N III INTERCOMBINATION LINES IN THE IUE SPECTRA OF GASEOUS NEBULAE

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ABSTRACT

Theoretical N III electron density-sensitive emission-line ratios involving intercombination transitions, derived using recent calculations of electron impact excitation rates and oscillator strengths, are presented for $R_1 = I(1754.0 \text{ Å})/I(1749.7 \text{ Å})$, $R_2 = I(1752.2 \text{ Å})/I(1749.7 \text{ Å})$, $R_3 = I(1748.6 \text{ Å})/I(1749.7 \text{ Å})$, and $R_4 = I(1746.8 \text{ Å})/I(1749.7 \text{ Å})$. The observed values of $R_1$, $R_2$, and $R_3$ for several gaseous nebulae, measured from high-resolution spectra obtained with the International Ultraviolet Explorer (IUE) satellite, imply electron densities that are compatible. However, values of $N_e$ derived from the $R_4$ ratio are up to several orders of magnitude smaller than those deduced from $R_1$, $R_2$, and $R_3$, which is probably due to the N III 1746.8 Å line being blended with Fe II 1746.8 Å. The electron densities deduced from the N III diagnostics are, in some objects, much larger than those estimated from line ratios in nebular ions such as O III, but are in good agreement with values deduced from the chromospheric C II intercombination transitions at $\lambda \sim 2325 \text{ Å}$. These results suggest that in these nebulae the N III emission may also be chromospheric in origin.

Subject headings: atomic processes — ultraviolet: ISM

1. INTRODUCTION

Nussbaumer & Storey (1979) first pointed out the diagnostic applications of emission-line ratios involving the N III $2s^22p^2P-2s2p^2P$ intercombination lines near $\lambda\sim1750 \text{ Å}$ and presented relative line strengths determined using electron impact excitation collision strengths calculated in the distorted-wave approximation (Eissner & Seaton 1972). Subsequently, Nussbaumer & Storey (1982) recalculated collision strengths in a six-state close-coupling approximation using the IMPACT code (Crees, Seaton, & Wilson 1978), which included the $2s^22p^2P$, $2s^22p^2D$, $2s^22p^2S$, and $2p^3S$ states. More recently, Blum & Pradhan (1992) produced excitation rates using an eight-state close-coupling $R$-matrix method (developed for the Opacity Project by Seaton 1987 and Berrington et al. 1987), which consisted of the six states considered by Nussbaumer & Storey, plus $2p^3S$ and $2p^3D$.

Very recently, Stafford, Bell, & Hibbert (1993a) have calculated excitation rates for N III in an 11-state $R$-matrix method, which consists of the eight states above plus $2s^22p^2P$ and $2s^22p^2S$. These new atomic data are different from the earlier results of Blum & Pradhan. For example, at $T_e = 5000 \text{ K}$, the effective collision strengths ($\gamma$) of Stafford et al. and Blum & Pradhan for the $2s^22p^2P_{3/2}-2s2p^2P_{1/2}$ and $2s^22p^2P_{3/2} - 2s2p^2P_{3/2}$ transitions differ by 18% and 17%, respectively, while at $T_e = 10,000 \text{ K}$, the discrepancies are 25% and 21%. The differences between the results of Stafford et al. and those of Nussbaumer & Storey (1982), which are normally adopted in the derivation of theoretical N III line ratios (see, for example, Czyzak, Keyes, & Aller 1986), are even more striking. For example, at $T_e = 10,000 \text{ K}$, Stafford et al. find $\gamma(2s^22p^2P_{1/2}-2s2p^2P_{3/2}) = 0.16$, compared with $\gamma = 0.08$ from Nussbaumer & Storey. Stafford et al. estimate that their excitation rates should be accurate to $\pm 10\%$.

In this paper we use the Stafford et al. (1993a) atomic data to derive theoretical emission line ratios for N III applicable to gaseous nebulae, and compare these with observations obtained with the International Ultraviolet Explorer (IUE) satellite.

2. ATOMIC DATA

The model ion for N III consisted of the 11 energetically lowest LS states, namely $2s^22p^2P$, $2s2p^2D$, $2s2p^2S$, $2p^3S$, $2p^3D$, $2p^3F$, $2s^23s^2S$, $2s^23p^2P$, and $2s^23d^2D$, making a total of 20 fine-structure levels, the energies of which were obtained from Bhatia & Kastner (1991). However, we note that test calculations excluding terms higher than $2s2p^2P$ lead to a negligible change in the $2s2p^2P$ level populations at the electron temperatures and densities considered in this paper.

Electron impact excitation rates for transitions in N III were obtained from Stafford et al. (1993a) while for the radiative rates the calculations of Stafford, Hibbert, & Bell (1993b) were adopted, apart from the $2s^22p^2P_{1/2}-2s2p^2P_{3/2}$ transition, where the result of Nussbaumer & Storey (1979) was utilized. As noted by, for example, Seaton (1964), excitation by protons may be important for fine-structure transitions. However, Nussbaumer & Storey (1979) found proton rates for the $2s^22p^2P_{1/2}-2s2p^2P_{3/2}$ transition, and those among $2s2p^2P$, to be typically a factor of 100 smaller than the corresponding
electron rates at the temperatures considered here. Hence, these rates should have a negligible effect on the theoretical line intensities for \( \text{N} \text{ III} \) and have not been included.

3. THEORETICAL RATIOS

Using the atomic data discussed in § 2 in conjunction with the statistical equilibrium code of Dufour (1977), the theoretical emission line ratios

\[
R_1 = \frac{I(2s^2p^2 P_{1/2} - 2s2p^4 P_{1/2})}{I(2s^2p^2 P_{3/2} - 2s2p^4 P_{3/2})} = \frac{I(1754.0 \text{ Å})}{I(1749.7 \text{ Å})},
\]

\[
R_2 = \frac{I(2s^2p^2 P_{3/2} - 2s2p^4 P_{3/2})}{I(2s^2p^2 P_{3/2} - 2s2p^4 P_{3/2})} = \frac{I(1752.2 \text{ Å})}{I(1749.7 \text{ Å})},
\]

\[
R_3 = \frac{I(2s^2p^2 P_{1/2} - 2s2p^4 P_{1/2})}{I(2s^2p^2 P_{3/2} - 2s2p^4 P_{3/2})} = \frac{I(1748.6 \text{ Å})}{I(1749.7 \text{ Å})},
\]

and

\[
R_4 = \frac{I(2s^2p^2 P_{1/2} - 2s2p^4 P_{1/2})}{I(2s^2p^2 P_{3/2} - 2s2p^4 P_{3/2})} = \frac{I(1748.6 \text{ Å})}{I(1749.7 \text{ Å})},
\]

were calculated for a range of electron temperatures \( T_e = 5000 \text{ K} \) and densities \( N_e = 10^{10} \text{ cm}^{-3} \). Details of the procedures involved and approximations made may be found in Dufour (1977) and Dufour et al. (1978).

The theoretical values of \( R_1 \) and \( R_2 \) are shown in Figures 1 and 2, respectively, where it may be seen that the temperature dependence of the ratios is small but that they vary with electron density for \( N_e \leq 10^4 \text{ cm}^{-3} \) and also for \( \geq 10^7 \text{ cm}^{-3} \). For example, at \( N_e = 10^3 \text{ cm}^{-3} \), the ratios vary by <5% between \( T_e = 5000 \text{ K} \) and \( 20000 \text{ K} \), but they change by more than a factor of 2 between \( N_e = 10 \) and \( 10^5 \text{ cm}^{-3} \). Unfortunately, \( R_1 \) does not decrease monotonically with \( N_e \); it reaches a minimum in the density interval \( N_e \approx 10^5-10^6 \text{ cm}^{-3} \). However, \( R_3 \) does vary monotonically, and hence it may be used to distinguish the density region of the plasma in question before applying the \( R_1 \) diagnostic.

We note that the ratios \( R_3 \) and \( R_4 \) have the same density dependence due to common upper levels as \( R_1 \) and \( R_2 \), respectively, but with

\[
R_3 = 0.995 \times R_1,
\]

\[
R_4 = 0.103 \times R_2.
\]

The present calculations of \( R_1 \) and \( R_2 \) may be compared with those derived using the atomic data of Nussbaumer & Storey (1979, 1982), which are normally adopted in studies of the \( \text{N} \text{ III} \) intercombination lines in gaseous nebulae. These diagnostics, taken from the compilation of Czyzak et al. (1986), are also plotted in Figures 1 and 2 for \( T_e = 10000 \text{ K} \). An inspection of the figures reveals that the current values of \( R_1 \) and \( R_2 \) are significantly different from those of Czyzak et al. For example, at \( N_e = 10^5 \text{ cm}^{-3} \) the present results are \( \sim 24\% \) (41) and \( \sim 12\% \) (3) smaller than those of Czyzak et al., while at \( 10^{10} \text{ cm}^{-3} \) they are 11% larger (41) and 6% smaller (3).

4. OBSERVATIONAL DATA

We have measured values of \( R_1-R_4 \) in a sample of gaseous nebulae, including the planetary nebulae NGC 3242, NGC 6572, and IC 4997, and the symbiotic stars RR Tel and V1016 Cyg. For these objects, we have reduced high-resolution short-wavelength IUE spectra using the Goddard Regional Data Reduction Facility. The IUE images used in the analysis are listed in Table 1, along with the derived emission-line ratios. In Figures 3 and 4 we plot the spectra of IC 4997 and RR Tel, respectively, to illustrate the quality of the observational data.

<table>
<thead>
<tr>
<th>Object</th>
<th>SWP Image Number</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( R_3 )</th>
<th>( R_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3242</td>
<td>15289</td>
<td>0.32</td>
<td>0.64</td>
<td>0.23</td>
<td>0.08</td>
</tr>
<tr>
<td>NGC 6572</td>
<td>42059</td>
<td>0.19</td>
<td>0.58</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>IC 4997</td>
<td>41903</td>
<td>0.25</td>
<td>0.40</td>
<td>0.18</td>
<td>0.08</td>
</tr>
<tr>
<td>RR Tel</td>
<td>29535</td>
<td>0.23</td>
<td>0.56</td>
<td>0.29</td>
<td>0.10</td>
</tr>
<tr>
<td>V1016 Cyg</td>
<td>13432</td>
<td>0.23</td>
<td>0.38</td>
<td>0.29</td>
<td>0.06</td>
</tr>
</tbody>
</table>
For NGC 3242 and NGC 6572, additional low-resolution images were considered and are discussed in § 5.

5. RESULTS AND DISCUSSION

In Table 2 we summarize the electron densities derived from the observed values of $R_1 - R_4$ in conjunction with our calculations in Figures 1 and 2. Also listed in the table are the adopted electron temperatures from the references listed. We note that the results are relatively insensitive to this choice with, for example, a change of a factor of 2 in temperature leading to typically a ±0.1 dex variation in the estimated $N_e$.

An inspection of Table 1 reveals that the electron densities deduced from $R_1$, $R_2$, and $R_3$ are generally in quite good agreement, with values that differ by typically ±0.3 dex from their mean (the $R_1 + R_2 + R_3$ column in Table 2). However for IC 4997, RR Tel and V1016 Cyg, the densities estimated from $R_4$ are several orders of magnitude smaller than those inferred from $R_1$, $R_2$, and $R_3$, while for NGC 6572 the observed $R_4$ ratio is greater than the theoretical low-density limit. One possible explanation for this is that the N iii 1746.8 Å line is blended, as it is in solar observations, with Fe ii 1746.8 Å (Doschek et al. 1976). To investigate this further, we compare in Table 3 the measured and theoretical values of the ratio $R = (2s^2 2p^2 4p^3 / 2s^2 2p^2 4s^2) / I(1746.8 Å)/I(1752.2 Å)$. As $R$ contains transitions with a common upper level, it will be insensitive to the plasma parameters and depend only on the ratio of the relevant A-values.

Theoretical values for R of 0.15 and 0.10 are found from the results of Nussbaumer & Storey (1979) and Stafford et al. (1993b), respectively. An inspection of Table 3 reveals that the observed ratios are larger than both these predictions in several instances, implying significant blending in the 1746.8 Å transition. In addition, we note that the lowest observed $R$ ratio in Table 3 is that for NGC 3242 ($R = 0.12$), which is smaller than the theoretical limit based on the Nussbaumer & Storey A-value but is larger than that predicted by Stafford et al. This would seem to provide some observational support for the radiative rates of Stafford et al.

The average electron densities determined from $R_1$, $R_2$, and $R_3$ in Table 2 may be compared with those derived from diagnostic line ratios in other species. In the case of NGC 3242 and NGC 6572, the results of Table 2 are consistent with densities deduced previously for these planetaries using line ratios in species such as S ii, O ii, Cl iii, and Ar iv, which give log $N_e$ ≈ 3.3–3.6 and 3.7–4.1 for NGC 3242 and NGC 6572, respectively (Stanghellini & Kaler 1989). However, for IC 4997, RR Tel, and V1016 Cyg, the densities estimated from N iii are much larger than those from other diagnostics, as noted previously by Nussbaumer & Schild (1981), Hayes & Nussbaumer (1986), and Hyung, Aller, & Feibelman (1993). For example, Hayes & Nussbaumer find log $N_e$ = 6.2 from Si iii lines in RR Tel, while Hyung et al. estimate log $N_e$ = 6.2 from C iii transitions in IC 4997.

The consistently higher densities derived in the earlier works for IC 4997, RR Tel, and V1016 Cyg have led Feibelman, Aller, & Hyung (1992) and Hyung et al. to suggest that the N iii emission in these objects may be of chromospheric origin, while the other species are nebular, as chromospheric and nebular plasmas typically have electron densities of ~10^9–10^10 and <10^7 cm^-3, respectively (Hayes & Nussbaumer 1986). The low values of $N_e$ derived for NGC 3242 and NGC

### Table 2

<table>
<thead>
<tr>
<th>Object</th>
<th>$T_e$ (K)</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_4$</th>
<th>$R_1 + R_2 + R_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3242</td>
<td>11,400</td>
<td>2.6</td>
<td>3.5</td>
<td>3.1</td>
<td>3.0</td>
<td>3.1</td>
</tr>
<tr>
<td>NGC 6572</td>
<td>10,000</td>
<td>3.5</td>
<td>3.7</td>
<td>3.0</td>
<td>1.0</td>
<td>3.4</td>
</tr>
<tr>
<td>IC 4997</td>
<td>12,500</td>
<td>8.8</td>
<td>8.2</td>
<td>9.3</td>
<td>2.4</td>
<td>8.8</td>
</tr>
<tr>
<td>RR Tel</td>
<td>13,000</td>
<td>8.8</td>
<td>8.2</td>
<td>9.3</td>
<td>2.4</td>
<td>8.8</td>
</tr>
<tr>
<td>V1016 Cyg</td>
<td>20,000</td>
<td>9.0</td>
<td>8.9</td>
<td>9.4</td>
<td>7.3</td>
<td>9.1</td>
</tr>
</tbody>
</table>

* Kaler 1986.
* Indicates that the observed line ratio is greater than the theoretical low-density limit.
* Schmid & Schild 1990.

### Table 3

<table>
<thead>
<tr>
<th>Observed (O) and Predicted (P) N iii Emission-Line Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R = I(1746.8 Å) / I(1752.2 Å)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3242</td>
<td>0.12 (O)</td>
</tr>
<tr>
<td>NGC 6572</td>
<td>0.31 (O)</td>
</tr>
<tr>
<td>IC 4997</td>
<td>0.20 (O)</td>
</tr>
<tr>
<td>RR Tel</td>
<td>0.18 (O)</td>
</tr>
<tr>
<td>V1016 Cyg</td>
<td>0.16 (O)</td>
</tr>
<tr>
<td>Nussbaumer &amp; Storey 1979</td>
<td>0.15 (P)</td>
</tr>
<tr>
<td>Stafford, Hibbert, &amp; Bell 1993b</td>
<td>0.10 (P)</td>
</tr>
</tbody>
</table>
6572 would, however, imply that the N\textsc{iii} emission is probably nebular in these cases. To further investigate this, we have examined in greater detail a number of low-dispersion spectra of NGC 3242, all taken through the large (10° × 23°) entrance aperture of the IUE cameras, and for different position angles. Some exposures were centered on the nucleus, while others were intentionally placed off-center but still showed the stellar continuum. The exposures ranged in time from 3 to 60 minutes duration. On many spectra, the strong emission lines of He\textsc{i} 1640 Å, C\textsc{iv} 1550 Å, and C\textsc{iii} 1909 Å are heavily saturated, but N\textsc{iii} 1750 Å was never overexposed. The position angles of the large aperture covered the following values: 12°, 73°, 77°, 103°, and 176°. For all spectra which were examined, the N\textsc{iii} flux was always largest when the aperture was centered on the nucleus. From a careful examination of about 10 spectra, as well as line-by-line analyses and inspection of the photowrite images, we conclude that the N\textsc{iii} emission in NGC 3242 is definitely of nebular origin, as the N\textsc{iii} 1750 Å feature extends for several channels beyond the central echelle orders of the stellar continuum. Furthermore, the photowrite image of a long exposure shows the N\textsc{iii} emission as an oval which extends for a few arcseconds on either side of the stellar continuum. A very similar geometry was found for the O\textsc{iii} 1661 and 1665 Å emission, while the strong nebular C\textsc{iii} 1909 Å extends over the entire area of the large aperture.

NGC 6572, being approximately only half the size of NGC 3242 and having fewer spectra available for study, is more difficult to assess but shows a similar pattern for the N\textsc{iii} 1750 Å emission on the photowrite images and from line-by-line analysis. Thus, we conclude that for both of the evolved planetary nebulae NGC 3242 and NGC 6572, the N\textsc{iii} emission is of nebular origin.

To further investigate the possibility that the N\textsc{iii} emission in the other objects is of chromospheric origin, we have compared the N\textsc{iii} electron densities with those determined from the C\textsc{ii} intercombination multiplet at ~2325 Å, which is believed to arise in the chromosphere (Judge 1990). We have measured intensities for components of this multiplet in long-wavelength IUE spectra of NGC 6572, IC 4997, and RR Tel, using methods discussed in § 4, and in Table 4 we summarize the line ratios

\[
\begin{align*}
R_1 &= I(2s^22p^2P_{3/2}-2s2p^24P_{1/2})/I(2s^22p^2P_{3/2}-2s2p^24P_{3/2}) \\
&= I(2328.1 \text{ Å})/I(2325.4 \text{ Å}) \\
R_2 &= I(2s^22p^2P_{3/2}-2s2p^24P_{1/2})/I(2s^22p^2P_{3/2}-2s2p^24P_{3/2}) \\
&= I(2328.1 \text{ Å})/I(2326.9 \text{ Å}) \\
R_3 &= I(2s^22p^2P_{3/2}-2s2p^24P_{1/2})/I(2s^22p^2P_{3/2}-2s2p^24P_{3/2}) \\
&= I(2324.7 \text{ Å})/I(2326.9 \text{ Å})
\end{align*}
\]

along with the IUE images used in the analysis. Unfortunately, the existing observational data for NGC 3242 and V1016 Cyg were of relatively low quality. In addition, we note that the weak 2s2p2P_{3/2}-2s2p^24P_{3/2} line at 2323.5 Å is contaminated by a reseau mark in all our spectra, so its intensity could not be accurately determined. The long-wavelength spectrum of RR Tel is plotted in Figure 5 to illustrate the quality of the observational data.

In Table 5, we summarize the electron densities determined from the observed values of \( R_1, R_2, \) and \( R_3 \) in Table 4 in conjunction with the theoretical C\textsc{ii} ratios of Lennon et al. (1985) for \( T_e = 10,000 \text{ K} \) (again the results are relatively insensitive to this choice). An inspection of the table reveals that the electron densities deduced from the different line ratios are generally in good agreement, with discrepancies of typically ~0.2 dex from the mean. The only exception to this is the \( R_1 \) ratio in IC 4997, which is greater than the theoretical low-density limit. As the \( R_2 \) and \( R_3 \) ratios in this object give consistent densities, the problem with \( R_1 \) most probably lies with the 2325.4 Å line intensity (which is a factor of ~2 too weak). Further observations of the C\textsc{ii} intercombination transitions in IC 4997 using either IUE or HST would be highly desirable in order to investigate this problem.

The mean C\textsc{ii} densities in Table 5 are in relatively good agreement with the average N\textsc{iii} estimates listed in Table 2 for IC 4997 and RR Tel, with discrepancies of only 0.6 and 0.1 dex, respectively. However, for NGC 6572 the difference in the N\textsc{iii} and C\textsc{ii} mean densities is several orders of magnitude. These results would appear to confirm that the N\textsc{iii} emission is nebular in NGC 6572, but for IC 4997 and RR Tel is chromospheric in origin. Direct determinations of the electron temperatures of the N\textsc{iii}-emitting regions in the nebulae, and a comparison with those deduced from C\textsc{ii}, would be a useful

\begin{table}[h]
\centering
\caption{Derived C\textsc{ii} Logarithmic Electron Densities}
\begin{tabular}{lllll}
\hline
Object & \( R_1 \) & \( R_2 \) & \( R_3 \) & Mean Value \\
\hline
NGC 6572 & 7.5 & 7.3 & 7.0 & 7.3 \\
IC 4997 & 1* & 8.1 & 8.2 & 8.2 \\
RR Tel & 9.2 & 8.6 & 8.4 & 8.7 \\
\hline
\end{tabular}
\footnote{* Indicates that the observed line ratio is greater than the theoretical low-density limit.}
\end{table}
test of this hypothesis. Such temperature determinations could be made from the flux ratios of the C II and N III 2s22p22P1/2 - 2s32p33P3/2 infrared lines (at 158 and 57 μm, respectively), relative to those of the 2s22p22P - 2s2p63P ultra-violet transitions (Hayes & Nussbaumer 1984). We intend to perform this work in a subsequent paper.

6. CONCLUSIONS

There are three main conclusions:

1. Theoretical N III electron density sensitive emission-line ratios, derived using recent calculations of electron impact excitation rates and oscillator strengths, are presented for \( R_1 = I(1754.0 \text{ Å})/I(1749.7 \text{ Å}) \), \( R_2 = I(1752.2 \text{ Å})/I(1749.7 \text{ Å}) \), \( R_3 = I(1748.6 \text{ Å})/I(1749.7 \text{ Å}) \), and \( R_4 = I(1746.8 \text{ Å})/I(1749.7 \text{ Å}) \). These differ from the theoretical diagnostics of Czyzak et al. (1986), which are based on the atomic data of Nussbaumer & Storey (1979, 1982).

2. The observed values of \( R_1 \), \( R_2 \), and \( R_3 \) for several gaseous nebulae, measured from short-wavelength IUE spectra, imply electron densities which are compatible, with discrepancies of typically ≤0.3 from the mean density. However, the estimates deduced from \( R_4 \) are up to several orders of magnitude lower than those inferred from \( R_1 \), \( R_2 \), and \( R_3 \), which is probably due to blending of the N III 1746.8 Å line with Fe II 1746.8 Å.

3. Electron densities determined from the N III diagnostics are, in some objects, much larger than those derived from line ratios in other species, such as O III. However for these nebulae the N III densities are in good agreement with those estimated from the chromospheric C II intercombination transitions at \( \sim 2325 \text{ Å} \), which suggests that the N III emission may also be chromospheric in origin.

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