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THE 157 MICRON [C II] EMISSION FROM NGC 2024: CORE AND HALO COMPONENTS

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ABSTRACT

We have mapped portions of the nebula NGC 2024 in the 157 μm [C II] line and find both a compact component centered on the radio-recombination line regions, and a more extended nebulosity. The central component emits 157 μm line and continuum fluxes at a level of 4×10^{-16} W cm^{-2} and 5×10^{-16} W cm^{-2} μm^{-1}, respectively, both somewhat lower than values reported earlier by Russell *et al.* but well within the errors of the earlier measurements. The continuum emission drops off more rapidly with distance from the peak, but line emission still is at ~ 30% of the peak value at a distance 18′ to the SE of the peak. In related observations carried out on M42, we confirmed our earlier measurements of the 157 μm line and continuum fluxes, but made no attempt to search for an extended halo.

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

I. INTRODUCTION

NGC 2024 is an intriguing but poorly understood region of optical nebulosity near ζ Orionis in the belt of Orion. It is split by a dark lane running north–south which is believed to be due to dust and molecular gas (Hudson and Soifer 1976). A search for the exciting star for the region and models for the H II region are discussed by Grasdalen (1974), Balick (1976), and Sarazin (1976). The strong far infrared emission due to cool dust was mapped by Harper (1974). Subsequently, carbon recombination lines were studied by Pankonin *et al.* (1977) and Rickard *et al.* (1977). Mapping the [C II] line at 157 μm can shed increased light on our understanding of temperature, density, and energetics of the gas in this region when taken in conjunction with the results of other observations.

In an earlier paper (Russell *et al.* 1980, hereafter referred to as Paper I), we reported on flights of the NASA Lear Jet, carried out on the nights of 1979 November 27 and 28. We reported a first set of observations of the fine-structure [C II] transition at 157 μm. This line, which had never been observed even in the laboratory, was found both in NGC 2024 and in M42. The observations carried out on NGC 2024 gave a strong line-to-continuum ratio at the position of peak far-infrared continuum radiation, within the 4′×7′ field of view of our liquid helium-cooled grating instrument (Houck and Ward 1979).

In a subsequent flight series carried out during 1980 March, we attempted to map the [C II] emission from NGC 2024 using a 1 arcmin^2 field of view on the Kuiper Airborne Observatory. We were only able to work with a chopper throw of 6′, in contrast to the 11′ chopper throw of our Lear Jet observations. Several positions centered on the position of peak [C II] radio recombination-line radiation were searched, but with no success. The signals obtained were weak, sometimes hinting positive and sometimes negative line strengths. This suggested the line emission might be extended over a very large region, since that way it was possible to account both for the weak signal strength in the greatly reduced field of view, as well as for the possible negative signals at the position of line emission, if we were viewing brighter emission patches in our negative beam.

To clarify these results we repeated our Lear Jet observations in 1980 December, this time mapping the extended region around NGC 2024 at least along one radial direction from the peak. The line and continuum fluxes observed at the continuum-peak position roughly agree with the measurements obtained a year earlier, and in addition, we find the emitting region to extend over an angle amounting to at least 18′ along a direction SE of the peak, which has been placed at $\alpha(1950)\sim 05^{\mathrm{h}}39^{\mathrm{m}}14^{\mathrm{s}}$; $\delta(1950)\sim -1°57^{\mathrm{m}}$, both by Harper (1974) observing at 93 μm, and by Hudson and Soifer (1976) observing at ~ 400 μm. The peak positions registered by

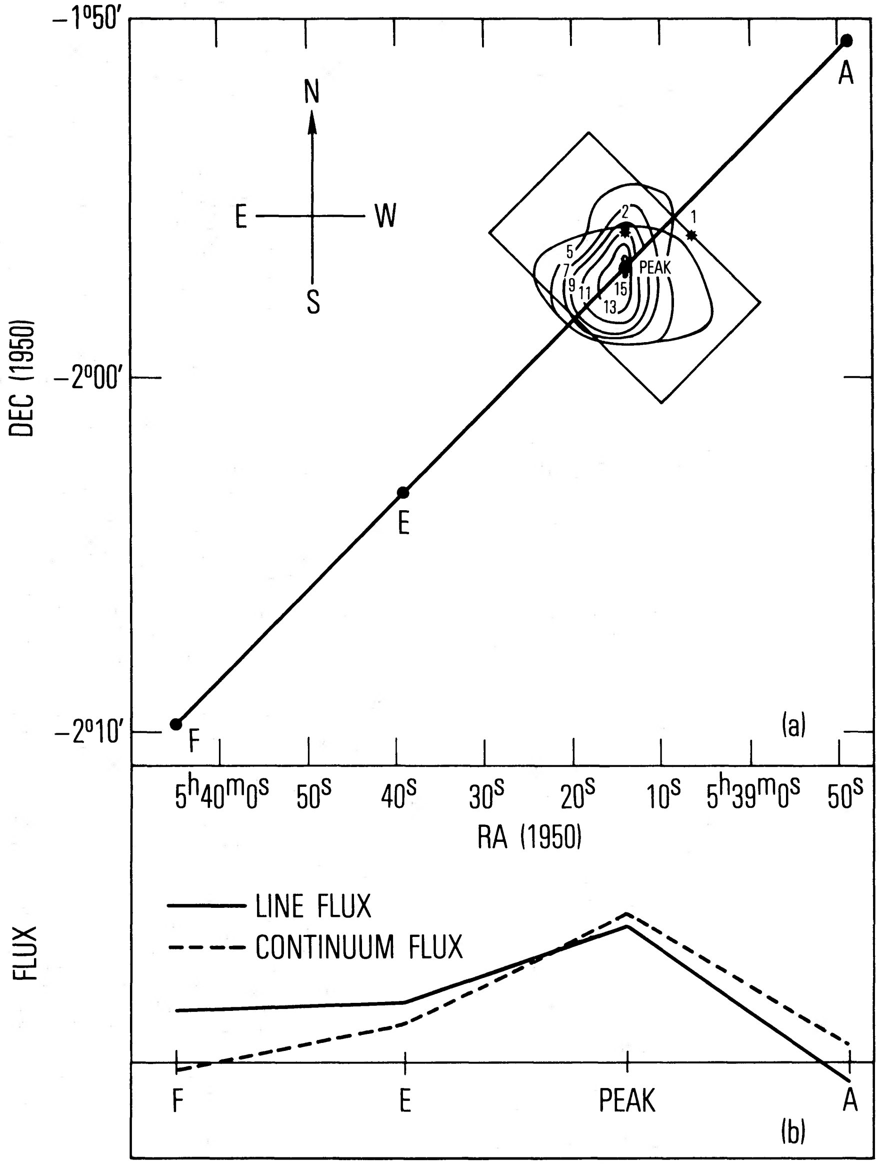

FIG. 1.—Observed continuum and [C II] line fluxes at 157 μm in NGC 2024. Dark filled circles show four positions at which reliable data were obtained, each point having been observed in at least two independent spectral runs with each of our two detectors. The line and continuum fluxes at each point as shown on an arbitrary scale. Actual values are cited in Table 1. The rectangular box surrounding the peak shows the 4′ × 7′ field of view of our instrument and its orientation on the sky. For comparison of scales, the 400 μm isophotal map of Hudson and Soifer 1976 is also shown. The heavy contour is the faintest isophote in the C76α radio combination line mapped by Krügel *et al.* 1982. Stars show Grasdalen's two candidates for sources of ionization (Grasdalen 1974). Our chopper throw was 11′ along a NE–SW direction.

these authors lie less than a minute of arc apart and were obtained with 2.′2 and 1.′6 fields of view, respectively.

II. OBSERVATIONS

Our 1980 observations were carried out with essentially the same instrument and procedures used a year earlier (Paper I). Figure 1 shows the 157 μm line and continuum fluxes at the four positions, A, C, E, and F, at which well defined results were obtained, as well as the 4′ × 7′ field of view projected on the sky. The direction of our 11′ chopper throw was NE–SW, and the data were obtained in a double beam mode. Thus, the measurements reported here refer to the difference between the signal strength measured at the points indicated in Figure 1 and the average of the signal strength

TABLE 1

CONTINUUM AND LINE FLUXES AT 157 MICRONS OBSERVED IN TWO DETECTOR CHANNELS

POSITION	CHANNEL 1		CHANNEL 2	
	Line (10^{-17} W cm^{-2})	Continuum (10^{-17} W cm^{-2} μm^{-1})	Line (10^{-17} W cm^{-2})	Continuum (10^{-17} W cm^{-2} μm^{-1})
A	-10 ± 2.3	7 ± 0.4	-0.4 ± 0.2	2 ± 2
Peak	48 ± 9	55 ± 18	33 ± 13	50 ± 10
E	22 ± 4	9 ± 4	10 ± 0.4	15 ± 2
F	23 ± 5	-7 ± 3	5 ± 3	1 ± 4
C	1 ± 30	0.7 ± 7	...	...

at the reference positions on either side. The presence of a more diffuse, widespread component of the line emission can have the effect of decreasing the apparent line flux at all positions, but this still represents the most direct observational approach.

We also observed a number of other positions lying off the straight line joining A to F. None of these positions, however, was observed at the line wavelength with both detectors; several were observed with only a single reference beam; and only one position was observed twice. That position, C, lies 24′ to the NE of the peak, where the signal strength was essentially zero, though the errors were large. The other measurements were not considered sufficiently reliable for inclusion in this study and are not shown in Table 1.

The fluxes reported in Table 1 were obtained in the following systematic way. Data had been taken generally at 10 different wavelengths separated by 0.4 μm, while the spectral resolution was ~ 1 μm. The three measurements at wavelengths straddling the [C II] line position were therefore averaged. Since the seven continuum points contain some wavelengths adjacent to water vapor bands and since the signals at these wavelengths sometimes vary erratically, we systematically dropped the two highest and two lowest continuum values and then averaged the remaining three values as representative of the continuum. These average values are the continuum values listed in Table 1. When the average continuum value was subtracted from the mean intensity observed in the three line-straddling positions, we had a measure of the line strength as modulated by our instrumental profile. The actual line strength, when corrected for this modulation, can be shown to be ~ 1.5 times this value and is given in Table 1. The errors given in Table 1 represent the root mean square deviation of the intensities obtained in different spectral runs made at the same position on the sky. The difference between measurements obtained in our two detector channels is generally somewhat larger than these rms deviations, but of the same general magnitude. The line strength and continuum values shown in Figure 1 are the mean of the intensities observed with our two detectors.

III. RESULTS

Two main results are to be noted. First, the [C II] line emission is seen over an extended region stretching toward the SE. A significant line flux is still observed 18′ SE of the continuum peak. Data in the transverse direction are sparse, but there appears to be no significant line emission 24′ to the NE of the far-infrared continuum peak (position C). Clearly, the line emission region is much more extended than that associated with the far-infrared continuum radiation from dust. It is also far more extended than the C II radio-recombination 76α radiation shown in Figure 1.

The second result is that our peak line and continuum fluxes are somewhat lower than the values previously reported (Paper I), though they agree within quoted errors. The differences may easily be explained by the relatively few spectra we had available for averaging in our 1979 series and by the possibility of differences in position on the sky used as the location of the far-infrared continuum peak. The continuum radiation is sufficiently weak to make reliable location of the precise point of peak emission somewhat difficult. We did check the line and continuum intensities in M42 in the 1980 series, and the agreement with 1979 data is excellent (Table 2).

IV. DISCUSSION

In Paper I we discussed the observed [C II] 157 μm line radiation in terms of contributions from the H II region and the region which emits the carbon recombination lines mapped in the radio by Krügel *et al.* (1982). The H II region was shown to contribute $\sim 10\%$ of the line flux of approximately 7×10^{-16} W cm^{-2} reported there. When we included the carbon recombination line region, and assumed a hydrogen density of $n_{\rm H} \sim 10^5$ cm^{-3} and a temperature $T \sim 100$ K (consistent with parameters derived by Pankonin *et al.* 1977, from their radio carbon recombination line observations), we obtained a total flux of $\sim 7 \times 10^{-16}$ ε W cm^{-2}. Carbon was assumed to have its cosmic abundance, 3.3×10^{-4} $n_{\rm H}$, and ε was the fraction of carbon in its singly ionized

TABLE 2

COMPARATIVE DATA ON OBSERVATIONS IN 1979 AND 1980

	1979[a]		1980[b]	
REGION	Line ($\mathrm{W\ cm^{-2}}$)	Continuum ($\mathrm{W\ cm^{-2}\ \mu m^{-1}}$)	Line ($\mathrm{W\ cm^{-2}}$)	Continuum ($\mathrm{W\ cm^{-2}\ \mu m^{-1}}$)
M42	1.0×10^{-15}	2.6×10^{-15}	9×10^{-16}	2.5×10^{-15}
NGC 2024 ...	7×10^{-16}	7×10^{-16}	4×10^{-16}	5×10^{-16}

[a] Russell *et al.* 1980.

[b] Present results.

form. To account for our previous, somewhat higher value of the line strength, either effectively all the carbon had to be in C II ($\varepsilon \sim 1$) or the temperature had to be higher than 100 K. This condition is eased in the present discussion due to two factors. First, we report a lower flux for the line of $\sim 4\times10^{-16}$ W cm^{-2} at the peak. Second, Figure 1 shows that our field of view is about twice the size of the carbon recombination line emitting region. In view of the extended nature of the [C II] emission reported here, we must now include a third extended component of line emission.

In a recent study of M17 (Russell *et al.* 1981, hereafter referred to as Paper II) we also found evidence for an extended [C II] halo emission component, similar in extent to that now observed in NGC 2024. We were able to explain this extended flux around M17 in terms of radiating carbon ions embedded in a neutral, atomic hydrogen region surrounding the H II domain. A similar explanation can be provided for NGC 2024. As explained in Paper II, the expected flux from a column of depth D is

$$F = L(T)\, n_{\mathrm{H}} n_{\mathrm{C}^+} D\Omega/4\pi \ \mathrm{ergs\ cm^{-2}\ s^{-1}},$$

where n_{H} and n_{C^+} are the neutral hydrogen and singly ionized carbon densities and $L(T)$ is the energy emitted per unit volume for unit carbon and hydrogen number densities. This equation assumes that the hydrogen density is below the critical density $n_{\mathrm{crit}} \sim 3\times10^3$ cm^{-3} at which collisional de-excitation equals spontaneous radiative de-excitation.

Lockhart and Goss (1978) have mapped the 21 cm absorption across the central six or seven minutes of arc across NGC 2024 and find evidence for a considerably more extended distribution of hydrogen than that contained in the area they actually mapped; no drop in the hydrogen column density strikes one at the edges of their maps. They find four velocity flows at flow velocities of 7.5, ~ 9.5, 10.8, and 11.6 km s^{-1}, close to the observed recombination lines velocities that range from 10 to 10.7 km s^{-1}, cited by Krügel *et al.* (1982). The optical depth at 21 cm is greater than unity in the 9.5 km s^{-1} flow and only a lower limit to the column density of $N_{\mathrm{H}} \sim 1.7\times10^{21}$ cm^{-2} can be given; a lower limit to the actual density $n_{\mathrm{H}} > 300$ cm^{-3} is also cited by these authors. The other three flows account for a total column density $N_{\mathrm{H}} = 2.8\times10^{21}$ cm^{-2} and number densities that range from 100 to $\gtrsim 300$. The column densities assume a temperature of 50 K in the gas, and the number densities assume that the cloud shapes are spherical.

For order of magnitude purposes we can estimate the line flux expected from the "peak region" (see Fig. 1) by taking the lower limit from above for the total column density, $n_{\mathrm{H}}D$, to be $\sim 4\times10^{21}$ cm^{-2} and assuming $n_{\mathrm{H}} \sim 10^3$ cm^{-3}. Taking a temperature of 100 K, as in Paper I, consistent with Lockhart and Goss's upper limit to the temperature, ~ 200 K, derived from Doppler line widths, we obtain $L(T) = 8\times10^{-24}$ ergs cm^3 s^{-1} from calculations published by Launay and Roueff (1977). Our field of view was $\Omega \sim 2.4\times10^{-6}$ sr, and for $n_{\mathrm{C}^+} =$

TABLE 3

MODEL FOR 157 MICRON LINE EMISSION FROM NGC 2024[a]

Variable	Value
Type 1. H II Region[b]	
Ionizing stars	Two O9.5 stars
H II radius	0.2 pc
Density, n_{H}	1.3×10^3 cm^{-3}
I (calculated)	$6\times10^{-17}\,\varepsilon_1$ W cm^{-2}
Type 2. C II Radio Recombination Region[b]	
Density, n_{H}	10^5 cm^{-3}
Column density, $n_{\mathrm{H}}D$	3×10^{21} cm^{-2}
Temperature	100 K
I (calculated)	$6\times10^{-16}\,\varepsilon_2$ W cm^{-2}
Type 3. C II Halo Region	
Density, n_{H}	1000 cm^{-3}
Column density, $n_{\mathrm{H}}D$	4×10^{21} cm^{-2}
Temperature	100 K
I (calculated)	$2\times10^{-16}\,\varepsilon_3$ W cm^{-2}

[a] Assumes cosmic abundance of carbon $n_{\mathrm{C}}/n_{\mathrm{H}} \sim 3.3\times10^{-4}$. ε_i is the fraction of the carbon in singly ionized form in region of type i.

[b] From Paper I.

$3.3\times10^{-4}\,n_H$ we then obtain

$$F\sim2.0\times10^{-9}\,\varepsilon\text{ ergs cm}^{-2}\text{ s}^{-1}=2\times10^{-16}\,\varepsilon\text{ W cm}^{-2}.$$

If we assume that there is an equal amount of neutral hydrogen on the far side of the radio-continuum-emitting region, we can double this amount of line radiation to obtain $F\sim4\times10^{-16}\,\varepsilon$ W cm^{-2}. This equals the amount of radiation observed from the peak as reported here if ε equals unity. ε becomes less than unity if we include flux of types 1 and 2 (see Table 3). Alternatively, we could take the neutral hydrogen layers to be flattened, i.e., take n_H to be somewhat higher with no change in $n_H D$. The column density cannot appreciably increase without excessive opacity to the carbon-ionizing radiation. A lower value of ε can also be easily accommodated if the temperature of the emitting region is somewhat higher. For example, if the entire Doppler broadening were due to thermal motions, implying a hydrogen temperature of 200 K, $L(T)$ would increase by over 60%. Thus ε could easily be $\lesssim 0.5$. The inclusion of type 3 flux allows ε to be lower for all regions. Table 3 summarizes these calculations. Fluxes of types 1, 2, and 3 contribute to the centrally observed flux. The halo only has contributions from flux of type 3.

V. CONCLUSIONS

We conclude that NGC 2024 has an extended [C II] 157 μm fine-structure emission region, though the most intense domain of 157 μm emission is centered on the C II recombination line region. The known recombination line parameters allow us to account for the observed radiation if carbon is assumed to have cosmic abundance, and approximately half of the carbon is in singly ionized form. The extended emission region can be explained by ionized carbon in adjoining atomic hydrogen regions, provided these regions are somewhat flattened along the line of sight or else if most of the carbon in these clouds is singly ionized or the hydrogen is somewhat warmer than usually assumed. At any rate, these simple explanations provide roughly the observed intensities without requiring unusual conditions in the observed clouds.

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