New Results Concerning the Fe II Lines of RR Tel

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**Abstract.** We continue our investigation of the formation region of the Fe II emission lines in RR Tel, applying the SAC method to obtain new information about some of the physical parameters of the emitting region. Since the results obtained by this method depend strongly on the accuracy of the flux measurements, we analyze high quality AAT optical spectra obtained in 2000 and compare these with observations taken in 1996.

1. Introduction

RR Tel is a well-known symbiotic nova whose only known outburst was observed in 1944, followed by a long, still on-going recovery phase. It is an interacting binary consisting of a Mira variable and a hot companion, thought to be a white dwarf, and has a circumstellar ionized nebula. Its optical spectrum consists almost entirely of emission lines. It is slowly evolving and progressing towards higher degrees of ionization with time (Thackeray 1977; McKenna et al. 1997). Numerous permitted and forbidden Fe II lines that occur in a wide spectral range from the UV to the IR have proved to be an excellent means for determining the physical conditions in the emitting regions (Muratorio & Friedjung 1988).

This study is a follow-up of our previous work (Kotnik-Karuza, Friedjung, & Selvelli 2002), in which we analyzed the Fe II emission line fluxes from optical spectra of RR Tel taken in 1996 and published by Crawford et al. (1999). We applied the Self-Absorption Curve (SAC) method to determine the limits of the column density and of the radii of the line-emitting region and, in particular, to estimate the lower limit to the mass loss rate of the Mira variable.

Since the results obtained by the SAC method are strongly dependent on the accuracy of the flux measurements, we have proceeded in this work with an aim to look for possible variations in the Fe II emission over the four-year period.
2. Observations and Methods of Analysis

We have used a 3180–8000 Å spectrum of RR Tel taken at the Anglo–Australian Telescope (AAT) in 2000 July with UCLES. Compared to the spectra taken in 1996, it is of higher signal-to-noise ratio and, more importantly, was obtained at higher spectral resolution, around 3.5 km s$^{-1}$ compared to the 6 km s$^{-1}$ of the 1996 data. The narrow slit AAT spectra were flux-calibrated against LTT 9239 and then again against a low resolution HST spectrum of RR Tel taken in 2000 October. The spectra have been dereddened using $R = 3.1$, the Howarth reddening law (Howarth 1983) and $E(B - V) = 0.08$. The Fe II line fluxes were measured by Gaussian fitting.

The calibration and measurement uncertainties yield an average error of 20% for $\lambda < 7000$ Å and 28% for $\lambda > 7000$ Å, where the calibration had to be extrapolated beyond the HST spectrum by 7000 Å.

The atomic data have been taken from the NIST and VALD databases, Moore (1945), Garstang (1962), and Kurucz (1981).

A total number of 141 Fe II lines belonging to different multiplets originating from transitions between the lowest levels with an excitation potential up to 9 eV have been used, applying the Friedjung–Muratorio SAC method (Friedjung & Muratorio 1987). The method, which has proved to be effective in determining limits to relative populations of upper and lower terms and in deriving other information about the line formation region, has been described and applied exactly as in our previous paper (Kotnik-Karuza et al. 2002).

3. Results

An empirical log–log plot of the normalized flux $F_{\nu} = F\lambda^3/gf$ vs. $gf\lambda$, which is related to the optical thickness of a transition, is used to find the self-absorption curve whose shape is determined by self-absorption effects. Examples of such plots leading to the presented results are given in Figures 1 and 2.

The limits to the parameters obtained in this work from the AAT 2000 spectra together with the corresponding values from spectra taken four years earlier are given in Table 1. There is also detailed information about the function and the procedure used, as well as the explanation of the limit to the relevant parameter. The parameters refer to are radius, $R$, of the surface area perpendicular to the line of sight, where radiation of a particular line at wavelength, $\lambda$, is emitted, temperature, $T$, of this region, its column density, $N_e$, and cool component mass loss rate $\mu$.

Our observations give evidence of a general line flux decrease with respect to the values obtained from the spectra taken four years earlier. We believe that this effect, leading to smaller radius upper limits, is due to a dust obscuration event, which would mean that some dust exists inside the region of Fe II line formation.

The lower limit to the mass loss rate has been calculated as a function of the size of the dust formation region by assuming a value of 5 Mira radii for its radius (Kotnik-Karuza et al. 2002). For comparison, mass loss rates determined by other authors using various methods have also been given.
Figure 1. Self-absorption curves of multiplets with a common upper term $z^6D^0$.

Figure 2. Self-absorption curves of multiplet pairs 27,38 and 28,37 with common upper terms $z^4D^0$ and $z^4F^0$ respectively.
Table 1. Limits to the parameters of the Fe II-emitting region in RRTel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2000</th>
<th>1996</th>
<th>Function</th>
<th>Limit, explanation</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$(K)</td>
<td>5800</td>
<td>6600</td>
<td>SACs (1) and (40)</td>
<td>minimum horizontal shift</td>
<td>horizontal shift between SACs with common upper term $z^6D^0$</td>
</tr>
<tr>
<td>$R_{\text{min}}$(cm)</td>
<td>$8.5 \cdot 10^{11}$</td>
<td>$1.8 \cdot 10^{12}$</td>
<td>line 6433 Å (40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{min}}$(K)</td>
<td>2500</td>
<td></td>
<td>SAC (37) - (6F,20F) meta b4F</td>
<td>$T_{\text{min}}$, $R_{\text{max}}$ in the perm. region</td>
<td></td>
</tr>
<tr>
<td>$R_{\text{max}}$(cm)</td>
<td>$7.3 \cdot 10^{13}$</td>
<td></td>
<td>perm.virt.line log(gfλ) = 1, t=1, logF_n+0.2</td>
<td>Different regions of formation of the perm. and forb. lines</td>
<td>common metastable term</td>
</tr>
<tr>
<td>$T_{\text{min}}$(K)</td>
<td>2600</td>
<td></td>
<td>SAC (28) - (4F) meta b4P</td>
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<td></td>
</tr>
<tr>
<td>$R_{\text{max}}$(cm)</td>
<td>$6.5 \cdot 10^{13}$</td>
<td></td>
<td>perm.virt.line log(gfλ) = 1, t=1, logF_n+0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{max}}$(K)</td>
<td>2500</td>
<td>2500</td>
<td>SAC (27) - (4F) meta b4P</td>
<td>Assumed $\tau = 1$ underestimated</td>
<td></td>
</tr>
<tr>
<td>$R_{\text{max}}$(cm)</td>
<td>$2.1 \cdot 10^{13}$</td>
<td>$1.6 \cdot 10^{14}$</td>
<td>perm.virt.line log(gfλ) = 1, t=1, logF_n+0.2</td>
<td>real $\tau_{\text{min}} = 1$</td>
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<tr>
<td>$T_{\text{F}}$(K)</td>
<td>7500</td>
<td>6600</td>
<td>Boltzmann distribution of metastable levels</td>
<td></td>
<td>forbidden lines</td>
</tr>
<tr>
<td>$R_{\text{min}}$(cm)</td>
<td>$1.5 \cdot 10^{12}$</td>
<td>$4.8 \cdot 10^{12}$</td>
<td>$R_{\text{min}} = f(T_{\text{F}}, \text{line 4416 A (6F)})$</td>
<td>assumption $\tau_{\text{max}} = 1$</td>
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<tr>
<td>$R_{\text{min}}$(cm)</td>
<td>$1.9 \cdot 10^{12}$</td>
<td>$5.3 \cdot 10^{12}$</td>
<td>$R_{\text{min}} = f(T_{\text{F}}, \text{line 4244 A (21F)})$</td>
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<td></td>
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<tr>
<td>$N_{\text{min}}$(cm$^{-2}$)</td>
<td>$5.5 \cdot 10^{22}$</td>
<td>$7.5 \cdot 10^{22}$</td>
<td>$N_{\text{min}} = f(\Phi_{\text{METAmin}}, T_{\text{F}})$</td>
<td>perm. $\tau_{\text{min}} = 1$, $\Phi_{\text{METAmin}}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha M_{\text{min}}(M_{\odot}yr^{-1})$</td>
<td>$2.8 \cdot 10^{-6}$</td>
<td>$3.5 \cdot 10^{-6}$</td>
<td>$\alpha M_{\text{min}} = f(N_{\text{min}}, R_{\text{dust}})$</td>
<td>$\Phi_{\text{METAmin}}$</td>
<td>$N_{\text{min}}$</td>
</tr>
<tr>
<td>other authors</td>
<td>$2.5 \cdot 10^{-6}$</td>
<td>$8.0 \cdot 10^{-6}$</td>
<td>$5.3 \cdot 10^{-6}$</td>
<td>$1.0 \cdot 10^{-6}$</td>
<td></td>
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4. Conclusion

This work is still in progress and the results should be taken as preliminary.

The column density and mass loss rate limits are more reliable than the radii of the Fe-II line-emitting region since they are unaffected by the absolute level of fluxes. Moreover, the mass loss rate agrees with our previous value as well as with values found by other authors using other methods.

There is evidence of dust inside the region of the Fe II line formation. Different permitted and forbidden line widths suggest that these lines are not formed in the same region.

References

Moore, Ch. E. 1945, A Multiplet Table of Astrophysical Interest (New Jersey:Princeton)
Thackeray, A. D. 1977, MmRAS, 83, 1

Discussion

Viotti: I would like to underline the additional ingredient to be taken into account in the analysis of emission line intensity; that is, the line opacity. This is well treated by the SAC method for rich line species, such as ionized metals. In symbiotic stars, these lines are largely optically thick in the ultraviolet; hence they are greatly weakened. Their statistical analysis is essential for deriving a quantitative estimate of the fluorescence processes giving rise to the many high excitation Fe II lines of RR Tel seen in the UV.