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ON THE ORIGIN OF THE DIFFUSE C^+ 158 MICRON LINE EMISSION

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ABSTRACT

We consider the relative importance of three types of region as global sources of the diffuse C^+ 158 μm emission in the Galactic interior. We find that they rank as follows: the extended low-density warm ionized medium (ELDWIM) ranks first in importance, the cold neutral medium (CNM) ranks second, and photodissociation regions (PDRs) rank third. Above a threshold intensity, we interpret the data as showing that the C^+ line is well correlated with other tracers of the ELDWIM. The C^+ intensity below the threshold is easily accounted for by the CNM. PDRs must also contribute. These conclusions should also apply to the inner portions of many external nonstarburst galaxies. The opacity of the C^+ line over long lines of sight in the Galactic plane is not negligible.

Subject headings: diffuse radiation — infrared: ISM: lines and bands — ISM: general

1. INTRODUCTION

The C^+ 158 μm line intensity correlates well with four observables: CO ($J = 1$–0) emission, the far-IR continuum (FIR), 5 GHz radio continuum (which is mainly thermal), and N^+ emission (see references below). CO and FIR are produced in neutral regions; FIR, radio continuum, and N^+ are produced in ionized regions. C^+ exists in both in neutral and ionized regions. In this paper, we consider the following question: Does the C^+ emission arise primarily from neutral or ionized regions?

Most previous authors have used the correlations with CO and FIR to argue that the C^+ comes predominantly from neutral regions, specifically from low-density photodissociation regions (PDRs), which are the interfaces between a molecular cloud and ionized gas. Wolfire, Hollenbach, & Tielens (1989, hereafter WHT) and Hollenbach, Takahashi, & Tielens (1991, hereafter HTT) have calculated the theoretical structure and observable emission from low-density PDRs. Working inward from the ionized gas interface we encounter, first, a region where hydrogen is atomic and carbon is singly ionized; next, a region where hydrogen is molecular and carbon is singly ionized; and finally, a region where the carbon is neutral or molecular. In a PDR, the FIR emission comes from starlight-heated dust in the outer regions; this dust, in turn, heats the gas through the photoelectric effect and the C^+ is the major gas coolant, so the FIR and C^+ emissions are very nearly proportional and come from the same physical regions. The CO emission comes from deeper within the PDR. The radio continuum and N^+ emission trace ionized gas, and the PDR interpretation must classify the correlations of the C^+ with both radio continuum and N^+ emission as indirect, ascribing them to the physical association of ionized regions with the PDRs.

In the present paper, we describe an alternative physical picture, namely, that most of the C^+ emission in the Galactic interior[1] comes predominantly from ionized regions, specifically the extended low-density ionized gas, denoted the ELDWIM for reasons explained below. We find that the second strongest global contribution to C^+ emission is ordinary neutral interstellar gas, specifically the cold neutral medium (CNM). PDRs rank third in the global contribution to C^+ emission. With our interpretation, we must classify the correlation of C^+ with the CO, and to some extent with the FIR, as indirect, ascribing it to the physical association of ionized regions with PDRs and their associated molecular clouds.

Our argument that C^+ emission arises predominantly from the ELDWIM is not compelling because of uncertainties in the temperature and density of the ELDWIM, the intensity of the interstellar radiation field, the elemental abundances, and the relevant collisional cross sections. Similarly, the conclusions of previous authors that C^+ arises predominantly from PDRs are also not compelling. Our main point in this paper is to emphasize that the ELDWIM is at least a close contender. In our opinion, it is the strongest contender.

We believe that the CNM ranks second and the PDRs rank third in importance, while previous authors emphasize the importance of PDRs. The distinction between the CNM and PDRs is one of degree. PDRs and the CNM are similar in that the heating and cooling mechanisms are identical: heating by photoelectric emission from grains and cooling by C^+. However, PDR's have much higher volume densities, pressures, and column densities. HTT's "standard" low-density PDR has hydrogen-nucleon density $n_H = 10^3$ cm^{-3}, temperature $T \gtrsim 100$ K, gas pressure $P \sim 10^5$ cm^{-3} K, interstellar radiation field (ISRF) 10^3 times the solar neighborhood value, and extinction $A_V \gg 1$ mag. In contrast, in the solar neighborhood the CNM has $n_H \sim 50$ cm^{-3}, $T \sim 50$ K, $P \approx 2500$ cm^{-3} K, and $A_V \lesssim 1$ mag. In the Galactic interior, where the supernova rate Σ is higher, the CNM pressure should be larger because it is expected to increase as $\sim\Sigma^{0.7}$ (McKee & Ostriker 1978).

The local version of the ELDWIM is called the warm ionized medium (WIM) and is responsible for pulsar dispersion and weak, diffuse Hα emission (Reynolds 1993). It has low density, is pervasive, and is much denser in the Galactic interior than in the solar neighborhood. It is produced by ionizing photons, primarily from O stars. Astronomers normally associate O stars with discrete (sometimes known as "radio")

[1] In the present paper, the term "Galactic interior" means the inner portion of the Galaxy where the star formation rate is high, i.e., 2 kpc $\lesssim R_{gal} \lesssim$ 5 kpc (where R_{gal} is the Galactocentric radius).

H II regions. However, only ~16% of the stars produce such H II regions (Mezger 1978); the remainder are located away from dense gas. Accounting for incomplete utilization of ionizing photons in actually ionizing hydrogen, Mezger finds that 87% of all radio free-free emission comes from the ELDWIM; this gas also produces "diffuse radio recombination lines" (diffuse RRLs). The ELDWIM has low volume density and relatively high pressure: Mezger obtains $T_4 \sim 0.5$, $n_e \sim 2$ cm^{-3}, so that its pressure is about 5 times greater than that of typical neutral gas in the solar neighborhood. Under these conditions, nearly all of the nitrogen is N^+, and for illustrative uniform low-n_e H II regions, Ferland's (1993) computer program CLOUDY predicts that most (e.g., in the outer half of the H II region volume, more than 90%) of the carbon is C^+. In the ELDWIM, the volume density is well below the critical density for the fine-structure lines of C^+ and N^+.

The ELDWIM in the Galactic interior is observationally associated with prominent H II regions because it exhibits similar velocities (Lockman 1980); presumably, this association arises because the H II regions are density bounded to some extent. The association of the ELDWIM, which emits C^+ radiation, with an H II region leads to C^+ emission also being (indirectly) associated with the H II region even though the C^+ emission cannot come from the H II region itself (because its volume density is too high).

We do not know much about either the morphology or the physical parameters of the ELDWIM. Derivation of physical parameters is complicated by the inability to isolate the emission from diffuse gas along the long path lengths in the Galactic plane. Lockman (1980) performed a multiparameter analysis and found an acceptable combination to be $n_e \sim 1$ cm^{-3}, EM ~ 300 cm^{-6} pc, and $T \sim 1000$ K. The values have large allowable ranges depending on the morphology of the gas; for example, if the gas lies in sheets, then T can be higher. Cersosimo (1990a, b) derives $T \lesssim 2000$ K. Anantharamaiah (1985, 1986) pictured most of the gas to be extended, low-density envelopes of ordinary H II regions of size 30 to 300 pc having $n_e = 1$–10 cm^{-3} and $T = 3000$–8000 K. Mezger (1978) pictured the gas to be low-density Strömgren spheres and for the inner Galaxy derived $\langle n_{e,\rm rms} \rangle \sim 0.6$ cm^{-3} and $T \sim 7000$ K. Temperatures comparable to this are also favored by Anantharamaiah, Payne, & Bhattacharya (1990).

Morphological information about the ELDWIM is limited because its main inner-Galaxy tracers, the radio free-free continuum and RRLs, are too weak to attain the required angular resolution using aperture synthesis techniques. The traditional viewpoint has the WIM distributed in "clouds" or as an "intercloud medium." In contrast, Heiles (1992) has ascribed it to the walls of worms and chimneys so that it is distributed in sheets; his interpretation, which is recent, is not (yet?) widely accepted. It is certain that at least some of the ELDWIM resides in worm structures. There is a prominent thermal spur associated with the H II region S54 where radio free-free continuum, diffuse RRL emission (Müller, Reif, & Reich 1987), and C^+ emission (Plate 7 of Nakagawa et al. 1993) are prominent. In this thermal spur, Müller et al. (1987) derive $T \approx 4000$ K from a comparison of free-free continuum and RRL line intensities. For the ELDWIM in the present paper, we adopt their value $T = 4000$ K because it is directly, unambiguously, and accurately determined.

In this paper we follow Petuchowski & Bennett (1993) and use the acronym ELDWIM, which encompasses most of the proposed morphologies and origins of this gas. The exact values of physical parameters of the ELDWIM are not of much concern for the present paper as long as the temperature is high enough to neglect the $\exp - (h\nu/kT)$ factor and as long as n_e is low enough for the C^+ line to be in the low-density limit. Both these conditions are certainly satisfied in the ELDWIM. The morphology is not relevant for the present paper, which concentrates only on typical observed intensities; we will discuss morphological details in future work.

On the global scale in the Galactic interior, the ELDWIM produces essentially all of the N^+ emission, most of the free-free radio continuum, most of the diffuse RRL emission, and, as we show below, probably most of the C^+ emission. In § 2 we calculate the expected intensity ratios from the ELDWIM using elementary physical principles, and in § 3 we compare with observations, finding good agreement. In § 4 we use the detailed correlation of C^+ and N^+ emissions to estimate the contribution from the neutral interstellar medium, the CNM; further, we estimate the opacity of the diffusely distributed C^+ in the Galactic plane and find it to be nontrivial. With our estimated contributions from the ELDWIM and the CNM, there is little room left for C^+ emission from PDRs; in § 5 we discuss the expected contribution from PDRs.

2. THEORETICAL ELDWIM INTENSITIES AND THEIR RATIOS

In the low-density limit, the total power emitted in a collisionally excited fine-structure emission line is the photon energy $h\nu$ multiplied by the upward collisional rate. For an ion interacting with electrons, the specific intensity integrated over the line width is given by

$$I_{X^+} = 6.87 \times 10^{-9} h\nu T_4^{-1/2} \frac{\Omega}{g_\ell} n_e n_{X^+} L . \quad (1)$$

Here we use cgs units so that I_{X^+} is the specific intensity integrated over the line of the ion X^+ in units of ergs cm^{-2} sr^{-1} s^{-1}; T_4 is the temperature in units of 10^4 K; we have omitted the usual $\exp - (h\nu/kT)$ factor because for the fine-structure lines it is nearly equal to unity; Ω is the collision strength; and g_ℓ is the degeneracy of the lower level.

The collision strength for the C^+ 158 μm line has been calculated by Hayes & Nussbaumer (1984, hereafter HN). It is somewhat uncertain because of uncertainties of the resonances in the energy dependence of the collisional cross section. We follow the recommendation of HN and adopt their case (b), which is a quasi-theoretical result that utilizes empirically derived energies for the resonances. Lennon et al. (1985) also calculated the collision strength and state that, with a similar utilization of empirical results, their results are almost identical; this lends confidence to the accuracy. A convenient approximation for $0.4 \lesssim T_4 < 1.0$ is $\Omega = 2.9 T_4^{0.15}$. We obtain all other line parameters from Aller (1984) and from Osterbrock (1989), which provide identical values. For the C^+ transition, $g_\ell = 2$, $A_{u\ell} = 2.29 \times 10^{-6}$ s^{-1}, and the critical density $n_{e,\rm cr} = 37 T_4^{0.35}$ cm^{-3}. For the N^+ 205 μm transition the collision strength, degeneracy, Einstein A, and critical density are 0.40, 1, 2.08×10^{-6} s^{-1}, and $181 T_4^{0.5}$ cm^{-3}, respectively.

We emphasize that the N^+ collision strength may not be very accurate. The collision strength for C^+ has been calculated with what appears to be considerable care by two independent groups, whose nearly identical results differ by a factor of about 2 from the older values that are quoted by Aller (1984) and Osterbrock (1989). This suggests that a similarly careful calculation for N^+ might yield similar differences from the older values.

Applying equation (1) to the 158 μm and 205 μm lines gives

$$I_{C^+,-4} = 1.55 \times 10^{-3}\,\delta_{C^+} T_4^{-0.35} n_e^2 L_{pc} \qquad (2)$$

and

$$I_{N^+,-4} = 8.36 \times 10^{-5}\,\delta_{N^+} T_4^{-0.5} n_e^2 L_{pc}\,, \qquad (3)$$

where the path length L_{pc} is in parsecs, the subscript -4 on the specific intensity I means units of 10^{-4} ergs cm^{-2} s^{-1} sr^{-1}, and we have assumed cosmic abundances $[C^+/H^+] = 4 \times 10^{-4}\delta_{C^+}$ and $[N^+/H^+] = 1 \times 10^{-4}\,\delta_{N^+}$ (Spitzer 1978), where the δ-values account for non–singly ionized forms of the element (either depletion onto dust grains or other ionization states in the gaseous phase). Thus we can write

$$\frac{I_{C^+}}{I_{N^+}} = 18.6 T_4^{0.15}\,\frac{\delta_{C^+}}{\delta_{N^+}}\,. \qquad (4)$$

At radio wavelengths, the continuum brightness temperature from the free-free emission process is given by (Mezger & Henderson 1967)

$$T_B = 3.3 \times 10^{-3} T_4^{-0.35} \nu_{GHz}^{-2.1} n_e n_{H^+} L_{pc}\ \mathrm{K}\,. \qquad (5)$$

The velocity-integrated brightness of a radio recombination line is given by (Mezger & Höglund 1967)

$$T_B \Delta V_{H^+} = 3.6 \times 10^{-4} T_4^{-1.5} n_e n_{H^+} L_{pc}\ \mathrm{K\ km\ s^{-1}}\,. \qquad (6)$$

Both equations assume that the free-free optical depth is negligible, which is certainly valid for the ELDWIM. Thus, for $\nu = 5$ GHz we can write

$$\frac{I_{C^+,-4}}{T_{B,5\,GHz}} = 13.8\,\delta_{C^+}\ \mathrm{K^{-1}}\,, \qquad (7)$$

and for any H^+ recombination line we can write

$$\frac{I_{C^+,-4}}{T_B \Delta V_{H^+}} = 4.3\,\delta_{C^+}\,T_4^{1.15}\quad (\mathrm{K\ km\ s^{-1}})^{-1}\,. \qquad (8)$$

The ELDWIM emits only weakly at radio wavelengths and is observable in the Galactic interior only because it is much more abundant there than in the solar neighborhood. In external galaxies, the radio emission from this gas is too weak to observe. However, the ELDWIM is observable at optical wavelengths in the Hα line. If there is no extinction, then the Hα intensity ratio in "case B" is given by Spitzer (1978), from which we calculate the C^+/Hα line ratio to be

$$\frac{I_{C^+}}{I_{H\alpha}} = 1.8\,\delta_{C^+}\,T_4^{0.55}\,. \qquad (9)$$

The C^+ emission is correlated with the FIR thermal continuum emission from dust grains. The primary heating source for dust is starlight, whose mean intensity can be highly variable so that the C^+/FIR ratio should not be constant. However, in ionized gas, an additional source of grain heating is Lyα photons, which are usually trapped (the case B situation) and eventually absorbed by dust grains. This provides a minimum FIR thermal emission $I_{FIR} = \int I\,d\nu_{grains}$. We estimate this by multiplying the total case B recombination rate by the fraction of recombinations that produce a Lyα photon, which is about $\frac{3}{4}$, and by the energy of a Lyα photon and obtain the upper limit

$$\frac{I_{C^+}}{I_{FIR}} \leq 0.194\,\delta_{C^+}\,T_4^{0.35}\,. \qquad (10)$$

3. OBSERVED VERSUS THEORETICAL INTENSITY RATIOS

In this section, we compare observed ratios to the theoretical ratios derived above. The above theoretical ratios predict only the C^+ power that must, necessarily, emanate from the ELDWIM. The total C^+ power should be larger than these minimum predicted values because C^+ also exists in neutral gas; we discuss this neutral gas contribution in §§ 4 and 5.

First, we consider the comparison of the Galactic C^+ emission with the radio free-free emission made by Shibai et al. (1991) in their Figure 4*c*, which is a scan across the Galactic plane running through the H II region W43. The relevant comparison includes only the emissions from ELDWIM, i.e., for $|b| \gtrsim 0\overset{\circ}{.}3$, and excludes the emission from W43 itself, which is a large discrete radio H II region where n_e greatly exceeds the critical density for the C^+ line. The result is given in their Table 2, viz.,

$$\left.\frac{I_{C^+,-4}}{T_{B,5\,GHz}}\right|_{obs} = 4.8\,.$$

Comparing with equation (7), we obtain $\delta_{C^+} = 0.35$.

Next, we compare C^+ and diffuse RRL emission in the Galactic interior. First, we note that the velocity-longitude dependencies for the C^+ line (Nakagawa et al. 1993) and for the diffuse RRL lines (Lockman 1976, 1980; Anantharamaiah 1986; Cersosimo 1990a, b) agree well, although it is not worth performing more than an eyeball comparison because of the wide velocity resolution of the C^+ data. To compare intensities, we use Plate 7 of Nakagawa et al. (1993) to estimate $I_{C^+,-4}$ at $b = 0°$ (instead of their Fig. 2, which averages $I_{C^+,-4}$ over a 4° range in b). For the Galactic longitude ranges 5°–20°, 332°–336°, and 340°–355°, we estimate

$$\frac{I_{C^+,-4}}{T_B \Delta V_{H^+}} \approx 1.1\,.$$

Comparing with equation (8) and using our adopted value $T_4 = 0.4$, we obtain $\delta_{C^+} = 0.73$.

Next, we compare C^+ and N^+ emission in the Galaxy. Below in § 4 we present a more detailed discussion; here we use the overall "average spectrum" of Wright et al. (1991), $I_{C^+}/I_{N^+} = 10.4$. Using equation (4) with $T_4 = 0.4$ yields $\delta_{C^+}/\delta_{N^+} = 0.64$. This is consistent with estimates of the relative depletions of these elements (see Jenkins 1987). In fact, we should find a value for $\delta_{C^+}/\delta_{N^+}$ that is smaller than the estimates given by Jenkins, because some of the C^+ emission must arise from neutral regions where nitrogen is neutral. The inevitable uncertainties in the cosmic abundances and collision strengths mean that our exact value $\delta_{C^+}/\delta_{N^+} = 0.64$ should not be taken too literally.

Next, we compare C^+ and FIR emission in the Galactic interior. Shibai et al. estimate this ratio to be 5.8×10^{-3} from their scans in Galactic latitude. For the reasonable values $\delta_{C^+} = 0.5$ and $T_4 = 0.4$, equation (10) predicts the ratio to be 0.07, which is 12 times larger than the observed value. This simply means that the Lyα is much less important than the ISRF for heating the grains, and we cannot derive any meaningful information from their observational ratio.

Finally, we compare C^+ and Hα emission for external galaxies. To our knowledge, the integrated intensities of both lines have been measured for only three galaxies. From Stacey et al. (1991), Kennicutt (1983), and Kennicutt & Kent (1983) we obtain $I_{C^+}/I_{H\alpha} = 0.32$, 0.08, and 0.20 for NGC 4736, NGC 5194, and NGC 6946, respectively; the average is 0.20. This must be corrected for extinction, which averages 1.2 mag (Kennicutt 1983), and for the fact that some of the Hα emanates from standard H II regions. We assume that the latter correction is the same as Mezger's (1978) determination for the Galactic interior, a factor of 0.87. Including these corrections increases the average ratio to $I_{C^+}/I_{H\alpha} = 0.53$. Using equation (9) with $T_4 = 0.4$, we obtain $\delta_{C^+} \approx 0.48$. This is in quite good agreement with the values estimated above for the Galactic interior.

We now summarize the above information on δ_{C^+}. In the Galaxy, we obtained $\delta_{C^+} = 0.35$ and 0.73 from radio continuum and diffuse RRL emission, respectively, and $\delta_{C^+}/\delta_{N^+} = 0.64$ from the N^+ line. It seems reasonable to adopt $\delta_{C^+} = 0.5$ as an observational average. Ultraviolet spectroscopic observations near the Sun show that δ_{C^+} typically is 0.3–0.7, depending on the mean volume density in the line of sight (see Jenkins 1987). Our derived value falls nicely in the middle of this range, which implies that the ELDWIM can reasonably account for most of the observed C^+ emission.

4. THE CORRELATION BETWEEN N^+ AND C^+

4.1. *The Observational Correlation*

For $0.06 < I_{C^+,-4} < 1.8$, Petuchowski & Bennett (1993, hereafter PB) and Bennett & Hinshaw (1993, hereafter BH) plotted I_{N^+} versus I_{C^+} and found a tight (peak-to-peak variation factor ~ 2) *nonlinear* correlation; for weaker intensities, the scatter is larger (peak-to-peak variation factor ~ 6). From their figures we estimate

$$I_{N^+,-4} \approx 0.10 I_{C^+,-4}^{1.54} . \quad (11)$$

A power-law relationship of 3/2, which is nearly equal to 1.54, would be produced by a volume/surface correlation, and this is their interpretation. However, we now present an alternative interpretation which is consistent in spirit with our above discussion.

For the higher ranges of intensity, $0.2 < I_{C^+,-4} < 1.8$, we fit the PB/BH plots, essentially equally well, by the following *linear* functions, which we determined by the cut-and-try method:

$$I_{N^+,-4} \approx -0.015 + 0.115 I_{C^+,-4} , \quad (12a)$$

and the entirely equivalent form

$$I_{C^+,-4} \approx 0.13 + 8.7 I_{N^+,-4} . \quad (12b)$$

The numerical coefficients in the above equations are, of course, only approximate, and the "constant" terms are not really constants, as we discuss in § 4.2.

4.2. *Physical Interpretation of Our Linear Correlation*

Our fit breaks down for $I_{C^+,-4} \lesssim 0.2$, where our fit predicts values for I_{C^+} that are too large compared to the observed values. However, we both anticipate and welcome this breakdown, because it has a simple physical interpretation. Our fit in equation (12b) corresponds to a contribution to I_{C^+} from, first, the N^+-containing ELDWIM having $\delta_{C^+}/\delta_{N^+} = 0.54$ (cf. eq. [4] with $T_4 = 0.4$), and, second, an additional component, totally unrelated to the ELDWIM, that we represent by a "constant" term.

We consider this "constant" term to correspond to the ordinary neutral atomic H I along typical lines of sight—more specifically, to the CNM and not the warm neutral medium (WNM), because the latter has much lower volume density and is inefficient in collisionally exciting the C^+ line. The numerical value of this "constant" term is roughly proportional to the CNM column density $N_{H\,I,CNM}$ and also (even more roughly) to $N_{H\,I}$, which are of course *not* the same in all directions; thus, the "constant" term is only an artifact to represent a typical value for the CNM-related C^+ emission in the PB/BH plots. The CNM/H I column densities vary both systematically with Galactic longitude and latitude, and randomly. Toward directions having low $N_{H\,I,CNM}$, $I_{C^+,-4}$ can easily be less than 0.13.

We now discuss the expected value of this "constant" term toward the Galactic interior (say, $l \lesssim 40°$) at $b = 0°$ using the locally observed value of the mean C^+ power per H I atom. As determined from UV observations, the C^+ power per H I atom is somewhat uncertain because of the systematic effects discussed by Gry, Lequeux, & Boulanger (1992). More reliable determinations utilize direct measurements of the 158 μm line intensity. Bock et al. (1993) sample a large number of positions at high Galactic latitude and obtain 2.6×10^{-26} ergs s^{-1} atom^{-1}, which corresponds to $I_{C^+,-4} = 2.1 \times 10^{-23}$ $N_{H\,I}$, where $N_{H\,I}$ is the *total* (CNM and WNM) H-atom column density in cm^{-2}. Application of this estimate to the Galactic interior is uncertain because of two compensating effects. First, it is an underestimate for the Galactic interior, where the ISRF (thus the grain photoelectric heating) and the CNM pressure (thus the intrinsic cooling rate per C^+ ion) are considerably larger than in the solar neighborhood. However, it is an overestimate for the Galactic interior where the fraction of CNM is smaller than in the solar neighborhood (Garwood & Dickey 1989, hereafter GD), because only the CNM is an effective C^+ emitter in H I gas. The former effects should amount to a factor of ~ 2 and the latter to ~ 1.3, so our estimate of the CNM-emitting C^+ power per H I atom is probably an underestimate by a factor of ~ 1.5. We adopt the local value of Bock et al. as a lower limit, for which the "constant" term in equation (12b) corresponds to an upper limit $N_{H\,I} \lesssim 6.3 \times 10^{21}$ cm^{-2}.

The H I volume density at $z = 0$ is about 0.3 cm^{-2} (see Burton 1988); thus, the "constant" term corresponds to a path length $\lesssim 7$ kpc. This length—which is itself an upper limit—is surprisingly short because the atomic gas exists along the line of sight through the *whole Galaxy*. Toward the Galactic interior, the path lengths—only to the opposite side of the solar circle—are ~ 16 kpc and, with $\langle n_{H\,I} \rangle \approx 0.3$ cm^{-3}, produce $N_{H\,I} \sim 1.5 \times 10^{22}$ cm^{-2}. With our adopted C^+ power per H atom (which is an underestimate for the Galactic interior), this corresponds to $I_{C^+,-4} > 0.31$. Even this lower limit is about one-fourth the *maximum observed* C^+ intensity and is indeed a *typically observed* intensity. If such a large fraction of the total observed C^+ intensity were to come from ordinary H I regions, then the C^+ intensity would not correlate well with any tracer of the ELDWIM. The resolution of this conundrum probably lies in the opacity of the C^+ line (§ 4.3).

The "constant" term is also increased by diffuse PDRs with large ISRFs that may happen to lie along the line of sight. In particular, we note that every significant H II region *must* have an associated large-ISRF PDR, and large H II regions such as W43 and NGC 6334 have very significant PDRs that were easily seen in C^+ emission by Shibai et al. (1991). Although such individual sources are powerful and prominent, they do not contribute significantly to the *global* C^+ emission because they are not sufficiently numerous.

4.3. *The Opacity of the* C^+ *Line in the Galactic Plane*

Our discussion in § 4.2 neglects the important—and widely overlooked—fact that the C^+ line in the Galactic plane is often *optically thick.* In the ELDWIM, CNM, and WNM, most of the C^+ ions lie in the lower state of the fine-structure line because the collision rate is very low, so the optical depth of the line is

$$\tau_{C^+} = \frac{N_{C^+,17}}{1.4\,\Delta V} = \frac{N_{H,21}\,\delta_{C^+}}{0.36\,\Delta V} . \qquad (13)$$

Here the line is assumed to be rectangular with width ΔV in km s^{-1}, $N_{C^+,17}$ is the C^+ column density in 10^{17} cm^{-2}, and $N_{H,21}$ is the H-nucleon column density in 10^{21} cm^{-2}. Note that both the CNM and the WNM contribute to τ_{C^+}, in contrast to the case for the C^+ emission. A convenient way to write the C^+ optical depth associated with the *neutral atomic gas component*, $\tau_{C^+,H\,I}$, is in terms of the 21 cm line opacity and intensity, which is particularly convenient because the 21 cm line provides the requisite value of ΔV. The optical depth ratio is

$$\frac{\tau_{C^+,H\,I}}{\tau_{H\,I,21\,cm}} = 0.52\,\delta_{C^+}\,T_{k,2} , \qquad (14)$$

where $T_{k,2}$ is the gas temperature in units of 100 K. We can also write $\tau_{C^+,H\,I}$ in terms of the 21 cm line brightness temperature:

$$\tau_{C^+,H\,I} = -0.52\,\delta_{C^+}\,T_{k,2}\ln\left(1 - \frac{T_{B,21\,cm}}{T_k}\right) . \qquad (15)$$

For typical H I profiles in the Galactic plane, the determination of an appropriate global value for T_k has been the subject of considerable historical discussion. For a continuous, random distribution the appropriate value is the density-weighted harmonic mean $\langle T_k^{-1}\rangle^{-1}$, a reasonable value for which is 120 K (Baker & Burton 1975). With this and the assumption $\delta_{C^+} = 0.5$, $\tau_{C^+} = 1$ for $T_{B,21\,cm} = 115$ K. At some velocities, 21 cm line profiles at $b = 0°$ in the Galactic interior are this intense, although uncertainties in observational intensity scales mean that this value, 115 K, is not very reliable; also, Baker & Burton emphasize that the use of a single temperature is inappropriate and that better global results are obtained with a two-component medium (the CNM and WNM). Burton (1988) provides a modern discussion of these matters. The upshot is that, in at least some directions, for at least some velocity ranges, $\tau_{C^+,H\,I} > 1$. Individual large CNM clouds provide additional discrete contributions to $\tau_{C^+,H\,I}$: measured 21 cm line optical depths $\tau_{H\,I,21\,cm}$ are sometimes $\gg 1$, with inferred gas temperatures $T_k \lesssim 50$ K; in these clouds, equation (14) shows that we can have $\tau_{C^+,H\,I} > 1$.

There is an additional $\sim 30\%$ contribution to the C^+ optical depth from the ELDWIM component. This contribution is proportional to the ELDWIM-associated portion of the C^+ column density, which is in turn proportional to the mean electron column density N_e; this is revealed by observations of pulsar dispersion, which show that $\langle n_e\rangle$ peaks at ~ 0.1 cm^{-3} at $R_{gal} \sim 3.5$ kpc (Taylor & Cordes 1993). This $\langle n_e\rangle$ is about one-third of the mean H I volume density at $z = 0$.

The C^+ opacity is not an absorption opacity. Rather, it is a scattering opacity because the collisional excitation rate is much less than the Einstein *A*. With the two-dimensional geometry of a galactic disk, the surface brightness for a long line of sight that lies in the plane of the disk is diminished approximately the same as if the opacity were a true absorption opacity, because most of the photons are scattered in directions that do not lie in the plane of the disk. For external galaxies seen roughly face-on, the scattering enhances the C^+ surface brightnesses by amounts that depend on the intensity and distribution of C^+ sources.

4.4. *Summary*

We now summarize the above discussion. In equations (12a) and (12b), the portion of the C^+ line intensity that is linearly correlated with the N^+ line intensity arises from the ELDWIM. The uncorrelated portion—the "constant" term—arises from the neutral medium and has a numerical value that increases with $N_{H\,I,CNM}$. However, it is not strictly proportional to $N_{H\,I,CNM}$ because it depends on $n_{H\,I,CNM}$ and because of opacity effects in the C^+ line, which depend on $N_{H\,I}$, N_e, and the velocity structure. The C^+ opacity probably prevents the "constant" term from dominating and destroying the observed correlation between the N^+ and C^+ lines represented in equations (12a) and (12b). With the significant contribution from neutral gas, the C^+ and N^+ emission should be correlated but not perfectly so. For example, Wright et al. (1991) found the C^+ emission to have a larger extent in Galactic latitude than the N^+ emission. We note that the C^+ line opacity is important only along long lines of sight in the Galactic plane; a natural consequence for external galaxies is a corresponding diminution of the apparent C^+ brightnesses of edge-on galaxies.

5. PDRs IN H I ABSORPTION AND C^+ EMISSION

Here we consider the observable characteristics of PDRs in both the 21 cm line and the C^+ line.

5.1. *Observable* H I *Absorption from PDRs*

The outermost region of a PDR contains H I and is observable in the 21 cm line. The total H I column density $N_{H\,I}$ is determined by the balance between H_2 formation on dust grains and H_2 photodestruction by far-ultraviolet (FUV) photons. $N_{H\,I}$ is expressible in terms of the ratio G_0/n, where G_0 is the interstellar FUV radiation field measured in terms of the local value 1.6×10^{-3} ergs cm^{-2} s^{-1} and n is the volume density of H nuclei in the region ($n = n_{H\,I}$ in this outermost region). For $G_0/n \lesssim 50^{-1}$ cm^3, $N_{H\,I}$ is limited by "self-shielding" of the dissociating FUV radiation by H_2; otherwise it is limited by dust extinction. Sternberg (1989) provides a convenient approximate analytic expression for $N_{H\,I}$:

$$N_{H\,I} = 5.3 \times 10^{20}\ln\left(1 + \frac{59G_0}{n}\right)\ cm^{-2} , \qquad (16)$$

where we have adopted the parameterization and numerical values used by WHT and Burton, Hollenbach, & Tielens (1990) and taken $G_0 = 1.7\chi$ (Hollenbach 1994), where χ is Sternberg's parameterization of the FUV intensity. For realistic astronomical situations in which $59G_0/n \gg 1$, i.e., when $N_{H\,I}$ is wholly determined by dust extinction, $N_{H\,I} \gtrsim$ few $\times\,10^{21}$ cm^{-2}, which is equivalent to an extinction $A_v \approx$ few mag; otherwise $N_{H\,I} \lesssim 6 \times 10^{20}$ cm^{-2}. In these two cases the 21 cm line optical depth $\tau_{H\,I,21\,cm} = N_{H\,I}/(1.8 \times 10^{18} T\,\Delta V)$ is either $\gg 1$ or $\lesssim 1$, respectively.

Observations of PDRs associated with strong discrete H II regions are consistent with this theoretical estimate. Dickey & Benson (1982) included four H II regions among their sample of 21 cm absorption line measurements: W3, NRAO572, W49A, and W51A. Each region exhibited an easily detectable 21 cm absorption line at the velocity of the H II region and associated molecular cloud. The velocity widths are ~ 10 km s^{-1}, larger than the few km s^{-1} adopted in theoretical models of WHT and HTT. The other observed parameters are reasonably consistent with the calculations. $\tau_{\rm H\,I, 21\,cm}$ ranged from 1.3 to more than 4, and upper limits on gas temperature were $\langle T_k^{-1} \rangle^{-1} \sim$ 75 K, which is consistent with HTT's predictions of the mean temperature $\langle T_k \rangle \sim 100$ K. Corresponding upper limits on $N_{\rm H\,I, 21} \sim 3$. From equation (16), the corresponding values of G_0/n range from 1.0 to 25,000 (the accuracy of large values is very poor); large values are expected for these powerful H II regions.

5.2. *Observable* C^+ *Emission from PDRs*

The C^+ emission comes from the outer two regions (H I/C^+ and H_2/C^+) of a PDR, the combined size of which is determined by dust opacity with $A_v \approx 2$ mag (HTT). Most of the incoming ISRF is absorbed by dust in this region. If G_0 is not excessively large, then this region is cool enough so that C^+ is the main coolant and the intensity of the C^+ line is simply related to the incoming ISRF because a roughly fixed fraction of the ISRF heats the gas via the photoelectric effect on grains. Judging from HTT's figures, for $G_0 \lesssim 100$ we have (within a factor of ~ 3)

$$I_{C^+, -4} \approx 10^{-2} G_0 \, . \quad (17)$$

Given the typically observed values $I_{C^+, -4} \approx 1$, we require $G_0 \approx 100/N_{\rm clouds}$, where $N_{\rm clouds}$ is the number of clouds along the line of sight. Shibai et al. (1991) used this argument and considered $N_{\rm clouds} \sim 5$ to be a reasonable value, so we adopt $G_0 = 20$ in the ensuing discussion.

5.3. *Comparison of* H I *Absorption and* C^+ *Emission from PDRs*

The C^+ line observations of the Galactic interior show that typically $I_{C^+, -4} \approx 1$ (see § 3). These observations are taken with angular resolution $\sim 10'$, and it is most reasonable to assume, as do the observers, that the C^+ power is distributed roughly uniformly within the beam area instead of arising from a large number of small sources.[2] With this assumption, any pencil-beam line of sight must encounter the same $I_{C^+, -4} \approx 1$. Such pencil beams are sampled by 21 cm line absorption measurements. Thus, if the C^+ emission arises primarily from PDRs, then the 21 cm line absorption results must be generally consistent with the C^+ observations and PDR theory. Specifically, if PDRs exhibit weak 21 cm absorption lines, then $59 G_0/n \lesssim 1$ and H_2 self-shields so that $\tau_{\rm H\,I, 21\,cm} < 1$ in the PDRs.

Observations of the 21 cm line absorption in the Galactic plane have been analyzed by GD, who find that *strong* 21 cm line absorption, with $\tau_{\rm H\,I, 21\,cm} > 1$, is rare in the Galactic interior. The mean H I absorption coefficient decreases toward the Galactic interior, and the decrease arises because the *number* of absorbing clouds decreases by a factor of ~ 2 relative to the solar neighborhood. This is graphically illustrated in the velocity-longitude diagram for 21 cm line absorption, which—in contrast to the diagram for C^+ emission—shows absorption components at all allowable velocities of Galactic rotation. In particular, GD find that for $4.25 < R_{\rm gal} < 8.5$ kpc, the mean free path between clouds having $\tau_{\rm H\,I, 21\,cm} > 1$ is about 4.3 kpc, while in most of the inner Galaxy—for $0.0 < R_{\rm gal} \leq 4.25$ kpc—the mean free path is much larger, about 11 kpc.

To summarize: although it is common to see strong C^+ emission along every line of sight, it is not common to see strong H I absorption. We conclude the following: if most of the C^+ emission arises from PDRs, then these PDRs cannot have deep 21 cm absorption lines. For $\tau_{\rm H\,I, 21\,cm} < 1$, $\langle T_k^{-1} \rangle^{-1} = 100$ K, and $\Delta V = 3$ km s^{-1} as representative examples, this means that $N_{\rm H\,I} \lesssim 5.4 \times 10^{20}$. From equation (16) we find that this, in turn, requires $G_0/n \lesssim 0.03$; with $G_0 = 20$, this means $n = n_{\rm H\,I} \gtrsim 700$ cm^{-3}. This is a high density and, with the assumed temperature of 100 K, implies a high pressure, more than 10 times the standard gas pressure in the interstellar medium.[3] In the PDR picture, high pressure arises naturally because the PDRs abut H II regions, which also have high pressure. A PDR in pressure equilibrium with its associated H II region has $G_0/n \approx 0.01 n^{0.33}$ (HTT). Unfortunately, we cannot combine these two equations to solve for G_0 and n separately because the results are overly sensitive to observational uncertainty. However, with the representative values $G_0 = 20$ and 100, HTT's relation provides $n = 300$ and 1000 cm^{-3}, respectively; these values are not too inconsistent with the 21 cm line constraint. Furthermore, they imply H II region electron densities ~ 200 times smaller, which are low enough to be considered ELDWIM.

Thus, if the observed C^+ emission arises primarily from PDRs, we must consider these PDRs to be the boundaries of the ELDWIM regions instead of ordinary H II regions. However, our discussion in §§ 3 and 4 favors the idea that the ELDWIM itself produces most of the C^+ emission. In fact, there must be a contribution from both regions, and the question is which is larger.

We believe that the theoretical and observational arguments presented in §§ 3 and 4 show that the ELDWIM contribution is larger. However, given the inevitable observational and theoretical uncertainties, our arguments are not ironclad. An additional theoretical input is provided by Carral et al. (1994), who calculate the relative contributions to C^+ emission of an H II region and its associated PDR. They find that the H II region contribution is larger for $n_e \lesssim 10$ cm^{-3}. If the physical parameters of the ELDWIM are, indeed, as pictured by many workers (see § 1), then n_e is substantially less than 10 cm^{-3} in the ELDWIM and our arguments are reinforced.

6. DISCUSSION

We first summarize the main points. A very significant fraction of the C^+ emission must necessarily come from the same ELDWIM that produces the diffuse radio free-free continuum radiation, the diffuse radio recombination line emission, and the N^+ emission. The exact value of this fraction is uncertain because of inaccuracies in physical conditions, collision strengths, cosmic abundances, and depletions, but we have argued that the ELDWIM predominates and that the remaining C^+ emission comes from neutral regions. For these neutral

[2] We do not correct for the presence of typical bright sources, which individually contribute a comparable intensity $I_{C^+, -4} \approx 1$, because the number of such bright sources is small and the probability that one lies within—and, especially, that many fill the solid angle of—a C^+ observing beamwidth is small.

[3] Because $\tau_{21\,\rm cm} \propto \langle T_k^{-1} \rangle^{-1}$, this derived pressure is roughly independent of assumed temperature T_k.

regions, the C^+ emission from the ordinary CNM is more than adequate, and indeed would be embarrassingly large if it were not for the opacity of the C^+ line along long lines of sight in the Galactic plane. PDRs also contribute. For example, individual PDRs surrounding strong H II regions are easily observed in the C^+ line. However, PDRs apparently rank third, behind the ELDWIM and the CNM, in their *global* contribution to the C^+ emission.

It might seem surprising that the ELDWIM produces most of the C^+ emission in the Galactic interior, because its volume and column densities are somewhat less than those of the CNM (the WNM contributes little C^+ emission). This is easily explained. For approximate pressure equilibrium, the C^+ emission rate *per H nucleon* is higher in the ELDWIM than in the CNM because the collisional cross section for electron excitation is much larger than for H I excitation. If we assume that the CNM is purely neutral and that the WIM is fully ionized with 1 electron per H nucleon, then the ratio of C^+ excitation rates (and thus photon emission rates) per H nucleon in the two media is

$$\frac{\gamma_{\rm WIM}}{\gamma_{\rm CNM}} = 0.39 \frac{P_{\rm WIM}}{P_{\rm CNM}} T_{\rm WIM,4}^{-1.35} T_{\rm CNM,2}^{0.93} \exp\left(\frac{0.92}{T_{\rm CNM,2}}\right) . \quad (18)$$

Here we have taken the H I collisional rate from Hollenbach & McKee (1989). A typical value for $T_{\rm CNM,2}$ is about 0.5. With $T_{\rm WIM,4} = 0.4$ and $P_{\rm WIM}/P_{\rm CNM} = 1$, equation (18) predicts $\gamma_{\rm WIM}/\gamma_{\rm CNM} = 4.4$. However, the value 4.4 is probably an underestimate because observations of the ELDWIM imply a $P_{\rm WIM} \sim 5$ times the local $P_{\rm CNM}$. In the Galactic interior, $P_{\rm CNM}$ should be higher than its local value, but probably not by a factor of 5. Probably, then, $P_{\rm WIM}/P_{\rm CNM} > 1$ in the Galactic interior, which would make equation (18) predict $\gamma_{\rm WIM}/\gamma_{\rm CNM}$ somewhat greater than 4.4. At $z = 0$, the ELDWIM density peaks at $\langle n_e \rangle \approx 0.1$ cm^{-3} in the Galactic interior; the CNM density (not the *total* H I density, because we exclude the WNM) dips to $\langle n_{\rm H\,I,CNM} \rangle \approx 0.15$ cm^{-3}. Thus, in the Galactic interior, almost half of the C^+ lies in the ELDWIM, which therefore produces most of the 158 μm line emission.

It might seem surprising that the C^+ emission is very well correlated with CO ($J = 1$–0) emission, both in external galaxies (Stacey et al. 1991) and in our own Galactic interior (see Fig. 4 of Shibai et al. 1991). The CO line is optically thick, so it is not directly related to the total molecular mass; the C^+ line is optically thin and arises primarily from ionized gas, not molecular regions or PDRs. To understand the C^+/CO correlation, first recall that WHT and HTT can explain it if the C^+ emission arises from PDRs. Then realize that the ELDWIM is, in part, associated with discrete H II regions as explained in § 1; thus both PDRs and the ELDWIM are associated with bright H II regions. Next, realize that with the limited angular resolution currently available, the exact location of the C^+ emission cannot be pinpointed accurately enough to distinguish between the PDRs and the ELDWIM. Finally, realize that the C^+ emission from the ELDWIM is comparable, within a factor of a few, to that from its associated PDR if $\langle n_e \rangle \lesssim 100$ cm^{-3} (see Carral et al. 1994). Thus, the ELDWIM-associated C^+ emission takes the place of the PDR-associated C^+ emission in the C^+/CO correlation predicted in the WHT and HTT models.

Our conclusion, that PDRs are the third most important contributor to C^+ emission, is contrary to the usual interpretations. In the Galactic interior, Petuchowski & Bennett (1993) concluded that slightly more than half the C^+ comes from PDRs, the remainder from the ELDWIM, and an insignificant portion from the CNM. In external galaxies, the PDR interpretation is commonly employed, following the original interpretations of early observations (see WHT and discussion in Stacey et al. 1991). We suspect that these original interpretations were biased against the ELDWIM because it is almost impossible to observe in external galaxies. In contrast, the CO emission was easy to observe and correlated well with C^+, as did the FIR continuum; the C^+ line was too strong to have come from standard H I regions. With the absence of knowledge about the ELDWIM, the PDR interpretation followed naturally.

A complete map of the C^+ emission from NGC 6946 by Madden et al. (1993) shows that $\sim$75% of the total *global* emission arises from a diffuse component which extends to large galactocentric radii. By comparing the C^+ intensity to the radio free-free continuum emission in the outer parts of NGC 6946, these authors find that $\lesssim$48% of the diffuse C^+ emission arises from the ELDWIM, with the majority arising from the CNM (and not PDRs). The predominance of the CNM for the diffuse C^+ emission must also be the case for the outer portions of our own Galaxy, e.g., in the solar neighborhood, where the ELDWIM is not very dense. However, for the Galactic *interior*, our estimates reverse the relative importance of these two components and the ELDWIM predominates the C^+ emission.

Our conclusions should also apply to many external spiral galaxies (but probably not starbursts, which probably have higher values of $\langle n_e \rangle$ that exceed the critical density for the C^+ line). An observational test would be a careful comparison of C^+ and Hα luminosities in a decently large sample, accounting for the contributions of ordinary H II regions (which produce little C^+ emission) and the effects of extinction. To our knowledge, no such data exist.

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