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COOLING OF THE INTERSTELLAR GAS: RESULTS FROM COBE

Charles L. Bennett[1] & Gary Hinshaw[2]
[1]Code 685, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
[2]USRA, Code 685.3, NASA Goddard Space Flight Center, Greenbelt, MD 20771

bennett@stars.gsfc.nasa.gov

ABSTRACT

We report the results of new analyses of far infrared spectral line observations from the FIRAS instrument on the *COBE* satellite with special attention to the spatial distributions of the 158 μm [C II] and the 122 μm and 205 μm [N II] emission lines. These distributions provide new insight into the large-scale distribution and excitation of gas in the Milky Way. Transitions of [C I] at 370 μm and 609 μm and CO J=2-1 through 5-4 are also discussed.

1. INTRODUCTION

An unbiased far infrared survey of the spectral line emission from our Galaxy has been reported from the Cosmic Background Explorer (*COBE*) mission by Wright *et al.* (1991). Unlike other observations that concentrate on specific small regions of the sky at particular wavelengths, the *COBE* FIRAS instrument observed nearly the entire sky with two decades of wavelength coverage. Thus, the *COBE* data show that the large scale diffuse emission from our Galaxy is dominated by a far infrared continuum that cools dust grains, and the 158 μm ground state transition of [C II] that cools the neutral gas in the Galaxy. Two transitions of [N II] trace the large-scale low-density extended ionized component of the galaxy. In addition, the 370 μm and 609 μm lines of [C I] and the J=2-1 through 5-4 lines of molecular CO were detected, and trace the interiors of neutral regions.

Mechanisms for heating interstellar gas include collisions, radiation from stars, shocks, and cosmic rays. Examination of the spectral lines that cool the gas can help determine the dominant excitation mechanisms and conditions. Studies of particular bright regions in our Galaxy and observations of external galaxies have suggested that stellar ultraviolet radiation can ionize vast volumes of a galaxy and that the UV radiation impinging on neutral cloud surfaces is responsible for a large fraction of the far infrared spectral line emission that cools the gas.

Tielens & Hollenbach (1985a) defined *photodissociation regions* (hereafter referred to as PDRs) as neutral "regions where FUV radiation dominates the heating and/or some important aspect of the chemistry. Thus photodissociation regions include most of the atomic gas in a galaxy, both in diffuse clouds and in the denser regions..."

Early conceptual work on PDRs includes Glassgold & Langer (1974, 1975, 1976), Langer (1976), Black & Dalgarno (1977), Clavel, Viala & Bel (1978), and de Jong, Dalgarno & Boland (1980). Tielens & Hollenbach (1985a) presented a detailed and quantitative model for one dimensional PDRs.

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The basic photodissociation process can be summarized as follows. Far ultraviolet photons in the energy range 6-13.6 eV, often from O and B stars, impinge on the surfaces of neutral clouds where they will be stopped by impacts with dust grains. The dust grains emit photoelectrons and cool by continuum far infrared emission. The photoelectrons result in the heating of the atoms and molecules in the gas. The UV generally photodissociates the molecules and photoionizes atoms with ionization potentials less than the Lyman limit. Most importantly, photoelectrons heat the gas, resulting in the excitation of C II atoms from their ground state to their first excited state, 91 K above the ground state. C II cools by the emission of 158 μm radiation. The process thus converts far UV radiation to far infrared continuum and spectral line emission. Only far UV radiation can contribute to this process since the typical work function of an interstellar grain is $\sim$6 eV (de Jong 1980). The photoelectric mechanism can typically convert a maximum of $\approx$4 % of the far UV energy into gas heating. This includes the assumption of a $\approx$ 10% probability that an absorbed photon results in an ejected electron (the photoelectric yield). Wright *et al.* (1991) determined, based on *COBE* data, that the 158 μm [C II] line alone emits 0.3% of the bolometric far infrared ($\approx$ UV) lumionosity in our Galaxy.

The UV flux incident on a neutral cloud, G_0, is usually expressed in units of the Habing (1968) flux of 1.6×10^{-3} ergs cm$^{-2}s^{-1}$. For unusually highly excited regions, such as Orion, the UV flux incident on the neutral PDR region is $G_0 \sim 10^{4-5}$ and the gas density is $n \sim 10^5$ cm^{-3}. The ionization potential of carbon is 11.3 eV, so carbon can be singly ionized where hydrogen is neutral. The ionization potential of oxygen is 13.6 eV, like that of hydrogen, so oxygen is neutral where hydrogen is neutral. In general, for high UV fields ($G_0 > 10^{2.5}$) and/or high densities ($n > 10^{3.5}$ cm^{-3}), [O I] fine structure lines at 63 μm and 145 μm contribute significantly to the cooling of the neutral gas. For lower densities and UV field strengths, the 157.741 μm (Cooksy, Blake, & Saykally 1986) transition of [C II] ($^2P_{3/2} -^2 P_{1/2}$) is the major cooling line. This is because in O I the ^{3}P$_1$ excited state is 228 K above the ^{3}P$_2$ ground state, and the ^{3}P$_0$ state is 326 K above the ground state. In C II the ^{2}P$_{3/2}$ excited state is only 91 K above the ground state. Dust grains become positively charged, especially near the surfaces of clouds, resulting in a decrease of the photoelectric heating efficiency. An increased electron density results in a higher dust-electron recombination rate, allowing the UV energy to be converted to gas heating more efficiently. Thus, an increase in density acts like an increase in the gas excitation.

The visual extinction into a neutral cloud, A_V, is related to the hydrogen column density, N_H, by $N_H/A_V = 1.8\times10^{21}$ cm^{-2} mag^{-1} (cf. Burstein & Heiles 1978; Bohlin, Savage & Drake 1978), where the exact value of the conversion factor depends on the local gas-to-dust ratio. Hydrogen in the PDR is predominantly in the form of H I for $A_V < 2$ and H$_2$ for $A_V > 3$. [C II] dominates the cooling of the outer regions of the cloud ($A_V < 4$) for low-excitation PDRs, as described by Hollenbach, Takahashi, & Tielens (1991). [C I] dominates the cooling for $4 < A_V < 6$ and CO rotational transitions dominate the cooling for $A_V > 6$. The A_V values, above, vary according to the detailed physical properties of the particular PDR (i.e. n, G_0, and geometrical effects). Significant UV shielding (i.e. $A_V \sim 10 - 20$) is required before OH, H$_2$O, and O$_2$ can be sustained. For $A_V > 6$ heating from cosmic rays and gas-grain collisions become significant relative to the UV heating.

The photodissociation model has been successfully applied to Orion, which is a face-on PDR (Tielens & Hollenbach 1985b), and to M17SW, which is an

edge-on PDR (Meixner *et al.* 1992). Wolfire, Tielens, & Hollenbach (1990) applied the model to the nuclear region of our Galaxy and to M82 to derive UV field strengths and gas densities. Low density PDR models, which are important for interpreting the average PDR conditions in our Galaxy, were computed by Hollenbach, Takahashi, & Tielens (1991). Wolfire, Hollenbach, & Tielens (1992) conclude that CO 1-0 emission from giant molecular clouds is primarily the result of the PDR physics. Crawford *et al.* (1985) and others have found that PDR models account for the excellent correlation both between 158 μm [C II] emission and CO 1-0 emission, and between [C II] and far IR continuum emission.

2. OBSERVATIONS & PREVIOUS RESULTS

Results are presented from the *COBE* Far InfraRed Absolute Spectrophotometer (FIRAS) instrument. The instrument is a scanning Michelson interferometer that covers the wavelength range from 100 μm to 1 cm. While the primary purpose of the instrument is to make precise measurements of the cosmic microwave background radiation, the instrument design offers many advantages for the large scale study of diffuse emission from our Galaxy. For example, the FIRAS has a 7° beam, is an instrument that makes absolute measurements of intensity with no beam switching, and has observed nearly the entire sky. For these reasons, the FIRAS is well-suited for measurements of diffuse emission. The nominal spectral resolution is 0.7 cm^{-1} (or R $\equiv \lambda/\Delta\lambda \approx 30$ at 500 μm). Some higher spectral resolution data exist, but are not discussed here.

The first cosmological results from the *COBE* FIRAS instrument were reported by Mather *et al.* (1990), and recent overall summaries of *COBE* results are found in Boggess *et al.* (1992) and Bennett *et al.* (1992a,b).

The first results of the *COBE* FIRAS unbiased far infrared survey of the Milky Way were published by Wright *et al.* (1991). Table 1 in that paper summarizes spectral line detections from *COBE* FIRAS: 158 μm [C II], 370 μm and 609 μm [C I], J=2-1 through J=5-4 CO, and 122 μm and 205 μm [N II]. Since that time, improved data processing algorithms and techniques have allowed for a more detailed examination of the data.

The [C II], [C I], and CO emission lines detected by *COBE* can immediately be recognized as the expected cooling lines from PDRs with low densities and small UV fields (Hollenbach, Takahashi, & Tielens 1991). The result that the galactic-averaged PDR properties are described by lower excitation conditions than objects such as Orion is strengthened by the lack of detection by *COBE* FIRAS of the 145 μm [O I] line.

The two transitions of [N II] are recognized as arising from the ionized medium. As pointed out by Wright *et al.* , this emission can not be coming from only classical, high-density, H II regions. The ratio of the intensities of the $^3P_2$ to $^3P_1$ 122 μm [N II] line to the $^3P_1$ to $^3P_0$ 205 μm ground state transition is a probe of the density of the ionized gas. Rubin (1985) provides a grid of classical H II region models that result in I(122 μm [N II])/I(205 μm [N II]) ranging from 3 (for $n_e \approx 10^2$ cm^{-3}) to 10 (for $n_e \approx 10^5$ cm^{-3}). In the low-density limit, $n_e \ll 100$ cm^{-3}, the expected intensity ratio is 0.7. The measured *COBE* ratio is 1.0 to 1.6, depending on the adopted values for the instrumental resolution at the two wavelengths. Thus the ionized gas measured by *COBE* FIRAS is likely to arise mostly from large, diffuse, regions. Reynolds (1990, and references therein) has extensively studied the warm ionized medium (WIM), concluding that a large fraction of the Galaxy contains $\sim$ 8000 K fully ionized gas with a

density of $n_e \approx 0.2$ cm^{-3}. However, the galactic disk is opaque to the Hα and other optical lines used to study this medium so only a local (typically < 2 kpc) view exists. The galactic disk is transparent to microwave continuum free-free emission, but it is difficult to separate the dust and synchrotron components from the overall microwave emission (Bennett *et al.* 1992c). Radio recombination line observations have not been sensitive enough to observe the WIM.

3. ANALYSIS RESULTS

In the Wright *et al.* (1991) analysis the dust continuum emission map of the sky was used as a spatial filter for averaging the emission from the spectral lines, effectively assuming that the spectral line intensities follow the continuum spatial distribution. That assumption is not made here. Rather, for each pixel we perform a simultaneous least squares fit of a continuum spectral "baseline" plus a series of Gaussian spectral line profiles centered on the wavelengths of known lines. The result are a set of spectral line intensities for each sky position. We find that while the [C II] emission (color Plate 5) follows the continuum closely, and the [N II] emission (color Plate 6) follows it approximately, the [C I] and CO emission are distinct from the continuum template used by Wright *et al.* , in that the [C I] and CO flux distributions are strongly concentrated towards the galactic center.

In Figure 1 the longitude profiles of the [C II] and 158 μm far infrared emission are shown for the entire galactic plane. The line and continuum emission are seen to track one another very well, as would be expected for PDR emitting gas. The emission appears to peak towards the molecular ring, the galactic center direction, and in the spiral arms. Only towards the galactic center does the [C II] emission appear to be relatively weak compared with the far infrared continuum. In contrast, the 609 μm [C I] emission, shown in Figure 2, peaks strongly towards the galactic center direction, as does the CO J=5-4 emission. These observed differences in the behavior of the spectral lines towards the galactic center may be explained in a number of ways. They may be indicative of a difference of mean PDR parameters. For example, emission from the galactic center direction may reflect significantly different UV field strength and/or color, gas density, dust properties (size distibution and photoelectric efficiency), gas-to-dust ratio, or the 158 μm [C II] may be saturated towards the galactic center. If the galactic center neutral material were less clumpy or of higher density, relatively more cooling could be done by [C I] and CO than by [C II] because of the higher relative filling factor of high-A_V neutral gas. The [C II] emission towards the galactic center may be self absorbed, but the 1.5 power law scaling with the [N II], discussed below, still holds in this region.

Figure 3 shows the profiles of the two [N II] transitions. Although the 122 μm transition is clearly noisier due to the poorer instrument sensitivity at that wavelength, the transitions clearly track one another, as expected. Figure 4 compares the [C II] and [N II] distributions. The distributions are unmistakably related, but the [N II] is relatively stronger than the continuum while the [C II] follows the continuum. Figure 5 shows that an excellent correlation exists between the fluxes of [C II] and [N II], in the sense that I(N II) $\propto$ I(C II)$^{1.5}$, as pointed out by Petuchowski & Bennett (1993a,b). They suggest that the 3/2 power law may be the result of a volume to surface area ratio sampling of the interstellar gas. Figure 6 shows that I(C II) $\propto$ I(FIR)$^{0.95}$ while I(N II) $\propto$ I(FIR)$^{1.55}$.

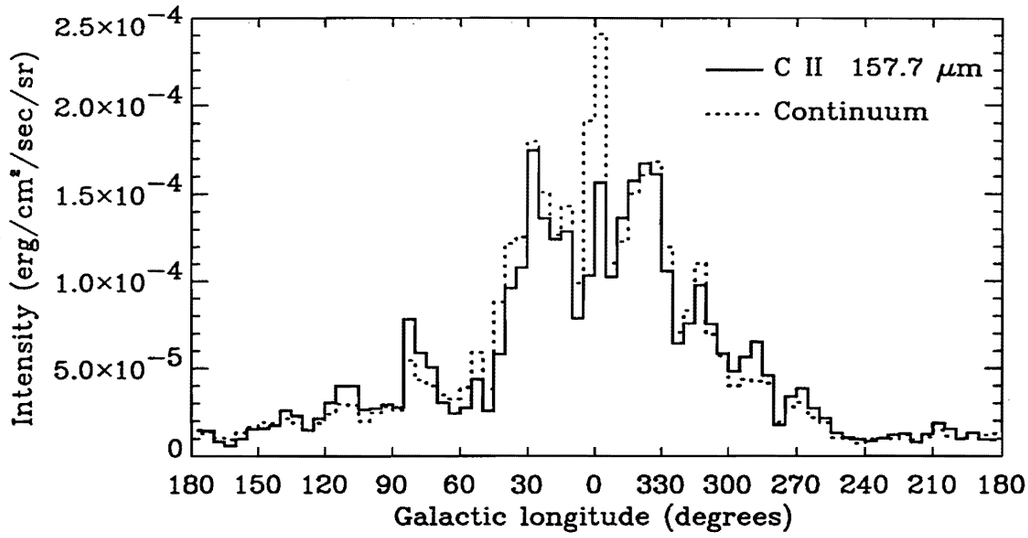

Figure 1: The longitude profile of the [C II] and 158 μm far infrared emission is shown for the entire galactic plane. The flux in each bin represents an average over 5° in galactic longitude and 10 ° in galactic latitude.

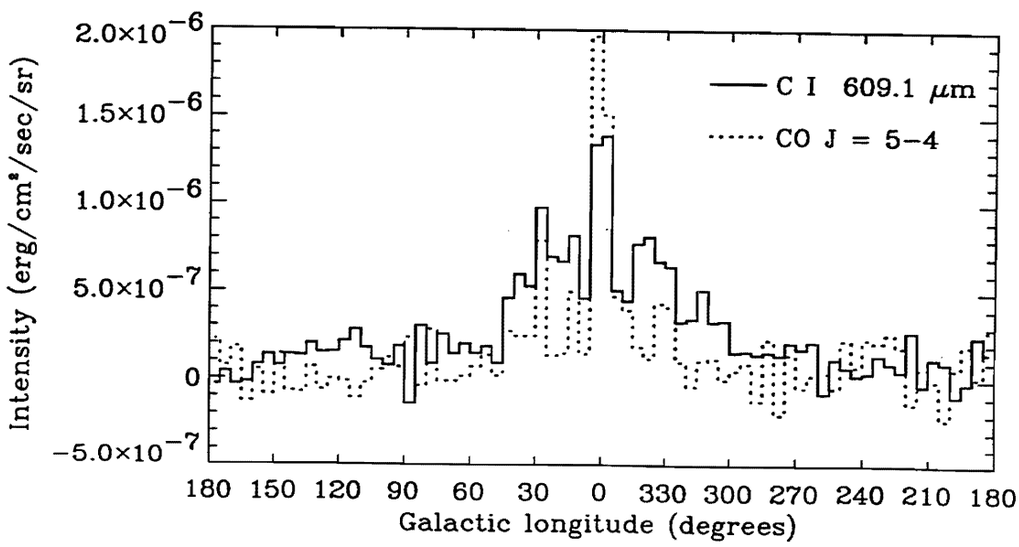

Figure 2: The 609 μm [C I] and CO J=5-4 emission peak strongly towards the galactic center direction.

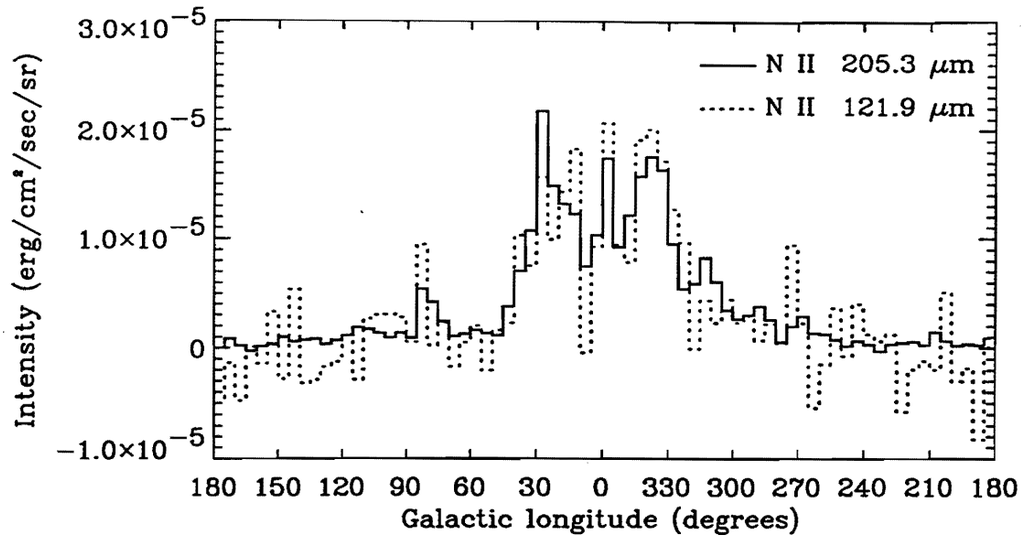

Figure 3: The intensity distributions of the two [N II] transitions.

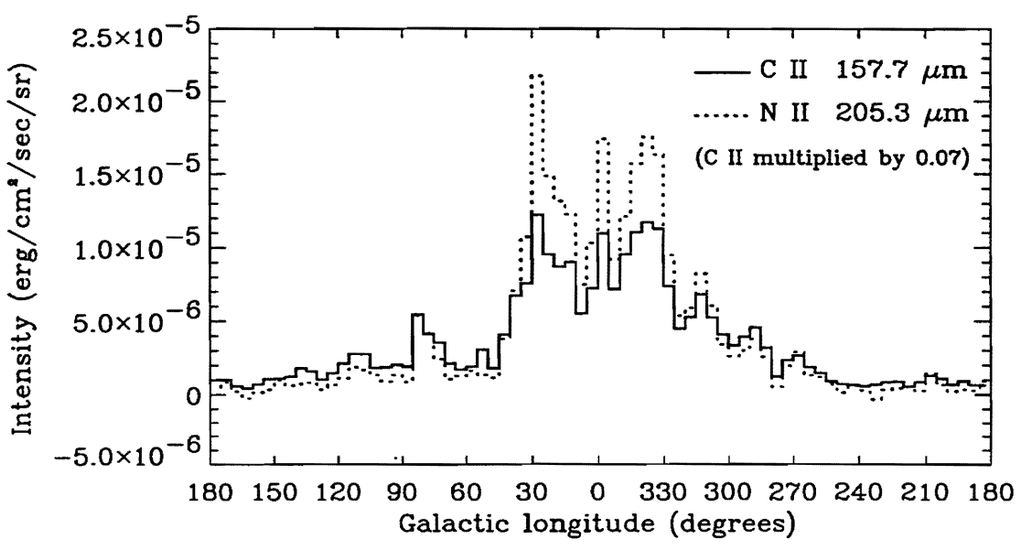

Figure 4: The [C II] and [N II] distributions. While the qualitative distributions are unmistakably related, the [N II] tends to be relatively stronger than the continuum where the [C II] follows the continuum.

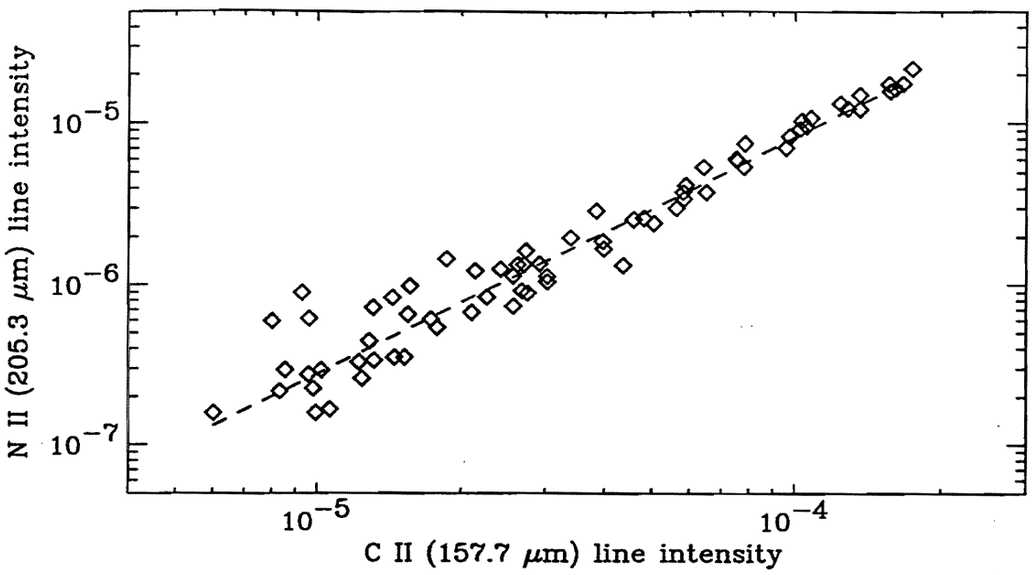

Figure 5: An excellent correlation exists between the intensity of the [C II] and [N II] intensities, in the sense that I(N II) $\propto$ I(C II)$^{1.5}$.

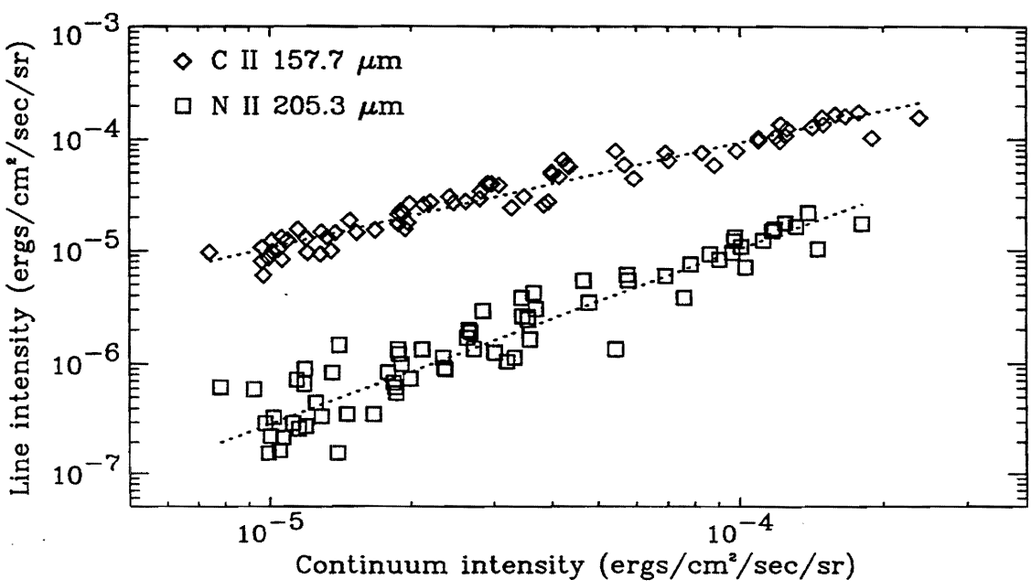

Figure 6: I(C II) $\propto$ I(FIR)$^{0.95}$ while I(N II) $\propto$ I(FIR)$^{1.55}$.

4. DISCUSSION & CONCLUSIONS

The 158 μm [C II] emission is linearly correlated with the far IR continuum. The 205 μm and 122 μm from [N II] also appears closely correlated with the far IR contiuum and the [C II] emission. The flux of the [N II] emission goes as the 3/2 power of the [C II] emission. This power-law may be considered suggestive of a volume to surface area ratio geometric effect. In such a scenario the volumes of very large internally ionized regions give rise to [N II] emission. These regions are partially surrounded by neutral gas with the interface surface traced by [C II] emission. If the emission from each line of sight is dominated by one such region that is characterized by an effective radius R_{eff}, then $I(N\ II) \propto R_{eff}^3$ and $I(C\ II) \propto R_{eff}^2$, so from one line of sight to another the ratio will be characterized by $I(N\ II)/I(C\ II) \propto R_{eff}^{1.5}$. For the 3/2 power law to hold each line of sight must be better characterized by an effective radius of an individual region than by the number of regions along each line of sight. If several regions contribute substantially to the emission along each line of sight, then $I(N\ II)$ would be linearly proportional to $I(C\ II)$. In this picture, the emission, which peaks in the direction of the molecular ring, is dominated by approximately beam-sized bubbles of ionized gas surrounded by neutral gas. For the *COBE* 7° beam, this corresponds to bubbles 1 kpc in diameter. Comparable size bubbles are known to exist in external galaxies (e.g. Bruhweiler, Fitzurka & Gull 1991; Kamphius, Sancisi & van der Hulst 1991). Note that the [N II] emission need not arise from the volume of the bubble, but could be from swept up gas so long as the amount of gas is characterized by the bubble volume.

The above scenario requires large-scale structures. Shibai *et al.* (1991) report results from a 3.4 arc-minute beam size survey of [C II] emission concluding that, "most [C II] emission of the Galactic disk is radiated not from discrete sources but from more extended and diffuse regions." Nakagawa *et al.* (1993), at this conference, have shown [C II] maps made from observations with a 12 arc-minute beam that also shows structures that are much larger than the beam size. Doi *et al.* (1993), at this conference, conclude that discrete sources are significant when looking through the length of the l=90° spiral arm.

Massive and luminous O and B stars tend to form in clusters and then become Type II supernovae that are correlated in space and time. The correlated supernovae create bubbles in the plane of the Galaxy. If the bubble is large enough it can "break through" the thickness of the disk. If the breakthrough is particularly energetic it will blow material into the halo of the Galaxy. These are called "blowout" bubbles. These "blowouts" lead to Galactic fountains. In these models significant amounts of material from the galactic plane are thrown out of the plane and at least some of this material rains back down onto the plane. These processes have been described by Bregman (1980), Houck & Bregman (1990), Mac Low & McCray (1988), Mac Low, McCray, & Norman (1989), Heiles (1990), Norman & Ikeuchi (1989), and Shapiro & Field (1976). Heiles (1990) estimates an area filling factor of breakthough bubbles of 23% in our Galaxy. McKee & Williams (1993a,b) derive the somewhat lower filling factor of superbubles of 10%. We feel that the cycle involving giant molecular clouds, massive clustered O and B stars, and clustered supernovae must be greatly enhanced in the molecular ring of the Galaxy so that the filling factors of bubbles, quoted above, are probably underestimates for the ring.

Petuchowski & Bennett (1993a, 1993b) examined the possible make-up of the *COBE* FIRAS line emission in terms of three morphologies: classical ioniza-

tion bounded H II regions, boundary ionized clouds, and an extended low density warm ionized medium. They conclude that the classical ionization bounded H II regions contribute very little to the total line emission intensities, largely because of their small volume filling factors. The other two morphologies can occupy large filling factors and contribute significantly to the total signal intensity. Since bubbles, superbubbles, and neutral material around their periphery are examples of large filling factor regions, they are capable of dominating observed signals along lines of sight that also contain several, much smaller, classical H II regions.

Volume-to-surface geometry is only one possible explanation for the 1.5 power scaling law between [C II] and [N II]. It may be that the [C II] scales proportionally with the far infrared continuum for the average PDR conditions in the Galaxy, but that $I([N\ II]) \propto I(FIR)^{\sim 1.5} \propto I(UV)^{\sim 1.5}$ for some other physical reason, for example, having to do with the mean galactic color of the UV radiation field in the Galaxy. It is worth noting that a similar 1.5 power law relation has been reported for different transitions in an external galaxy (Petuchowski & Bennett 1993a, 1993b).

Bock *et al.* (1993) conclude that at a high galactic latitude the [C II] cooling rate is $(2.3 \pm 0.3) \times 10^{-26}$ erg/s per H-atom. Using this value with the estimated total [C II] luminosity from our Galaxy from *COBE* of $10^{7.7}$ solar luminosities (Wright et al. 1991), we derive the 158 μm line from [C II] is cooling $> 10^9$ solar masses of gas. It is not known if the H I gas in the outer Galaxy and halo is dominated by PDR physics, but it is still likely to be the case that 158 μm [C II] emission is the dominant coolant.

Preliminary analysis results from the *COBE* DIRBE experiment, reported at this conference by Hauser, is interpreted by Sodroski *et al.* , who conclude that 90% of the far IR dust emission comes from neutral regions. This conclusion is consistent with the PDR model results suggested here. The fact that H I and C II *appear* to have different spatial distributions is not contradictory with the picture that C II cools H I gas. Except where the emission is self-absorbed, the H I flux is directly proportional to the H I column density. On the other hand, the 158 μm [C II] flux does not, in general, scale directly with the gas density. Since [C II] emission is the result of a collisional process between electrons and carbon ions, one might naively expect [C II] emission to scale as the square of the gas density. In the low excitation PDR models of Hollenbach, Takahashi, & Tielens (1991), the 158 μm [C II] emergent intensity scales somewhat less than the square of the density for low densities and low UV field strengths. Nevertheless, since H I and C II intensities scale differently with density the fact that they have *apparently* different spatial distributions is not surprising.

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