Mon. Not. R. Astron. Soc. **309**, 195–198 (1999)

[Al II] in the ultraviolet spectrum of the symbiotic star RR Telescopii

F. P. Keenan,[1] B. R. Espey,[2] M. Mathioudakis,[1] K. M. Aggarwal,[1★] F. L. Crawford,[1] W. A. Feibelman[3] and F. C. McKenna[1]

[1] *Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast BT7 1NN*
[2] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[3] *Laboratory for Astronomy and Solar Physics, Code 681, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*

Accepted 1999 May 19. Received 1999 April 9

ABSTRACT

An inspection of a GHRS/*HST* spectrum of the symbiotic star RR Telescopii reveals the presence of the [Al II] $3s^2\ ^1S - 3s3p\ ^3P_2$ line at a vacuum wavelength of 2661.06 ± 0.08 Å, 8.89 ± 0.08 Å away from the Al II] $3s^2\ ^1S - 3s3p\ ^3P_1$ intercombination transition at 2669.95 Å, in good agreement with the theoretical prediction of $\Delta\lambda = 8.80$ Å. We also find that the Al II] line profile is asymmetric, showing a strong low-density component with a weak high-density wing, redshifted by $30\,\mathrm{km\,s^{-1}}$, in agreement with the findings of Schild & Schmid, which were based on optical observations. Our measurement of the emission-line ratio $R = I(2661.06\,\text{Å})/I(2669.95\,\text{Å}) = 0.027 \pm 0.003$ implies $\log N_e = 5.8 \pm 0.2$, in good agreement with the densities found from other ions, such as Si III. These results provide strong evidence that we have detected the [Al II] line, the first time (to our knowledge) that this feature has been reliably identified in an astrophysical or laboratory spectrum.

Key words: atomic data – binaries: symbiotic – stars: individual: RR Tel – ultraviolet: stars.

1 INTRODUCTION

The forbidden ($J = 2$) and intercombination ($J = 1$) components of the $2s^2\ ^1S - 2s2p\ ^3P_J$ and $3s^2\ ^1S - 3s3p\ ^3P_J$ multiplets in Be-like C III and N IV, and Mg-like Si III, respectively, provide well-known electron density diagnostics for gaseous nebulae, including symbiotic stars and planetary nebulae (see, for example, Keenan, Feibelman & Berrington 1992a; Keenan et al. 1995). Johnson, Smith & Parkinson (1986) calculated the first forbidden to intercombination line ratio for Mg-like Al II, but subsequently Keenan et al. (1992b) showed that these calculations were seriously in error, principally as a result of the adoption of inaccurate electron excitation rates for transitions among the 3s3p ^3P levels. Unfortunately however, Keenan et al. (1992b) were only able to marginally identify the [Al II] forbidden line in the IUE spectra of two gaseous nebulae, in contrast to the situation for C III, N IV and Si III, where the forbidden lines have been widely detected (Keenan et al. 1992a, 1995).

In this paper we search for the Al II forbidden and intercombination lines in better quality spectra obtained by the Goddard High Resolution Spectrograph (GHRS) on the *Hubble Space Telescope* (*HST*). Additionally, we recalculate the Al II forbidden to intercombination line ratio as a function of temperature and density, and investigate its usefulness as an electron density diagnostic.

2 ATOMIC DATA

The model ion for Al II consisted of the five energetically lowest fine-structure levels, namely $3s^2\ ^1S$, $3s3p\ ^3P_{0,1,2}$ and $3s3p\ ^1P$. Energies for all these levels were taken from Kaufman & Hagan (1979). We note that test calculations including the higher lying $3p^2$ terms led to a negligible change in the 3s3p ^3P level populations at the electron temperatures and densities considered in this paper.

In Keenan et al. (1992b), preliminary electron impact excitation rates calculated by Aggarwal & Keenan (1994) using the **R**-matrix code of Berrington et al. (1978) were adopted in the analysis. However as Aggarwal & Keenan did not publish data for transitions among 3s3p ^3P (their results were given in LS coupling only), rates for these were listed by Keenan et al. We have now finalized our calculations for Al II (Aggarwal & Keenan 1998), and we note that these are slightly different from the preliminary values, especially for the $3s3p\ ^3P_J - 3s3p\ ^3P_{J'}$ transitions. For example, at $T_e = 5000$ K, Aggarwal & Keenan (1998) derive an effective collision strength of $\Upsilon = 1.90$ for the $^3P_0 - {}^3P_1$ transition, compared to the $\Upsilon = 1.62$ of Keenan et al. (1992b). Similarly for the $^3P_1 - {}^3P_2$ transition at this temperature, Aggarwal & Keenan and Keenan et al. find $\Upsilon = 6.71$ and 6.41, respectively. The Aggarwal & Keenan data should be accurate to better than

★ Permanent address: Department of Physics and Astrophysics, University of Delhi, Delhi-110 007, India.

10 per cent, and have therefore been adopted in the present analysis.

For Einstein *A*-coefficients, the calculations of Tayal & Hibbert (1984) and Hibbert & Keenan (1987) based on configuration interaction wavefunctions were adopted, apart from the value for the $3s^2$ ^1S – 3s3p $^3P_1$ intercombination line, where the measurement of Johnson et al. (1986) was preferred. As noted by, for example, Seaton (1964), excitation by protons may be important for transitions with small excitation energies, i.e. fine-structure transitions. However test calculations for Al II setting the proton rates for 3s3p ^3P_J – 3s3p $^3P_{J'}$ equal to the equivalent electron rates, or 10 times these values, had a negligible effect on the level populations, showing that this atomic process is unimportant, at least under the temperature and density conditions considered here.

3 RESULTS AND DISCUSSION

Using the atomic data discussed in Section 2 in conjunction with the statistical equilibrium code of Dufton (1977), relative Al II level populations and hence emission-line strengths were generated for a range of electron temperatures (T_e = 5000–30000 K) and densities ($N_e = 10$–10^8 cm^{-3}). Details of the procedures involved and approximations made may be found in Dufton (1977) and Dufton et al. (1978). Given uncertainties of typically less than 10 per cent in the adopted atomic data (see Section 2), we estimate that the derived theoretical line ratios should be in error by at most 15 per cent.

In Fig. 1 we plot the theoretical emission-line ratio $R = I(3s^2\,{}^1S\text{–}3s3p\,{}^3P_2)/I(3s^2\,{}^1S\text{–}3s3p\,{}^3P_1)$ as a function of electron density at three values of electron temperature, namely T_e = 5000, 10 000 and 15 000 K. (The ratios for $T_e >$ 15 000 K are similar to those at T_e = 15 000 K). It may be seen from Fig. 1 that the temperature dependence of the ratio is small, but that it varies strongly with density for $N_e \geq 10^2$ cm^{-3}, making it an excellent diagnostic for the cooler regions of nebular plasmas. We note that the present calculations of *R* are up to 6 per cent larger than those of Keenan et al. (1992b), which is a result of the adoption of somewhat different electron excitation rates in the current analysis, in particular for the 3s3p ^3P_J – 3s3p $^3P_{J'}$ transitions (see Section 2).

In Keenan et al. (1992b), we presented observed values of *R* for two gaseous nebulae, namely the planetary nebula NGC 7027 and the symbiotic star RR Telescopii (RR Tel). However these measurements were made from very poor quality *International Ultraviolet Explorer* (*IUE*) spectra, and the observed emission line fluxes were very similar to the noise level of the data (see figs 2 and 3 of Keenan et al.). In addition, the wavelength resolution of *IUE* spectra is relatively poor (~ 0.27 Å at 2660 Å; Howarth & Phillips 1986), making it difficult to accurately determine wavelengths for emission features. It was therefore impossible to reliably measure the wavelength of the proposed [Al II] emission line, even relative to that of the intercombination transition, and hence the identification of the former by Keenan et al. is at best only very tentative.

However RR Tel has since been observed at better signal-to-noise ratio and spectral resolution by the GHRS on *HST*. In Fig. 2 we show spectrum Z2QM010XT, a 1200-s exposure of the 2635–2680 Å region containing the Al II lines of interest, which was taken with the G270M grating on 1995 July 16. The photometric calibration of this spectrum has an accuracy of better than ±10 per cent in the region containing the Al II lines, and the spectral resolution is ~ 0.11 Å (FWHM). Data were wavelength calibrated

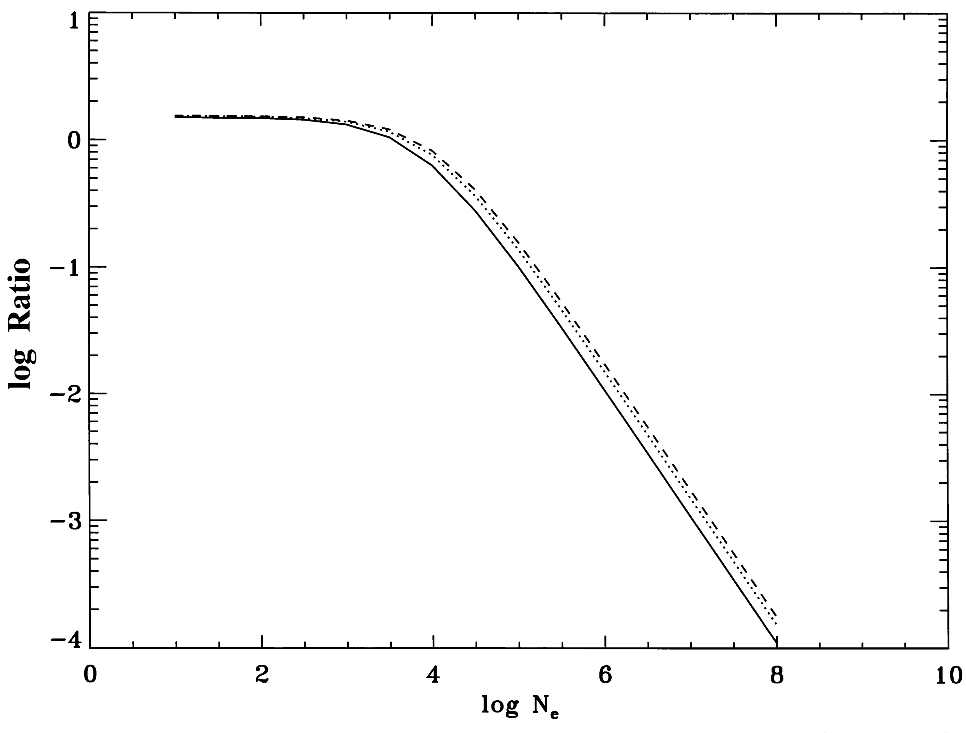

Figure 1. The theoretical Al II emission-line ratio $R = I(3s^2\ {}^1S - 3s3p\ {}^3P_2)/I(3s^2\ {}^1S - 3s3p\ {}^3P_1) = I(2661.06\,\text{Å})/I(2669.95\,\text{Å})$, where *I* is in energy units, plotted as a function of logarithmic electron density (N_e in cm^{-3}) for three values of electron temperature, namely T_e = 5000 K (solid line); T_e = 10 000 K (dotted line); T_e = 15 000 K (dashed line). We note that the values of *R* for $T_e >$ 15 000 K are similar to those at T_e = 15 000 K.

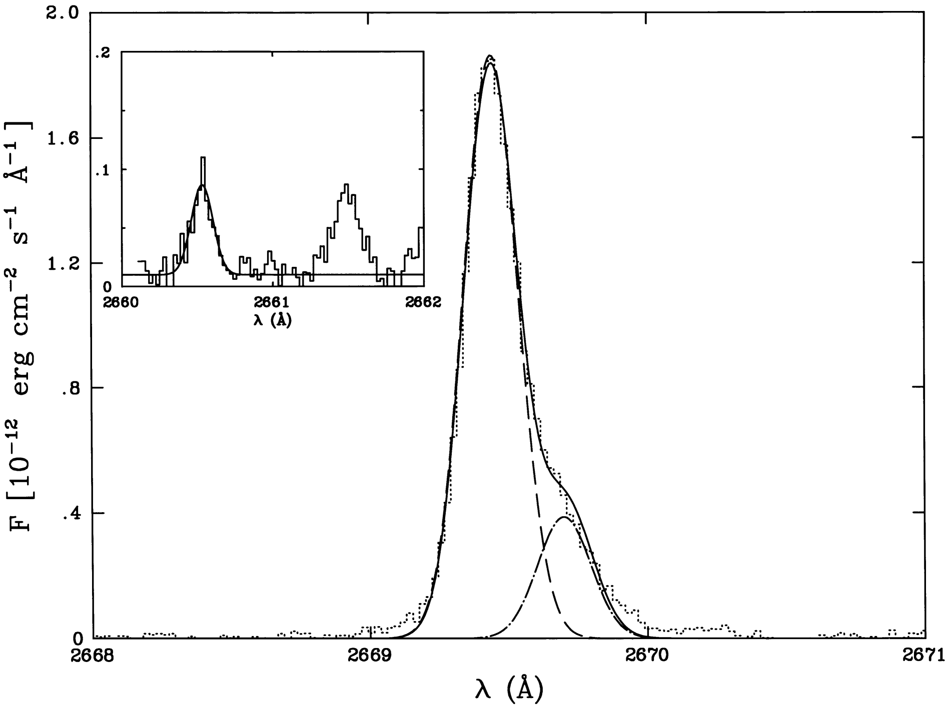

Figure 2. GHRS/*HST* spectrum (Z2QM010XT) of the symbiotic star RR Tel showing the Al II] $3s^2$ ^1S – 3s3p $^3P_1$ intercombination line at a vacuum wavelength of 2669.95 Å (Kaufman & Hagan 1979), and the [Al II] $3s^2$ ^1S – 3s3p $^3P_2$ forbidden line at 2661.06 Å. The intercombination line profile has been fitted using two components, separated by 0.263 Å (corresponding to 30 km s^{-1}) and indicated by dashed and dotted lines, while the solid line shows the sum of these. However the forbidden line profile has been fitted using a single component model.

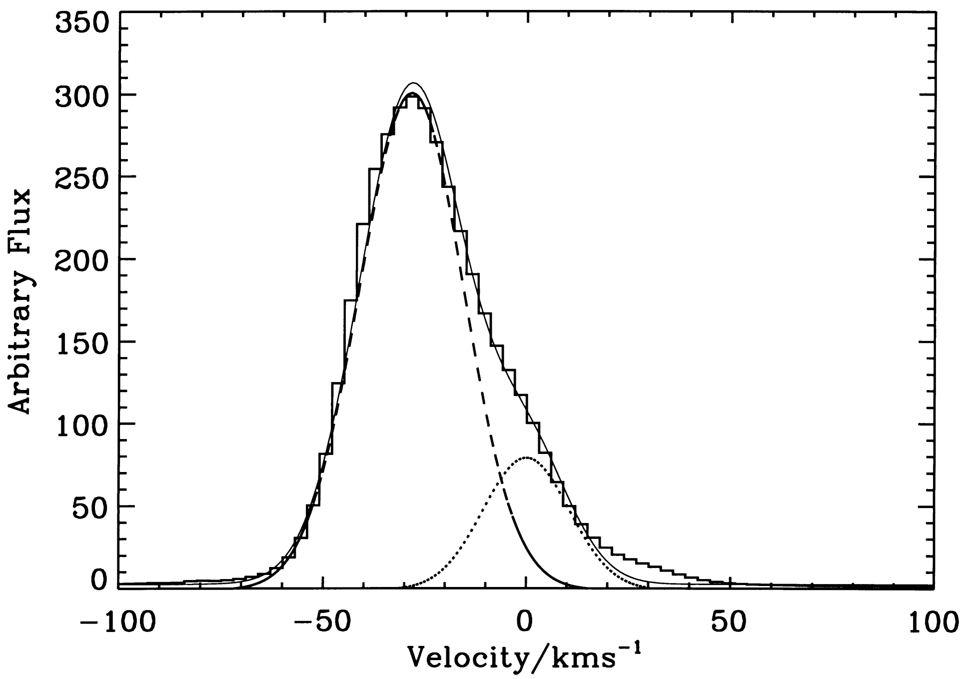

Figure 3. The [O III] 4363-Å line profile in RR Tel, obtained using the UCL Echelle Spectrograph on the Anglo-Australian Telescope during an observing run in 1996 July. The line profile has been fitted using two components, separated by 28 km s^{-1} and indicated by dashed and dotted lines, while the solid line shows the sum of these. The excess emission observed at the right-hand edge of the profile is probably owing to the presence of the Fe II 4363.26-Å line.

using the arc line spectra obtained at the same time, and each sub-stepped exposure was thus brought into alignment to reduce errors in the wavelength scale. The rms wavelength accuracy of the fitted arc lines is 0.013 Å in the region spanning the Al II lines.

The Al II] intercombination line at a vacuum wavelength of 2669.95 Å (Kaufman & Hagan 1979) shows a clear asymmetry, which we have fitted using a two component model (see Fig. 2). We derive a wavelength separation of 0.263 ± 0.020 Å, corresponding to a velocity separation of 30 ± 2 km s^{-1}. Schild & Schmid (1996) have noted that the [O III] 4363- and 5007-Å line profiles in RR Tel show a two-component structure, and consist of a strong low-density feature ($\log N_e \leq 5.5$), with a weak high-density wing ($\log N_e \geq 8$), redshifted by approximately $20\,km\,s^{-1}$. This is in qualitative agreement with our observations of the Al II] line profile. We note that we have also detected this component structure in high-resolution ($\sim 6\,km\,s^{-1}$ FWHM) optical spectra obtained with the Anglo-Australian Telescope (see Fig. 3), which confirm the findings of Schild & Schmid (Crawford et al. 1999).

Kaufman & Hagan (1979) predict a vacuum wavelength for the [Al II] line of 2661.15 Å, i.e. 8.80 Å away from the Al II] feature, which as noted above has an experimental wavelength of 2669.95 Å. The [Al II] line profile would not be expected to show the high-density component, as for $\log N_e \geq 8$ the predicted forbidden to intercombination line ratio is ≤ 0.0002 (Fig. 1). An inspection of Fig. 2 reveals the presence of an emission feature 8.89 ± 0.08 Å from the low-density Al II] component. Although the line is quite weak, it appears to be symmetrical as expected, showing no evidence for a redward wing. The measured intensity ratio of this feature to the low-density component of the intercombination line is $R = 0.027 \pm 0.003$, which for an adopted electron temperature of $T_e = 13\,000$ K (Hayes & Nussbaumer 1986) implies $\log N_e = 5.8 \pm 0.2$ from Fig. 1. This density is in excellent agreement with the values found for RR Tel from line ratios in ions formed at similar temperatures to Al II. For example, Hayes & Nussbaumer (1986) measured a value of the Si III line ratio $I(1883\,Å)/I(1892\,Å) = 0.03$, which implies $\log N_e = 6.0$ from the diagnostic calculations of Keenan et al. (1992a).

The good agreement between the predicted and observed wavelengths, in conjunction with the similarities of the densities derived from R and other spectral diagnostics, provides strong evidence that we have detected the [Al II] line at a vacuum wavelength of 2661.06 ± 0.08 Å. This is the first time (to our knowledge) that the line has been reliably identified in an astronomical or laboratory spectrum. Unfortunately, a search of the *HST* and *IUE* archives revealed no other convincing detections of the [Al II] feature in the spectrum of a gaseous nebula, owing to the poor signal-to-noise ratio of the data. However hopefully in the future further high-quality nebular observations will be made of this wavelength region, which will allow our diagnostic calculations for the R ratio in Al II to be fully exploited.

ACKNOWLEDGMENTS

KMA and FCM are grateful to EPSRC and PPARC, respectively, for financial support. BRE was supported by Space Telescope Science Institute Grant No. AR–07525.01–96A to the Johns Hopkins University. We also gratefully acknowledge the support provided by NATO travel grant CRG.930722.

REFERENCES

Aggarwal K. M., Keenan F. P., 1994, J. Phys. B: At. Mol. Opt. Phys., 27, 5321
Aggarwal K. M., Keenan F. P., 1998, J. Phys. B: At. Mol. Opt. Phys., 31, 4545
Berrington K. A., Burke P. G., Le Dourneuf M., Robb W. D., Taylor K. T., Lan V. K., 1978, Comput. Phys. Commun., 14, 367
Crawford F. L., McKenna F. C., Keenan F. P., Aller L. H., Ryan S. G., Feibelman W. A., 1999, A&AS, in press
Dufton P. L., 1977, Comput. Phys. Commun., 13, 25
Dufton P. L., Berrington K. A., Burke P. G., Kingston A. E., 1978, A&A, 62, 111
Hayes M. A., Nussbaumer H., 1986, A&A, 161, 287
Hibbert A., Keenan F. P., 1987, J. Phys. B: At. Mol. Phys., 20, 4693
Howarth I. D., Phillips A. P., 1986, MNRAS, 222, 809
Johnson B. C., Smith P. L., Parkinson W. H., 1986, ApJ, 308, 1013
Kaufman V., Hagan L., 1979, J. Opt. Soc. Am., 69, 232
Keenan F. P., Feibelman W. A., Berrington K. A., 1992, ApJ, 389, 443
Keenan F. P., Harra L. K., Aggarwal K. M., Feibelman W. A., 1992, ApJ, 385, 375
Keenan F. P., Ramsbottom C. A., Bell K. L., Berrington K. A., Hibbert A., Feibelman W. A., Blair W. P., 1995, ApJ, 438, 500
Schild H., Schmid H. M., 1996, in Mikolajewska J., ed., Physical Processes in Symbiotic Binaries and Related Systems. Kluwer, Dordrecht, p. 169
Seaton M. J., 1964, MNRAS, 127, 191
Tayal S. S., Hibbert A., 1984, J. Phys. B: At. Mol. Phys., 17, 3835

This paper has been typeset from a TEX/LATEX file prepared by the author.