HOW IMPORTANT IS NEUTRAL CARBON TO AN UNDERSTANDING OF THE DENSE INTERSTELLAR MEDIUM?

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1. Introduction

In virtually all of the dense interstellar medium, H_2 is the most abundant form of hydrogen, but it is not directly observable in the bulk of the gas. As a result, we are forced to use trace constituents of the gas as surrogates when we want to know the distribution of material in the dense ISM. Most commonly, we employ the lowest few rotational transitions of CO and its isotopes as the trace species. One of the most hotly debated issues in the study of the molecular ISM is the extent to which one can trust CO or isotopic CO lines to reflect reliably the underlying H_2 distribution (see Shier, Rieke, & Rieke (1994), Sodroski et al. (1995) for recent comments on the $I(^{12}CO)/N(H_2)$ ratio and Lada et al. (1994) for a recent analysis of the relationship between isotopic CO and total cloud column densities). CO becomes increasingly unreliable as a tracer of H_2 as the average column density between cloud surfaces exposed to ultraviolet photons and the shielded centers of clouds becomes smaller. Young stars in the galactic plane perfuse atomic and molecular clouds with far–UV ($\lambda > 91$ nm) radiation. This radiation tends to dissociate CO more readily than it dissociates H_2 (Van Dishoeck & Black 1988). The differences in susceptibility of H_2 and CO to photodissociation may lead to the existence of significant portions of the molecular medium where the usual trace species are underabundant or even absent. In addition, there is dense H I at the cloud boundaries, immediately outside the molecular material. In the UV–illuminated cloud surfaces, the gas-phase carbon is in the form of C I or C II. It is important, therefore, to determine the amount and location of large-scale C I emission

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if one hopes to know how much molecular and dense atomic gas is missing from studies using CO as a tracer and to what extent photodissociation is responsible for the absence of this CO. We discuss here some of the relevant theoretical and observational work on the relationship between C II, C I, CO and H_2. Our principal aim is to see if and how observations of C I might help us to improve our knowledge of the distribution of dense neutral gas in the Milky Way.

2. Origin of C I Emission: Photon Dominated Regions

Photon dominated regions (PDR's) form at the surfaces of molecular clouds wherever far–UV photons strike the gas. The PDR is a zone in a molecular cloud where UV photons dominate the energetics, chemistry, and ionization state (de Jong, Dalgarno, & Boland 1980, see Hollenbach & Tielens 1995 for recent references). At the PDR boundary, H rapidly makes a transition to H_2 as self-shielding begins to protect the molecules against photodissociation. In the outer part of the molecular cloud, CO cannot self-shield as effectively as H_2, so a region exists where the hydrogen is already molecular but C II and, somewhat farther in, atomic carbon are the dominant forms of gas–phase carbon. The transition from C II to C I comes at a depth into the cloud where the far-UV field has been sufficiently attenuated to allow C II to recombine (on the order of A_v=1 for a typical giant molecular cloud). The C I/CO transition occurs a bit farther in ($A_v \simeq$2–3) as re-formation of CO overcomes photodissociation. The exponential attenuation of far-UV radiation by dust results in a weak dependence of the C II column density on the incident UV field when the UV field is high (Tielens & Hollenbach 1985, Van Dishoeck & Black 1988). For weaker UV fields, the C II column density can vary somewhat more rapidly with the strength of the field. As an effect of its position in a transition zone, the column density of carbon in the neutral atomic region is relatively insensitive to variations in the strength of the incident UV field and the local density. The corresponding surface brightness in the lower C I transition also varies very slowly with cloud conditions (Hollenbach, Takahashi, & Tielens 1991).

Most PDR models consider the effects of far-UV radiation on uniform clouds, either plane parallel or spherical. These uniform models imply that a large fraction of the molecular ISM is photon dominated material. One can use the linewidth–size relation for molecular clouds (Solomon et al. 1987) to estimate the typical column density through the clouds. This column density corresponds to $A_v \sim$10. Given the thickness of typical C II and C I layers, this result implies that CO is the majority gas-phase carbon species in only 1/2 to 2/3 of the dense material.

The clumpy structure of real molecular clouds can lead to even higher

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mass fractions of the cloud in regions where CO is not the dominant form of gas-phase carbon. Most clouds are highly clumpy with high density contrasts observable over a large range of scale sizes (see recent reviews by Blitz 1993, and Stutzki 1994). The clumpy nature of the clouds affects their interaction with far-UV radiation and therefore the pattern of C II, C I, and CO emission. Mapping of high column density molecular clouds reveals C II emission far within clouds where there are no embedded sources of far-UV radiation; the scale–length over which the C II intensity drops going into the cloud is 10–100 times longer than it would be for a uniform source (Howe et al. 1991). Models taking clumpiness into account can explain both the absolute intensity and distribution of the C II emission, if the volume filling factor of clumps in the clouds is modest (0.1–0.3) and if the area filling factor of clumps and the density of the interclump material allow UV radiation to penetrate through the cloud to reach clump surfaces 1–2 pc inside the cloud (Stutzki et al. 1988, Howe et al. 1991). In this case, each clump throughout the cloud has a PDR on its surface. For gas at a given density, then, clumpy clouds can have a much larger fraction of their volume in regions affected by UV photons than do correspondingly massive monolithic clouds.

3. Tracers of UV–Influenced Material

3.1. C II: THE IDEAL TRACER?

The structure of PDR's we have described here implies that the 158 μm C II line might be the best way to trace gas near UV illuminated surfaces. C II extends all the way from the H II/H I interface in to an $A_v \sim 2$. There are already extensive observations of the C II 158 μm line throughout the inner Galaxy which one might hope to use to study the distribution of UV–influenced molecular material (Shibai et al. 1991, Nakagawa et al. 1993, Bennett et al. 1994). Several problems combine, however, to limit the usefulness of the C II line as a quantitative PDR tracer. For the 158 μm transition, E_u/k is 92 K. Although electrons ejected from grains through the photoelectric effect heat the gas in the outer layers of the cloud significantly above typical dark cloud temperatures of 6–10 K, the temperature in these layers is not high enough to keep the emissivity of C II from varying rapidly over the range of far-UV fields incident on typical GMC's in the inner Galaxy. As a result, C II intensities do not reflect the amount of PDR material except near strong far–UV sources. A second problem is that ionized gas in extended, low density H II regions may contribute diffuse C II emission. For nebulae ionized by stars with surface temperatures below ~34,000 K, most of the carbon in the H II region will be C II (Rubin 1985). The critical density for electron collisions for the 158 μm line is only

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$\sim$40 cm^{-3} (Hayes and Nussbaumer 1984) making significant emission possible even at low volume density. Estimates of the fractional contribution of diffuse ionized gas to the global C II emission vary from $\sim$0.1 (Stacey et al. 1985) to $\sim$ 0.5 (Shibai et al. 1991). There is also an observational problem with the C II line. Spectrometers relying on incoherent techniques do not have enough resolving power to examine line profiles or resolve different velocity components along the line of sight. Heterodyne spectroscopy at 2 THz is still in its infancy and does not offer enough sensitivity, in particular to extended C II emission, to be especially useful except in the brightest regions.

3.2. C I: A BETTER CHOICE

The C I ground state is a triplet. The two fine structure transitions arising from this state lie in the submillimeter at 492 GHz ($^3P_1 \rightarrow ^3P_0$, λ = 609 μm) and 810 GHz ($^3P_2 \rightarrow ^3P_1$, λ = 370 μm). The upper state of the 492 GHz transition is only 23 K above ground. For this transition, the critical density for collisions with H_2 molecules is only 1000 cm^{-3} (Schröder et al. 1991), comparable to the critical density of the CO J = 1$\rightarrow$0 transition.

The low upper state energy and critical density of the C I $^3P_1 \rightarrow ^3P_0$ transition mean that it is relatively easily excited. The line is detectable even when emitted by moderate density interstellar gas exposed only to a radiation field equal to the mean interstellar radiation field in the solar neighborhood. For the majority of clouds in the inner Galaxy, where the incident far–UV radiation field is 1-100 times the mean solar neighborhood field, the column density of the C I layer will have reached its asymptotic value as long as A_v through the cloud is $\geq$5 (Van Dishoeck 1994, personal communication). Although the strength of the 158 μm line varies quite a bit, the C II column density at cloud surfaces depends less strongly on the intensity of the incident UV field. We can therefore correct from the amount of C I observed to the total amount of C II plus C I in the molecular gas and use the 492 GHz C I transition to trace the substantial fraction of dense cloud material where most of the carbon is not in the form of CO.

Throughout the discussion in this paper, we assume that C I emission from PDR's dominates over any other possible sources. Is this a reasonable assumption? Most chemical equilibrium models indicate that the C I/CO ratio is very small in clouds without incident far–UV radiation. Recent calculations suggest, however, that in a part of temperature–density space, the chemical reaction network may have two stable solutions, one with high electron abundance and a large C I/CO ratio and another with low electron abundance and C I/CO ratio (Le Bourlot et al. 1993). The models yield C I/CO ratios in the range of 0.05–0.18 in the high ionization phase.

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Several other groups are now searching for or have made searches for similar evidence of these effects in their own chemical equilibrium models.

From an observational point of view, the possible existence of shielded regions with substantial C I/CO ratios may be irrelevant. Plume, Jaffe, & Keene (1994) argue that PDR models produce enough C I column density to explain their observations of the large-scale 492 GHz emission from S140. Photon dominated regions can also explain the detailed morphology of the C I and ^{13}CO emission in S140 as well as the large-scale coincidence of the C II and C I distributions elsewhere (see Plume et al. 1995). In addition, the global C I/CO ratio in S140 is $\sim$0.5, considerably higher than the most optimistic values quoted for the dark cloud models with higher electron abundance. The proponents of these models agree that PDR's will dominate the observable C I emission from clouds under most circumstances, even if the proposed high atomic carbon abundance in shielded regions really exists (Flower et al. 1994).

4. C I Observations and the Distribution of Dense, Neutral Gas

The 492 GHz C I line has been observed in a large variety of contexts in the dense interstellar medium (see Keene (1995) for a recent review). The bulk of the observations, however, consist of high angular resolution maps covering only small areas near known star forming cores or ionization fronts. For most observations, the beam sizes are only 10–20$''$ and the total mapped areas are no more than a few arc minutes on a side. The results show that the C I distribution is highly clumpy on small scales (White and Padman 1991, Büttgenbach 1993).

At the other extreme, there are very large scale C I observations of both our Galaxy and of the nuclei of a few nearby galaxies. The COBE satellite detected both ground-state C I lines along the Galactic Plane with a 7^o beam (Bennett & Hinshaw 1993). C I is an important coolant of the neutral ISM; the ratio of C I $^3P_1 \rightarrow ^3P_0$ to CO J=2$\rightarrow$1 intensity is 2.3$\pm$0.6 (Wright et al. 1991), averaged over the whole Galaxy. The ratio is similar in the inner few hundred parsecs of IC342 (1.5$\pm$0.4; Büttgenbach et al. 1992) and M82 (1.3-1.6; Schilke et al. 1993, Wild et al. 1992).

For our own Galaxy, there is an enormous gap between the scale of the global COBE results and the small maps of selected cloud cores and ionization fronts. Several small, dedicated telescopes designed to plug this gap in spatial scales, the SWAS satellite and the ASTRO telescope for the South Pole, are now under construction. In the meantime, Plume and collaborators at the University of Texas and Caltech have been mapping the large-scale distribution of galactic C I emission using a reimaging device on

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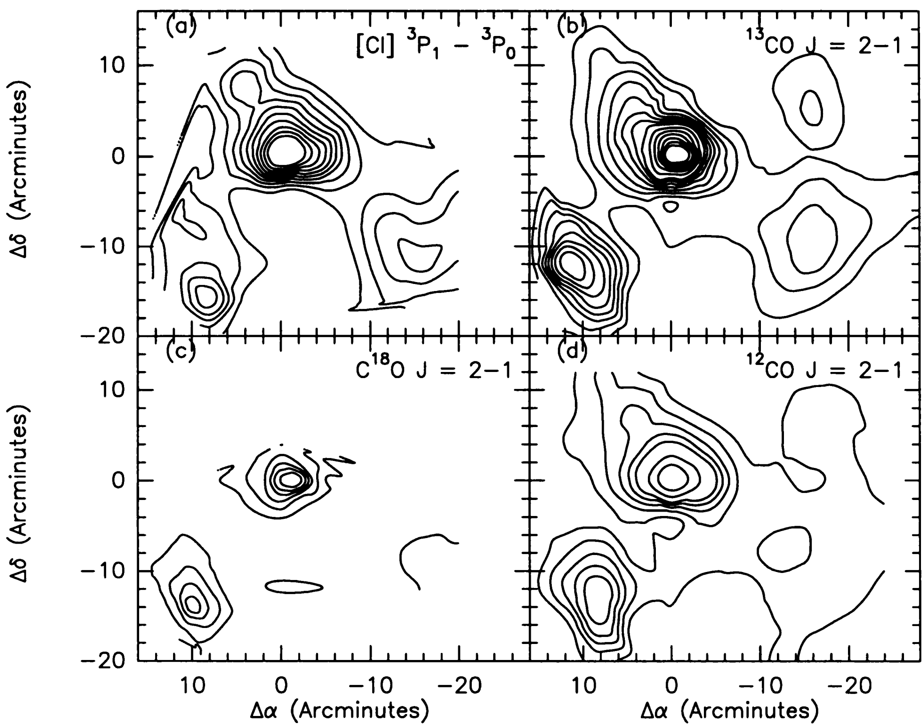

Figure 1. Integrated intensity distributions of C I and CO isotopomers toward W3 (Plume et al. 1995). The 0,0 position is (α=02^{h}21^{m}53.1^s, δ=61°52'22"), near W3 IRS5.

the Caltech Submillimeter Observatory 10.4m telescope. This device causes the facility receivers to underilluminate the primary mirror and creates a smaller telescope with 3 arc minute beams at both 220 and 492 GHz (Plume & Jaffe 1995). The reimaging device can be used in the daytime when the CSO telescope is normally idle. Since it is an off-axis system with good surface quality, the reimaging device has a clean beam which allows one to obtain an accurate representation of the very extended C I emission. In two, two-month observing seasons, the Texas group has used the reimaging instrument to map a sample of five GMC's over ~30′×30′(Plume, Jaffe, & Keene 1994; Plume et al. 1995) as well as to make a strip map of the Galactic Center (Jaffe, Plume, & Pak, this volume) and a crude survey of the first quadrant.

The large-scale distribution of 492 GHz C I emission is similar to that of CO and isotopic CO J=2→1 lines, in particular the ^{13}CO line. Figure 1 shows the distribution of C I $^3P_1 \rightarrow {}^3P_0$ and CO, ^{13}CO, and C^{18}O J=2→1 emission from the W3 molecular cloud complex (Plume et al. 1995). The

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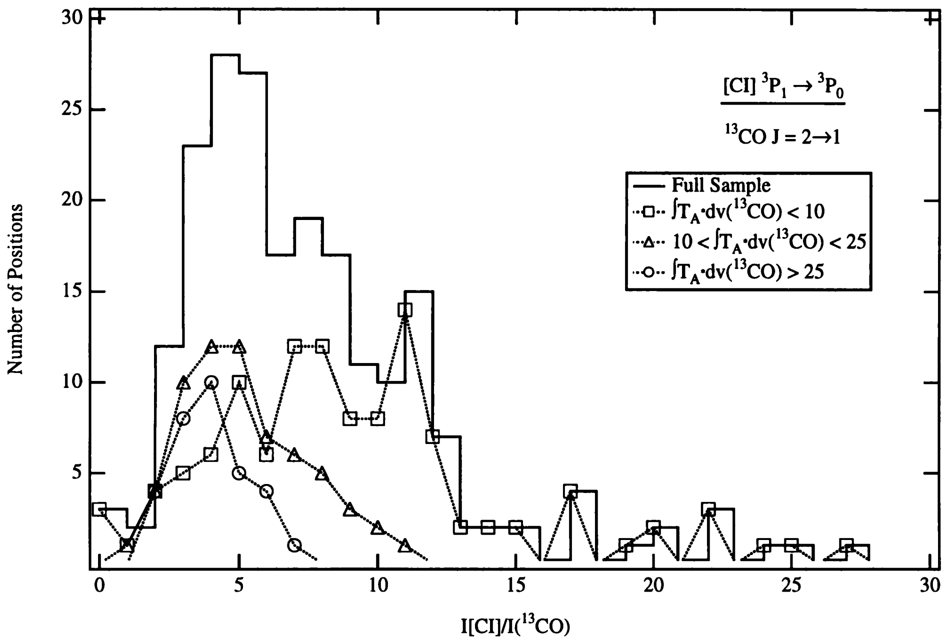

Figure 2. Frequency distribution of C I/CO intensity ratios for the molecular cloud sample of Plume et al. (1995). The three subgroups correspond fairly closely to macroscopic cloud edges ($I_{^{13}CO}$ <10 Kkms^{-1}), the bulk of the cloud (10<$I_{^{13}CO}$ <25 Kkms^{-1}), and dense, star forming cores ($I_{^{13}CO}$ >25 Kkms^{-1}).

lineshapes of C I and the lower opacity isotopic CO lines match fairly well. Plume, Jaffe, & Keene (1994) argue that the agreement in the lineshapes implies that the C I emission arises from the surfaces of individual clumps throughout the cloud rather than from an envelope belonging to the entire cloud. Globally, in the clouds we have surveyed, there is about half as much neutral atomic carbon as CO (Plume, Jaffe, & Keene 1994; Plume et al. 1995). If one takes into account the C II in the very outer part of the cloud, the majority of the gas-phase carbon in the clouds is in a form other than CO (Jaffe et al. 1994). Typically, the regions near the cloud cores have lower C I/CO ratios than the cloud edges (Figure 2).

The high observed fraction of neutral and ionized carbon in the gas in GMC's with typical column densities corresponding to A_v ~10 leads one to wonder whether there might be a population of clouds in which the vast majority of the gas-phase carbon is not in the form of CO. This could come about in two different ways. First, clouds with only somewhat lower A_v than typical will have disproportionately larger amounts of carbon in

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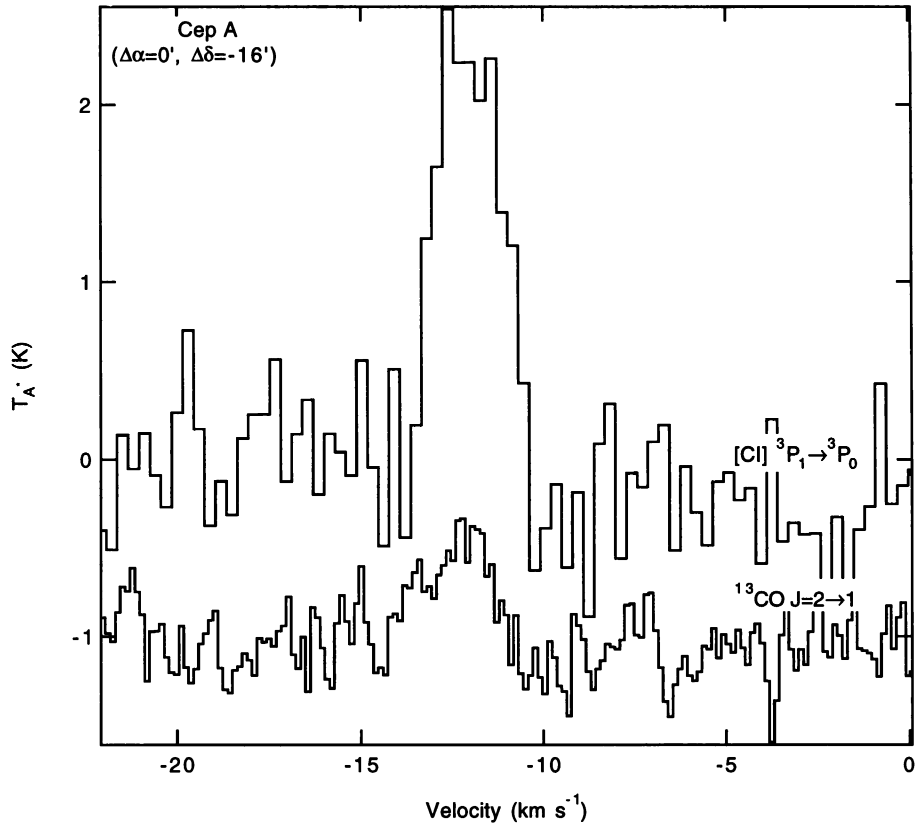

Figure 3. Spectra of C I $^3P_1 \rightarrow {}^3P_0$ and ^{13}CO J=2→1 toward a secondary C I peak in CepA (Plume et al. 1995). The relative intensities imply a C I/CO column density ratio ~3. The 0,0 position for CepA was (α=22^{h}54^{m}19.2^s, δ=61°45'44").

atomic form. Second, the surface area to volume ratio of clouds can change, i.e., clouds can be more or less clumpy and therefore more or less subject to the influence of UV radiation. The huge variations in the N(^{13}CO)/A_v ratio for low A_v (Lada et al. 1994) indicate that, along some lines of sight, much of the carbon is in forms other than CO. Reach et al. (1994) present additional evidence for large molecular regions containing little CO. They have corrected 100 μm maps of diffuse clouds for the contributions of H I regions and compared the resulting "H_2" maps to the CO distribution in a sample of high latitude clouds. The "H_2" zone is much larger than the portions of the clouds in which there is detectable CO emission. In the GMC study of Plume et al. (1995), there is at least one example of a predominantly C I cloud core. Figure 3 shows C I and ^{13}CO spectra toward a

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secondary maximum in the C I distribution toward CepA. At this position, the C I column density is $\sim 8\times10^{16}$ cm^{-2} while the CO column density inferred from ^{13}CO is $\sim 3\times10^{16}$ cm^{-2} (assuming ^{12}CO/^{13}CO=50).

5. Do We Really Need to Trace C I?

The basic result of our large-scale mapping of C I emission from GMC's is that a large fraction ($\sim$1/2) of the gas-phase carbon in the dense interstellar gas is in C II or C I rather than CO. Since the variance of this fraction is not particularly large, one needs to decide if there is any reason not to simply go on using CO to trace H_2, correcting as necessary for additional material in the surface layers of clouds. In general, there is not a lot that speaks against this simple approach. There are, however, a few possible reasons why it may be a little too soon to give up on C I entirely:

(1) Even the Texas group's large-scale observations are biased toward regions known to have strong CO emission. A more unbiased large-scale survey may indicate a higher fraction of dense C II and C I bearing gas.

(2) If the characteristic column density between UV-exposed surfaces and the centers of clumps in GMC's were only slightly smaller, the fraction of molecular gas with carbon in C II, C I would rise dramatically. A more complete C I survey could show whether such clumpy, wispy regions are common.

(3) In addition to dissociating CO, the far–UV radiation also elevates the electron densities in the cloud surfaces by several orders of magnitude above the equilibrium level set by cosmic ray ionization and thereby lowers the ambipolar diffusion rate. If ambipolar diffusion plays a role in relaxing clouds toward a state where they are unstable to gravitational collapse (Shu, Adams, & Lizano 1987), the far–UV radiation may be an important inhibitor of star formation (McKee 1989). Observations of C I and CO together can provide an estimate of the fraction the gas in which the far–UV radiation affects the ambipolar diffusion rate (Plume et al. 1995).

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