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Al II EMISSION-LINE STRENGTHS IN LOW-DENSITY ASTROPHYSICAL PLASMAS

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ABSTRACT

Theoretical Al II emission line ratios, determined using electron impact excitation rates calculated with the **R**-matrix code, are presented for $R = I(3s^2\,{}^1S–3s3p\,{}^3P_2)/I(3s^2\,{}^1S–3s3p\,{}^3P_1) = I(2660\ \text{Å})/I(2669\ \text{Å})$. This ratio is a useful electron density diagnostic for $N_e \geq 10^2$ cm^{-3}, its use being illustrated for the planetary nebula NGC 7027 and the symbiotic star RR Tel.

Subject headings: atomic processes — planetary nebulae: individual (NGC 7027) — stars: individual (RR Telescopii)

1. INTRODUCTION

In a previous paper, Dufton, Keenan, & Kingston (1984) used accurate electron impact excitation rates for transitions in Si III, calculated with the **R**-matrix code of Berrington et al. (1978), to derive the theoretical emission-line ratio $R = I(3s^2\,{}^1S–3s3p\,{}^3P_2)/I(3s^2\,{}^1S–3s3p\,{}^3P_1) = I(1883\ \text{Å})/I(1892\ \text{Å})$. The ratio was found to be relatively insensitive to variations in the electron temperature but to vary strongly with density for $N_e \geq 10^4$ cm^{-3}, so that it should be useful as an N_e diagnostic. This usefulness was illustrated by Dufton et al., who compared their theoretical results with *IUE* observations of the planetary nebula NGC 7662 and the symbiotic star V1016 Cygni.

In this paper we extend the above work by deriving theoretical emission-line ratios involving the analogous transitions in Al II, namely $3s^2\,{}^1S–3s3p\,{}^3P_2$ and $3s^2\,{}^1S–3s3p\,{}^3P_1$ at 2660 and 2669 Å, respectively. These ratios are subsequently compared with *IUE* observations of the planetary nebula NGC 7027 and the symbiotic star RR Tel, to investigate similarly their usefulness as electron density diagnostics.

2. ATOMIC DATA

The model ion for Al II consisted of the 12 energetically lowest *LS* terms, namely $3s^2\,{}^1S$; $3s3p\,{}^3P$, ${}^1P$; $3p^2\,{}^1D$; $3s4s\,{}^3S$; $3p^2\,{}^3P$; $3s4s\,{}^1S$; $3s3d\,{}^3D$; $3s4p\,{}^3P$, ${}^1P$; $3s3d\,{}^1D$ and $3p^2\,{}^1S$, making a total of 20 fine-structure levels, the energies of which were obtained from Martin & Zalubas (1979). However we note that test calculations excluding terms higher than $3s3p\,{}^3P$ lead to a negligible change in the $3s3p\,{}^3P$ level populations at the electron densities considered in this paper.

Electron impact excitation rates for forbidden and intercombination transitions in Al II have been calculated by Tayal, Burke, & Kingston (1984, 1985) using the **R**-matrix code of Berrington et al. (1978). These results accurately include the important effects of resonances in the scattering process (see, for example, Fig. 1 in Tayal et al. 1984 for the $3s^2\,{}^1S–3s3p\,{}^3P_1$ intercombination line), and they have therefore been adopted in the present analysis. Unfortunately, Tayal et al. did not publish rates for transitions among $3s3p\,{}^3P$, and we hence summarize their results for these in Table 1.

The transition probability of the $3s^2\,{}^1S–3s3p\,{}^3P_1$ intercombination line was obtained from Johnson, Smith, & Parkinson (1986), who found $A(3s^2\,{}^1S–3s3p\,{}^3P_1) = (3.33 \pm 0.23) \times 10^3$ s^{-1} from time-dependent observations of metastable ions stored in an ion trap. For all other transitions, the calculations of Tayal & Hibbert (1984) and Hibbert & Keenan (1987) based on configuration interaction wavefunctions were adopted.

As noted by, for example, Seaton (1964), excitation by protons may be important for fine-structure transitions. However, Nicolas (1977) found proton rates for transitions among $3s3p\,{}^3P$ in Si III 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 Al II.

3. THEORETICAL RATIOS

Using the atomic data discussed in § 2 in conjunction with the statistical equilibrium code of Dufton (1977), the theoretical emission line ratio $R = I(3s^2\,{}^1S–3s3p\,{}^3P_2)/I(3s^2\,{}^1S–3s3p\,{}^3P_1)$ was calculated for a range of electron temperatures (T_e = 5000–20,000 K) and densities ($N_e \geq 10$ cm^{-3}). Details of the procedures involved and approximations made may be found in Dufton (1977) and Dufton et al. (1978).

The theoretical values of R are shown in Figure 1, where it can be seen that the temperature dependence of the ratio is small, and that it varies strongly with density for $N_e \geq 10^2$ cm^{-3}. For example, at $N_e = 10^3$ cm^{-3}, the ratio only varies by 8% between T_e = 5000 and 20,0000 K, while it changes by a factor of nearly 100 between $N_e = 10^2$ and 10^6 cm^{-3} at T_e = 10,000 K. In Figure 1 the density range is restricted to $N_e \leq 10^6$ cm^{-3}, as for larger values R will be less than 0.01 and hence difficult (if not impossible) to determine from *IUE* spectra. However, if required, values of the ratio for $N_e \geq 10^6$ cm^{-3} are available from one of the authors (F. P. K.) on request.

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TABLE 1

EFFECTIVE COLLISION STRENGTHS FOR TRANSITIONS IN Al II

	Electron Temperature (K)			
Transition	5000	10000	15000	20000
$3s3p\,^3P_0$–$3s3p\,^3P_1$	1.62	1.67	1.69	1.71
$3s3p\,^3P_0$–$3s3p\,^3P_2$	1.97	2.00	2.09	2.19
$3s3p\,^3P_1$–$3s3p\,^3P_2$	6.41	6.54	6.79	7.02

The present calculations of R may be compared with those of Johnson et al. (1986), which are also plotted in Figure 1. These authors adopted similar atomic data to ours, apart from electron excitation rates among $3s3p\,^3P$, where they used data for transitions among $2s2p\,^3P$ in C III calculated by Dufton et al. (1978), as no rates for Al II were available. An inspection of Figure 1 reveals that our values of R are approximately a factor of 3 smaller than those of Johnson et al. and (more importantly) become density sensitive for $N_e \geq 10^2$ cm^{-3} as opposed to the $N_e \geq 10^5$ cm^{-3} estimated by these authors. These discrepancies are principally due to the adoption of accurate electron rates for transitions among $3s3p\,^3P$ in the present calculations.

4. RESULTS AND DISCUSSION

We illustrate the use of the R ratio through *IUE* observations of the planetary nebula NGC 7027 and the symbiotic star RR Tel. For these objects, we have reduced high-resolution long-wavelength spectra, namely LWR 2571 (NGC 7027) and LWR 16187 (RR Tel), using the Goddard Regional Data Reduction Facility. The spectra of NGC 7027 and RR Tel are plotted in Figures 2 and 3, respectively, to show the quality of the observational data.

A value of $R = 0.72$ was deduced for NGC 7027, which from our calculations in Figure 1 implies log $N_e = 4.2$ for $T_e = 14{,}000$ K (Keyes, Aller, & Feibelman 1990). This is consistent with densities deduced previously for this planetary nebula [log N_e(S II, N II) = 4.5; Keyes et al. 1990]. For RR Tel, we find $R = 0.034$. Adopting $T_e = 13{,}000$ K (Hayes & Nussbaumer 1986) then implies log $N_e = 5.8$, in reasonable agreement with the value of log $N_e = 6.2$ deduced from the Si III I(1883 Å)/I(1892 Å) ratio by Hayes & Nussbaumer (1986).

The examples discussed above indicate that the Al II ratio should be a reliable density diagnostic. For *IUE* observations, it will be useful for plasmas with 10^2 cm^{-3} $\leq N_e \leq 10^6$ cm^{-3}, but for instruments with a larger dynamic range, it could be applied to observations of higher density plasmas.

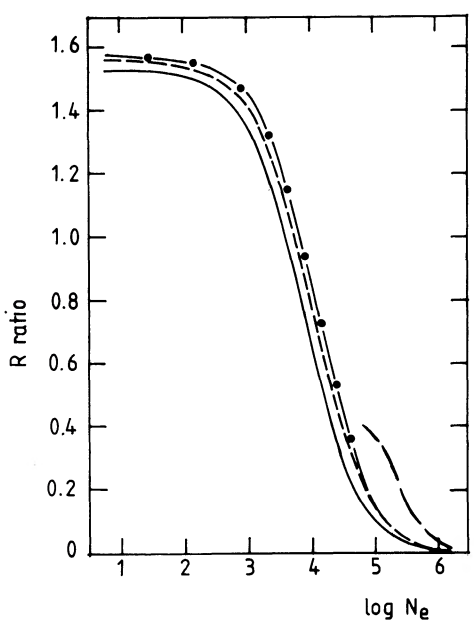

FIG. 1.—The theoretical Al II emission line ratio $R = I(3s^2\,^1S$–$3s3p\,^3P_2)/I(3s^2\,^1S$–$3s3p\,^3P_1) = I(2660$ Å$)/I(2669$ Å$)$, plotted as a function of logarithmic electron density (N_e in cm^{-3}) at electron temperatures of $T_e = 5000$ K (*solid line*), $T_e = 10{,}000$ K (*short dashed line*) and $T_e = 15{,}000$ K (*dash-dot line*). The results for $T_e \geq 15{,}000$ K are similar to those for $T_e = 15{,}000$ K. Also shown in the figure are the calculations of Johnson, Smith, & Parkinson (1986) (*long dashed line*).

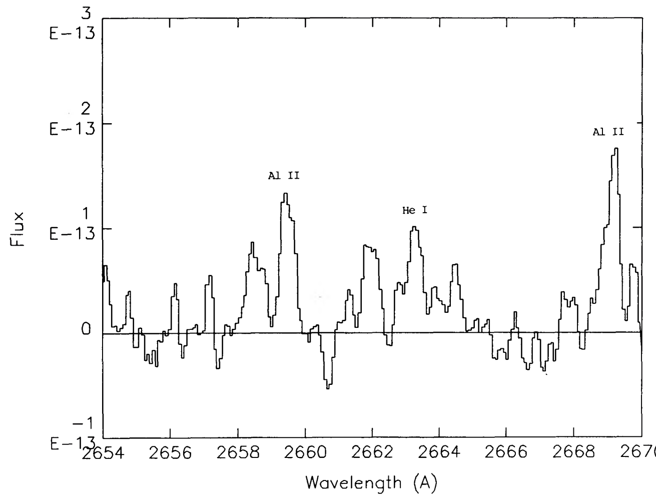

FIG. 2.—High-resolution 300 minute *IUE* spectrum (LWR 2571) of the planetary nebula NGC 7027 in the wavelength region 2654–2670 Å, where the flux is in units of ergs cm^{-2} s^{-1}. The Al II $3s^2\,^1S$–$3s3p\,^3P_2$ and $3s^2\,^1S$–$3s3p\,^3P_1$ transitions at 2660 and 2669 Å, respectively, are clearly labeled in the figure.

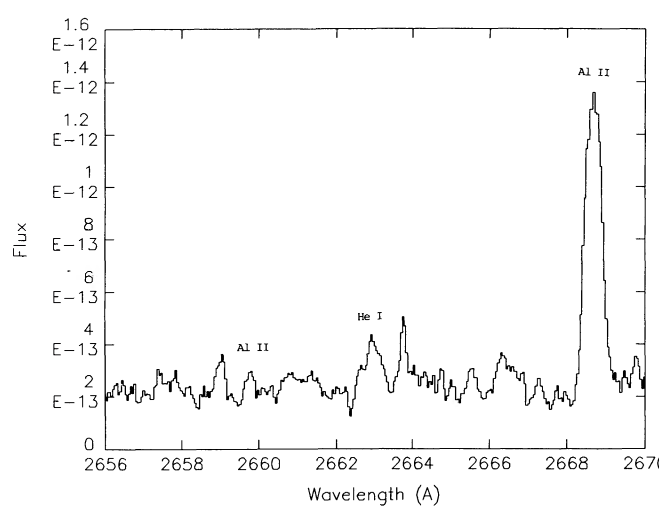

FIG. 3.—High-resolution 524 minute *IUE* spectrum (LWR 16187) of the symbiotic star RR Tel in the wavelength region 2656–2670 Å, where the flux is in units of ergs cm^{-2} s^{-1}. The Al II $3s^2\,^1S$–$3s3p\,^3P_2$ and $3s^2\,^1S$–$3s3p\,^3P_1$ transitions at 2660 and 2669 Å, respectively, are clearly labeled in the figure.

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REFERENCES

Berrington, K. A., Burke, P. G., Le Dourneuf, M., Robb, W. D., Taylor, K. T., & Lan, V. K. 1978, Comput. Phys. Comm., 14, 367
Dufton, P. L. 1977, Comput. Phys. Comm., 13, 25
Dufton, P. L., Berrington, K. A., Burke, P. G., & Kingston, A. E. 1978, A&A, 62, 111
Dufton, P. L., Keenan, F. P., & Kingston, A. E. 1984, MNRAS, 209, 1P
Hayes, M. A., & Nussbaumer, H. 1986, A&A, 161, 287
Hibbert, A., & Keenan, F. P. 1987, J. Phys. B, 20, 4693
Johnson, B. C., Smith, P. L., & Parkinson, W. H. 1986, ApJ, 308, 1013
Keyes, C. D., Aller, L. H., & Feibelman, W. A. 1990, PASP, 102, 59
Martin, W. R., & Zalubas, R. 1979, J. Phys. Chem. Ref. Data, 8, 817
Nicolas, K. R. 1977, Ph.D. thesis, Univ. Maryland
Seaton, M. J. 1964, MNRAS, 127, 191
Tayal, S. S., Burke, P. G., & Kingston, A. E. 1984, J. Phys. B, 17, 3847
———. 1985, J. Phys. B, 18, 4321
Tayal, S. S., & Hibbert, A. 1984, J. Phys. B, 17, 3835