THE RATIO OF OPTICAL-TO-INFRARED EMISSION LINE STRENGTHS IN Ar III AS 
ELECTRON DENSITY DIAGNOSTICS FOR PLANETARY NEBULAE

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ABSTRACT

Electron impact excitation rates for transitions in Ar iii, calculated with the R-matrix code, are used to derive the electron density sensitive emission line ratio \( R_i = \frac{I(3s^2 3p^4 \ 3P_2 - 3s^2 3p^4 \ 1D)}{I(3s^2 3p^4 \ 3P_2 - 3s^2 3p^4 \ 3P_1)} \) for a range of electron temperatures \( T_e = 5000-30,000 \) K and densities \( N_e = 10^2-10^6 \) cm\(^{-3}\) applicable to planetary nebulae. Electron densities deduced from the observed values of \( R_i \) in several planar elliptical, measured using ground-based instrumentation, are in good agreement with those derived from \( N_e \)-sensitive line ratios in other species, which provides observational support for the accuracy of the atomic data adopted in the calculations. The potential usefulness of the Ar iii emission line ratio \( R_2 = \frac{I(3s^2 3p^4 \ 3P_1 - 3s^3 3p^4 \ 3P_0)}{I(3s^2 3p^4 \ 3P_2 - 3s^2 3p^4 \ 3P_1)} \) as an \( N_e \)-diagnostic is briefly discussed.

Subject headings: atomic processes — infrared: interstellar: lines — planetary nebulae: general

1. INTRODUCTION

Emission lines arising from transitions among the \( 3s^2 3p^4 \ 3P_1, 1D, \) and \( 1S \) levels of Ar iii are frequently observed in the visible and infrared spectra of planetary nebulae (Aller & Keyes 1987; Aitken & Roche 1982; Roche & Aitken 1986). The \( 3P_2 - 1D \) and \( 1D - 1S \) transitions at 7135, 7751, and 5192 Å, respectively, are extremely useful as electron temperature diagnostics through the \( R = \frac{I(7135 + 7751)}{I(5192) \text{ Å}} \) intensity ratio, although to calculate \( R \) reliably, accurate atomic data must be employed, especially for electron impact excitation rates (see, for example, Czyzak, Keyes, & Aller 1986).

Recently, Johnston & Kingston (1990) have calculated electron impact excitation rates for transitions in Ar iii using the R-matrix code of Burke & Robb (1975). These are significantly different from the earlier results of Krueger & Czyzak (1970), especially at low temperatures, due principally to the presence of resonance structure at low impact energies in the \( R \)-matrix collision strengths. For example, at \( T_e = 5000 \text{ K} \), the data of Johnston and Kingston for the \( 3P_2 - 3P_1 \) and \( 3P_2 - 1D \) transitions are approximately 60% and 15% larger, respectively, than those of Krueger and Czyzak, while at \( T_e = 20,000 \text{ K} \), the discrepancies are 50% and 7%.

In this paper we use the Johnston & Kingston (1990) results to derive theoretical line ratios for Ar iii, and compare these with optical and infrared observations of planetary nebulae. This allows us to investigate the accuracy of the atomic data, as well as the potential usefulness of optical/infrared line ratios in Ar iii as electron density diagnostics.

2. LEVEL POPULATIONS

The model ion for Ar iii consisted of the three energetically lowest LS states, namely \( 3s^2 3p^4 \ 3P_1, 1D, \) and \( 1S \), making a total of five levels when the fine structure splitting was included. Energies of all the ionic levels were obtained from Mendoza (1983). Test calculations including higher terms, such as \( 3s3p^6 \ 3P_1, \) and \( 3P \), found to have a negligible effect on the \( 3s^2 3p^4 \) populations at the electron densities typical of planetary nebulae, and hence these states were not included in the analysis.

Electron impact excitation rates for transitions in Ar iii were taken from Johnson & Kingston (1990), while for Einstein A-coefficients the calculations of Mendoza & Zeippen (1983) were adopted, as they are more elaborate than those of Biemont & Hansen (1986). As discussed by, for example, Seaton (1964), excitation by protons may be important for transitions with small excitation energies, i.e., fine-structure transitions such as \( 2P_1 - 2P_2 - 2P_1 \) in the \( 2s^2 2p^2 \) ground term of fluorine-like ions (Keenan & Reid 1989). However, test calculations with Ar iii setting the proton rates for \( 3P_2 - 3P_1, 3P_2 - 3P_0, \) and \( 3P_1 - 3P_0 \) equal to the equivalent electron excitation rates or 10 times these values had a negligible effect on the level populations, showing that this atomic process is unimportant, at least under conditions prevalent in planetary nebulae.

Using the above atomic data in conjunction with the statistical equilibrium code of Dufton (1977), relative Ar iii level populations were derived for a range of electron temperatures \( 5000 \text{ K} \leq T_e \leq 30,000 \text{ K} \) and densities \( 10^2 \text{ cm}^{-3} \leq N_e \leq 10^6 \text{ cm}^{-3} \) applicable to planetary nebulae (Kaler 1986; Stanghellini & Kaler 1989), and these are summarized in Table 1. The following assumptions were made in the calculations; (i) that ionization to and recombination from other ionic levels is slow compared with bound-bound processes, (ii) that photoexcitation and de-excitation rates are negligible in comparison with the corresponding collisional rates, (iii) that all transitions are optically thin. Further details of the procedures involved may be found in Dufton (1977) and Dufton et al. (1978).

3. RESULTS AND DISCUSSION

Relative level populations may be used to derive emission line ratios \( R \) through the well-known expression

\[
R = \frac{I(\lambda_{ij})}{I(\lambda_{kl})} = \frac{N_j A_{ij}}{N_k A_{kl}} \times \frac{\lambda_{kl}}{\lambda_{ij}} \tag{1}
\]

where \( \lambda_{ij} \) and \( \lambda_{kl} \) are the wavelengths and intensities (in units of energy) of the lines, respectively, \( N_j \) and \( N_k \) are the upper level populations of the relevant transition and \( A_{ij} \) and \( A_{kl} \) are the Einstein A-coefficients. In Figure 1 we use the data in Table 1 and the A-values of Mendoza & Zeippen (1983) to plot the theoretical emission line ratio \( R_i = \frac{I(3s^2 3p^4 \ 3P_2 - 3s^2 3p^4 \ 1D)}{I(3s^2 3p^4 \ 3P_2 - 3s^2 3p^4 \ 3P_1)} = I(7135 \text{ Å})/I(9 \text{ μm}) \).
as a function of electron density at temperatures of $T_e = 5000$, 8000, 10,000, 15,000, 20,000, and 30,000 K. An inspection of the figure reveals that $R_1$ is sensitive to variations in $N_e$, and hence in principle should be useful as an electron density diagnostic. For example, at $T_e = 5000$ K, $R_1$ varies by a factor of $\approx 8.3$ between $N_e = 10^3$ and $10^6$ cm$^{-3}$, while at $T_e = 20,000$ K the variation is a factor of $\approx 5.5$ over the same density interval. In addition, we note that $R_1$ is density sensitive for values of $N_e \geq 10^4$ cm$^{-3}$, where many of the optical diagnostics, such as $I_6(6717 \AA)/I_6(6730 \AA)$ in $S_1$, no longer vary with $N_e$ (see, for example, Rubin 1989).

Also shown in Figure 1 are the $R_1$ ratios at $T_e = 10,000$ K calculated using the electron impact excitation rates of Krueger & Czyzak (1970), which are normally adopted in the analysis of Ar III lines in planetary nebulae. An inspection of the figure reveals that the present line ratios are up to 30%
different from those derived using the Krueger and Czyzak atomic data.

The $3s^23p^6\ 3P_2-3s^23p^4\ 3P_1$ transition in Ar III at 9 µm lies in the 8–13 µm atmospheric window, so that it is possible to determine the intensities of both this and the $3s^23p^6\ 3P_2-3s^23p^4\ 1D$ line at 7135 Å using ground-based instrumentation, and hence estimate values of $R_1$. Beck et al. (1981) have measured the $R_1$ ratio in several planetary nebulae using a Fabry-Perot interferometer on the Shane Telescope at the Lick Observatory, and the duPont Telescope at the Las Campanas Observatory. These measurements are summarized in Table 2, along with the electron temperatures in these planetary determinations from line ratios in species that have similar ionization potentials and hence spatial distributions to Ar III, such as $I(4959 + 5007 \, \text{Å})/I(4363 \, \text{Å})$ in O III. Also listed in the table are the values of $N_e$ deduced from $R_1$ [log $N_e(R_1)$] using both the current line ratio calculations in Figure 1 and those es-

<table>
<thead>
<tr>
<th>PLANETARY NEBULA</th>
<th>log $R_1$</th>
<th>$T_e$(K)</th>
<th>Present Calculations</th>
<th>Krueger &amp; Czyzak (1970)</th>
<th>log $N_e$ (other)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 6210</td>
<td>0.08</td>
<td>9700*</td>
<td>4.1</td>
<td>L*</td>
<td>3.6*</td>
</tr>
<tr>
<td>NGC 6572</td>
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<td>10000*</td>
<td>4.7</td>
<td>4.0</td>
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<td>NGC 6741</td>
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<td>11700*</td>
<td>4.2</td>
<td>L</td>
<td>3.9*</td>
</tr>
<tr>
<td>IC 418</td>
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<td>13300*</td>
<td>4.6</td>
<td>4.2</td>
<td>3.9*</td>
</tr>
<tr>
<td>IC 4997</td>
<td>0.91</td>
<td>14500*</td>
<td>5.8</td>
<td>5.6</td>
<td>5.8*</td>
</tr>
<tr>
<td>IC 5117</td>
<td>0.15</td>
<td>11600*</td>
<td>4.3</td>
<td>L</td>
<td>4.8*</td>
</tr>
</tbody>
</table>

* Kaler 1986.
* Indicates that the observed line ratio is smaller than the theoretical low-density limit.
* Stanghellini & Kaler 1989.
mated with the excitation rates of Krueger & Czyzak (1970). In addition, we list the mean densities \[ \log N_e (\text{other}) \] derived from line ratios in species which should be spatially coincident with Ar \text{III}, including \( I(5517 \text{ Å})/I(5537 \text{ Å}) \) in Cl \text{III} (Stanghellini & Kaler 1989) and \( I(1661 + 1667 \text{ Å})/(4959 + 5007 \text{ Å}) \) in O \text{III} (Keenan & Aggarwal 1987).

An inspection of Table 2 shows that the electron densities determined from the present \( R_i \) calculations are in good agreement with those deduced from other line ratios, with discrepancies of typically less than 0.4 dex. In contrast, the observed values of \( R_i \) for NGC 6210, NGC 6741, and IC 5117 all lie below the theoretical low-density limit of those line ratios calculated with the excitation rates of Krueger & Czyzak (1970). These results provide observational support for both the accuracy of the atomic data adopted in the present Ar \text{III} line ratio calculations, and the techniques used to derive the theoretical values of \( R_i \).

We note that the Ar \text{III} emission line ratio \( R_2 = I(3s^23p^4 \text{ } 3p_1)/I(3s^23p^4 \text{ } 3p_0)/I(3s^23p^4 \text{ } 3p_1)/I(21.8 \text{ μm})/I(9 \text{ μm}) \) is potentially a better \( N_e \)-diagnostic than \( R_i \), as it is sensitive to variations in electron density but not temperature. This is illustrated in Figure 2, where we plot our calculations of \( R_2 \) as a function of electron density at \( T_e = 10,000 \) and 15,000 K. An inspection of the figure reveals that \( R_2 \) varies by a factor of 2.9 between \( N_e = 10^3 \) and \( 10^6 \text{ cm}^{-3} \). More importantly however, there is a negligible dependence on \( T_e \) (unlike \( R_i \)), a change of 5000 K in temperature leading to only a 3% variation in \( R_2 \) at \( N_e = 10^3 \text{ cm}^{-3} \), which decreases to less than 1% at \( N_e = 10^6 \text{ cm}^{-3} \). Also shown in Figure 2 are the calculations of Rubin (1989) for \( T_e = 10,000 \text{ K} \), which employ the electron excitation rates of Krueger & Czyzak (1970). These results are approximately 10% larger than the present diagnostics at low density, although for \( N_e \geq 10^5 \text{ cm}^{-3} \) they differ by \( \leq 4\% \).

Pottasch et al. (1986) have searched for the 21.8 μm line of Ar \text{III} in the low-resolution spectra of planetary nebulae obtained with the Infrared Astronomical Satellite (IRAS) unfortunately without success. However, a further search for this line perhaps using data obtained with the upcoming Infrared Space Observatory (ISO), would be highly desirable. If the 21.8 μm line is detected, the \( R_2 \) ratio would provide an electron density which would be virtually independent of the adopted electron temperature.

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