STRONG [N II] EMISSION AND ABUNDANCES IN THE RING NEBULA*

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ABSTRACT

Measurements of line intensities at six positions in the Ring Nebula showing variations in the degree of ionization are presented. Analysis of forbidden-line intensities indicates that the temperature decreases outward from the central star, while the electron density correlates well with the flux in Hβ. Ionic abundances of He ii, He iii, O ii, O iii, Ne iii, N ii, and S ii relative to H ii are derived for each position; total abundances of Ne, N, and S are estimated, using the oxygen ionization distribution to provide corrections for unobserved states of ionization. It is found that the derived total abundances of N and S agree very well over the six positions, even though the corrections for unobserved states vary by nearly a factor of 30. The correction formula for Ne is less successful in providing consistent abundances. It is concluded that the enhanced [N ii] lines observed near the edge of the nebula result entirely from N being nearly all N n in these regions. The N abundances derived agree well with those found in other planetary nebulae.

Subject headings: nebulae: abundances — nebulae: planetary

I. INTRODUCTION

[N II] emission lines which are strong relative to nearby Hα are observed near the nuclei of many external galaxies (Burbidge and Burbidge 1962), but the reasons are not clear for their apparent enhancement relative to intensities observed in normal H ii regions and planetary nebulae. Peimbert (1968) suggested that the abundance of nitrogen is above normal in two galaxies which he studied. Unfortunately, the determination of the abundance of nitrogen usually depends entirely on observed strengths of the red [N II] lines, and a correction must be made for the unobserved stages of ionization in order to derive the total N abundance. Since the ionization potential of N ii is 29.6 eV, this correction can be large in any objects that are of moderate or higher ionization level, as are most planetary nebulae. Peimbert and his collaborators (e.g., Peimbert and Torres-Peimbert 1971) have used relative abundances of O ii and O iii to estimate correction factors for unobserved N ionization states, since the ionization potential of O ii is 35.1 eV, roughly similar to that of N ii. They also used a similar approach to allow for unobserved ionization states of other elements. The situation is less clear in the nuclei of galaxies, as the ionization and heating mechanisms of the gas are not as obvious as they are in planetary nebulae and H ii regions. As an alternative to abundance effects, Burbidge, Gould, and Pottasch (1963) suggested that [N II] enhanced relative to Hα could be produced in regions where the electron temperature T e is relatively high, since forbidden-line excitation increases strongly with T e, while recombination rates decrease. Louise (1969) proposed varying electron temperatures as the cause of a variable Hα/[N II] ratio in the planetary nebula NGC 7293.

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Fig. 1.—Observing positions in the Ring Nebula. North is at the top, and east is at the left. The scale is 0.49 arcsec mm$^{-1}$. 
the nebular observations were alternated with those of a sky position well outside the nebula. Spectra were obtained at two grating settings which covered the approximate wavelength ranges 3500–5600 Å and 4600–6900 Å at a resolution of about 8 Å full width at half-maximum (FWHM); supplemental observations made with another grating provided twice that resolution. The two entrance apertures used on the nebula were each 2" x 4" and separated by 35′00 along an east-west line. Since the off-set guider reticle used for positioning has very accurate readouts, it is possible to determine and repeat slit placements to an accuracy of better than 0.5; and the coordinates of the six observing positions in seconds of arc from the central star are given in Table 1. To make these coordinates more useable for the discussion in § III, Figure 1 shows them superposed on a picture of the Ring Nebula. The positions are numbered in order of decreasing reddening.

Table 1 gives the average measured line intensities $F(\lambda)$ normalized to the scale $F(H\beta) = 100$. We have estimated the accuracies of the intensities based on comparisons of the absolute fluxes obtained on the individual nights and in the wavelength region common to the two principal grating settings. Though positions 3 and 6 were observed on only one night, the errors estimated on the basis of the quality of the data and experience with the other observations are not significantly larger than for the other positions. We estimate that line intensities with $F(\lambda) > 50$ have accuracies of about 10%; those with $10 < F(\lambda) < 50$ about 25%; and those with $F(\lambda) < 10$ about 35%–50%. Also given at the top of the $F(\lambda)$ column is the measured absolute flux in $H\beta$ in units of ergs cm$^{-2}$ s$^{-1}$; we estimate these to have an accuracy of about 15%.

### III. DISCUSSION OF THE OBSERVATIONS

#### a) Reddening Corrections

The amount of interstellar reddening of a nebula can be estimated from the Balmer decrement. We have used the $H\alpha$ and $H\beta$ lines for this, as they are the strongest and best measured Balmer lines we observed. Adopting $I(H\alpha)/I(H\beta) = 2.87$ for the intrinsic, unreddened ratio (Brocklehurst 1971), we have calculated the color excess in magnitudes $E(\beta - \alpha)$ (Miller and Mathews 1972) for each of the positions and list these in Table 1. The relative intensities measured for higher reddening curve given by Miller and Mathews (1972) for each of the positions and list these in Table 1. The relative intensities measured for higher reddening curve given by Miller and Mathews (1972) for each of the positions and list these in Table 1. The relative intensities measured for higher reddening curves.
contamination of Hα with the strong [N II] lines seen at this position is definitely ruled out by the higher-resolution measurements. As an alternative to increased reddening, we must consider the possibility of some admixture of collisionally produced Balmer emission, since, for small amounts of collisional contribution, the decrement mimics the effects of reddening accurately (see Miller 1974b for a discussion of this effect in the Cygnus Loop). Also, collisional excitation could be expected to be most likely near the edge, where the expanding nebula may interact with the ambient interstellar medium. However, on the opposite edge of the nebula, position 6 also shows strong [N II], but has a Balmer decrement typical of remaining places in the nebula. Furthermore, the helium line ratio F(λ5876)/F(λ4471), which one would not expect to be influenced by collisional effects to the same degree, is also larger for position 5 than for the other positions. The helium line strengths have larger uncertainties, but their intensities are consistent with the same amount of enhanced reddening derived from the Balmer lines. In summary, we feel that variations in reddening are the source of the significantly larger value of the Balmer decrement at position 5.

b) Temperatures and Densities

The intensity ratios I(λ5007 + λ4959)/I(λ4363) of [O III], I(λ6548 + λ6584)/I(λ5755) of [N II], and I(λ6717 + λ6731)/I(λ4469 + λ4473) of [S II] were used to calculate T_e, and the ratio I(λ6717)/I(λ6731) of [S II] was used to calculate N_e. The calculations were made using a multilevel atom computer program incorporating transition probabilities and collision strengths listed by Osterbrock (1974), except that the N II and O III collision strengths came from Seaton (1975) and Eisner and Seaton (1974), respectively. The values derived and their estimated errors are listed in Table 2. For the density calculation, it was assumed that S II and N II exist at the same T_e, since the errors estimated for the S II temperatures are large and the result is relatively insensitive to the value of T_e used. We list the values of T_e from [S II] for the discussion below on the abundance of S; these values have larger estimated errors because of the weakness of the violet pair. The high [S II] T_e for positions 1 and 2 most likely results from blending of the violet [S II] lines with other lines that can occur in this spectral region (Miller 1968). For positions 5 and 6, the upper limit is based on the limits of detectability estimated from other weak lines. The difference between T_e at positions 3 and 4 appears real, but must be considered uncertain until the possibility of blending with other lines is investigated. At the densities indicated by [S II], the T_e determination from [N II] is insensitive to N_e. Since [O III] was weak at positions 5 and 6, for the abundance calculations below, T_e was taken to be 10,000 K by analogy with the other positions for which the [N II] and [O III] temperatures are very similar. It can be seen that, as a general trend, T_e is highest near the center and tends to decrease outward, while N_e is correlated with surface brightness. The rough correlation between T_e from [N II] and that from [O III] is interesting, since one would expect them to occupy largely different volumes. This should not be given undue attention, because the total range of T_e measured from these lines is fairly small, and the errors associated with the [N II] T_e values are relatively large.

c) Ionic and Total Abundances

The calculation of ionic abundances from the line intensities given in Table 1 was carried out in the standard manner (see Seaton 1960 for example), using the atomic constants for S II, O III, and N II given in § IIIB. We used transition probabilities for Ne III and O III and collision strengths for O II from Osterbrock (1974), while collision strengths for Ne III were taken from Pradhan (1974). The helium abundances were calculated using recombination coefficients given by Brocklehurst (1971, 1972). For He, Ne III, and O III, the T_e from [O III] was used; while for O II, S II, and N II, the [N II] T_e and [S II] N_e were used. The derived abundances relative to H are given in Table 2. The principal source of error in these results comes from uncertainties in the temperatures; from the estimated errors in T_e, we estimate them to be accurate to 50% or better. We have not used the temperature variation method of Peimbert (1971), because the difference between O III and N II is small, the total range in T_e measured is also relatively small, and the extensive study of abundances in planetary nebulae by Barker (1974) suggested that Peimbert overestimated the impact of the temperature variation effects to some degree.

The corrections from ionic to total abundances are difficult because of the extreme deviation from thermodynamic equilibrium; various approximate schemes have been devised. The Peimberts (1971) and Peimbert and Costero (1969) have adopted a set of simple formulae which make use of fairly close agreements in ionization potentials between ions where more than one ionization state is observed and those where important stages are not observable. As the alternative is detailed model calculations for each nebula observed, their approach is very useful, and this section will explore its accuracy. Their ionization correction formulae for O, Ne, and N and that of Barker (1974) for S are as follows:

\[
\frac{N(O)}{N(H)} = \frac{N(He \text{ II} + He \text{ III}) \cdot N(O \text{ II} + O \text{ III})}{N(He \text{ II})},
\]

\[
\frac{N(He)}{N(H)} = \frac{N(He \text{ III})}{N(He \text{ II})},
\]

\[
\frac{N(N)}{N(H)} = \frac{N(O) \cdot N(N \text{ II})}{N(O \text{ II}) \cdot N(N \text{ II})},
\]

\[
\frac{N(S)}{N(H)} = \frac{N(O) \cdot N(S \text{ II})}{N(O \text{ II}) \cdot N(H \text{ II})}.
\]

Using the above, we have calculated the ionization correction factors \( \lambda_{\text{c}} \) and list them and the derived...
<table>
<thead>
<tr>
<th>Position</th>
<th>Tempeatures, Densities, and Abundances Relative to Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12000 ± 500 10500 ± 1000 10600 ± 2000 10700 ± 600 10800 ± 2000 10900 ± 600 11000 ± 1500 11200 ± 400 11500 12000 13000 15000 20000 30000 50000 80000 100000 1000000 1000000</td>
</tr>
<tr>
<td>2</td>
<td>1.22 x 10^-4 1.23 x 10^-4 1.24 x 10^-4 1.25 x 10^-4 1.26 x 10^-4 1.27 x 10^-4 1.28 x 10^-4 1.29 x 10^-4 1.30 x 10^-4 1.31 x 10^-4 1.32 x 10^-4 1.33 x 10^-4 1.34 x 10^-4 1.35 x 10^-4 1.36 x 10^-4 1.37 x 10^-4 1.38 x 10^-4 1.39 x 10^-4</td>
</tr>
<tr>
<td>3</td>
<td>0.07 0.08 0.09 0.10 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18 0.19 0.20 0.21 0.22 0.23 0.24 0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.129 0.128 0.127 0.126 0.125 0.124 0.123 0.122 0.121 0.120 0.119 0.118 0.117 0.116 0.115 0.114 0.113</td>
</tr>
<tr>
<td>5</td>
<td>0.1 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18 0.19 0.2 0.21 0.22 0.23 0.24 0.25</td>
</tr>
<tr>
<td>6</td>
<td>0.089 0.090 0.091 0.092 0.093 0.094 0.095 0.096 0.097 0.098 0.099 0.100 0.101 0.102 0.103 0.104 0.105</td>
</tr>
</tbody>
</table>

* Adapted.  
† Omits position 6.  
‡ Omits positions 5 and 6.
The various abundances listed in Table 2 all behave consistently over the six positions in showing the systematic decrease in levels of ionization. Except for positions 2 and 3, this decrease agrees with the increasing distance from the central star. Position 2 is slightly farther from the central star than position 3, but has higher ionization. This of course merely reflects the fact that the Ring Nebula is not circularly symmetric in its projected ionization structure; the color photograph of the Ring Nebula discussed by Miller (1974a) illustrates clearly that ionization falls off faster toward position 2 than toward position 3.

The interpretation of the He abundances is straightforward. Allowing for an estimated uncertainty of about 15% in the values for each position, we see a smooth progression through the six positions in the relative amounts of He III and He II, although their sum is constant to within the estimated errors for all positions except 6. It is likely that at position 6 the line of sight passes through regions where He is neutral and H is ionized.

The $i_{\alpha}$ for O varies by a factor of 2.5, but the total abundance is constant over the six positions to within the estimated errors. The average agrees well with the results from other nebulae, and we conclude that equation (1) for the O $i_{\lambda}$ produces consistent and probably quite reliable results.

The situation for Ne is not understood. Unfortunately, because of a lack of ultraviolet sensitivity of the ITS, we were not able to measure [Ne v] $\lambda$3425, so the total abundance depends entirely on Ne III. Nevertheless, the results for positions 1 through 4 agree reasonably well, but are about 4 times the values for other nebulae. Positions 5 and 6 yield total abundances about a factor of 5 larger than the average of the other positions (the [Ne III] lines are still strong at these positions), suggesting that the $i_{\alpha}$ is a large overestimate in these regions of low ionization. If the average abundance of Ne given is reasonably accurate for the Ring Nebula, then it would appear that even in regions of very low ionization a substantial portion of Ne is in the form Ne III. This would be surprising, since the ionization potential of Ne III is 41 eV, larger than the 35 eV for O II, while O II dominates the ionization distribution for O in positions 5 and 6. This matter deserves further study.

The situation for N appears very satisfactory in the sense that, even though the N II $i_{\alpha}$ varies by a factor of nearly 30, the total abundances agree remarkably well among the various positions and with that considered typical of planetary nebulae. Therefore it is reasonable to interpret these results as showing that the abundance of N is constant over the nebula, that the Ring Nebula N abundance is similar to that found in other planetary nebulae, and that the strong [N II] lines at the edge result entirely from N being predominantly N II in the outer regions of the nebula. Aller and Epps (1975) have reported that the N ionization correction scheme used in this paper did not give consistent results for different positions in NGC 7009. However, since they adopted intensities for the all-important [O II] $\lambda$3727 lines from earlier work, not measuring them at the same positions with the same equipment used for the other lines, we feel that their conclusions about N abundance determinations must be viewed with caution, and that the observations should be repeated.

The behavior of the S abundances is very similar to that of N, with the derived total S abundance agreeing very well in the various positions in spite of the large $i_{\alpha}$ variation. The average agrees well with that found by Barker (1974) for planetary nebulae in general. However, this abundance for S is about a factor of 10 less than what has been determined for H II regions and the Sun (Peimbert and Costero 1969). There are several possible explanations for this apparent discrepancy. The most likely is that equation (4) considerably underestimates the total S abundance, because there must be significant amounts of S III in the region where O and N are in the forms O II and N II. Nevertheless, it is surprising that the total abundances derived agree so well. Observations of [S II] lines would give further insight into this problem. Also we must consider the possibility that an even lower $T_{e}$ than the [N II] value should be used for the abundance calculations. If $T_{e}$ were around 6000 K for the region which produces the dominant [S II] radiation, then the values for the S II abundance given in Table 2 would be underestimated by a factor of about 10. Some evidence for this is given by the [S II] derived values of $T_{e}$ discussed in §IIIb, which were considerably lower in the regions where they were best determined. If correct, these results would require some explanation of why $T_{e}$ in the S II region is significantly lower than in the N II region. Since the S I ionization potential is 10.4 eV and that of N I is 14.5 eV, S II could exist in regions where N is predominantly N I. In principle, these regions could have lower $T_{e}$ because of more effective cooling or lower heating rates resulting from partial H ionization.

IV. SUMMARY

In §III we concluded that the strong [N II] lines observed near the edge of the Ring Nebula could be explained entirely by low ionization; in these regions, N exists predominantly as N II. There is no need for alternative explanations such as elevated temperatures or enhanced abundances. Furthermore, the use of a simple equation to correct the measured abundance of N II for the unobserved stages of ionization gives remarkably consistent total N abundances at the various observing positions, even though the correction factors vary by nearly a factor of 30. This gives evidence in favor of the physical assumption embodied in equation (3), which is that O II and N II occupy essentially identical volumes. The N abundance determined agrees well with the average value adopted by Peimbert and Torres-Peimbert (1971). We feel that,
unless there are unknown, systematic sources of error, the abundance of N can be reliably determined, and the Peimberts' conclusion that N is up a factor of 2 to 4 in abundance in planetary nebulae relative to H II regions is considerably strengthened.

In assessing the implications of this study for interpretation of strong [N II] lines in the nuclei of galaxies, one must keep in mind that the ionization and heating mechanisms are not understood and are likely to be considerably different from those which exist in planetary nebulae. However, it appears from the results of this paper that the oxygen ionization distribution is a rather good guide to that of nitrogen; thus one can probably make fairly reliable N ionization corrections in general if the ionization distribution for O is determined. It must be strongly stressed that, in any case, temperature determinations are exceedingly important. There is no general guarantee at all that the temperatures appropriate for the O III region are applicable to the N II and O II regions, and one may suspect that in many objects they could be quite different. In view of the exponential dependence on temperature of abundance determinations from forbidden lines, reliable temperatures for both the O III and the N II regions should be determined to give confidence in any abundance determinations of these elements in gaseous nebulae.

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