THE ASTROPHYSICAL JOURNAL, 303:638–648, 1986 April 15

OBSERVATIONS OF THE 157.7 MICRON [C II] EMISSION FROM THE GALACTIC H II REGIONS W3 AND W51

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Received 1985 May 23; accepted 1985 October 9

ABSTRACT

We have detected the 157.7 μm ground-state fine-structure transition of singly ionized carbon from three positions each in the galactic H II regions W3 and W51. These observations show that the 157.7 μm [C II] emission is extended beyond both the compact H II regions and the carbon recombination region in each source, in agreement with the findings of previous observations of the H II regions NGC 2024 and M17. Our observations establish a lower limit to the luminosity in the 157.7 μm [C II] line of 360 $L_\odot$ from W3, assuming a distance of 2 kpc, and 410 $L_\odot$ from W51, assuming a distance of 7 kpc. We discuss mechanisms for the excitation of the 157.7 μm line and conclude that much of the observed emission originates in the thin carbon recombination line–emitting region bordering on the H II regions and the warm ($T_{gas} > 100$ K) atomic and molecular gas at the surface of the adjacent molecular clouds. Excitation by electrons present in the diffuse, low-density ionized gas surrounding W51 may contribute to the extended 157.7 μm [C II] line emission from this region, though the contribution to the total 157.7 μm [C II] flux from the compact H II regions in the center of both W3 and W51 is negligible. Finally, we find that the [C II]/FIR continuum ratios for W3 and W51 are in agreement with those of other galactic H II regions.

Subject headings: infrared: sources — nebulae: H II regions — nebulae: individual

I. INTRODUCTION

The atomic transition region between the ionized gas within H II regions and the cold, molecular gas in nearby molecular clouds has been studied theoretically by several authors (e.g., Werner 1970; Glassgold and Langer 1975; Tielens and Hollenbach 1985). In these models, an atomic hydrogen region is created and maintained by the far-ultraviolet (FUV) radiation field from nearby stars. Within this atomic layer, it is believed that carbon exists predominately in the form of C^+ until the stellar radiation is sufficiently attenuated that either carbon recombination exceeds carbon ionization or the FUV field is no longer strong enough to disrupt the ion-molecular reactions that assist in transforming C^+ to CO. Although the exact value of the characteristic hydrogen column density required for the transition from C^+ to either neutral carbon or CO is model-dependent, most values are between 3 and 8×10^{21} cm^{-2}. If the average density in the neutral gas is approximately 10^3 cm^{-3}, then the C^+ region could extend several parsecs beyond the H II/H I transition zone.

Evidence that such extended C^+ halos exist was first obtained through 157.7 μm [C II] fine-structure line observations of the Galactic H II region M17 (Russell *et al.* 1981). These observations revealed the presence of C^+ emission over more than 0°.25 of the sky around this object. Subsequent observations of the Galactic H II region NGC 2024 (Kurtz *et al.* 1983) showed similarly extended emission. In conjunction with 63.2 and 145.5 μm [O I] data, the 157.7 μm [C II] line strengths have been used to show that the atomic gas region has a temperature between about 200 and 600 K, establishing this region as clearly distinct from the colder molecular gas (e.g. Russell *et al.* 1980; Stacey *et al.* 1983). A similar conclusion has been reached by Wannier, Lichten, and Morris (1983), whose H I emission observations near the isolated edges of several molecular clouds imply the existence of atomic hydrogen halos with temperatures well above the ~ 100 K galactic H I background. While interest in this warm atomic component of the interstellar medium has grown, the total number of sources observed in the C^+ line remains small (see Stacey 1985 for a summary of observations). In this paper, we present the results of 157.7 μm [C II] observations of the Galactic H II regions W3 and W51. Like Orion, NGC 2024, and M17, these two regions are sites of active star formation in which embedded O stars have created H II regions in close proximity to molecular clouds. These molecular clouds are, in turn, illuminated by significant amounts of FUV radiation from these stars. These regions are therefore particularly useful for studying the conditions in the photodissociated gas.

II. OBSERVATIONS AND RESULTS

Our observations were conducted in 1983 June using the 30 cm telescope aboard the NASA Lear Jet Observatory while flying at an altitude of 13 km with an improved version of the far-infrared, liquid-helium-cooled grating spectrometer described by Houck and Ward (1979). Two stressed Ge:Ga photoconductive detectors were used (Haller, Hueschen, and Richards 1979) permitting observations from 105 to 195 μm. The beam size, as determined by cross scans of Jupiter, was 3′.8 × 6′.2 (FWHM) and the wobbling secondary provided a chopper throw of 10′ in azimuth. The system resolution, $\lambda/\Delta\lambda$, was ~ 210 at 157 μm and the in-flight NEP, including all losses, was approximately 5×10^{-14} W Hz$^{-1/2}$. Throughout the flight series, each spectrum was sampled at intervals of 0.34 μm, or about 2.2 points per resolution element, and the integration time was 10 s per point per individual spectrum.

All together, six data flights were flown during which W3 was observed on four flights and W51 was observed on two flights. Two additional flights were flown in order to acquire calibration spectra of Venus and Jupiter. The source positions observed and the spectra obtained are shown in Figures 1 and 2. In total, 15 spectra were taken of the central position in W3,

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six spectra were taken of the position NW of center, and six spectra were taken of the position SE of the center. For W51, 11 spectra were obtained of the central region, and one spectrum each of the regions NE and SE of the center.

The CENTER position for each object is defined as that position which resulted in the maximum flux at 118 μm. For W3 (G133.7+1.2), the separation between the peak of the 100 μm continuum emission (Werner *et al.* 1980) and the peak of the 1.95 cm radio continuum emission (Schraml and Mezger 1969) is less than 30″. For W51 (G49.5+0.4), the separation between the 74 μm continuum peak (Thronson and Harper 1979) and the 1.95 cm radio continuum peak (Schraml and Mezger 1969) is approximately 1′, hence the displacement of the CENTER beam position from the center of the H II region in Figure 2.

Jupiter was used as our calibrator and was assumed to radiate like a blackbody with a temperature of 121 K in this wavelength range (Wright 1976). The resulting continuum intensities are in good agreement with the broad-band measurements of Harper (1974) for W3 and the extrapolated data of Ward, Gull, and Harwit (1977) and Thronson and Harper (1979) for W51. Spectra of Venus between 156 and 160 μm were compared to the Jupiter data in order to ensure that the Jupiter spectra contained no intrinsic absorption or emission features in this wavelength range that might affect the shape of the final source spectra.

The spectra obtained are shown in Figures 1 and 2 and the line intensities are summarized in Table 1. Column (1) of Table 1 refers to the beam positions shown in Figures 1 and 2, while columns (2) and (3) give the R.A. and decl. of these beam positions. Column (4) lists the measured 157.7 μm [C II] line fluxes, and column (5) lists the [C II] surface brightnesses from each position, derived under the assumption that the [C II] emission uniformly fills our beam. Column (6) lists the minimum C^+ column densities required to account for the observed 157.7 μm [C II] line intensities. A further discussion of the column densities given in column (6) is presented in § III. A Gaussian curve provides a good fit to the instrumental response to a narrow line measured in the laboratory and was therefore used to fit the data in the neighborhood of the [C II] line. The error bars in each spectrum, and hence the errors in the line flux, are the rms errors resulting from averaging the data plus systematic errors due to pointing inaccuracies, flux calibration, and continually changing water vapor along the

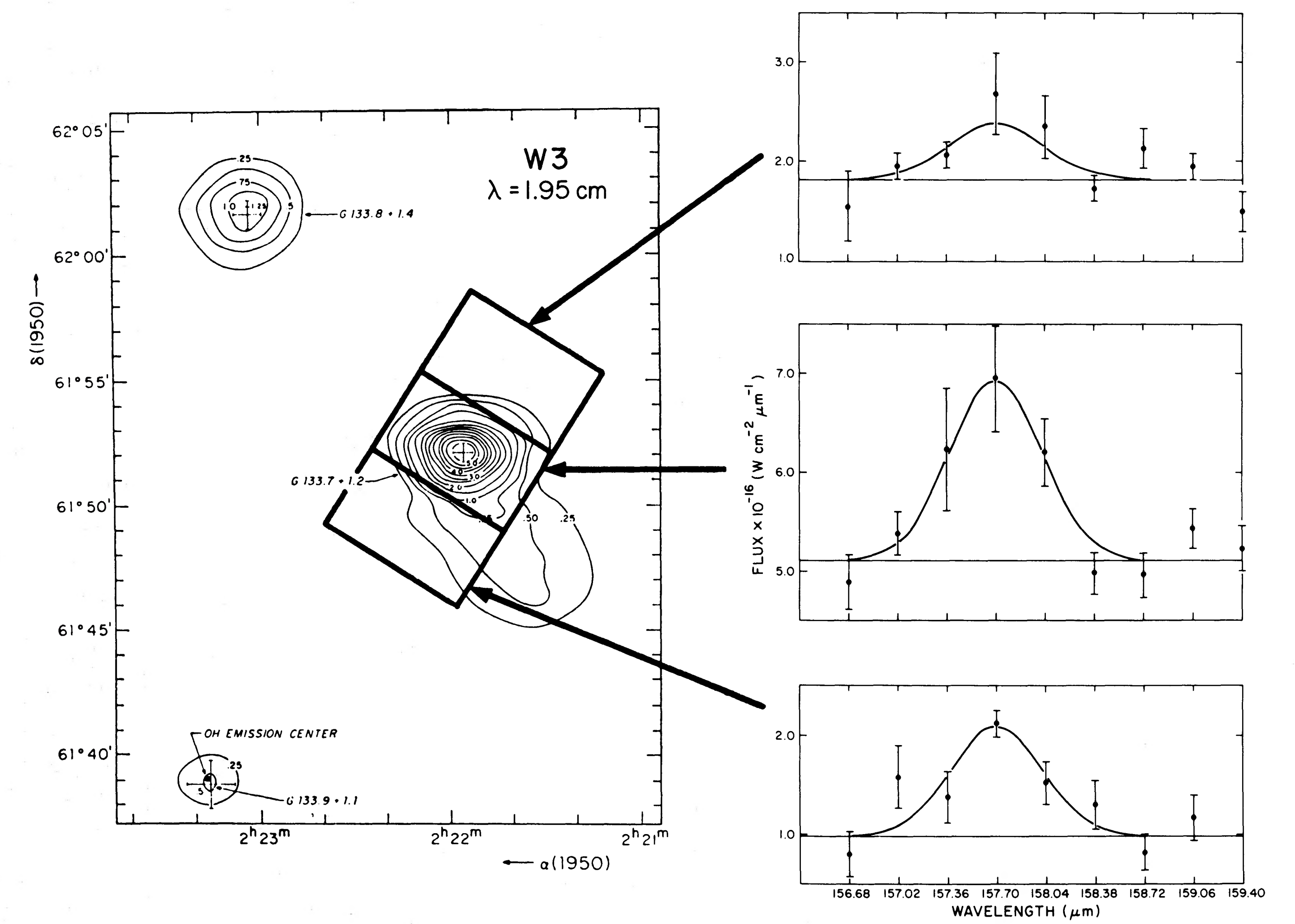

FIG. 1.—Spectra obtained of the 157.7 μm [C II] line toward W3. The size and position of the heavily outlined rectangles correspond to the beam size used and the three positions observed. These are superposed on the 1.95 cm map of the region made by Schraml and Mezger (1969). The R.A. and decl. of the positions observed along with the measured 157.7 μm [C II] line fluxes are given in Table 1.

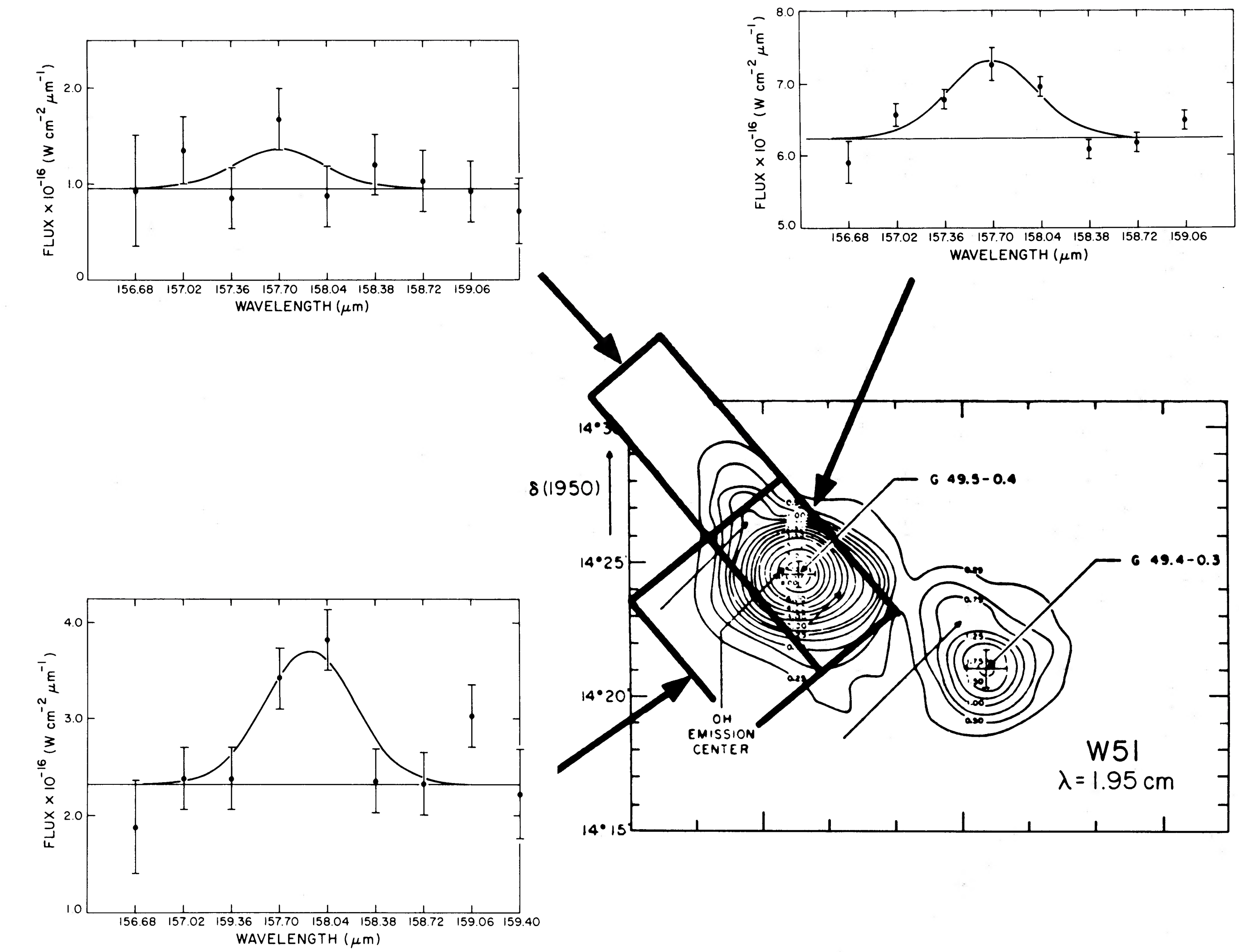

FIG. 2.—Spectra obtained of the 157.7 μm [C II] line toward W51. The size and position of the heavily outlined rectangles correspond to the beam size used and the three positions observed. These are superposed on the 1.95 cm map of the region made by Schraml and Mezger (1969). The R.A. and decl. of the positions observed along with the measured 157.7 μm [C II] line fluxes are given in Table 1.

TABLE 1

SUMMARY OF RESULTS

Position (1)	α(1950) (2)	δ(1950) (3)	C^+ Line Flux $\times 10^{-17}$ (W cm^{-2}) (4)	Minimum Surface Brightness $\times 10^{-4}$ (ergs s^{-1} cm^{-2} sr^{-1}) (5)	Minimum N_{C^+} $\times 10^{17}$ (cm^{-2}) (6)
		W3			
CENTER	$2^h21^m56^s$	61°52′06″	14.4 ± 3.3	7.2 ± 1.7	6.4 ± 1.4
3′.8 SE	2 22 11	61 49 00	8.8 ± 1.4	4.4 ± 0.7	3.8 ± 0.6
3′.8 NW	2 21 38	61 55 14	4.5 ± 1.9	2.3 ± 1.0	2.0 ± 0.8
		W51			
CENTER	19 21 22	14 25 12	6.3 ± 1.1	3.2 ± 0.6	2.8 ± 0.5
3′.8 SE	19 21 32	14 23 00	11.1 ± 2.6	5.6 ± 1.3	4.9 ± 1.1
6′.2 NE	19 21 38	13 30 26	3.2 ± 2.6	1.6 ± 1.3	1.4 ± 1.1

line of sight. The latter sources of error dominated our system noise.

In 1985 January we observed a 1 arcmin^2 area within the CENTER region of W3 using the 91 cm bent Cassegrain telescope on board the NASA Kuiper Airborne Observatory (KAO). Spectra were obtained using our interferometer/spectrometer with an NEP, including all losses, roughly equivalent to that of the system flown on the Lear Jet Observatory. The instrumental resolution, and thus the width of each spectral bin was set at $\lambda/\Delta\lambda \approx 3000$, or $\Delta\lambda \approx 0.052$ μm. For a line with a width less than 100 km s^{-1} and centered within one resolution element, it is therefore expected that each spectrum will exhibit one high point at the line wavelength and hence be undersampled. For a detailed description of the instrument and the data processing techniques see Harwit *et al.* (1981) and Stacey (1985). The absolute line flux for the KAO data was obtained by using Venus as a calibration source.

During the KAO flights, we took low-resolution grating spectra similar to those taken on the Lear Jet. We also acquired the high-resolution spectrum shown in Figure 3. This spectrum represents an unapodized co-average of two independent scans, each of which clearly displayed the [C II] line, with a total integration time per point of 20 s. Crawford *et al.* (1985) have measured the wavelength of the [C II] line as 157.737 $\pm$ 0.002 μm using gas cell calibration lines of H_2S and D_2O. Our results, using the absolute calibration properties of the interferometer, agree with this previous determination. The 157.7 μm [C II] line flux, measured in both the low- and the high-resolution modes, is approximately 2.5×10^{-17} W cm^{-2}. This value may be in error by up to 30% due to the uncertainty in the calibration measurements.

The Lear Jet data suggest that the intensity of the [C II] line flux averaged over the 3'.8 by 6'.2 field of view and centered on W3 is $\sim 7.2 \times 10^{-11}$ W cm^{-2} sr^{-1}. The KAO data yield a surface brightness for the center of this region of $\sim 3.0 \times 10^{-10}$ W cm^{-2} sr^{-1}. This is a factor of 4 higher, which implies that the distribution of the [C II] 157.7 μm emission is not uniform but is concentrated toward the central 0.6 pc of W3. Possible reasons for this peaked distribution will be discussed in § IV*a*.

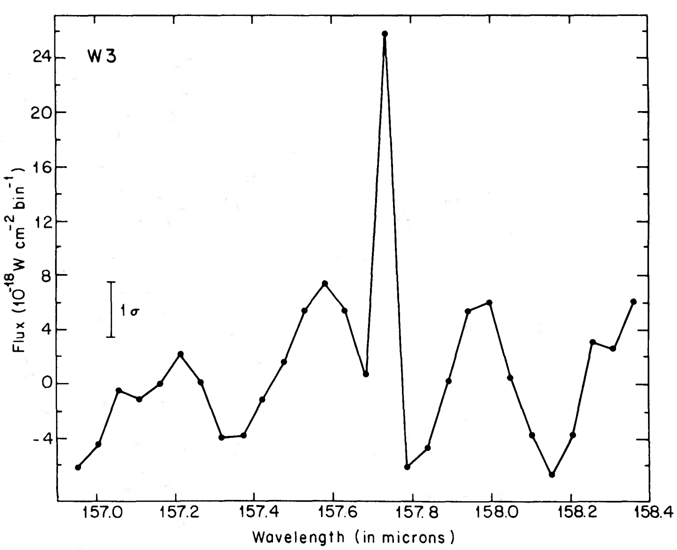

FIG. 3.—High-resolution ($\lambda/\Delta\lambda \approx 3000$) spectrum of the 157.7 μm [C II] line from the central 1' of W3 obtained from the KAO.

III. SOURCES OF 157.7 MICRON [C II] EMISSION

a) Ionized Gas

Because neutral carbon can be ionized by photons with energies exceeding 11.26 eV, and photons with energies less than the H I ionization energy of 13.598 eV readily escape H II regions, it is expected that [C II] emission will arise not only from within the fully ionized gas of the H II region but also from the partially ionized/neutral gas surrounding H II regions. As a result, the upper $^2P_{3/2}$ level of the ground state of C^+ can be populated through collisions with electrons, atomic hydrogen, or molecular hydrogen. To assess the contribution to the total 157.7 μm [C II] line flux from [C II] fine-structure emission originating within the ionized gas of W3 and W51, the optically thin, collisionally excited line flux, F, can be expressed in terms of several radio-determined quantities as

$$F(e^-)_{[\mathrm{C\,II}]} = \frac{hc}{4\pi\lambda} A\left[\mathrm{EM}\,\frac{1}{n_e}\,\epsilon\,\frac{n_\mathrm{C}}{n_e}\right] f_u \Omega \Phi_B\,, \qquad (1)$$

where A is the $^2P_{3/2} \rightarrow {}^2P_{1/2}$ transition probability, 2.29×10^{-6} s^{-1}, EM is the emission measure; n_e and n_C are the electron and carbon density, respectively; ϵ is the fraction of all carbon in the form of C^+; f_u is the fraction of C^+ in the $^2P_{3/2}$ state; Ω is the solid angle of the infrared beam; and Φ_B is the fraction of the infrared beam filled with 157.7 μm [C II] emission. It is assumed throughout the paper that in both W3 and W51 the abundance ratio of carbon to hydrogen does not differ significantly from the solar value of 3×10^{-4}.

Since the ionization energy required to produce C^{++} lies only 0.204 eV below that required to ionize He, the fractional abundance of doubly ionized carbon, $x(C^{++}) \equiv [C^{++}]/([C^0] + [C^+] + [C^{++}])$, will be approximately equal to that of singly ionized helium, $x(He^+) \equiv [He^+]/([He^0] + [He^+])$. Thus, an upper limit to ϵ in the ionized gas is $1 - x(C^{++}) \approx 1 - x(He^+)$. Using the collision strength calculated by Tambe (1977), solutions for the relative level populations of C^+ as a function of electron density and temperature are straightforward and values of $f_u[\equiv n(^2P_{3/2})/n(\mathrm{C\,II})]$ are plotted in Figure 4. For $n_e \geq 10^3$ cm^{-3}, $f_u \approx 0.66$ and equation (1) can be rewritten as

$$I(e^-)_{[\mathrm{C\,II}]} \leq 2.9 \times 10^{-19} \times \sum_{i=1}^{n} \left\{\mathrm{EM}\,\frac{1}{n_e}\left[1 - x(\mathrm{He}^+)\right]\Phi_B\right\}_i \mathrm{W\ cm^{-2}}\,, \qquad (2)$$

where the summation applies when there are n discrete H II regions within the beam. In this case, the quantities within the brackets are those appropriate to the ith compact ionized region.

Model calculations of dust-free H II regions imply that stars hotter than spectral type O7, like those responsible for ionizing the gas in W3 and W51, produce a sufficiently high flux of photons with energies greater than 24.587 eV to maintain all of the helium in the form of He^+, and therefore all of the carbon in the form of C^{++} (Bieging 1975; Mezger and Wink 1975; Balick and Sneden 1976). However, since the absorption cross section of dust for He-ionizing photons is about 6 times that for H-ionizing photons (Smith 1975), the presence of dust within the H II region causes the stellar Ly continuum radiation field to become depleted of He-ionizing photons. As a result, some C^+ may be found in H II regions ionized by stars

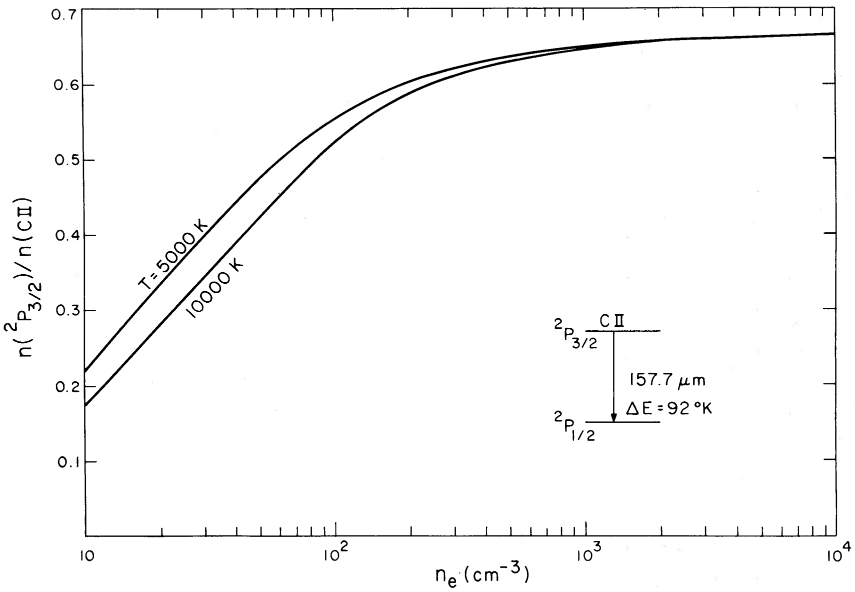

FIG. 4.—Plot of the relative population of the upper $^2P_{3/2}$ level as a function of temperature and density assuming excitation of C^+ by electrons

hotter than O7. Alternatively, those H II regions whose ionizing stars have effective surface temperatures less than 3.5×10^4 K, roughly equivalent to an O8 star or cooler (Panagia 1973), are incapable of maintaining a significant fraction of carbon in the C^{++} state. In such cases, the ratio of 157.7 μm [C II] line emission from within the ionized gas to the total 157.7 μm [C II] line flux may be higher than in those regions ionized by hotter stars.

Observations of the 157.7 μm [C II] line from the galactic H II regions M42, ionized by an O4–O6 star (Walborn 1981), and NGC 2024, ionized by an O9 star (Thompson, Thronson, and Campbell 1981), indicate that the ionized gas is not the dominant source of the [C II] fine-structure emission in these objects. Analysis similar to that outlined above shows that in M42 and NGC 2024 less than 5% and 10%, respectively, of the total observed 157.7 μm [C II] emission originates from within the H II region (see Russell *et al.* 1980; Russell *et al.* 1981; Kurtz *et al* 1983).

b) Photodissociation Regions

Recent models of the physical conditions in the neutral gas enveloping H II regions show that FUV photons escaping the ionized gas region create a hot (100–1000 K) layer ($A_v < 3$) of atomic gas between the H II regions and molecular clouds (Tielens and Hollenbach 1985). In these models, FUV photons absorbed by dust grains outside of the H II region cause the photoejection of electrons which in turn heat the gas. This gas is then subsequently cooled by 63.2 μm [O I] and 157.7 μm [C II] fine-structure line emission. Deeper into the molecular cloud, around $A_v \approx 3$–4, gaseous carbon is predominantly in the form of C and CO. Within this region, the warm (50–100 K) gas is largely heated by photoelectrons from dust grains but is now cooled primarily by rotational lines from CO. Thus, the most intense 157.7 μm [C II] emission will originate from the surface of molecular clouds near H II regions and, depending on the geometry, may appear displaced from the centers of the ionized gas, the far-infrared continuum, and the CO emission (cf. Stacey *et al.* 1985).

Under conditions expected in the photodissociation region, the flux, F, in an optically thin, collisionally excited line is

$$F(H)_{[\mathrm{C\,II}]} = \frac{hc}{4\pi\lambda} A\left(N_{\mathrm{H}} \epsilon \frac{n_{\mathrm{C}}}{n_{\mathrm{H}}}\right) f_u \Omega \Phi_B \,, \tag{3}$$

where N_{H} is the hydrogen column density in the C^+ emitting region and f_u is now the fraction of all C^+ ions in the $^2P_{3/2}$ state resulting from collisions with atomic hydrogen. For the regions of interest here, excitations to the ^2D and ^2S levels are negligible and all electrons can be assumed to be in the ^2P ground state. Using the rate coefficients calculated by Launay and Roueff (1977) and Tambe (1977), the equilibrium population equations for the ground-state levels of C^+ have been evaluated as functions of temperature, fractional ionization, $\chi(\equiv n_e/n_{\mathrm{H}})$, and hydrogen density, n_{H}. Values of f_u are plotted in Figure 5. Although much of the C^+ is coincident with the atomic hydrogen region, according to the model by Tielens and Hollenbach, for $A_v > 2$, most of the hydrogen is in molecular form and some of the 157.7 μm [C II] emission we observe could result from H_2—C^+ collisions. Using the cooling rate coefficients computed by Flower, Launay, and Roueff (1977), we may calculate the relative population of the $^2P_{3/2}$ level as a function of temperature and molecular hydrogen density. These results indicate that the values of f_u are not very sensitive to whether the exciting species is atomic or molecular hydrogen—the uncertainties in the density will usually dominate the small differences between the two. For this reason, it is not as crucial to the analysis that follows to distinguish between the atomic or molecular nature of the gas as it is to obtain a reliable estimate of the neutral gas density.

For excitation by either atomic or molecular hydrogen, the critical density at which the population of the ground-state levels begins to assume a Boltzmann distribution is ~ 3000 cm^{-3} and is reflected in Figures 4 and 5 by the small change in the relative population of the $^2P_{3/2}$ level for densities greater than 10^4 cm^{-3}, regardless of temperature above 50 K. Further, as illustrated in Figure 5, the value of f_u also becomes

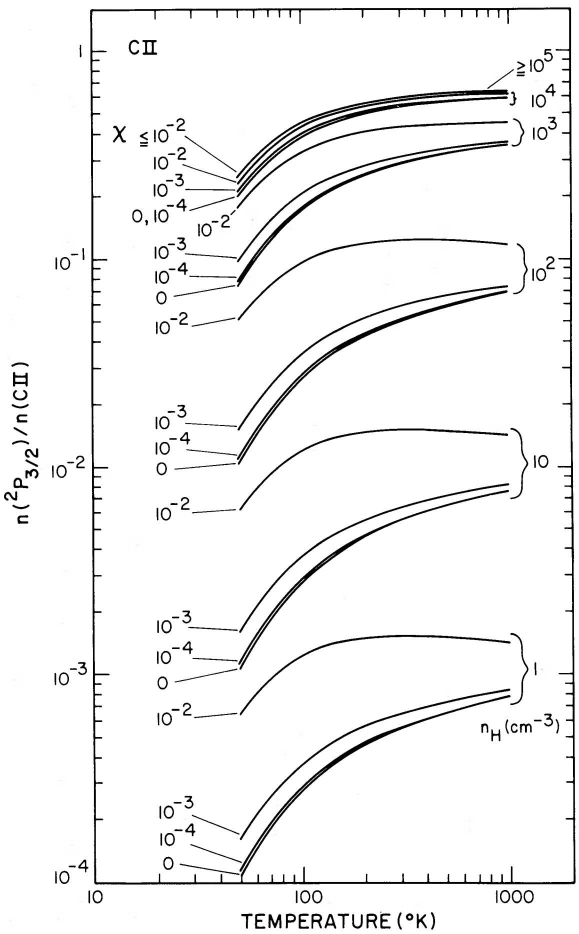

FIG. 5.—Plot of the relative population of the upper $^2P_{3/2}$ level as a function of temperature, hydrogen density, n_H, and fractional ionization, $\chi(\equiv n_e/n_H)$, assuming excitation of C^+ by atomic hydrogen and electrons.

insensitive to the fractional ionization at densities greater than the critical density.

The photodissociation region models by Tielens and Hollenbach (1985) characterize the C^+ emitting region as permeating the molecular cloud surface to an A_v of 3–4 mag. Lyα absorption measurements of interstellar H I obtained from the *Copernicus* satellite indicate that $\langle N_H/A_v \rangle = 1.9 \times 10^{21}$ mag^{-1} cm^{-2} for $A_v/E_{B-V} = 3$ (Bohlin, Savage, and Drake 1978), which implies that the C^+ region penetrates to a depth such that $N_H \approx 6$–8×10^{21} cm^{-2}. If $\langle n_H \rangle \approx 10^2$–$10^3$ cm^{-3} for most of the neutral gas, then the dimensions of the 157.7 μm [C II] emission region could extend several parsecs or more from the source of the FUV radiation, creating large 157.7 μm [C II] halos like those observed around M17 and NGC 2024 (Russell *et al.* 1981; Kurtz *et al.* 1983). As noted earlier (Russell *et al.* 1981), for the range of densities expected in the carbon recombination line region, i.e., $10^4 < n_H < 10^5$ cm^{-3} (Pankonin, Payne, and Terzian 1977), $I_{157.7\,\mu m} \propto n_e$, while $I_{\rm recombination} \propto n_e^2$. Therefore, it is expected, and observed, that the carbon recombination region will be more compact than the carbon fine-structure region.

The product of terms in parentheses in equation (3) is the column density of C^+, N_{C^+}. If most of the 157.7 μm [C II] emission arises in the photodissociation region, then a lower limit for the C^+ column densities needed to account for the observed line fluxes can be computed if it is assumed that $\epsilon = 1$, $T_{\rm gas} \geq 100$ K, and the emission fills our beam, i.e., $\Phi_B = 1$. If $n_H \geq 3 \times 10^3$ cm^{-3}, then f_u approaches its maximum value of $\sim$0.5 and the minimum C^+ column densities can be computed from equation (3). These values are listed in column (6) of Table 1. For gas temperatures less than 100 K and densities less than about 3×10^3 cm^{-3}, f_u is less than 0.5 and, from equation (3), higher C^+ column densities are then required to produce the observed line flux.

IV. DISCUSSION

a) W3

W3 is a giant H II region/molecular cloud complex located in the Perseus spiral arm, approximately 2 kpc from the Sun (Ogura and Ishida 1976) and 12 kpc from the Galactic center. Included within our CENTER beam position (see Table 1) is the brightest radio source in the W3 complex—the central 1′.5 × 2′.5 core of W3 Main. Within this region there are six embedded compact H II regions (Wink, Altenhoff, and Webster 1975), seven near-infrared sources (Wynn-Williams, Becklin, and Neugebauer 1972), and a number of OH and H_2O masers (Rogers *et al.* 1967; Goss, Lockhart, and Fomalont 1975; Genzel and Downes 1977; Forster, Welch, and Wright 1977). Far-ultraviolet emission from these embedded objects is believed responsible for heating most of the far-infrared emitting dust as well as for ionizing nearly all of the carbon we observe.

Far-infrared (30–300 μm) observations have shown that the total luminosity of the W3 core is 1–2 × 10^6 $L_\odot$ (Harper 1974; Furniss, Jennings, and Moorewood 1975; Fazio *et al.* 1975; Thronson, Campbell, and Hoffmann 1980). Higher angular resolution infrared observations (Harris and Wynn-Williams 1976; Werner *et al.* 1980) have been used to determine the luminosity, and thereby infer the spectral type of the exciting star(s), of each of the core sources. These results are summarized in Table 2. For comparison, the 157.7 μm [C II] luminosity from the CENTER position is $\sim$180 $L_\odot$. A *lower* limit to the total 157.7 μm [C II] luminosity from W3 Main, obtained by summing the line flux from three regions sampled is $\sim$360 $L_\odot$ for an assumed distance of 2 kpc. The relative role of the compact H II regions and the photodissociation region is now discussed.

Wink, Altenhoff, and Webster (1975) have obtained a high-resolution radio continuum map of W3 and have derived the size, emission measure, and electron density for each of the resolved subcomponents in the core. Using equation (2) and summing over the contributions from the compact H II regions W3 (A–D) indicates that the total 157.7 μm [C II] emission arising from within the ionized gas is $F(e^-)_{\rm [C\,II]} \approx 1 \times 10^{-23}[1 - x({\rm He}^+)]$ W cm^{-2}. It is clear, therefore, that the 157.7 μm line flux from within the compact H II regions is negligible.

A comparison of the flux density derived from single-dish high-resolution radio observations with the sum of flux densities of the individual components, derived from aperture synthesis observations, reveals that the ionized gas in W3 Main is all contained in the well-defined H II regions, with no evidence for an extended, low-density ionized region surrounding the core (Mezger and Wink 1975). This implies that the compact H II regions are still ionization-bounded within the neutral gas. Thus, electron excitation of the $^2P_{1/2}$ level whether from inside or outside of the compact H II regions, does not play a significant role in W3 Main.

TABLE 2

W3 Core Sources

Object	Luminosity ($L_\odot$)	Exciting Star	H II Region[a] Size (arcsec)	n_e[a] $\times 10^4$ (cm^{-3})	EM[a] $\times 10^7$ (cm^{-6} pc)
IRS 1/W3(A)	2–4 × 10^5[b,c,d]	IRS 2/2a[e]	17 × 12	1	4.0
			8 × 4	1	1.3
			8 × 4	1	4.0
			13 × 5	1	4.0
			14 × 6	1	4.0
IRS 2[f]	...	O6–O5[c]	...	...	...
IRS 2a[f]	...	B0.5–O6.5[c]	...	...	...
IRS 3/W3(B)	1 × 10^5[b]	O7[b]	6.5 × 5	1.7	3.5
			13 × 5	1.1	2.1
			8 × 4	1.1	1.4
			4 × 1.5	2.5	3.5
			<3 × 3	4.6	4.6
IRS 4/W3(C and D)	1 × 10^5[b]	Late B[c]	...	2.5	3.3
		or early O	21 × 15	0.3	0.4
IRS 5	2 × 10^5[b]	>O6.5[b]	...	...	...
IRS 6[g]	...	...	...	...	...
IRS 7[g]	...	...	...	...	...
$L_{157.7\ \mu m\ [C\ II]}$ (TOTAL)	≥360[h]	...	...	...	...

[a] Wink *et al.* 1975.

[b] Werner *et al.* 1980.

[c] Harris and Wynn-Williams 1976.

[d] Tielens and de Jong 1979.

[e] W3(A) is excited internally by IRS 2 and IRS 2a, the former being responsible for about 90% of the ionizing photons (Harris and Wynn-Williams 1976).

[f] Both IRS 2 and IRS 2a are obscured by more than 18 mag of visual extinction and are seen at 2 μm, but are not seen against IRS 1 at 20 μm (Wynn-Williams *et al.* 1972).

[g] IRS 6 and IRS 7 are much fainter than the other core sources and were detected only at 20 μm, at which wavelength their flux densities are each about 60 Jy (Wynn-Williams *et al.* 1972). At 5 GHz, IRS 6 is a point source with a flux density of less than 12 millijanskys while IRS 7 has diameter of about 3″ and a flux density of 150 ± 40 millijansky (Harris and Wynn-Williams 1976).

[h] This work (for an assumed distance of 2 kpc).

The most likely origin of the 157.7 μm [C II] emission we observe is in the neutral gas beyond the compact H II regions, a volume that may be divided into a small, high-density recombination component that exists within a much larger, lower density atomic and molecular region. About half of the 157.7 μm line flux we measure from the W3 CENTER position probably arises from within the recombination region, while the remaining [C II] flux, along with all of the 157.7 μm line flux from the SE and NW positions, have their source in the lower density neutral gas. Studies of the recombination region in W3 have been made in the C166α, C158α, C109α, C199β, C137β (Pankonin *et al.* 1977), and the C90α (Jaffe and Wilson 1981) radio lines. These results show that the carbon recombination emission is centered at $\alpha(1950) = 02^h21^m50\overset{s}{.}6$, $\delta(1950) = 61°52'31''$—southwest of IR 2/W3(A) and toward IRS 3/W3(B)—and that the extent of the C90α emission is about $2\overset{'}{.}0 \times 1\overset{'}{.}5$. Further, the similarity in both the spatial and velocity distribution of the C II recombination emission and that of the ionized gas suggests that the carbon recombination lines originate from a thin shell at the interface between the ionized gas and the surrounding neutral cloud (Jaffe and Wilson 1981), in support of earlier models by Zuckerman and Palmer (1968). Model calculations intended to reproduce the observed recombination line strengths generally require a shell thickness of ~0.01–0.06 pc, atomic hydrogen densities of $\sim 10^5$ cm^{-3}, and gas temperatures of between 100 and 200 K (Pankonin *et al.*). Unfortunately, the complexity of the line formation mechanism along with large beam sizes has made the direct determination of the electron density and temperature from the Cnα and Cnβ line observations difficult beyond setting rather wide limits: $n_e = 1$–30 cm^{-3} ($\Leftrightarrow n_H = 3 \times 10^3$–$1 \times 10^5$ cm^{-3}) and $T_{gas} = 10$–1000 K. Assuming that pressure equilibrium applies, the densities and temperatures required by these models are corroborated by ^{13}CO observations along the line of sight to the core which indicate that the molecular gas, which presumably lies immediately beyond the atomic layer, is characterized by $\langle n_{H_2} \rangle \approx 5 \times 10^4$ cm^{-3} and $35 \leq T \leq 100$ K (Dickel 1980). The strength of the 157.7 μm [C II] emission from the carbon recombination region can be estimated if it is assumed that the recombination lines originate from a $2\overset{'}{.}0 \times 1\overset{'}{.}5$ shell of thickness dl. Using equation (3), the 157.7 μm [C II] line flux from a shell of average diameter, d_s, where $dl \ll d_s$, can be written as

$$F(H)_{[C\ II]} = 3.8 \times 10^{-13}[\tan(\langle \theta_{d_s} \rangle/3600)]^2 n_H\, dl \text{ W cm}^{-2}\,, \tag{4}$$

where $\langle \theta_{d_s} \rangle$ is the average angular diameter of the shell in arc seconds, dl is in parsecs, and $n_H\, dl$ is the hydrogen column density through the shell. Assuming that approximately half of the [C II] emission from the CENTER position arises in the recombination shell, and that $T_{gas} \geq 100$ K and $n_H \approx 10^5$ cm^{-3} within this region, then the 157.57 μm [C II] line flux we observe can be produced if $dl \approx 0.007$ pc.

In order to ionize the carbon in the recombination region, the FUV radiation traverses a hydrogen column density $n_H\, dl \approx 2 \times 10^{21}$ cm^{-2}. If the total C^+ region penetrates a column density $N_H \approx 6 \times 10^{21}$ cm^{-2}, then this FUV radiation is capable of maintaining a C^+ region through an additional hydrogen column density of approximately 4×10^{21} cm^{-2} beyond the carbon recombination region. This is in agreement with the average H I column density of $2 \pm 2 \times 10^{21}$ cm^{-2} derived from 21 cm observations of W3 by Chaisson (1972). The extent of the C^+ halo depends on the gas density. Based upon the observation of a number of molecular lines, Dickel (1980) has modeled the core of W3 and concludes that the average molecular hydrogen density falls approximately 5×10^3 cm^{-3} within about 4′ of the core to about 10^2 cm^{-3} over the remainder of the W3 molecular cloud. Thus, the C^+ region may extend from a few arc minutes to as far as 0°.33 from the core of W3 depending on the density gradient.

In the extended region sampled by our SE and NW beam positions (see Table 1), $F(\mathrm{H})_{[\mathrm{C\,II}]} = 1.4 \times 10^{-37} N_{\mathrm{H}} f_u \epsilon \Phi_B$ W cm^{-2} from each of these beam positions. If, averaged over our SE and NW beam positions, $\epsilon \approx 1$, $\langle n_{\mathrm{H}} \rangle \sim 10^3$ cm^{-3}, $T_{\mathrm{gas}} \geq 100$ K, and the emission fills our field of view, then a column density $N_{\mathrm{H}} \approx 2 \times 10^{21}$ cm^{-2} ($\Leftrightarrow N_{\mathrm{C^+}} \approx 6 \times 10^{17}$ cm^{-2}) can reproduce the observed 157.7 μm [C II] line fluxes. If $\epsilon < 1$, then $N_{\mathrm{H}} \approx (2 \times 10^{21})/\epsilon$ cm^{-2} would be required. Under these conditions, about half of the carbon could be in dust grains, CO, or neutral carbon before requiring that N_{H} exceed the upper limit of 4×10^{21} cm^{-2} suggested by the H I data. Similarly, if $\Phi_B < 1$, as might be expected if most of the [C II] emission comes from the higher density core, then this too would require an increase in either N_{H} or n_{H} or both to account for the observed line strengths. Unfortunately, the value of ϵ is not subject to direct measurement, though higher spatial resolution studies in this line could be used to set useful limits on Φ_B.

The optical depth in the core of the 157.7 μm [C II] line can be written as (cf. de Jong, Chu, and Dalgarno 1975)

$$\tau_{157.7\,\mu\mathrm{m}} = \frac{A\lambda^3}{8\pi \Delta V} N_{\mathrm{C^+}} f_u \left[\left(\frac{f_l g_u}{f_u g_l} \right) - 1 \right] = 3.58 \frac{N_{\mathrm{C^+(18)}}(2 - 3f_u)}{\Delta V_5}, \quad (5)$$

where f_l is the fractional population of the $^2P_{1/2}$ level $(= 1 - f_u)$; g_u, and g_l are the statistical weights of the upper and lower ground-state levels, 4 and 2, respectively; $N_{\mathrm{C^+(18)}}$ is the C^+ column density in units of 10^{18} cm^{-2}; and ΔV_5 is the line-of-sight velocity gradient (FWHM) within the 157.7 μm [C II] emitting region in km s^{-1}. Within the recombination region, the Cnα and Cnβ lines are approximately 7 km s^{-1} wide (Pankonin *et al.* 1977; Jaffe and Wilson 1981), which implies that $\tau_{157.7\,\mu\mathrm{m}} \approx 0.1$.

Dickel *et al.* (1980) have obtained ^{12}CO line widths for a large number of positions in and near the W3 core and find that $\Delta V_5 = 7.2$ km s^{-1} at the center of our 3′.8 SE beam position and $\Delta V_5 = 9.3$ km s^{-1} at the center of our 3′.8 NW beam position. If these values correspond to the internal gas velocities within the 157.7 μm [C II] emitting region, then, for $\langle n_{\mathrm{H}} \rangle \approx 10^3$ cm^{-3}, $\tau_{157.7\,\mu\mathrm{m}} \approx 0.5/\epsilon\Phi_B$ and $0.2/\epsilon\Phi_B$ for the SE and NW positions, respectively. If $N_{\mathrm{H}} \leq 4 \times 10^{21}$ cm^{-2}, then $\epsilon\Phi_B \geq 0.6$ and 0.3, respectively, resulting in $\tau_{157.7\,\mu\mathrm{m}} \leq 0.8$ for both the SE and NW beam positions. If $\langle n_{\mathrm{H}} \rangle \geq 5 \times 10^3$ cm^{-3} in the [C II] emitting region, then the optical depth in the [C II] line drops to less than 0.3 from both positions.

b) *W51*

W51 is a large, complex H II region situated in the Sagittarius spiral arm at a kinematic distance of 7 kpc (Genzel *et al.* 1981). Because of its size, W51 has been separated into two main components: W51A, comprising the sources G49.5−0.4 and G49.4−0.3; and W51B consisting of G49.2−0.4 and G48.9−0.3 along with two weaker components G49.0−0.3 and G49.1−0.4. The 157.7 μm [C II] observations reported in this paper encompass G49.5−0.4, the stronger of the two main H II regions comprising W51A and the brightest radio source in the W51 complex. High-resolution radio continuum observations by Martin (1972) have shown that G49.5−0.4 contains at least eight compact components embedded in a diffuse ionized envelope. The two strongest compact radio sources, W51d and W51e, are also associated with bright 5–500 μm sources, W51 IRS 2 and W51 IRS 1 (Wynn-Williams, Becklin, and Neugebauer 1974; Harvey, Hoffmann, and Campbell 1975; Thronson and Harper 1979; Erickson and Tokunaga 1980; Hackwell, Grasdalen and Gehrz 1982; Genzel *et al.* 1982; Jaffe, Becklin, and Hildebrand 1984), as well as strong OH and H_2O masers (Genzel *et al.* 1981).

The total luminosity of G49.5−0.4 is $1.5 \times 10^7\ L_\odot$ (Rengarajan *et al.* 1984). Summing the line flux from the three positions sampled and assuming a distance of 7 kpc yields a corresponding *lower* limit to the 157.7 μm [C II] luminosity of $4.1 \times 10^3\ L_\odot$. The discrete sources associated with this emission, as deduced from the 2.7 and 5 GHz radio observations by Martin (1972), are given in Table 3. Martin finds that the sum of the flux densities for the eight components is about 70% of the total flux density of G49.5−0.4. Similarly, the total measured luminosity is almost twice as large as that obtained by summing the luminosities of the individual sources in Table 3. These discrepancies suggest that the compact sources are embedded in a diffuse ionized envelope that probably results from older H II regions which have expanded and merged. Consideration is now given to the possible sources of the 157.7 μm [C II] emission.

The 157.7 μm [C II] emission attributable to the compact H II regions G49.5−0.4 (a–h) can be obtained from equation (2) and the radio data from Martin (1972). These data indicate that $F(e^-)_{[\mathrm{C\,II}]} \approx 1.2 \times 10^{-22}[1 - x(\mathrm{He^+})]$ W cm^{-2}. Thus, even if all the carbon within the compact H II regions is in the singly ionized state, the 157.7 μm [C II] emission from this gas is negligible.

The carbon recombination region in W51A has been investigated through several lines (C92α, Chaisson 1974; C109α, Palmer *et al.* 1969; C166α, Payne and Terzian 1976; C221α and C248α, Pankonin, Parrish, and Terzian 1974). Payne and Terzian (1976) conclude that within the carbon recombination region $T_{\mathrm{gas}} \approx 100$ K and $\langle n_e \rangle \approx 20$ cm^{-3} ($\Leftrightarrow n_{\mathrm{H}} \approx 7 \times 10^4$ cm^{-2}). Further, in each of the observed transitions the carbon recombination lines are wider than usually encountered ($\Delta V_5 \approx 15$ km s^{-1}). Unfortunately, insufficient spatial resolution makes it difficult to measure the dimensions of the carbon recombination region and impossible to determine the compact components mainly associated with the Cnα emission. An estimate of the possible 157.7 μm [C II] emission from the carbon recombination regions may be obtained by assuming that each of the compact H II regions is surrounded by a shell-like recombination region. Substituting the dimensions of the compact H II regions given by Martin into equation (4) and assuming that each recombination region has a characteristic thickness dl, a density greater than a few $\times 10^4$ cm^{-3}, and $\epsilon \approx 1$ results in a 157.7 μm [C II] flux from all the recombination regions of $F(\mathrm{H})_{[\mathrm{C\,II}]} \approx 8 \times 10^{-20} n_{\mathrm{H}}\, dl$ W cm^{-2}, where dl is in parsecs. If approximately half of the

TABLE 3

W51 CORE SOURCES

Object (G49.5−0.4)	Luminosity[a] ($L_\odot$)	Exciting Star[a,b]	H II Region Size[a] (arcsec)	n_e[a] $\times 10^3$ (cm^{-3})	EM[a] $\times 10^6$ (cm^{-6} pc)
a	2.5×10^5	O6	41 × 25	>1.0	>1.2
b	1.3×10^6	O4	16 × 33	4.6	17.3
c	6.8×10^5	O5	47 × 82	0.8	1.4
d	1.3×10^6	O4	11 × 25	>7.9	>36.5
e	3.3×10^6	2 × O4 + O5	14 × 31	9.9	72.5
f	2.5×10^5	O6	26 × 44	1.2	1.8
g	6.8×10^5	O5	40 × 39	1.2	1.9
h	2.5×10^5	O6	39 × 84	0.4	0.4
$L_{157.7\,\mu m\,[C\,II]}$ (TOTAL)	$\geq 4.1 \times 10^3$[c]	...	...	...	...

[a] Martin 1972.
[b] Panagia 1973.
[c] This work (for an assumed distance of 7 kpc).

157.7 μm [C II] emission from the CENTER position originates within the recombination region, then the line flux we observe can be reproduced if $n_H \approx 10^5$ cm^{-3} and $dl \approx 0.005$ pc. Without more detailed information about the sizes of and the velocity dispersions within the individual carbon recombination regions, nothing can be said about the optical depth in the 157.7 μm line originating in this region. All that can be said is that within the range of accepted carbon recombination region densities and thicknesses, a significant fraction of the 157.7 μm [C II] flux we measure from the CENTER position *could* arise from within this gas. The presence of substantial 157.7 μm [C II] line flux in the other two beam positions, however, argues strongly for additional regions of emission, such as the extended ionized and atomic gas.

As mentioned earlier, there is evidence for an extended, low-density component of the ionized gas. This gas has been investigated through observations of a number of Hnα recombination lines and has been found to extend over 40″ around W51A (MacLeod and Doherty 1968; Parrish *et al.* 1972; Parrish 1972; Pankonin, Parrish, and Terzian 1974; Payne and Terzian 1976). Parrish *et al.* (1972) and Pankonin, Parrish, and Terzian (1974) conclude that this diffuse ionized component has a temperature of 10^4 K, a density of about 20 cm^{-3}, and an emission measure of 10^4 cm^{-6} pc. Under these conditions $f_u \approx 0.25$ and, assuming that $\epsilon = 1$, equation (1) yields $F(e^-_{\rm extended})_{[C\,II]} \approx 5 \times 10^{-17}$ W cm^{-2} into each 3′.8 by 6′.2 beam. This is comparable to the 157.7 μm [C II] flux measured from both the CENTER and 6′.2 NE beam positions. Further, if the 157.7 μm [C II] line shares the velocity gradient of ~30 km s^{-1} measured in the Hnα lines, then $\tau_{157.7\,\mu m} \leq 0.1$ and the 157.7 μm line from this component of the gas is optically thin.

Observations of the atomic gas around W51A have been made in the 21 cm line of neutral hydrogen (Burton 1970). Using a beam size slightly greater than 0°.5 in diameter, large enough to encompass both major components of W51A, these measurements indicate that $N_H = 5 \times 10^{21}$ cm^{-2} and $T_{\rm gas} \approx$ 93 K averaged over this region. Neutral gas densities estimated from molecular line observations range between 200 and 1000 cm^{-3} over most of the cloud (Scoville and Solomon 1973). Assuming that $\epsilon \approx 1$ within the atomic gas region and that $\Phi_B = 1$ within our beam, then under the above conditions, atomic hydrogen excitations could produce a 157.7 μm [C II] line flux of between about 3 and 12×10^{-17} W cm^{-2} in a 3′.8 by 6′.2 beam. As before, if a non negligible fraction of the carbon in the 157.7 μm emitting region is neutral, in CO, or in dust grains, or the [C II] region is clumpy, then N_H and/or n_H must exceed the above values in the line emitting region. This is particularly true of the SE position where $\epsilon\Phi_B$ must be close to unity if the column density and the volume density derived from the H I and molecular data, respectively, are characteristic of the [C II] region.

The velocity dispersion derived from the atomic hydrogen measurements is 6.7 km s^{-1} (Burton 1970). For a gas temperature of 93 K and an average atomic hydrogen density of 200 cm^{-3}, $\tau_{157.7\,\mu m} \approx 1.5$. If the average atomic hydrogen density is closer to 1000 cm^{-3}, then $\tau_{157.7\,\mu m} \approx 1.2$. If $\epsilon\Phi_B < 1$, requiring an increase in N_H in the emitting region, then the line optical depth will increase proportionately. Only if $n_H > 10^3$ cm^{-3} while $N_H \leq 5 \times 10^{21}$ cm^{-2} in the C^+ region will $\tau_{157.7\,\mu m}$ drop below unity. In either case, optical depth effects in the 157.7 μm line could be significant if most of the emission we observe originates in this atomic gas.

Whether most of the extended 157.7 μm [C II] emission arises in the diffuse ionized or the atomic gas, or whether it is evenly divided, is not known. Higher spectral resolution studies capable of determining the $V_{\rm LSR}$ of the 157.7 μm line may be able to link this emission to either the HNα emission, at a $V_{\rm LSR}$ of about 58 km s^{-1} (Pankonin, Parrish, and Terzian 1974; Payne and Terzian 1976; Pankonin, Payne, and Terzian 1979), or the 21 cm H I absorption feature, at a $V_{\rm LSR}$ of 65 km s^{-1} (Burton 1970).

Finally, one of the more curious features of the 157.7 μm [C II] flux distribution in W51 is its apparent asymmetry; the 157.7 μm line emission appears about twice as strong in the 3′.8 SE beam position as in either the CENTER or the 6′.2 NE beam position. There are several possible reasons for this:

1. *Optical depth effects.*—As was shown above, the 157.7 μm line may have an optical depth near unity in all three beam positions if most of the emission is produced in the atomic hydrogen gas. Since the line optical depth is inversely proportional to the dispersion velocity in the [C II] emitting region, variations in the dispersion velocity across our field of view could modulate the observed 157.7 μm line flux. Likewise, fluctuations in the density and the column density could affect the line optical depth. Unfortunately, our observations lack the spectral resolution to resolve the 157.7 μm line, thereby allowing a direct determination of this dispersion velocity, and the spatial resolution to measure Φ_B. Future observations with

spectral resolutions exceeding a few $\times 10^4$, sufficient to measure the line width, and higher spatial resolution will be better able to unravel the possible effects of varying line optical depth in this region.

2. *Atomic gas distribution.*—The large beam size used to obtain the 21 cm absorption profiles measured by Burton (1970) provides little information about the distribution of atomic gas on the size scale of our measurements. However, molecular line observations, such as the 6 cm H_2CO measurements by Scoville and Solomon (1973), which employ a beam size comparable to ours, have found significant displacements of the peak molecular line optical depths away from G49.5−0.4. Several peaks are measured at different line-of-sight velocities, but the peak opacity in the 6 cm H_2CO line most closely associated with the V_{LSR} of G49.5−0.4 is displaced to the south and east of the H II region, in the same direction as the peak in the 157.7 μm [C II] emission. The photodissociation region of this molecular cloud may contribute to the asymmetry we observe. Observations of the 157.7 μm [C II] line toward the other opacity peaks, all of which are outside of the region surveyed here, would provide some measure of the influence these molecular clouds have on the observed 157.7 μm line flux.

3. *Observational problems.*—Observations of the 157.7 μm [C II] line from a number of galactic H II regions and from the Galactic plane show that the 157.7 μm emission is ubiquitous (Russell *et al.* 1981; Kurtz *et al.* 1983; Stacey *et al.* 1985). In the absence of a larger scale line survey in W51, it is impossible to know whether any significant 157.7 μm [C II] emission was present in our reference beam positions. Such contamination in the reference beams of the CENTER and 6′.2 NE beams could lower the line flux we observe from these positions. Second, the least amount of spectral data was obtained for the 3′.8 SE beam position. While we are confident that there is 157.7 μm [C II] emission from this position, we cannot rule out the possibility that additional spectra might not indicate a somewhat lower line flux. A resolution of this uncertainty will have to await further observations.

c) [C II]/*FIR Continuum Ratio*

The total luminosity in the [C II] line we estimate for W3 ($\sim 360\ L_\odot$) and W51 ($\sim 4.1 \times 10^3\ L_\odot$) is $\sim 5 \times 10^{-4}$ times the total FIR luminosity for both these sources (Table 2). These ratios are well within the typical values for galactic H II regions, which range from $\sim 10^{-4}$ to 10^{-3} (Russell *et al.* 1980, 1981; Kurtz *et al.* 1983; Crawford *et al.* 1985). However, this is in contrast to the [C II]/FIR continuum ratios of $\sim 3 \times 10^{-3}$ and $\sim 5 \times 10^{-3}$ estimated for the Galaxy (Stacey *et al.* 1985) and for external galaxies (Crawford *et al.* 1985), respectively. This apparent discrepancy is caused by the difference in intensity between the average FUV radiation fields of galaxies and the more intense FUV fields near Galactic H II regions. The penetration of carbon ionizing (912 Å $\leq \lambda \leq$ 1101 Å) FUV photons into neutral gas clouds is limited by the absorption of these photons by dust—not by the balance between photoionization and radiative recombination of carbon atoms. Thus, while the FIR continuum intensity, which is due to thermal emission from the FUV–heated dust, varies directly with the intensity of incident FUV radiation field, the [C II] intensity varies in a slower, logarithmic manner (Tielens and Hollenbach 1985). The lower [C II]/FIR continuum ratios observed in Galactic H II regions is therefore the result of the more intense FUV fields in these sources. Further, since the [C II] line radiation is a major coolant of the gas, the lower line-to-continuum ratio also indicates less efficient conversion of FUV energy into heating of the gas (through photoionization of grains) for the high-intensity FUV fields in the vicinity of galactic H II regions.

V. CONCLUSIONS

It appears that the 157.7 μm [C II] line flux from the CENTER beam position in W3 probably results from a combination of emission from the high-density carbon recombination region and from the lower density atomic gas beyond the carbon recombination region, with no measurable contribution from the compact H II regions in the core. The 157.7 μm line fluxes from the 3′.8 SE and 3′.8 NW beam positions in W3 almost certainly arise from interactions in the warm neutral gas.

The 157.7 μm optical depth in W3 is ~ 0.1 for that portion of the line arising within the carbon recombination region and is probably less than 0.8 for the line emission originating in the more extended atomic gas. Observations with a spectral resolution sufficient to measure the 157.7 μm [C II] line width would settle this question.

The compact H II regions within W51 (G49.5−0.4), like those in the core of W3, do not contribute in any significant way to the total 157.7 μm [C II] line flux measured. We have shown that the strength of the 157.7 μm [C II] emission we observe can be produced from the carbon recombination region, the diffuse ionized gas, and the atomic gas. At present, however, insufficient spectral resolution and poor corollary data on the small-scale structure of these various regions limits our ability to determine the degree to which each of them may contribute to the overall line flux. The asymmetry of the 157.7 μm line flux about the center of G49.5−0.4 may or may not be real. If it is real, it may result from varying line optical depth across our field of view, asymmetries in the atomic or diffuse ionized gas distribution, or from contamination in our reference beams, or a combination of these.

Finally, our data indicate that the [C II]/FIR continuum ratio for both W3 and W51 are within the range found for other Galactic H II regions.

We thank Dr. Martin Harwit for reviewing this manuscript. We also wish to thank the pilots, navigators, and ground crew associated with the NASA Lear Jet Observatory and the NASA Kuiper Airborne Observatory for their excellent support. This work was supported by NASA grants NAG2–188 and NRG 33–010–146.

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