THE ASTROPHYSICAL JOURNAL, 425:L49–L52, 1994 April 10

OBSERVATIONS OF LARGE-SCALE [C I] EMISSION FROM S140

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Received 1993 October 20; accepted 1993 December 22

ABSTRACT

We have mapped the large-scale distribution of the 492 GHz [C I] $^3P_1 \rightarrow {}^3P_0$ and 220 GHz ^{13}CO $J = 2 \rightarrow 1$ lines across the S140 molecular cloud. The observations employed the University of Texas Gaussian Focal Reducer on the Caltech Submillimeter Observatory telescope to produce a high surface accuracy off-axis telescope with a 3′ beam. The [C I] emission covers a ≥ 8 by ~ 10 pc region which closely matches the extent of the S140 molecular cloud as seen in ^{13}CO. The line shapes of [C I] and ^{13}CO are also quite similar. Typical column densities of C^0 are ~ 15 times those of ^{13}CO. In this source, the neutral carbon emission most likely arises in the photon-dominated surface layers of molecular clumps. The layer in which C^0 is the dominant form of gaseous carbon contains $\geq 20\%$ of all the neutral material in the extended cloud. The ratio of the [C I] $^3P_1 \rightarrow {}^3P_0$ to CO $J = 2 \rightarrow 1$ cooling integrated over the cloud is ~ 1.3, similar to the global value of this ratio in our Galaxy and to the value in the inner 100 pc of IC 342 and M82.

Subject headings: ISM: abundances — ISM: atoms — ISM: individual (S140) — ISM: molecules — radio lines: ISM

1. INTRODUCTION

The lines arising in the ground-state fine-structure triplet of neutral carbon should be readily observable over a large fraction of the dense interstellar medium. The lowest lying transition ($^3P_1 \rightarrow {}^3P_0$, 492 GHz) arises in a state which is only 23 K above ground. The critical density for this transition is $\sim 10^3$ cm^{-3} for collisions with H_2 (Schröder et al. 1991).

Many of the initial chemical equilibrium models of molecular clouds predicted a high neutral carbon abundance in a relatively thin layer near the cloud surface (e.g., Langer 1976; Clavel, Viala, & Bel 1978; de Jong, Dalgarno, & Boland 1980). Later, more elaborate, models of the photon-dominated surface layers of molecular clouds (PDRs) showed that these layers would have a fairly constant column density of C^0 ($N_C \sim 3 \times 10^{17}$ cm^{-2}; van Dishoeck & Black 1988; Hollenbach, Takahashi, & Tielens 1991) over a large range of interstellar UV field strengths and cloud densities. Some recent chemistry models indicate that there may be a substantial C^0 abundance (C^0/CO ~ 0.1) in cloud interiors at low densities (Pineau des Forêts, Roueff, & Flower 1992; see also Graedel, Langer, & Frerking 1982).

Large-scale observations of our Galaxy show that the ground state fine-structure transitions of C^0 are important coolants of the dense neutral interstellar medium. On scales of tens of degrees, the 492 GHz line has a larger intensity than any individual ^{12}CO rotational line (Wright et al. 1991). Observations of the inner Galaxy show that the 492 GHz [C I] line has a higher intensity than CO $J = 5 \rightarrow 4$ everywhere but at $l = 0$ (Bennett & Hinshaw 1992). In the inner 100 pc of IC 342, the ratio of the 492 GHz [C I] line flux to the flux in the ^{12}CO $J = 2 \rightarrow 1$ line (1.5 ± 0.4; Büttgenbach et al. 1992) is comparable to the same ratio in the inner region of M82 (1.3–1.6; Schilke et al. 1993; Wild et al. 1992) and on large scales in our own Galaxy (2.3 ± 0.6; Wright et al. 1991).

On smaller scales, the distribution of [C I] emission has been studied in a number of interstellar clouds (Phillips & Huggins 1981; Keene et al. 1985; Genzel et al. 1988; White & Padman 1991; Büttgenbach 1993). These observations take the form of small numbers of spectra or maps or strips of limited areas, often without complete spectral information at each position. Studies of the [C I] $^3P_2 \rightarrow {}^3P_1$ transition imply that both [C I] lines have low or moderate opacity ($\tau \leq 1$; Zmuidzinas et al. 1988; Genzel et al. 1988).

The large-scale [C I] observations show that the line emission must also arise away from the immediate vicinity of sites of massive star formation where most observations have been made. We have little knowledge, however, of the typical C^0 distribution and abundance over extended regions in molecular clouds. The observations of S140 we present here include the first large-scale [C I] map of a molecular cloud.

The S140 molecular cloud (distance 900 pc; Crampton & Fisher 1974) has, along its southwest side, and edge-on ionization front illuminated by the B0 V star (HD 211880). At the ionization front (1.85 pc from HD 211880), Keene et al. (1985) calculate that the far-UV flux is 2.4×10^{-4} W m^{-2}, about 150 times the mean interstellar radiation field. At the northeast side of the cloud, the unextincted far-UV flux from HD 211880 is about an order of magnitude smaller. There is also a cluster of three infrared sources embedded within the cloud northeast of the ionization front (Beichman, Becklin, & Wynn-Williams 1979). The embedded sources have luminosities of 2 to 5×10^3 $L_\odot$ (Lester et al. 1986). Radio continuum observations imply that the three IR sources may be main-sequence objects with spectral types from B1.5 to B2 (Evans et al. 1989).

2. OBSERVATIONS

At the frequency of the [C I] $^3P_1 \rightarrow {}^3P_0$ transition ($\nu = 492.1607$ GHz; Frerking et al. 1989), the beam size of the 10.4 m Caltech Submillimeter Observatory telescope is only 15″ (FWHM). A much smaller telescope could survey large areas of the sky in the [C I] 492 GHz line emission more quickly. The (relatively) poor atmospheric transmission at 492 GHz ($\tau_{492} \sim 0.9$ for 1 mm precipitable water vapor), however, means that any such telescope must be at a high dry site. This requirement and the need for a sensitive high-frequency receiver and an elaborate spectrometer make *dedicated*, small [C I] telescopes very costly. In order to survey large-scale [C I] emission, we have therefore constructed a "Gaussian Focal Reducer" (Plume et al. 1994a) which reduces the effective aperture of the CSO to $\sim$60 cm (at 492 GHz). Looking outward from the CSO facility 490 GHz receiver, the system consists of three mirrors which can be inserted into the beam as it travels along the telescope elevation axis. These mirrors cause the receiver to underilluminate the primary mirror. The resulting telescope has an excellent effective surface quality and a large beam (Plume et al. 1994a). This device has the additional advantage that it allows observations to be made during the day, when the CSO is normally idle.

We used the Gaussian Focal Reducer on the CSO to observe the [C I] $^3P_1 \rightarrow {}^3P_0$ transition and the ^{13}CO and C^{18}O $J = 2 \rightarrow 1$ transitions ($\nu = 220.3897$ and 219.5604 GHz) in 1993 February, March, and June. The typical atmospheric opacity was 0.7 for the [C I] observations and 0.1 for the CO observations. We measured the size and efficiency of the beam by scanning across Jupiter and the Moon and 220 GHz and across the Moon at 490 GHz. The deconvolved beamsize was 3′ at 490 and 220 GHz, and the coupling efficiency of our beam to the Moon ($\eta_{\rm Moon}$) was $\sim$0.8 at both frequencies. A direct measurement of the illumination pattern on the primary mirror [1/*e* beam radius (ω_p) = 26 cm at 492 GHz, implying a full width to half-power of 181″ in the far field] confirmed the beam size determined from the lunar limb scans. We calibrated the data to the T_A^* scale using the chopper-wheel method (Penzias & Burrus 1973). For the column density determinations, we converted to the T_R^* scale (Kutner & Ulich 1981) using $T_R^* = T_A^*/\eta_{\rm Moon}$. This value of η is appropriate, given the extent of the emission and the likely quality of the beam (Plume et al. 1994b). The absolute temperature scale is probably accurate to better than $\pm$30%. The largest pointing errors were less than 30″.

We observed by switching at $\sim$40 s intervals between the source and a reference position 2° away in azimuth. We used the CSO facility SIS receivers at both 490 GHz (Walker et al. 1992) and at 220 GHz (Kooi et al. 1992). The backend was a 1024 channel acousto-optical spectrometer with a total bandwidth of 50 MHz. For [C I], typical SSB system temperatures were $\sim$2000 K. When smoothed to a resolution of 0.3 km s^{-1}, the typical rms noise was $\sim$0.2 K. For the CO $J = 2 \rightarrow 1$ lines, the system temperature was typically 300 K. At a resolution of 0.13 km s^{-1}, the ^{13}CO data used in our maps had an rms noise $\sim$0.1 K.

Figures 1*a* and 1*b* show the distribution of [C I] $^3P_1 \rightarrow {}^3P_0$ and ^{13}CO $J = 2 \rightarrow 1$ integrated line strength toward S140. The box near the emission peak represents the extent of the previous [C I] map of this source (White & Padman 1991). Figure 2 shows sample spectra at selected positions from our map (spectra taken elsewhere have similar rms noise).

3. RESULTS AND DISCUSSION

The [C I] emission is very extended. It begins at the ionization front in the southwest and continues to the end of the mapped region some 30′ (8 pc) to the northeast. Parallel to the ionization front, the [C I] emission extends over at least 10 pc. The [C I] emission follows the general morphology of the

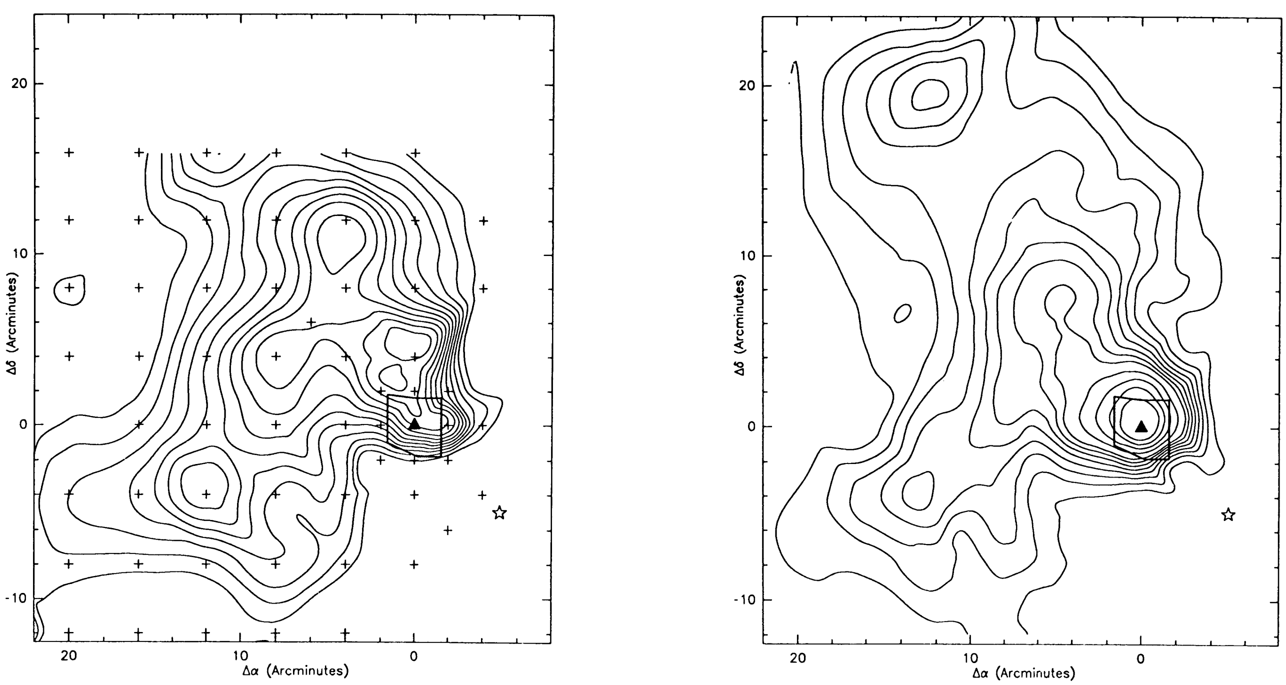

FIG. 1*a* FIG. 1*b*

FIG. 1.—Integrated line strength ($\int T_A^* dV$) toward S140. The (0, 0) position is $\alpha(1950) = 22^{\rm h}17^{\rm m}42^{\rm s}$, $\delta(1950) = 63°03'45''$, the position of IRS 1. The small box marks the area mapped by White & Padman (1991). The solid triangle marks the position of IRS 1, and the star shows the position of HD 211880 (*a*) [C I] $^3P_1 \rightarrow {}^3P_0$. The contour levels run from 3 to 13 K km s^{-1} in steps of 1 K km s^{-1}. The crosses show where data were taken. (*b*) ^{13}CO $J = 2 \rightarrow 1$. The contour levels run from 2.5 to 20 K km s^{-1} in steps of 2.5 K km s^{-1} and from 20 to 40 K km s^{-1} in 5 K km s^{-1} steps.

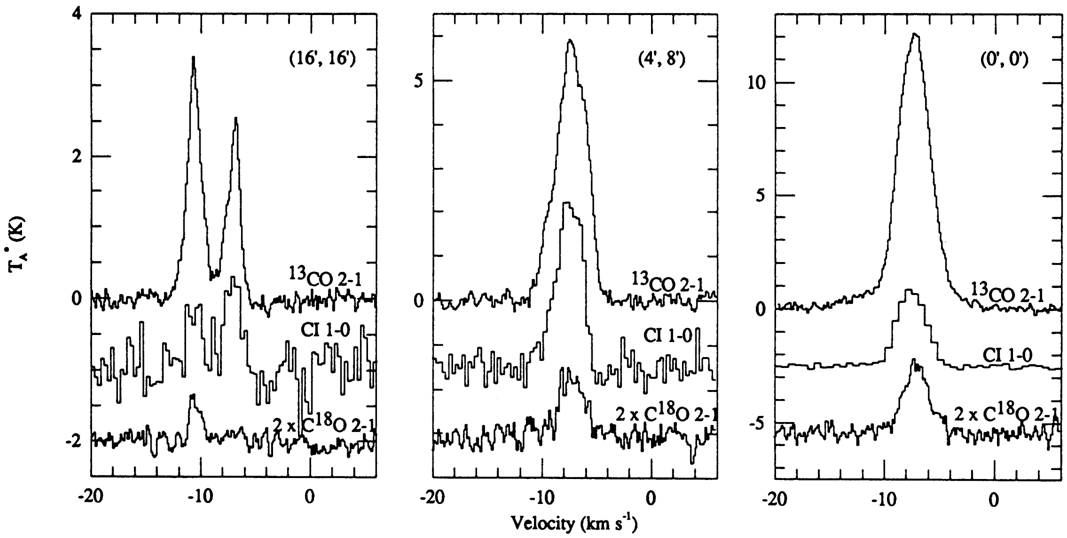

FIG. 2.—^{13}CO, C^{18}O, and [C I] spectra toward selected positions in S140. The positions of the spectra ($\Delta\alpha$, $\Delta\delta$), shown in the upper right-hand corner of each box, are the offsets from (0, 0) in arcminutes.

molecular gas as seen in the ^{13}CO $2 \rightarrow 1$ line. In particular, the emission in [C I] and ^{13}CO has the same overall extent with a sharp edge at the ionization front in the southwest and a ridge running from southwest to northeast over the position of the S140 IR sources. In agreement with the scan of Keene et al. (1985), we find that the peak of the [C I] emission lies farther from the ionization front than the peak of the molecular emission along a cut through IRS 1. Cross scans elsewhere across the I-front show the integrated strength of the [C I] and ^{13}CO lines peaking at around the same distance from the front. Toward IRS 1, we see no evidence for the high-velocity ($\Delta V \sim 15$ km s^{-1}) [C I] emission reported by Hernichel et al. (1992), in a 3′ simulated beam, at a level a factor of 5 below their reported intensity (Fig. 2, *right panel*).

The [C I] line shapes and widths are similar to those of ^{13}CO. More generally, the emission occurs over the same velocity intervals, and when there are multiple features in ^{13}CO, these features also appear in [C I] (Fig. 2, *left panel*). The ^{13}CO/C^{18}O intensity ratio is ~ 10 over most of the source implying that the ^{13}CO opacities are usually small. The narrow [C I] 492 GHz lines argue for the low opacities inferred elsewhere from observations of both [C I] transitions (Zmuidzinas et al. 1988; Genzel et al. 1988).

Since the C^0 ground state is a three-level system with closely spaced levels, the calculation of neutral carbon column densities from the measured $^3P_1 \rightarrow {}^3P_0$ intensities is reasonably insensitive to the physical conditions in the emission region. In LTE ($n_{H_2} >$ a few 10^3 cm^{-3}), we have $N(C^0) = 1.7 \times 10^{16} \int T_A^*[C\,I]\,dv$, where we have assumed $\eta_{MB} = 0.8$ and an excitation temperature of 20 K (the ^{12}CO $J = 1 \rightarrow 0$ line has $T_A^* \sim 20$ K [in a 2.′6 beam] across much of S140 [N. J. Evans, private communication]). This $N(C^0)/\int T_A^*[C\,I]\,dv$ relation is good to ± 5% for $18 \leq T_{ex} \leq 60$ K. For the 3′ region around IRS 1, $\int T_A^*[C\,I]\,dv = 11$ K km s^{-1} implying a column density $N(C^0) \simeq 2 \times 10^{17}$ cm^{-2}. From the ^{13}CO integrated line strength (again assuming $\tau \ll 1$, $T_{ex} = 20$ K, and LTE), we derive a column density ratio toward IRS 1 of $N(C^0)/N(^{13}CO) \simeq 5.8$. More typically, in the bulk of the cloud, $N(C^0)$ is 1.2×10^{17} cm^{-2} and $N(C^0)/N(^{13}CO) \simeq 15$. Integrating over the entire region mapped in [C I], we have $\int N(C^0)\,dA = 5 \times 10^{55}$ atoms, and $\int N(C^0)\,dA/\int N(^{13}CO)\,dA = 25$, implying that there is about half as much gas-phase carbon in the form of C as in the form of CO in S140 (assuming CO/^{13}CO = 50).

Given the detailed agreement of the [C I] morphology and spectral line shapes with those of ^{13}CO, it appears that neutral carbon in PDRs on molecular clumps can explain the observed emission. The ratio of the typical observed beam averaged C^0 column densities to the value predicted by appropriate plane parallel PDR models in $(N_{obs}/N_{model}) \approx 0.6$–1.3 (van Dishoeck & Black 1988) or $(N_{obs}/N_{model}) \approx 0.3$–1 (Hollenbach et al. 1991).

In order for PDRs to be the source of the [C I] emission, the gas must be clumpy enough to allow far-UV radiation to reach molecular clump surfaces throughout the cloud. Stutzki et al. (1988) and Howe et al. (1991) have used [C II] observations to argue for deep far-UV penetration of molecular clouds elsewhere. Based on the typical ^{13}CO column density ($\langle A_v \rangle \sim 5$) through the S140 cloud, only a small degree of clumpiness will permit UV radiation to permeate the cloud. Such clumpiness probably exists since the volume average density derived by dividing the ^{13}CO column density by the cloud size ($\langle n(H_2) \rangle \sim$ 300 cm^{-3}) is not consistent with the observed ^{13}CO $J = 2 \rightarrow 1$ brightness temperature unless the cloud is clumpy. There is also direct evidence for clumpy structure in the inner region of S140 from small-scale [C I] and C^{18}O results (White & Padman 1991; Johnen, Krause, & Stutzki 1993), and in the extended cloud from 30″ resolution ^{13}CO mapping (T. H. Büttgenbach, private communication). There is additional evidence from observations of other sources that extended [C I] emission arises in PDRs. In NGC 2024 and Orion A the [C I] and [C II] emission are coextensive on the large scale (Jaffe et al. 1994; Plume et al. 1994b; Phillips & Huggins 1981; Stacey et al. 1993).

The PDR models agree that there is sufficient C^0 column density in the PDR to explain the observed [C I] emission. Does this rule out the possibility of a substantial C^0 abundance in the region where CO is the dominant form of gas-phase carbon? Pineau des Forêts et al. (1992) argue for a two-phase chemistry in the cloud cores in which the low-density (n_{H_2} <

5×10^3 cm^{-3}) phase in the molecular gas has a high neutral carbon abundance. For models with $n_{H_2} > 10^3$ cm^{-3}, they obtain a C^0/CO ratio of 0.07–0.1. If we assume $^{12}CO/^{13}CO = 50$, the integrated value of C^0/CO over our map is 0.5. Locally, the value can be even higher. Further, in those parts of the map with lower C^0/CO values, the densities significantly exceed 5×10^3 cm^{-3} (Mundy et al. 1987; Snell et al. 1984), and the chemistry is in the phase where the C^0 abundance is low. We conclude, therefore, that even if the low-density molecular material actually has the high neutral atomic carbon abundance predicted by the Pineau des Forêts et al. models, most of the C^0 in S140 is in the PDR. If we assume a solar [C/H_2] abundance (3×10^{-4}) and a mean mass per particle (H_2 + He) of 4.3×10^{-24} g, then the total number of carbon atoms ($\int N(C^0)\,dA = 5 \times 10^{55}$) yields a gas mass of ~ 400 $M_\odot$ in the C^0 layer. Using a ^{13}CO abundance [$^{13}CO/H_2$] $= 2 \times 10^{-6}$ the total mass in the CO dominant region is ~ 2100 $M_\odot$. This implies that $\geq 20\%$ of the gas mass is in the neutral carbon–bearing layer of the PDR. The "greater than" symbol comes from the possibility that the carbon abundance may be lower than the solar value in PDRs (Cardelli et al. 1993).

The ratio of the total cooling in the [C I] $^3P_1 \rightarrow {}^3P_0$ line to that in the ^{12}CO $J = 1 \rightarrow 0$ line (N. J. Evans, private communication) is 10.6 (in units of ergs cm^{-2} s^{-1} sr^{-1}, averaged over a $\sim 12' \times 12'$ region centered at [+6, 0]). If the CO $J = 2 \rightarrow 1$ line has the same integrated line strength as CO $J = 1 \rightarrow 0$, as is usually the case in warm, optically thick gas, the ratio of the [C I] $^3P_1 \rightarrow {}^3P_0$ cooling to the CO $J = 2 \rightarrow 1$ cooling is [C I]/CO ~ 1.3, similar to the corresponding ratio in the inner regions of IC 342 and M82. The [C I]/CO cooling ratio in the inner 3′ of S140 is considerably lower than this average value ([C I]/CO ~ 0.7). In the parts of the $12' \times 12'$ comparison region well away from the near-IR sources, the [C I]/CO cooling ratio ranges from 1.2 to 2.8. Wright et al. (1991) derive a global Galactic value of [C I]/CO $= 2.3 \pm 0.6$. If the global ratio lies in the upper part of the allowed range, the CO and [C I] emission from the Galaxy (or at least from the local region which contributed most heavily to the *COBE* survey) must be dominated by clouds similar to the outer parts of S140, where the cooling ratio is large.

We thank J. Booth and G. Wesley for help with the Focal Reducer, K. Tatematsu for assistance with the observations, E. van Dishoeck for helpful comments, and T. G. Phillips for his advice and support. The assistance and cooperation of Darek Lis, Thomas Büttgenbach, and the CSO day crew were also greatly appreciated. This work was supported by the David and Lucile Packard Foundation and by NSF grant 90-17710 to the University of Texas. The CSO is supported by NSF grant 90-15755.

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