ATOMIC CARBON AND CO ISOTOPE EMISSION IN THE VICINITY OF DR 15

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ABSTRACT

We present observations of the $^3P_1-^3P_0$ fine-structure transition of atomic carbon [C I], the $J = 3–2$ transition of CO, and the $J = 1–0$ transitions of $^{13}$CO and C$^{18}$O toward DR 15, an H II region associated with two mid-infrared dark clouds (IRDCs). The $^{13}$CO and C$^{18}$O $J = 1–0$ emissions closely follow the dark patches seen in optical wavelength, showing two self-gravitating molecular cores with masses of 2000 and 900 $M_{\odot}$, respectively, at the positions of the cataloged IRDCs. Our data show a rough spatial correlation between [C I] and $^{13}$CO $J = 1–0$. Bright [C I] emission occurs in the relatively cold gas behind the molecular cores but does not occur in either highly excited gas traced by CO $J = 3–2$ emission or in the H II region/molecular cloud interface. These results are inconsistent with those predicted by standard photodissociation region models, suggesting an origin for interstellar atomic carbon unrelated to photodissociation processes.

Subject headings: H II regions — ISM: atoms — ISM: molecules — radio lines: ISM

1. INTRODUCTION

The amount and distribution of atomic carbon is important for understanding the physical and chemical structure, formation processes, and thermal balance of interstellar molecular clouds. Since the ionization potential of neutral atomic carbon (11.266 eV) is close to the dissociation energy of CO (11.09 eV), C$^0$ is thought to be confined in the thin layer near the surface of molecular clouds. Chemical models of molecular clouds exposed to ultraviolet (UV) radiation demonstrate the concentration of C$^0$ in the range $A_V = 3–6$ mag (Tielens & Hollenbach 1985; van Dishoeck & Black 1988; Hollenbach, Takahashi, & Tielens 1991).

The $^3P_1-^3P_0$ fine-structure line of neutral atomic carbon [C I] (492.160651 GHz; Yamamoto & Saito 1991) has been known to be a good tracer of interstellar atomic carbon. After the first detection (Phillips et al. 1980), the rapid advance in receiver sensitivity in the submillimeter wavelength has resulted in the $^3P_1-^3P_0$ line being well studied at present in many Galactic sources. Large-scale observations have revealed that [C I] emission is widespread throughout molecular clouds (Plume, Jaffe, & Keene 1994; Plume et al. 1999; Maezawa et al. 1999; Ikeda et al. 1999) and is thus not confined in the vicinities of UV sources. Observations on scales of tens of degrees have shown that [C I] emission is widespread on Galactic scales also (Wright et al. 1991; Bennett et al. 1994).

There have been some arguments (Keene et al. 1985; Schilke et al. 1993, 1995; Maezawa et al. 1999; Ikeda et al. 1999) that C$^0$ also exists deep within molecular clouds, where UV radiation is attenuated. Models of time-dependent chemistry (Suzuki 1979; Leung, Herbst, & Huelner 1984; Suzuki et al. 1992; Lee et al. 1996) predict that C$^0$ can be abundant in the interior of a newly formed dense core since the conversion timescale of C$^0$ to CO is comparable to the dynamical timescale of the core. Even in steady states, some models predict that under certain circumstances [C I] can be abundant in the absence of UV radiation (Pineau des Forêts, Roueff, & Flower 1992; Le Bourlot, Pineau des Forêts, & Roueff 1993, 1995a; Le Bourlot et al. 1995b; Lee et al. 1998). Such models give two stable solutions of chemical equilibrium at low densities: the low-ionization phase (LIP) and the high-ionization phase (HIP).

[C I] line observations from objects with high visual extinction ($A_V$) may be crucial to answering the question of whether C$^0$ really exists deep inside molecular clouds. In this study, we chose DR 15, an H II region in the Cygnus X region, as a target. DR 15 is associated with two mid-infrared dark clouds (IRDCs); Egan et al. 1998) that belong to a population of compact objects with significant mid-infrared extinctions ($A_{8.6\mu m} > 2$, which corresponds to $A_V$ $\gtrsim$ 200). H$_2$CO observations (Carey et al. 1998) have shown that IRDCs are cold ($T_{k} < 20$ K) and dense ($n(H_2) > 10^5$ cm$^{-3}$). The lack of mid- to far-infrared emission associated with these clouds suggests that they do not contain currently forming high-mass stars. DR 15 itself is formed by one or two B0 zero-age main-sequence stars(s), observed as the far-infrared (FIR) source FIR 1 (Odenwald et al. 1990) and having a total luminosity of $\sim 3 \times 10^6 L_{\odot}$. Assuming that all the flux of FIR 1 was initially emitted in the UV (6–13.6 eV), a UV enhancement factor $G_0$ is estimated to be $\sim 550$ at 1 pc from the ionizing star(s).

This paper presents the results of $C + ^3P_1-^3P_0$, CO $J = 3–2$, $^{13}$CO $J = 1–0$, and C$^{18}$O $J = 1–0$ observations of...
the DR 15 region. These data are used to study the C\(^0\) column density and C\(^0\)/CO abundance ratio as well as their spatial variations, especially in relation to the UV source and the IRDCs.

2. OBSERVATIONS

2.1. Mount Fuji Observations

The C \(^1\) \(^3\)P\(_1\)–\(^3\)P\(_0\) (492.160651 GHz) and CO \(J = 3–2\) (345.795991 GHz) observations were performed with the Mount Fuji submillimeter-wave telescope (Sekimoto et al. 2001) in 1999 March and December and 2000 January. The diameter of the telescope is 1.2 m, which gives half-power beamwidths of 22\(^\circ\) at 492 GHz and 3\(^\circ\) at 346 GHz. The pointing of the telescope was checked and corrected by observing the Sun and the full Moon every month, and its accuracy was maintained within 20\(^\circ\) (rms) during the observing season. The beam efficiencies, including radome loss \(\eta_{\text{radome}}\), were measured by observing the full Moon to be 72\% (492 GHz) and 75\% (346 GHz), and the main-beam efficiencies are estimated to be 45\% (492 GHz) and 67\% (346 GHz). The telescope efficiencies and beamwidths at the observed frequencies are summarized in Table 1.

The telescope is equipped with three SIS receivers (346, 492, 809 GHz) operated in the double-sideband (DSB) mode. The typical DSB system noise temperatures during the observations were 700 K for 492 GHz and 500 K for 346 GHz. Calibration of the antenna temperature was accomplished by chopping between an ambient temperature load and the sky. Reproducibility of intensities was checked by monitoring the calibration sources Orion KL and DR 21 and was found to be reliable within 9\% (1\(\sigma\)) at 492 GHz and 11\% (1\(\sigma\)) at 346 GHz\(^{10}\) during the DR 15 observations. All spectra were obtained with a 1024 channel acousto-optical spectrometer (AOS), which covers an instantaneous bandwidth of 700 MHz with a spectral resolution of 1.6 MHz. These correspond to a 430 km s\(^{-1}\) velocity coverage and a 1 km s\(^{-1}\) velocity resolution at the [C i] line frequency.

The [C i] observations were performed in a frequency switching mode. Switching frequency was set to 80 MHz and intervals were set to 10 s. The on-source integration time was 100 s for each position, and rms noise was 0.1 K in \(T^*_A\). The CO \(J = 3–2\) observations were performed by position switching to a clean reference position, \((\alpha_{1950}, \delta_{1950}) = (20^h45^m00^s, +42^\circ09'00'')\). Typical on-source integration time was 350 s, which yielded an rms noise of 0.2 K in \(T^*_A\). We mapped a 27\(\times\)27\' area in the [C i] line and a 42\(\times\)30\' area in the CO \(J = 3–2\) line, on a 1.5\' grid. We subtracted baselines of the spectra by fitting fourth order polynomial lines.

2.2. Nobeyama Radio Observatory 45 m Observations

The \(^{13}\)CO and \(^{18}\)O \(J = 1–0\) observations were made with the Nobeyama Radio Observatory (NRO) 45 m telescope in 2000 January. The NRO 45 m telescope has a 17\"\(\pm\)1\" full width at half-maximum (FWHM) beam at 110 GHz. Pointing errors were corrected every 2 hr by observing the SiO maser source, UX Cyg, with the HEMT amplifier receiver at 43 GHz. The pointing accuracy of the telescope was good to \(\pm3\"\) in both azimuth and elevation.

We used the 2 \(\times\) 2 focal plane array SIS receiver, S115Q. Typical system noise temperature was 400 K during the observations. Calibration of the antenna temperature was accomplished by a standard chopper-wheel method. Since the mixers in S115Q work in a quasi-single sideband mode, we scaled the antenna temperature for each channel referring to that taken with the single-beam SIS receiver S100, equipped with a quasi-optical image rejection filter. Every observing day, we took spectra of DR 21 (CO) (Richardson et al. 1986) at \((\alpha_{1950}, \delta_{1950}) = (20^h43^m09^s, +42^\circ09'00'')\) near its transit with each channel of S115Q and calculated scaling factors by comparing \(T^*_A(^{12}\text{CO}) = 12.8\) K or \(T^*_A(^{13}\text{CO}) = 2.12\) K. We used high-resolution AES, each of which covers an instantaneous bandwidth of 40 MHz with a spectral resolution of 37 kHz. At the \(^{13}\)CO \(J = 1–0\) frequency, these correspond to a 110 km s\(^{-1}\) velocity coverage and a 0.1 km s\(^{-1}\) velocity resolution, respectively.

All data were obtained by position switching to a reference position \((\alpha_{1950}, \delta_{1950}) = (20^h45^m13^s, +42^\circ38'52'\)\). To conduct the survey effectively, three on-source positions were observed for one reference position observation. We mapped a 20\'\(\times\)20\' area in the \(^{13}\)CO line and a more restricted area in the \(^{18}\)O line on a 34\' grid. We also made a 17\’\ grid \(^{13}\)CO mapping in 2.5 \(\times\) 2.5 areas around the two mid-IRDCs and the CO \(J = 3–2\) emission peak. Typically 20 s on-source integration gave spectra with rms noise of 0.5 K (\(T^*_A\)) at a velocity resolution of 0.1 km s\(^{-1}\). We subtracted baselines of the spectra by fitting first- or third-order polynomial lines.

3. RESULTS

The integrated intensity map in the [C i] and CO \(J = 3–2\) line are shown in Figure 1 with the optical image. Figure 2 shows the observed spectra of [C i] \(^3\)P\(_1\)–\(^3\)P\(_0\), CO \(J = 3–2\), \(^{13}\)CO \(J = 1–0\), and \(^{18}\)O \(J = 1–0\) toward four

### TABLE 1: Telescope Parameters

| Line | Transition | Frequency (GHz) | Telescope | HPBW | \(T^*_A\) (K) | \(\eta_{\text{sys}}\) | \(\eta_{\text{radome}}\) | \(\eta_{\text{beam}}\) | Spectra |
|------|------------|----------------|-----------|-------|-------------|----------------|----------------|----------------|--------|
| C i 1 | \(^3\)P\(_1\)–\(^3\)P\(_0\) | 492.160651 | Mount Fuji | 2.2\(^\text{a}\) | 900 | 0.72 | 0.45\(^\text{a}\) | 539 |
| CO | \(J = 3–2\) | 345.795989 | Mount Fuji | 3.1\(^\text{b}\) | 500 | 0.75 | 0.67\(^\text{b}\) | 324 |
| \(^{13}\)CO | \(J = 1–0\) | 110.201353 | NRO 45 m | 17\(^\text{c}\) | 400 | 0.58 | 0.48 | 1088 |
| \(^{18}\)O | \(J = 1–0\) | 109.782182 | NRO 45 m | 17\(^\text{c}\) | 400 | 0.58 | 0.48 | 624 |

\(^{a}\) The effective main-beam efficiencies, including the effect of optical depth and the average temperature difference between the chopper inside the radome and the outside atmosphere.

\(^{b}\) Units are arcminutes.

\(^{c}\) Units are arcseconds.
Fig. 1.—(a) Optical image of DR 15 from the Digitized Sky Survey. Data are taken from the SkyView Web page. White triangle, the position of the brightest FIR source, DR 15 FIR 1; white circles, the positions of cataloged IRDCs G79.27 + 0.38 and G79.34 + 0.33. (b) Map of the $^{13}$CO $J = 3$–$2$ emission, integrated over the velocity range $V_{\text{LSR}} = -7.5$ to $+7.5$ km s$^{-1}$ and smoothed with the FWHM = 120$''$ Gaussian weighting function. Contours are set at intervals of 0.5 K km s$^{-1}$. (c) Map of CO $J = 3$–$2$ emission, integrated over the velocity range $V_{\text{LSR}} = -7.5$ to $+7.5$ km s$^{-1}$ and smoothed with the FWHM = 120$''$ Gaussian weighting function. Contours are set at intervals of 1.5 K km s$^{-1}$.

Fig. 2.—Observed spectra of C I $^2P_{1/2}$–$^2P_{3/2}$, CO $J = 3$–$2$, $^{13}$CO $J = 1$–0, and C$^{18}$O $J = 1$–0 lines toward (a) the C I peak, (b) the centers of G79.37 + 0.33, (c) G79.27 + 0.38, and (d) the CO $J = 3$–$2$ peak.
C I and CO Isotope Emission

Fig. 3.—(a) Map of the $^{13}$CO $J = 1–0$ emission, integrated over the velocity range $V_\text{LSR} = -7.5$ to $+7.5$ km s$^{-1}$ and smoothed with the FWHM = 45" Gaussian weighting function. Contours are set at intervals of 2 K km s$^{-1}$; white contours begin at 26 K km s$^{-1}$. (b) Map of the C$^{18}$O $J = 1–0$ emission; velocity range and smoothing width are the same as for panel (a). Contours are set at intervals of 0.8 K km s$^{-1}$; white contours begin at 7.2 K km s$^{-1}$. (c) Map of the $^{13}$CO $J = 1–0$ integrated intensity overlaid on the Digitized Sky Survey image. Contours are set at intervals of 4 K km s$^{-1}$. (d) Map of the C$^{18}$O $J = 1–0$ integrated intensity overlaid on the Digitized Sky Survey image. Contours are set at intervals of 1.6 K km s$^{-1}$.

3.1. C I Distribution

The [C I] emission is extended over the map with patchy morphology, as it is not restricted to a region adjacent to the H II region, DR 15. It roughly follows dark patches in the optical image. An intense [C I] lump with a size of 8' x 6' (2.3 x 1.7 pc$^2$) lies farther from the ionization front than the two IRDCs do. The [C I] lump has a “hump” in its southern portion near the position of G79.34+0.33, while G79.27+0.38 has no [C I] counterpart. The [C I] lump has a weak extension to the south that follows the brightest part of the optical nebula.

3.2. CO $J = 3–2$ Distribution

The CO $J = 3–2$ emission is extended over the map with smoother distribution than [C I]. It peaks strongly at the position of DR 15 FIR 1 (Odenwald et al. 1990), which may coincide with the ionizing star(s), and exhibits a poor spatial correlation with the [C I] distribution. The displacement of the CO $J = 3–2$ peak from that of [C I] is about 7' (2 pc). A weak-intensity western emission hump may correspond to G79.27+0.38, while G79.34+0.33 is included in the bulk emission associated with DR 15.

3.3. $^{13}$CO and C$^{18}$O Distributions

The $^{13}$CO $J = 1–0$ and C$^{18}$O $J = 1–0$ maps show two prominent cores with diameters of 2'–3' (0.6–0.9 pc) that
spatially coincide with the IRDCs G79.27 + 0.38 and G79.34 + 0.33. Both the \(^{13}\)CO and C\(^{18}\)O emissions closely follow dark patches in the optical image. The most intense CO peak lies at the G79.34 + 0.33 core, being associated with a C I counterpart. A low-intensity envelope of the \(^{13}\)CO emission extends over the upper half of the map, showing a rough spatial correlation with the [C I] lump (Fig. 4). A weak \(^{13}\)CO emission peak at \((\alpha_{1950}, \delta_{1950}) = (20^h30^m22^s, +40^\circ13^\prime)\) corresponds to the northwest corner of the [C I] lump. No CO counterpart of the [C I] peak was found. Two small clumps at \((\alpha_{1950}, \delta_{1950}) = (20^h39^m40^s, +40^\circ06^\prime)\) and another larger clump in the south correspond to the CO \(J = 3-2\) peak and its southern extension. Since the two small clumps coincide with a band of obscuration separating the optical emission nebula, they must be in front of the H II region.

The two molecular cores that correspond to G79.27 + 0.38 and G79.34 + 0.33 have local thermodynamic equilibrium (LTE) masses of \(2.0 \times 10^3\) and \(9.1 \times 10^2\) \(M_\odot\), respectively, if we assume \(T_K = 20\) K (see § 4.2). These masses are similar to their virial masses of \(1.3 \times 10^3\) and \(9.2 \times 10^2\) \(M_\odot\), suggesting that the cores are gravitationally bound. The mean densities derived from LTE masses are \(n(H_2) \approx 1.2 \times 10^4\) and \(\approx 1.3 \times 10^4\) \(\mathrm{cm}^{-3}\), which are consistent with the densities determined from large velocity gradient (LVG) analysis of H\(_2\)CO lines (Carey et al. 1998).

### 3.4. Integrated Line Intensities

Figure 5 shows correlation plots between the line intensities integrated over the range \(V_{LSR} = -7.5\) to \(+7.5\) km \(s^{-1}\). All the data are smoothed with the FWHM = 2\('\) Gaussian weighting function and are resampled to the same regular grids with 1\('\) spacings. There is a rough correlation between the [C I] intensity and the \(^{13}\)CO \(J = 1-0\) intensity (correlation coefficient \(R = 0.62\); Fig. 4a). A least-squares regression to a linear relation gave the following relation:

\[
\int T_{MB}(\text{C I})dV = (0.66 \pm 0.46) + (0.25 \pm 0.02) \int T_{MB}(^{13}\text{CO})dV .
\] (1)

No correlation between the [C I] intensity and the \(^{18}\)C O \(J = 1-0\) intensity has been found \((R = 0.35\); Fig. 4b). The \(^{18}\)C O intensity is well correlated with the \(^{13}\)CO intensity \((R = 0.85\); Fig. 4c). The CO \(J = 3-2\) intensity shows a poor correlation with the [C I] intensity \((R = 0.42\); Fig. 4d). This seems to be remarkable because both line emissions are generally thought to arise from UV-irradiated cloud surfaces (e.g., Warin, Benayoun, & Viala 1996).

### 4. DISCUSSION

#### 4.1. Column Densities

Since the critical densities of C I \(^3P_1-^{3}P_0\) and CO \(J = 1-0\) lines are similar to each other \((\approx 10^5\) \(\text{cm}^{-3}\)), we expect similar excitation temperatures \((T_{ex})\) for both transitions if C\(^0\) and CO reside in the same or adjacent layers. We have calculated the C\(^0\) and CO column densities by assuming homogeneous clouds in LTE.

The total beam-averaged [C I] column density is given by

\[
N(C^0) = 1.98 \times 10^{15} \int T_{MB}dV Q(T_{ex}) \exp \left( \frac{E_1}{kT_{ex}} \right) \times \left[ 1 - \frac{J_s(T_{MB})}{J_s(T_{ex})} \right]^{-1} \frac{\tau_{C I}}{1 - e^{-\tau_{C I}}} ,
\] (2)

where \(Q(T_{ex})\) is the ground-state partition function for the carbon atom,

\[
Q(T_{ex}) = 1 + 3 \exp \left( -\frac{E_1}{kT_{ex}} \right) + 5 \exp \left( -\frac{E_2}{kT_{ex}} \right) .
\] (3)
Here $E_1$ is the energy of the $J = 1$ level ($E_1/k = 23.6$ K) and $E_2$ is the energy of the $J = 2$ level ($E_2/k = 62.5$ K). The factor $\tau_c/(1 - e^{-\tau_c})$ is a correction factor for the velocity-averaged optical depth and is unity at the optically thin limit ($\tau_c < 1$). We substitute the optical depth at the peak velocity for the velocity-averaged optical depth. This substitution makes the derived column density an upper limit, while the optically thin assumption gives a lower limit. The peak C I optical depth is given by

$$\tau_{CI} = -\ln \left\{ 1 - \frac{T_{MB}}{\eta_f [J_v(T_{ex}) - J_v(T_{BB})]} \right\},$$

where $\eta_f$ is the beam filling factor and $J_v$ is the radiation temperature,

$$J_v(T) = \frac{h v/k}{\exp (h v/k T) - 1}.$$  

We assumed that $\eta_f = 1$ in the C I optical depth estimation. Arguments based on observations of the C I $3P_2 - 3P_1$ and $3P_1 - 3P_0$ ratio suggest that the C I $3P_1 - 3P_0$ opacity is usually $\lesssim 1$ (Zmuidzinas et al. 1988; Genzel et al. 1988). Our observations also gave $\tau_{CI} < 1$, even for the [C I] intensity peak position ($\tau_{CI} = 0.6$). The uncertainty in the estimated C O column density brought by the optical depth correction may be less than 33%. Although the subbeam filling effect may raise the optical depth, it does not make a significant revision to the column density as long as the C I line is optically thin. The calibration error of submillimeter line intensity also causes uncertainty in the column density (9%).

The general equation for estimating the CO column density is given by

$$N(\text{CO}) = 5.55 \times 10^{17} \int T_{MB} dV T_{ex} \exp \left( \frac{E_u}{k T_{ex}} \right) \times \left[ 1 - \frac{J_v(T_{MB})}{J_v(T_{ex})} \right]^{-1} \frac{\tau_{CO}}{1 - e^{-\tau_{CO}}},$$

where $E_u$ is the upper level energy and $\tau_{CO}/(1 - e^{-\tau_{CO}})$ is a correction factor for the velocity-averaged optical depth of
parallel PDR models. In M17 and S140, similar arrangements have been reported by Keene et al. (1985). We have also found the C\(^+\)/CO\(^0\) arrangement in the Orion KL region (M. Ikeda et al. 2001, in preparation) and the \(\rho\) Ophiuchi main cloud (L1688; K. Kamegai et al. 2001, in preparation). If the [C \(\iota\)] peak is shadowed by G79.37 +0.33, the visual extinction between the ionization front and the [C \(\iota\)] peak position exceeds 80 mag. The [C \(\iota\)] peak direction itself has a line-of-sight extinction of 20–30 mag. On the other hand, models for plane-parallel PDRs have shown that the layer with \(N(C(\iota)/N(CO) > 0.1\) has a depth smaller than 7 mag. Clumpy structure may help UV photons penetrate deep into molecular clouds. However, if we assume \(n(H_2) = 10^4 - 10^5\) cm\(^{-3}\) and an empirical relation \(N(H_2) = 1.6 \times 10^{21} A_p\) cm\(^{-2}\), \(N(C(\iota)/N(CO) < 0.1\) requires clumps with sizes larger than 0.4–4 pc, which is larger than the resolution of our observations (NRO 45 m: 0.16 pc; Mount Fuji: 0.64 pc).

In addition, the integrated intensity of the CO \(J = 3–2\) line, which also arises from UV-irradiated cloud surfaces (e.g., Gierens, Stutzki, & Winnewisser 1992), shows poor spatial correlation with the [C \(\iota\)] intensity (Fig. 1). The CO \(J = 3–2\) intensity strongly peaks at DR 15 FIR 1, having an extent of \(5' \times 10'\) (1.5 x 3 pc\(^2\)), while the [C \(\iota\)] intensity peaks farther into the molecular cloud from the ionization front than either of the \(J = 1–0\) lines of the CO isotope do. The situation is illustrated well in Figure 6, which shows a plot of integrated intensities along a line passing through the [C \(\iota\)] peak and DR 15A, a compact radio source located at the brightest part of FIR 1 (Colley 1980). A hump at DR 15 in the [C \(\iota\)] intensity is the southern extension of the [C \(\iota\)] lump (§ 3.1), and it could correspond to the emission from the thin photodissociated layer near surfaces of UV-irradiated clouds.

The variation of the density could account for the observed arrangement. Lower density produces a lower temperature photodissociated layer with low rates of OH production and consequently increases C\(^0\) by shutting off the CO formation route through OH (e.g., Hollenbach et al. 1991). Following this idea, the observed C\(^0\) column densities require gas density around DR 15 to be at least an order of magnitude higher than the [C \(\iota\)] peak and the dense molecular core G79.37 +0.33. G79.27+0.38 has a C\(^0\) column that is lower than that of G79.37+0.33 by a factor of 3, although both have similar densities (§ 3.3) and UV environments. Apparently G79.37 +0.33 has a [C \(\iota\)] counterpart while G79.27 +0.38 does not. The mean H\(_2\) density toward the CO \(3–2\) peak, estimated from the \(^{13}\)CO column density, is not so high: \(n(H_2) < 2 \times 10^4\) cm\(^{-3}\). This suggests that the density is unlikely a key parameter in determining the C\(^0\) column density in the DR 15 region.

The C\(^0\) column density toward the CO 3–2 peak is estimated to be \(9.3 \times 10^{16}\) cm\(^{-2}\). According to Hollenbach et al. (1991), a plane-parallel PDR with \(G_0 = 500\) and \(n_0 = 10^4\) cm\(^{-3}\) has a C\(^0\) column density of 2.5 \(\times 10^{17}\) cm\(^{-2}\). This value differs from the observed value by more than a factor of 2. Indeed, \(G_0\) may be higher than 500 at the position close to DR 15A; if so, the discrepancy between theory and observation would be more significant. The hypothesis of unresolved high-density clumps does not change the situation; it decreases the C \(\iota\) column density of each clump while it increases the surfaces, to be consistent with the observed \(^{13}\)CO intensity. We therefore conclude that the steady state PDR models are not able to give reasonable
interpretations of the observed CO 3–2 H/II/CO/C I arrangement or of the deficit of C\(^0\) toward DR 15.

4.2.2. Origin of Atomic Carbon Unrelated to Photodissociation

The similarity in the distributions of the [C I] and \(^{13}\)CO lines may be an indication that these lines arise from the same spatial regions. This implies that C\(^0\) basically coexists with molecular gas except for in the dense regions in molecular clouds such as the molecular cores G79.37+0.33 and G79.27+0.38. This idea is supported by the results of our large-scale C I surveys of nearby molecular clouds (e.g., Ikeda et al. 1999). To account for the coexistence of C\(^0\) and CO, some revisions to the steady state PDR models or the application of models unrelated to photodissociation may be inevitable. It may be constructive to examine the other ideas for the origin of atomic carbon unrelated to photodissociation processes.

Time-dependent chemistry models (e.g., Lee et al. 1996; Störzer, Stutzki, & Sternberg 1997; Suzuki et al. 1992) can explain the observed [C I] and CO distributions. The dynamical timescale of a dense core with \(n(H_2) = 10^5\) cm\(^{-3}\) is \(t_{\text{dyn}} \approx 10^7\) yr, while its chemical timescale (timescale for conversion from C\(^0\) to CO) is \(t_{\text{chem}} \approx 10^4\) yr. Thus the carbon in a high-density core is incorporated into CO completely before the core collapses. In the less dense region with \(n(H_2) = 10^4\) cm\(^{-3}\), the dynamical timescale and the chemical timescale become comparable \((\sim 3–4) \times 10^5\) yr, and hence C\(^0\) can coexist with CO for a while even after UV radiation is shielded. The C I-rich cloud found in Heiles Cloud 2 (Maezawa et al. 1999) may be typical of such a chemically young molecular cloud. It is likely that the high-density cores G79.37+0.33 and G79.27+0.38 are chemically evolved, while the less dense envelope is chemically young.

Another idea is based on the chemical models with bistable solutions. These models predict that there exist two phases in the chemical equilibrium state at low densities \((n_H \leq 5500\) cm\(^{-3}\); Pineau des Forêts et al. 1992). The two stable solutions, the HIP and the LIP, lead to two different C\(^0\)/CO ratios in clouds with identical density and temperature. This means that the gas-phase abundance of C\(^0\) can be large (C\(^0\)/CO = 0.1–0.2) in HIP, even in the absence of a UV field. For the core clouds, where the density exceeds the critical value for bistability, the system necessarily takes a solution with a low C\(^0\)/CO ratio (\(\leq 0.01\)). The chemical bistability can be applicable to the DR 15 case if we consider the [C I] peak as HIP and the cores of G79.37+0.33 and G79.27+0.38 as LIP. The bistability model can also account for the ubiquitous value of the C\(^0\)/CO ratio (0.1–0.2) over the bulk of molecular clouds, although its applicability is still controversial.

5. CONCLUSIONS

We have studied the distributions of the C I \(^3\)P\(_1\)–\(^3\)P\(_0\) line, the CO J = 3–2 line, and the J = 1–0 transition of \(^{13}\)CO and C\(^18\)O toward DR 15, an H II region associated with two IRDCs. Neutral atomic carbon is extended over the molecular clouds traced by the \(^{13}\)CO J = 1–0 line. The two dense molecular cores, with masses of \(2.0 \times 10^3\) and \(9.1 \times 10^2\) M\(_\odot\), corresponding to the IRDCs, have been found in the \(^{13}\)CO and C\(^18\)O data. The [C I] integrated intensity peaks farther into the molecular cloud from the ionization front behind the IRDCs. The column density ratio N(C\(^0\))/N(CO) toward the [C I] peak is 0.15, which is similar to those observed in giant molecular clouds and nearby dark clouds, while the dense cores (IRDCs) exhibit very low ratios (\(\sim 0.02\)). The CO J = 3–2 emission strongly peaks at the DR 15 FIR 1, exhibiting a poor spatial correlation with the [C I] distribution. The CO J = 3–2 H/II/CO/C I arrangement and the deficit of C\(^0\) toward DR 15 are inconsistent with the prediction of PDR models and suggest an origin for interstellar atomic carbon unrelated to photodissociation. Models with time-dependent chemistry or chemical bistability could account for the observed H/II/CO/C\(^0\) arrangement and the C\(^0\)/CO ratios as well.

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