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A FAR-INFRARED STUDY OF THE N/O ABUNDANCE RATIO IN GALACTIC H II REGIONS

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ABSTRACT

We have measured far-infrared lines of N^{++} and O^{++} in several galactic H II regions in an effort to probe the abundance ratio N/O in different parts of the Galaxy. New measurements are presented for W43 (G30.8−0.0), Orion A, and G75.84+0.4, which are located at widely differing distances from the galactic center. The combination of [N III] 57.3 μm and [O III] 88.4 and 51.8 μm yields measurements of N^{++}/O^{++} that are largely insensitive to electron temperature and density uncertainties and to clumping of the ionized gas, because of the similarity of the critical densities for these transitions. We argue that for the observed nebulae, N^{++}/O^{++} should be indicative of N/O, a ratio that is of special importance in nucleosynthesis theory. Our measurements are compared with previous measurements of M17 and W51, which lie at intermediate galactocentric distances. For nebulae in the solar circle, we find that N^{++}/O^{++} is greater than the N/O values derived from optical studies of N^{+}/O^{+} in low-ionization zones of the same nebulae. Possible sources of this discrepancy are discussed. We find that N^{++}/O^{++} in W43 is significantly higher than for the other H II regions in the sample. Since W43 is located at $R = 5$ kpc, which is the smallest galactocentric distance in our sample, our data appear consistent with the presence of a negative abundance gradient $d(\mathrm{N/O})/dR$.

Subject headings: nebulae: abundances — nebulae: H II regions — infrared: spectra

I. INTRODUCTION

Our understanding of the history of star formation in our Galaxy relies to a large extent on our knowledge of the present distribution of the nucleosynthetic products of previous generations of stars. The presence of radial abundance gradients in several external galaxies is well established (Kwitter and Aller 1981; Rayo, Peimbert, and Torres-Peimbert 1982), and there is mounting evidence for similar gradients within a few kiloparsecs of the solar circle in our own Galaxy (Janes 1979; Talent and Dufour 1979; Pagel and Edmunds 1981).

Although enrichment of the interstellar medium is largely due to the primary production of elements in supernovae from massive stars, certain isotopes, such as ^{13}C and ^{14}N, are produced by the CNO process in stars which have already been seeded with C and O from previous nucleosynthesis. For this reason, the ratio of the abundance of a secondary isotope, such as ^{14}N, which accounts for most of the nitrogen that is observed, to that of a primary isotope, such as ^{16}O (the dominant isotope of oxygen), is an important constraint on models of nuclear-chemical evolution. The interpretation of this ratio has been discussed by Talbot and Arnett (1974) and by Edmunds and Pagel (1978).

The measurement of infrared forbidden lines has great potential for addressing the problem of large-scale variations in galactic abundances. In this paper, we discuss the use of three far-infrared lines, [N III] 57.3 μm, [O III] 51.8 μm, and [O III] 88.4 μm, for measuring N/O, and we present new observations of galactic H II regions in these lines. Previous determinations of N/O in ionized nebulae, based on optical observations of [O II], [O III], and [N II], have been restricted to galactocentric distances greater than $R = 8$ kpc because of extinction in the galactic disk (Peimbert 1979). These optical studies generally make use of the similar ionization potentials of O^{+} and N^{+}, and assume that $N^{+}/O^{+} \sim$ N/O. In most H II regions, however, particularly the luminous ones that are seen at the largest distances, a substantial fraction of nitrogen and oxygen is expected to be doubly ionized. In the far-infrared, extinction is not a serious problem, and H II regions at much larger distances in the galactic disk can be analyzed. Collisionally excited [N III] is visible only in the 57.3 μm line and in the far-UV. Although collisional quenching makes the values of N^{++}/H^{+} and O^{++}/H^{+} derived from the fine-structure lines sensitive to the electron density, we show below that the ratio N^{++}/O^{++} is determined very accu-

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rately by this technique. The technique has been applied previously to M17 by Moorwood *et al.* (1980), who also review earlier measurements of the [O III] lines.

II. OBSERVATIONS

The measurements were made with a piezoelectrically scanned Fabry-Perot spectrometer on the Kuiper Airborne Observatory. This spectrometer and its operation have been described by Storey, Watson, and Townes (1980). The Fabry-Perot was used in high order, with $\lambda/\Delta\lambda \sim 2000$. Of the measurements discussed in this paper, those for W43 and G75.84+0.4 were made in 1981 June with a 45″ FWHM beam (1′ equivalent disk), and those of Orion A were made in 1982 January with a similar-sized beam (but with a 52″ equivalent disk). All three lines, [N III] 57.3 μm, [O III] 51.8 μm, and [O III] 88.4 μm, were measured for W43 and Orion A. The line measurements for M17 and W51 were reported by Watson *et al.* (1981).

W43 and Orion A were selected for observations because of their very different locations in the Galaxy. Orion ($R = 10.5$ kpc) is a benchmark for nebular abundance determinations (Peimbert and Torres-Peimbert 1977; Lester, Dinerstein, and Rank 1979). Measurements of Orion A were made at the peak of the ionized gas emission, 15″ west and 10″ south of θ^1 Ori C (Martin and Gull 1976). W43, which is at $R = 5.4$ kpc (Downes *et al.* 1980), is a bright source at radio and far-infrared wavelengths. The luminosity from the core of W43 (G30.8−0.0) is concentrated in two distinct sources that are approximately 2′ apart in the north-south direction (Lester *et al.* 1983; Pipher, Grasdalen, and Soifer 1974; Turner *et al.* 1974). Measurements of [N III] 57.3 μm and [O III] 88.4 μm were made at several positions in W43. These spectra, which typify the signal-to-noise ratio for all of the line measurements in this study, are shown in Figure 1. Positions 1 and 3 in this figure are coincident with the two main radio and infrared continuum peaks. These spectra show that the line emission peaks along a ridge connecting the two main peaks, and that the ratio of the [N III] line to the [O III] line is fairly uniform along this ridge. The [O III]

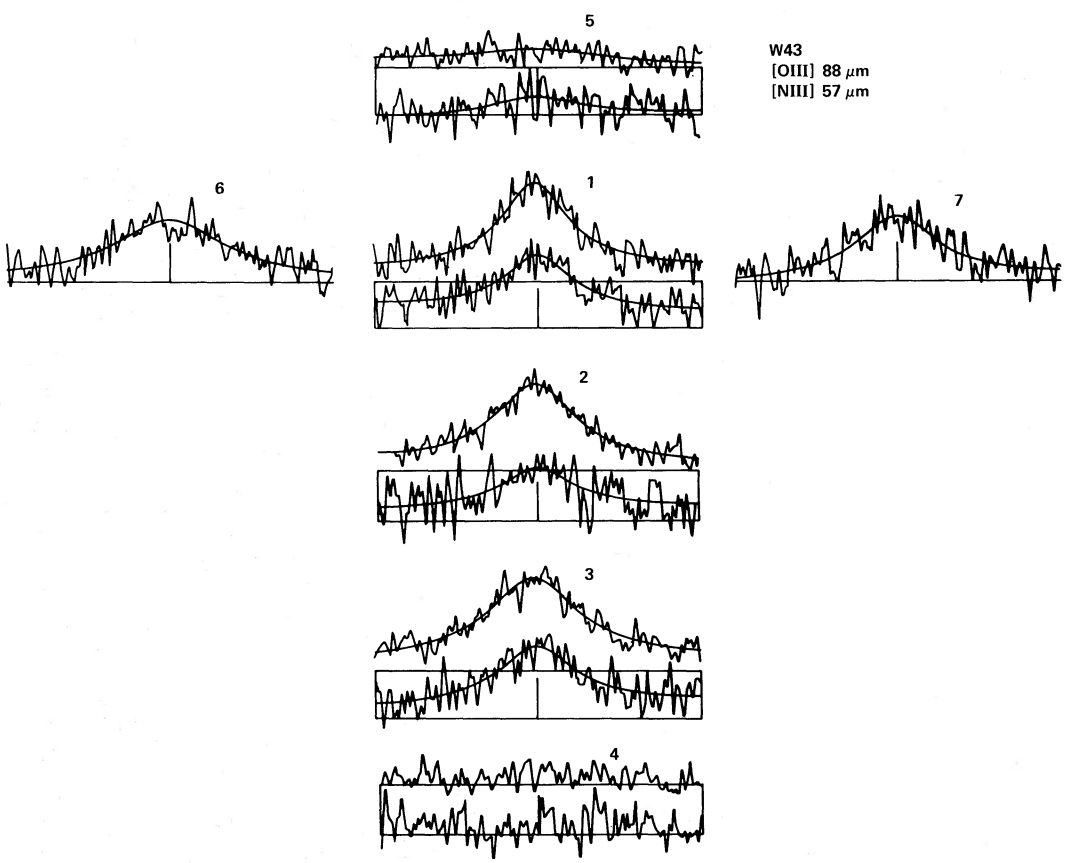

FIG. 1.—Spectra of [O III] 88 μm (*lower*) and [N III] 57 μm (*upper*) are shown for several positions in W43. North is to the top, and east is to the left. These positions are separated by approximately one beamwidth, or 40″. The central position (position 2) corresponds to the single-dish radio peak and is the position at which the ionic ratio was determined. The three sets of spectra at positions 7, 1, and 6 cover the ridge of emission that is seen in the radio synthesis and near-infrared maps. These spectra are indicative of the signal-to-noise ratio on the spectra that are analyzed in this paper.

TABLE 1

LINE FLUX MEASUREMENTS

Source/ Position	[N III] 57.3 μm (W cm^{-2})	[O III] 88.4 μm (W cm^{-2})	[O III] 51.8 μm (W cm^{-2})
W43 (G30.8−0.0)			
Pos 2[a]	6.4×10^{-17}	5.6×10^{-17}	1.4×10^{-16}
Orion A			
Radio peak[b].......	5.7×10^{-17}	4.3×10^{-17}	3.0×10^{-16}
G75.84+0.4			
Radio peak[c].......	2.6×10^{-17}	1.2×10^{-17}	...

[a](1950) $18^h45^m00^s$, −02°00′.0.
[b](1950) $5^h32^m48^s$, −05°25′.5.
[c](1950) $20^h19^m47^s$, +37°21′.5.

51.8 μm line was measured at our position 2 by Watson *et al.* (1981), and it is for this position that the electron density and ionic ratio are derived. G75.84+0.4 is a compact H II region in the ON 2 maser complex at $R = 10.2$ kpc. Radio synthesis maps of this region (Harris 1976; Turner *et al.* 1974) show a compact source with a diameter of about 1′.

Flux calibration was done relative to the underlying continuum. For Orion, the continuum flux at the observed position is from the maps of Werner *et al.* (1981). We have measured the continuum fluxes for W43 and G75.84+0.4 (Lester *et al.* 1983). The main conclusions of this paper depend on the line ratios rather than on the absolute intensities of the lines, and therefore, errors in the continuum fluxes do not significantly affect our results. Table 1 lists the observed line fluxes for W43, Orion A, and G75.84+0.4. The fluxes are estimated to be accurate to 30% in absolute intensity, and the line intensity ratios should be accurate to about 15%. Our [O III] surface brightnesses in Orion are similar to those measured by Furniss *et al.* (1982) and Storey, Watson, and Townes (1979).

III. DETERMINATION OF N/O ABUNDANCE

a) Derivation of N^{++}/O^{++}

The ground-state energy levels of O^{++} and N^{++} are shown in Figure 2. The far-infrared [O III] lines connect the ^3P fine-structure levels. The far-infrared [N III] line connects the two levels in the ^2P state, and there are no other transitions within the ground configuration of [N III]. Since these lines arise from levels with energies that are small compared with the kinetic energy of the exciting electrons, the line emissivities are insensitive to electron temperature variations within the nebulae. The critical densities of the three lines are similar (2×10^3, 5×10^3, and 7×10^2 cm^{-3} for 57.3, 51.8, and 88.4 μm, respectively), and the upper level of each transition is substantially collisionally de-excited at the densities observed in compact H II regions. This effect is illustrated in Figures 3 and 4, which show the behavior of the volume emissivity ratios. These ratios were calculated using a five-level atom code for [O III], in which the electron temperature and density were the only variables. Collision strengths for the ^3P–^1S and ^3P–^1D transitions of O^{++} were taken from Seaton (1975) for $T = 10^4$ K, while those for the fine-structure lines of both O^{++} and N^{++} are from Saraph, Seaton, and Shemming (1969). Transition probabilities are from the NBS compilation (Wiese, Smith, and Miles 1969). We

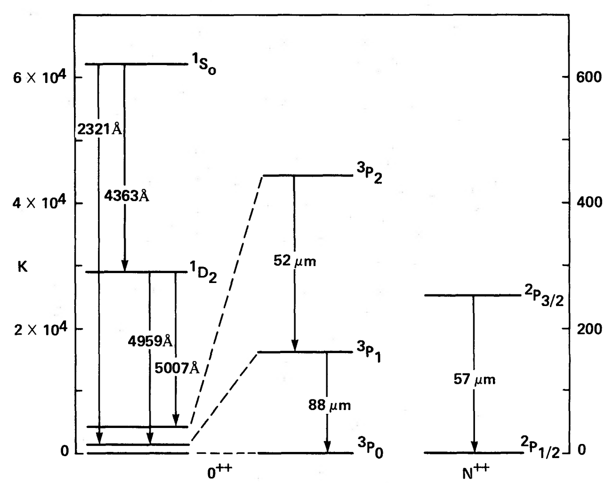

FIG. 2.—The energy level diagrams for O^{++} and N^{++} are shown with the relevant emission lines indicated. The vertical scale is in degrees K. The far-infrared [O III] lines connect the triplet ground state of that ion. The relationship of these lines to familiar optical and UV lines is also indicated. The far-infrared [N III] line connects the doublet ground state. The next higher level in this ion is well above the ground state, in a different electronic configuration, and this ion is thus not represented in the optical part of the spectrum.

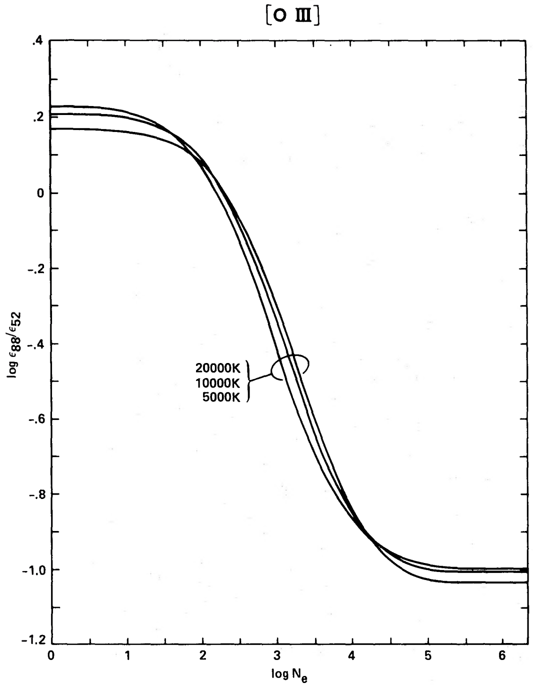

FIG. 3.—The ratio of [O III] 88 and 52 μm emissivities is plotted as a function of electron temperature and electron density. Given a ratio of [O III] line fluxes, this figure yields an electron density that is insensitive to electron temperature. The electron densities in Table 2 were derived from this figure using the fluxes in Table 1.

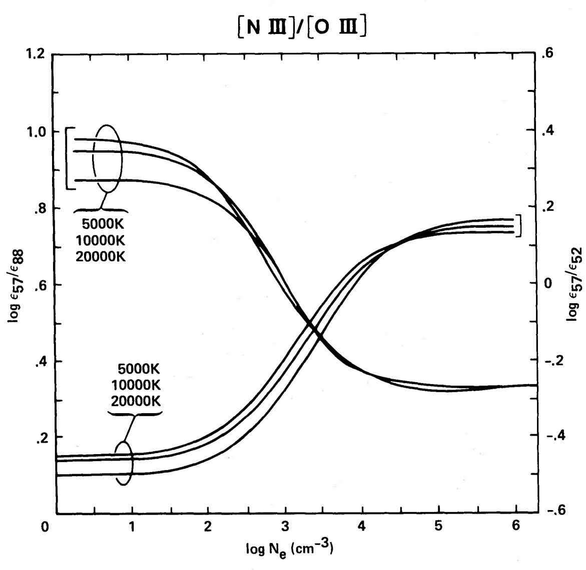

FIG. 4.—The ratios of [O III] and [N III] emissivities are plotted as a function of electron density and electron temperature. The two sets of curves correspond to the two ratios 57/88 and 57/52, and the curves connect to the appropriate ordinate. This figure is used in conjunction with Figure 3 to derive line emissivity ratios that are appropriate for a given nebula, and these ratios have been used to derive the N^{++}/O^{++} values given in Table 2.

assume throughout this paper that the lines are optically thin, an assumption which will be justified in § IV.

It can be seen from Figure 3 that the ratio of the two oxygen lines can be used to measure the electron density in the line-emitting region, as done by Watson *et al.* (1981) and Moorwood *et al.* (1980). The electron densities derived from the present data for the H II regions considered here are in the range 10^3 to 2×10^4 cm^{-3} (see Table 2). In the high density limit $n_e > n_{crit}$, the population of the upper level of each transition approaches a value appropriate to its statistical weight, and $\varepsilon \propto n_i$, where ε is the volume emissivity (energy per unit volume per unit time), and n_i is the ion density. This can be contrasted with the case $n_e < n_{crit}$, a condition which is appropriate for hydrogen and for the higher-lying $^1D_2$ and $^1S_0$ levels of O^{++}. In this low density limit, $\epsilon \propto n_e n_i \propto n_e^2$. Because of these dependences, values of N^{++}/H^+ and O^{++}/H^+ derived from the ratio of far-infrared measurements to the radio continuum emission are sensitive to the assumed electron density. However, N^{++}/O^{++} should be measurable with high accuracy in either density regime. While the individual emissivities of these fine-structure lines change by many orders of magnitude over the relevant range of electron densities (cf. Simpson 1975), the ratio of the emissivity of the [N III] line to that of either of the [O III] lines changes by at most a factor of 3 (see Fig. 4). Given measurements of [N III] and either [O III] line, even in the absence of any information about nebular temperature and density, N^{++}/O^{++} can be determined to within a factor of 2. Coincidentally, the precision with which this can be done is nearly the same for both $I(57\ \mu m)/I(52\ \mu m)$ and $I(57\ \mu m)/I(88\ \mu m)$, although the ratio with the 52 μm line might be preferred because it is the brighter of the two oxygen lines for most nebulae. Also, conversion from an equivalent width ratio to line flux ratio is nearly unity for lines that are so close together in wavelength, because the effect of differential extinction is negligible.

The accuracy with which N^{++}/O^{++} is determined is further improved, of course, by observing both oxygen lines and deriving an electron density from their ratio (see Fig. 3). This electron density, often larger than the nebular rms density because of clumping, is appropriate for the [N III]- and [O III]-emitting regions, which will occupy a similar volume because of the similarity of their ionization potentials. The similarity in the emitting volume and in the critical densities for these lines makes the derived values of N^{++}/O^{++} fairly insensitive to nebular inhomogeneities.

b) N^{++}/O^{++} *as an Indicator of* N/O

Our expectation that $N^{++}/O^{++} \sim$ N/O is based on the models of Grandi and Hawley (1978) and Grandi (1975), which suggest that the ionization of N and O track each other over a large range in stellar effective

TABLE 2

ADOPTED AND DERIVED PARAMETERS OF H II REGIONS

	Adopted Parameters			Derived Parameters	
Source	R^a (kpc)	He^+/H^{+b}	N_e (cm^{-3})	N^{++}/O^{++c}	O^{++}/H^{+d}
W43	5.4	0.093	870	0.43	3×10^{-4}
W51	7.6	0.089	10000	0.25	4×10^{-4}
M17	8.0	0.102	1000	0.20	4×10^{-4}
G75.84	10.2	0.052[e]	22000[f]	0.25	2×10^{-4}
Orion A ...	10.5	0.072	8900	0.30	6×10^{-4}

NOTE.—Solar neighborhood: N/O = 0.1; O/H = 6×10^{-4}; He/H = 0.1.

[a] Galactocentric distance based on kinematic distance.

[b] Lichten, Rodriguez, and Chaisson 1979, except G75.84.

[c] The error in this ionic ratio is dominated by the [N III]/[O III] line intensity ratio and is probably less than 15% for all sources in this list (see text).

[d] The error in this ionic ratio depends on many factors, the dominant ones being beam size correction, optical thickness in radio continuum, and possible clumping. As such, this ratio is probably only accurate to a factor of 2 or 3.

[e] Churchwell *et al.* 1978.

[f] From [S III] line ratio (Herter *et al.* 1982).

temperature. These results are supported by optical observations at positions of different ionization within the same nebula (see, for example, Peimbert and Torres-Peimbert 1977). Although the ionization equilibria involved ($O^+ + 35$ eV $\rightarrow O^{++}$, $N^+ + 30$ eV $\rightarrow N^{++}$) require photons of somewhat different energies, these models indicate that these ionization equilibria are dominated by optical depth effects from the He continuum. The N^{++} and O^{++} Strömgren spheres should be approximately locked to that of He^+, so that the volume occupied by these ions should be very similar. For H II regions ionized by stars hotter than about 37,000 K, which is probably the case for these luminous sources, N^{++} and O^{++} will be the dominant ions of each element.

c) *Application to the Observations*

Table 2 lists the derived electron densities and N^{++}/O^{++} ratios for W43, Orion A, and G75.84+0.4 from this study. These values were derived using the line fluxes in Table 1 in conjunction with the data in Figures 2 and 3. Results for M17 and W51 derived from the fluxes in Watson *et al.* (1981) are included for comparison. In the absence of a 52 μm measurement for G75.84 +0.4, an electron density of 2.2×10^4 cm^{-3} has been assumed for this object, based on the ratio of the 18.7 and 33.4 μm [S III] lines (Herter *et al.* 1982). This is substantially larger than the rms electron density of 10^4 derived from radio measurements, a fact which is evidence of clumpiness. The errors in the derived value of N^{++}/O^{++} are small because, as described above, the accuracy is essentially limited by the accuracy of the emission-line equivalent widths.

Two points are immediately apparent from Table 2. First, the N^{++}/O^{++} ratios in these H II regions are substantially larger than the currently accepted solar neighborhood N/O ratio. In particular, Peimbert and Torres-Peimbert (1977) have derived N/O = 0.13 in Orion, in a smaller beam than we used and on the basis of optical N^+, O^+, and O^{++} lines. Peimbert and Costero (1969) derived N/O = 0.1 for the outer regions of M17. Second, we note that while the derived N/O values for Orion A, G75.84+0.4, W51, and M17 are in the range 0.20–0.30, the value for W43, which is the H II region with the smallest galactocentric distance in the sample, is significantly higher at 0.43. While this latter result is tantalizing, and suggests the existence of a substantially elevated N/O ratio in the inner Galaxy, it must be considered tentative in view of the discrepancy between the far-infrared abundance ratio and the optical abundance ratio for Orion and M17. This discrepancy will be discussed further in the following section.

IV. DISCUSSION

In view of the discrepancy with the optical studies, several checks on our Orion A measurement have been made. Our derived [O III] electron density of 8900 cm^{-3} is almost identical to that derived from the optical [S II] line ratio at the same position in the nebula (Lester, Dinerstein, and Rank 1979) and similar to that derived from the same [O III] lines in a much larger beam (Melnick, Gull, and Harwit 1979). Furthermore, an O^{++}/H^+ ratio of 6×10^{-4} can be derived from our far-infrared line data, taking a radio flux of 8 Jy within our beam (Schraml and Mezger 1969; Martin and Gull 1976). This is consistent with that derived from optical

[O III] and Balmer-line measurements at that position in the nebula (Peimbert and Torres-Peimbert 1977). It thus seems justified to conclude that the same ionized gas is being observed at all wavelengths.

The assumption that these lines are optically thin has been investigated by Rubin (1968) and Simpson (1975), who pointed out that in a source with a high emission measure and small velocity dispersion, the optical depth at line center can be significant. Since the absorption coefficients per ion are similar for the three lines, and since the column density of N^{++} is smaller than that of O^{++}, the [N III]/[O III] line ratio could be made to appear anomalously high if the [O III] lines were almost saturated. We can test for this possibility by comparing the surface brightness at line center (assuming a velocity dispersion of 10 km s^{-1}) with that of a blackbody at nebular temperatures. We find τ ([O III] 52 μm) < 0.01, and thus an enhancement of N/O by selective self-absorption seems unlikely. Although the effects of reddening are, at these wavelengths, probably unimportant, we point out that the effect of an extinction that decreases toward longer wavelengths would be to decrease the measured N^{++}/O^{++} rather than increase it.

Another interesting possibility is that, in an ionization-bounded H II region with a radial density gradient, the contribution of the innermost highest density gas would be suppressed because of collisional quenching in favor of the outer lower density regions. The far-infrared lines would be biased toward the lower density shell in which these ions are found. This would have the effect of biasing the measurements of [O III] and [N III] toward that region, just inside the He^+ Strömgren sphere, where the difference between N^{++}/N and O^{++}/O is most pronounced. Since the lower ionization potential of N^+ as compared with that of O^+ would result in a slightly larger volume of N^{++} than O^{++}, this explanation might account for the large values of N^{++}/O^{++} that we infer from the far-infrared lines. While there is some evidence for enhanced N^{++}/O^{++} at the periphery of M17 (Watson *et al.* 1981) and Orion A (Furniss *et al.* 1982), no definite ionization gradient is seen in our measurements of W43. The presence of UV-absorbing dust may decouple the ionization structure of N^{++} and O^{++} from that of He^+, leaving N^{++} with a larger ionized volume. Such an effect is seen in the calculations of dusty nebulae by Sarazin (1977). We are presently working with ionization models of these nebulae, and the results of this work, with application to N/O, will be discussed in a forthcoming paper.

The difference between the derived N^{++}/O^{++} ratio in W43 and that of H II regions with larger galactocentric distances may reflect an abundance enhancement of about a factor of 1.8 in this source. Although the precision with which N^{++}/N tracks O^{++}/O breaks down for very high ($T_{eff} > 50{,}000$ K) and very low ($T_{eff} < 35{,}000$ K) temperature ionizing stars in Grandi's models, it is unlikely that the W43 result can be simply an ionization effect. In Table 2 we list He^+/H^+ measurements from radio recombination lines for H II regions in this study. The values for Orion A, W51, W43, and M17 are taken from Lichten, Rodriguez, and Chaisson (1979), and these values compare well with the results of McGee and Newton (1981) and Thum, Mezger, and Pankonin (1980) for sources in common. The measurement of G75.84+0.4 is from the low-frequency measurements of Churchwell *et al.* (1978). No correlation between our N^{++}/O^{++} measurements and these He^+/H^+ values is apparent. Another check on the ionization structure can be made by using the oxygen line strengths, the derived electron density for the line-emitting region, and the radio continuum measurements to derive values of O^{++}/H^+. These values are given in Table 2. The comparatively large (2'.5) radio continuum beam (Schraml and Mezger 1969) smooths out the spike in emission measure at the cores of these H II regions and leads to an overestimate of O^{++}/H^+, but our values can still be used to compare the ionization of different H II regions. Although the potential for error in O^{++}/H^+ is fairly large because of the electron density dependence when this ratio is derived from the far-infrared lines, there is no compelling evidence for a correlation between the derived N^{++}/O^{++} and O^{++}/H^+ values.

Probably the greatest source of uncertainty in our results is the values of the atomic constants that are used in the analysis. The collision strengths adopted here for both [N III] and [O III] were computed using simple interaction theory (Saraph, Seaton, and Shemming 1969). More recent and detailed calculations for [N III] and [O III] agree within 30% of the older values (Nussbaumer and Storey 1979; Aggarwal, Baluja, and Tully 1982). However, at these high electron densities, the far-infrared line strengths are sensitive not only to the collision strengths, but even more to the transition probabilities. Calculations of the latter using accurate wave functions are currently in progress (P. J. Storey, private communication). When these results become available, our anomalously high N^{++}/O^{++} values for Orion and M17 will have to be reevaluated in the context of the revised line emissivities. However, the *differential* comparison among the regions is independent of this problem, and the higher N/O abundance in W43, the one "inner-Galaxy" H II region in our sample, seems well established.

Our results are not inconsistent within the observational uncertainties with the optically derived N/O gradient of $d\log(N/O)/dr = -0.4$ kpc^{-1} (Peimbert 1979), and they suggest that the gradient may extend inward to the 5 kpc "ring," where star formation is currently very active. It is of interest to compare these results with recent measurements of isotopic ratios that have been reviewed by Wannier (1980) in the giant molecular clouds associated with these H II regions. The ratio $^{12}C/^{13}C$ has been derived for W43, W51, and other regions from measurements of isotopic formaldehyde lines associated with molecular clouds (Henkel, Walmsley, and Wilson 1980). Marginal evidence is found for a change in $^{12}C/^{13}C$ from an approximately terrestrial value of 80 for $R > 7$ kpc, to 40 in W43 at 5.4 kpc. Such a decrease in $^{12}C/^{13}C$ would be expected to accompany an increase in $^{14}N/^{16}O \sim N/O$ as a result of CNO processing.

V. SUMMARY

New far-infrared line measurements of [N III] (57.3 μm) and [O III] (51.3 and 88.4 μm) are presented for the galactic H II regions W43, Orion A, and G75.84+0.4. These are used to determine the ionic ratio N^{++}/O^{++} in these regions with the expectation that this ratio is indicative of the elemental N/O abundance ratio. Our major results are

1. The technique of using far-infrared emission-line ratios is a powerful one for investigating large-scale abundance variations in the galactic disk.

2. We derive a value $N^{++}/O^{++} \sim 2\times(N/O)$ for objects in which N/O has been independently determined by optical measurements of N^+ and O^+. This effect is not predicted by simple ionization models. Possible explanations for the discrepancy include errors in the presently available atomic parameters, an amplification of an otherwise small difference in the ionization structure by collisional quenching, or perhaps the presence of dust selectively absorbing ionizing radiation in the nebulae, although an error in the optical determination of N/O at present cannot be excluded.

3. The ratio N^{++}/O^{++} is approximately a factor of 2 higher in the inner-Galaxy H II region W43 than in sources with $R > 7$ kpc. If this ratio is proportional to N/O, then a negative galactic gradient in N/O is indicated. This conclusion must be considered tentative, however, until the discrepancy in ionization structure can be resolved.

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