas et al. (1988) and the $^3P_1$–$^3P_0$ intensity measured by themselves. Zmuidzinas et al. (1988) calculated the above value by correcting the negative contribution from the off position (7′ away from the on position), assuming that the source size is 16′. However, the source structure of C I in the Orion KL region is complicated in the 10′ scale (Ikeda et al. 1999), and hence it seems difficult to eliminate the negative intensity contribution from the off position by a simple assumption for the source structure. As a consequence, the contribution would be overestimated in their analysis, which yielded the high-excitation temperature mentioned above. In fact, they reported the excitation temperature to be 42 K, if no correction for the off-beam contribution is taken into account. This value is close to our estimate.

From Figure 2*b*, it can be seen that the excitation temperature is considerably high toward the eastern to southern positions of the map. This high-excitation temperature is the result of the spatial proximity to the exciting source, θ^1 Orionis C. On the other hand, the excitation temperature toward Orion KL is found to be similar to, or even lower than, those toward surrounding positions. According to the CO ($J = 2$–1) observation by White & Sandell (1995), the gas kinetic temperature is reported to be 110 K toward Orion KL with the 80″ beam. The hot core source in Orion KL is known to have a gas kinetic temperature as high as about 300 K on the basis of observations of various molecules (Blake et al. 1987). The excitation temperature of C I derived from our observations is significantly lower than the gas kinetic temperature of the hot core region. Because of the low critical density of the $^3P_2$–$^3P_1$ line (3000 cm^{-3}), the excitation temperature should be comparable to the gas kinetic temperature, if C I really existed in the hot core. The derived excitation temperature suggests that the C I emission does not come mainly from such a hot and dense region, where most of C I has been converted into CO.

5. ORIGIN OF RELATIVELY WEAK C I INTENSITY TOWARD ORION KL

The distribution of the excitation temperature of C I observed around Orion KL suggests that the C I emission arises from a photodissociation region layer on the molecular cloud. The column density of C I in this region is almost constant within a factor of 2, indicating a uniform thickness of the layer. These results are qualitatively consistent with the picture of this region proposed by Tielens & Hollenbach (1985) and Stacey et al. (1993).

Figure 3 shows variations of $T_{\rm mb}$ ($^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$), the excitation temperature, and the column density along the north to south line passing through Orion KL. This clearly indicates the relative reduction in the C I intensity toward Orion KL. However, the C I column density does not follow the intensity variation. Rather, the reduction should be ascribed to a decrease in the excitation temperature. In fact, the excitation temperature observed toward Orion KL is 44 K, which is the second lowest among the 11 positions.

One plausible explanation for the low-excitation temperature is based on the radiative transfer effect. Since the hot core of Orion KL is located on the back side of the photodissociation layer (e.g., Stacy et al. 1993), the dust emission from the hot core plays the role of background radiation for the C I emission. An increase in the background radiation from the cosmic background level results in a decrease of the $(h\nu/k)[J_\nu(T_{\rm ex})–J_\nu(T_b)]$ factor, where $J_\nu(T)$ represents the Planck function. The low-excitation temperature of C I toward Orion KL would therefore be an apparent effect caused by neglecting the background continuum emission from the hot core. According to the 350 μm continuum emission observations (Lis et al. 1998), its peak intensity is as high as 1300 Jy with the 12″ beam toward Orion KL. We convolved the distribution of the 350 μm emission with the 80″ Gaussian beam and evaluated its brightness temperature

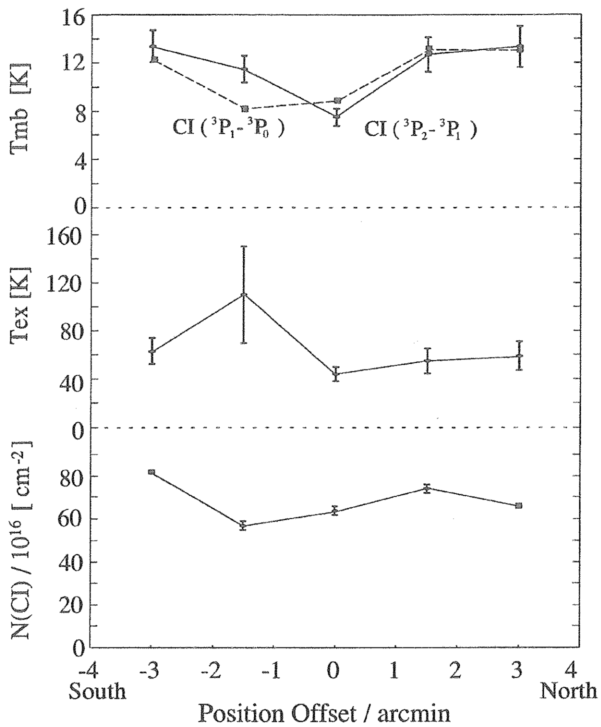

FIG. 3.—Variations of $T_{\rm mb}$ ($^3P_2$–$^3P_1$ and $^3P_1$–$^3P_0$), $T_{\rm ex}$, and N(C I) along the north (*right*) to south (*left*) line passing through Orion KL (zero offset position).

to be 4.4 K toward Orion KL. This temperature cannot be negligible when it is compared with $(h\nu/k)J_\nu(T_{\rm ex})$, i.e., 27 K toward Orion KL. Therefore, the background continuum emission seems to contribute at least in part to the relative reduction in the C I intensity toward Orion KL. Local anticorrelation between the distribution of the C I emission and that of the dust emission (White & Sandell 1995) also supports this picture. We have estimated the intrinsic excitation temperature and the C I column density, including the effect of the background continuum emission. For this purpose, we slightly modified the equations by Zmuidzinas et al. (1988) so as to include the background emission. The excitation temperature is thus determined to be 52 K, whereas the C I column density is unchanged. This new excitation temperature is closer to those in the northern positions.

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