Variation of Fluxes of RR Tel Emission Lines
Measured in 2000 with Respect to 1996

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Abstract

The aim of this work is to make available unpublished non-Fe^+ emission line fluxes from optical spectra of the symbiotic nova RR Tel, which were taken in 2000, and to compare them with fluxes of the same lines from spectra taken in 1996. After leaving out blends and misidentifications, as well as the unreliable far-red and violet lines, we present the $\log(F_{2000}/F_{1996})$ flux ratios for identified non-Fe^+ lines. The mean values of $\log(F_{2000}/F_{1996})$ for different ionization potential ranges of the ions producing the lines are shown separately for the permitted and forbidden lines. All means show fading, which is larger in the lowest range of the ionization potential. Provisional interpretations are suggested. We also measured the values of FWHM in 2000; the previously known decrease with time of the FWHM of lines due to the same ion has continued.

Key words: stars: circumstellar matter — stars: individual (RR Tel) — stars: symbiotic

1. Introduction

Symbiotic binaries consist of a cool giant and a more compact companion, which is thought to be in most cases a white dwarf. Accretion occurs from the cool giant to its compact companion. States of "activity", shown by brightening of the compact companion and spectral changes, are now believed to be at least often associated with thermonuclear burning in the outer layers of the white dwarf. Some symbiotic binaries are called "symbiotic novae", as only one activity stage, associated with a larger amplitude brightening than the brightenings of other symbiotic binaries, has been observed. In a subclass of symbiotic binaries, called symbiotic Miras, the cool giant is a Mira variable and is surrounded by dust (Whitelock 1987). Accretion in symbiotic Miras is thought to occur from strong wind of the giant. This sort of symbiotic binary, unlike the large majority of normal single Miras, undergoes obscuration events, involving an increase of absorption by dust (Whitelock 2003).

The compact component of RR Tel is both a symbiotic nova, with an outburst in 1944, and a symbiotic Mira binary system. It has faded in the optical since 1950, with its spectrum showing emission lines from atoms, whose maximum ionization potential increased with time over many years, while the lines from more ionized atoms tended to be wider. This development was summarized by Thackeray (1977). Ultraviolet

observations with IUE were described by Penston et al. (1983). In addition, like other symbiotic Miras, RR Tel has dust obscuration events, which produce decreasing continuum fluxes in the infrared and decreasing optical Fe^+ emission line fluxes. In previous work we studied the time-variable and wavelength-dependent absorption of the continuum of the cool component in the infrared, the characteristics of the regions producing permitted and forbidden Fe^+ emission lines, and the variation of the Fe^+ emission line fluxes due to variable obscuration, and what may be considered to be a dust obscuration event at the time of observations in 2000 (Kotnik-Karuza et al. 2002, 2006). The variation Fe^+ emission line flux, between an epoch of much dust absorption and one of less dust absorption was relatively simple, and might be interpretable as being due to the presence of separate, optically thick, absorbing dust clouds further from the cool component than the wavelength dependent infrared absorption.

2. Observations and Methods of Analysis

Optical spectra of RR Tel taken with the Anglo Australian Telescope in 1996 and 2000 have been compared. The former was obtained and calibrated by Crawford et al. (1999) with a resolution of about 50000. The second spectrum, taken in 2000 July in the wavelength range of 3180–8000 Å with almost twice the spectral resolution, was flux calibrated with an HST spectrum taken in 2000 October. The values of the line flux F_{2000} were dereddened using $R = 3.1$, the Howarth reddening law (Howarth 1983) and $E(B-V) = 0.08$ (Jordan et al. 1994).

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Table 1. List of emission lines from the spectra of RR Tel taken in 2000 and 1996.*

(1) λ (Å)	(2) Ion	(3) Mult	(4) IP (eV)	(5) F_2	(6) FWHM (km s^{-1})	(7) F_1	(8) $\log(F_2/F_1)$	(9) exc	(10) w
3183.61	Mn II		7.434	4.7E−02	19	1.1E−01	−0.37	g	x
3185.72	O IV	7	77.413	2.1E−02	19	4.6E−02	−0.35	r	x
3187.74	He I	3	24.587	1.2E−01	53	3.8E−02	0.50	r	x
3193.10	Si II		16.346	1.7E−02		5.1E−02	−0.48	r	x
3196.07	Fe II	7	7.902	7.6E−02	19	9.7E−02	−0.11	g	x
3203.10	He II	1	54.416	3.82	41	5.01	−0.12	r	x
3213.31	Fe II	6	7.902	6.0E−02	21	8.2E−02	−0.14	g	x
3220.84	Fe II	106	7.902	2.0E−01	57	1.6E−01	0.09	g	x
3227.73	Fe II	6	7.902	5.5E−02	24	9.7E−02	−0.25	g	x
3234.92	Fe II	1	7.902	3.7E−03	11	1.3E−02	−0.55	g	x

* The complete data of this table is available at ⟨http://pasj.asj.or.jp/v61/n2/610201/⟩.
Column (3) — Multiplet number.
Column (4) — Ionization potential of the corresponding ion.
Column (5) — Line fluxes from the spectra taken in 1996 and 2000 respectively, given in units of 10^{-12} erg^{-1} cm^{-2}.
Column (6) — FWHM: of lines from the spectrum taken in 2000.
Column (7) — Line fluxes from the spectra taken in 1996 and 2000 respectively, given in units of 10^{-12} erg^{-1} cm^{-2}.
Column (9) — Excitation mechanism: g = collisions from the ground state, B = Bowen mechanism, r = recombination.
Column (10) — Statistical weight (a = 3, b = 2, c = 1), x: Means that the line is beyond the limits of the studied wavelength range.

The line fluxes were measured by Gaussian fitting. Crawford et al. (1999) corrected the 1996 spectra for interstellar extinction using the coefficients listed in Cardelli et al. (1989) and the same $E(B-V) = 0.08$.

We identified and measured 523 emission lines, covering the wavelength region 3180–9230 Å, most of which were found in the spectra of RR Tel observed in 1996 (Crawford et al. 1999). In order to compare lines from the two spectra, the ratios of the fluxes were determined for each line. The flux ratios in the far red ($\lambda > 7000$ Å) and far violet ($\lambda < 3400$ Å) were left out from our study because of greater measurement errors in these regions. After the elimination of blends and misidentifications, a set of 490 lines was accepted for further analysis. For each line in table 1 the following information has been given: laboratory wavelength, ion identification, multiplet number, ionization potential of the contributing ion, line flux F_{2000} (in units of 10^{-12} erg s^{-1} cm^{-2}) and FWHM (km s^{-1}) from the spectrum taken in 2000, line flux F_{1996} from the spectrum taken in 1996 in the same flux units, excitation mechanism and statistical weight as a measure of the error of the flux determination. Note that the multiplet number is missing for lines for which this labeling has not been given in the databases used for identification. The missing FWHM values refer to lines that could not be satisfactorily Gaussian fitted, and their flux was obtained by adding the counts above a defined continuum region over a defined lambda range. The mean FWHM values for each ion derived from the corresponding values of individual lines together with the standard deviations of the means are given in table 2. In this paper we analyze 367 lines of ions other than Fe II, while the remaining 156 Fe$^+$ lines were the subject of our previous paper (Kotnik-Karuza et al. 2006).

Errors were calculated by performing multiple measurements of the lines, as well as comparing the fluxes measured from overlapping orders and overlapping gratings. The error in each line flux over the wavelength range 4920 Å $< \lambda <$ 6370 Å

was estimated as up to 25%. Outside this wavelength range, except for the very blue lines, the error is about 15%. For the bright lines the errors lie considerably under these limits, while for the faint lines, due to the uncertainty in the flux calibration process, the errors can exceed the given limits by even 15%. For $\lambda > 7000$ Å not included in our analysis, where the calibration had to be extrapolated beyond the HST spectrum, the calibration and measurement uncertainties yield an average error of 28%.

We took account of the errors in line fluxes by separating the lines into three groups and by assigning them different statistical weights. In our notation, group "a" has the largest weight of 3 and contains lines with errors smaller than 15%. Weak lines and lines from the less certain wavelength range are in group "b", which has a weight of 2. In group "c", with the smallest weight of 1, the very weak lines, those identified with a certain degree of uncertainty, badly fitted lines and possible blends are included.

3. Data Analysis

The behaviour of the log flux ratios of the non-Fe$^+$ lines from the 2000 and 1996 spectra is here examined. Plots of $\log(F_{2000}/F_{1996})$ against wavelength with the means and the standard deviation of the means for different ranges of ionization potential determined for the permitted and forbidden lines separately are shown in figures 1a–d. In determining the means and standard deviations, weights have been given to the lines, depending on to which of our three groups each line belongs. A plot of the mean log fadings against ionization potential is shown in figure 2. The choice of the most appropriate ionization potential for the contributing ions depends on the mechanism of excitation. In the case of the forbidden lines of ions and permitted metallic lines from singly ionized atoms (except for the high excited lines of Al II and Mg II), presumably excited

**Table 2.** Mean FWHM values for individual ions from the spectra of RR Tel taken in 2000.

Ion	FWHM (km s^{-1})	N	σ	IP (eV)	Ion	FWHM (km s^{-1})	N	σ	IP (eV)
H I	64.0	24	5.1	13.598	[Ar IV]	68.0	1		40.74
He I	40.4	24	2.4	24.587	[Ar V]	50.0	2	2.7	59.81
He II	56.0	26	1.8	54.416	Ar II	24.0	1		27.629
C II	56.0	3	22.7	11.26	[K IV]	41.0	1		45.806
C III	45.0	7	3.7	47.888	[K V]	92.0	1		60.91
C IV	50.7	2	3.5	64.492	[Ca V]	61.0	2	8.8	67.27
[N I]	18.0	1		0	[Ca VI]	80.0	1		84.5
[N II]	105	1		14.534	Ca I	66.0	3		0
N I	18.0	1		14.534	Sc I	13.0	2	7.2	0
N II	24.7	3	2.4	29.601	Sc II	54.0	1		6.561
N III	33.0	10	3.7	47.448	Ti I	45.0	3	18.4	0
N IV	81.0	1		77.472	Ti II	19.9	7	5.3	6.828
N V	59.0	1		97.89	[V II]	14.9	3	1.2	6.746
[O I]	15.8	2	0.0	0	V II	25.0	10	6.5	6.746
[O III]	55.7	3	8.4	35.117	[Cr II]	11.0	2	4.0	6.766
O I	22.0	1		13.618	[Cr V]	72.0	1		49.16
O II	37.0	15	7.3	35.117	Cr II	44.0	10	9.8	6.766
O IIIB	35.0	7	5.8	35.117	[Mn III]	115.0	1		15.64
O IIInB	36.0	6	4.6	54.93	[Mn IV]	24.3	3	13.0	33.668
O IV	43.0	6	8.2	77.413	Mn I	68.0	1		0
[F IV]	32.0	1		62.708	Mn II	54.0	9	8.8	7.434
F II	75.0	1		34.97	[Fe II]	28.3	58	2.9	7.902
[Ne III]	35.0	3	10.6	40.963	[Fe III]	51.0	13	4.6	16.188
[Ne IV]	45.2	3	1.2	63.45	[Fe IV]	39.5	11	2.7	30.652
Ne II	47.8	4	21.5	40.963	[Fe V]	49.2	10	4.8	54.8
[Na V]	54.0	1		98.91	[Fe VI]	49.5	10	4.7	75
Mg I	22.0	1		0	[Fe VII]	69.9	3	1.1	99.1
Mg II	15.0	1		15.035	Fe II	18.0	81	1.6	7.902
Al II	70.0	1		18.828	Fe III	27.2	6	5.2	16.188
Si I	34.0	1		0	[Co II]	29.0	1		7.881
Si II	29.5	11	3.7	16.345	[Co VII]	83.0	1		103
Si IV	64.0	1		45.142	[Ni II]	27.0	4	10.1	7.639
[S II]	19.2	2	2.9	10.36	[Ni IV]	26.0	1		35.19
[S III]	55.0	2	5.0	23.338	[Ni V]	36.0	1		54.9
S II	39.6	5	9.4	23.337	[Ni VIII]	50.0	1		134
S III	18.5	2	0.5	34.79	Ni II	38.0	1		7.639
Cl II	67.0	1		23.814	Ni III	17.0	1		35.19
[Ar III]	41.0	1		27.629	Ni V	20.0	1		75

* B refers to the lines excited by Bowen mechanism while the nB lines are excited by recombination.

from the ground level by collisions, it is justified to adopt the ionization potential of the previous ionization stage. For neutral atoms a value of zero was assigned to the corresponding ionization potential. Excitation from the ground level was also assumed for the lines excited by the Bowen mechanism i.e., O III 3430, 3444, 3754, 3757, 3774, 3791, 3810; the others are not excited in this way (M. Eriksson, 2008, private communication). We have assumed that the Bowen mechanism is not important for N III, as found by Eriksson et al. (2005), but we must note that Selvelli et al. (2007) come to the opposite conclusion, taking into account what happens when the optical thickness is very large. We can also assume excitation from the ground level for all lines arising from levels far from the ionization limit not due to hydrogen or helium. Note that this

condition has been chosen quite arbitrarily. On the other hand, all H I, He I, and He II lines, as well as lines arising from levels closer to the ionization level, have been taken to be excited by recombination from the following stage of ionization, and the ionization potential of the ion which produces the lines studied, was adopted.

The new additional evidence for the fading of emission line fluxes in 2000 during a dust obscuration event with respect to the fluxes in 1996, shown in figures 1 and 2, might be considered to be surprising, in view of the fact that Selvelli et al. (2007) found no indication for wavelength-dependent absorption in the optical region. It is therefore useful to check the reliability of the data used by us. We previously found no evidence for fading at an earlier time (Kotnik-Karuza et al.
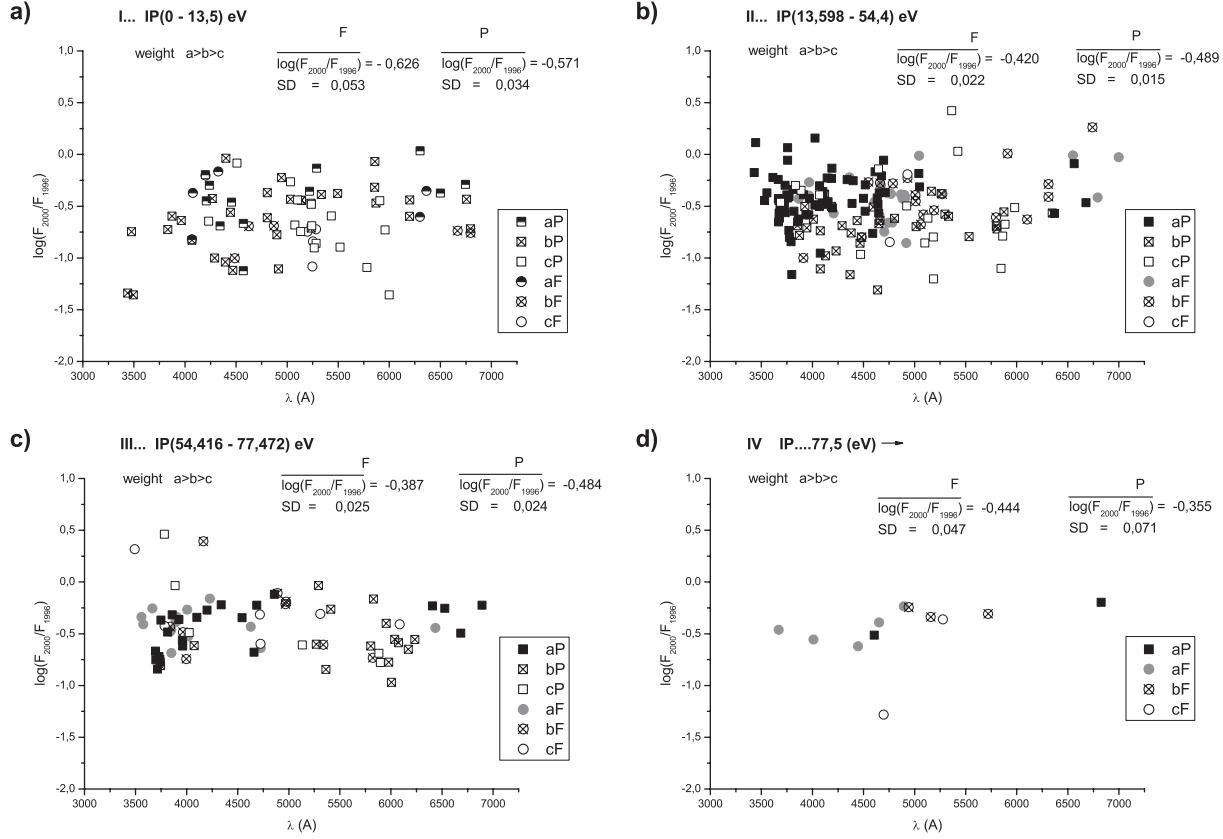
Fig. 1. Log (F_{2000}/F_{1996}) vs. wavelength for ions other than Fe II in the potential range a) 1–13.5 eV, b) 13.598–54.4 eV, c) 54.416–77.472 eV, d) more than 77.5 eV. The mean values of log (F_{2000}/F_{1996}) and standard deviations SD of the means for the permitted and forbidden lines are given in the figure. F_{2000} and F_{1996} are emission line fluxes from the spectra taken 2000 and 1996 respectively. Permitted (P) lines are marked with rectangular and forbidden (F) lines with circular symbols. "a" is for lines with a statistical weight of 3, "b" for lines with a statistical weight of 2 and "c" for lines with a statistical weight of 1.
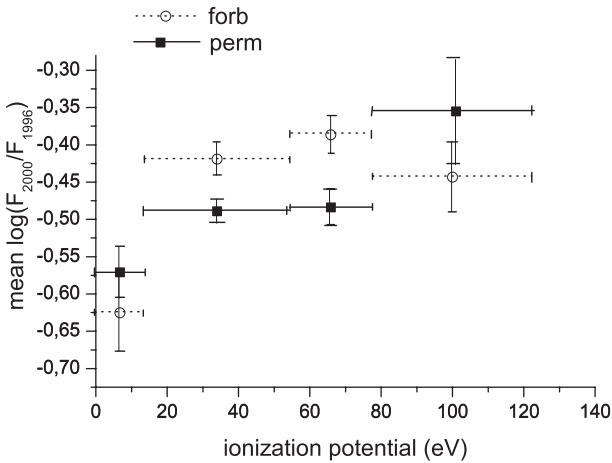
Fig. 2. Log (F_{2000}/F_{1996}) vs. ionization potential for ions other than Fe II averaged over four ionization potential ranges: 1–13.5 eV; 13.598–54.4 eV; 54.416–77.472 eV; more than 77.5 eV. The horizontal bars indicate ionization potential ranges.

2002) by comparing the measurements of Crawford et al. (1999) with those of McKenna et al. (1997). It is imaginable that the apparent fading could be an artifact due to a non-linearity of the 2000 calibration spectrum. To eliminate this as a possible explanation of our result, we have looked for a dependence of fading on the line center flux, the latter being indicated by the ratio of the total line flux in 2000 (F_{2000}) to the corresponding FWHM. Such a test is best undertaken for both the permitted Fe II and the forbidden [Fe II] lines, where lines not fitting the Self-Absorption Curve relation between a function of flux and the oscillator strength were eliminated as being badly identified. This method, previously used by us (Kotnik-Karuza et al. 2002) was applied in a different way to another star by Muratorio et al. (2006). The result of the test for non-linearity is shown in the graph of figure 3, where a small tendency for log (F_{2000}/F_{1996}) to increase as a function of log (F_{2000}/FWHM) has been found. A calculation of the correlation suggests an increase of 0.07 between values of log (F_{2000}/FWHM) of -4 and -2 for the permitted lines and an increase of 0.19 for the forbidden lines over the same range. Even if the effect is really due to non-linearity, it is clear that the mean fadings for the two groups of emission lines of ionized iron (Kotnik-Karuza et al. 2006), as well as those found in the present work, are considerably larger.
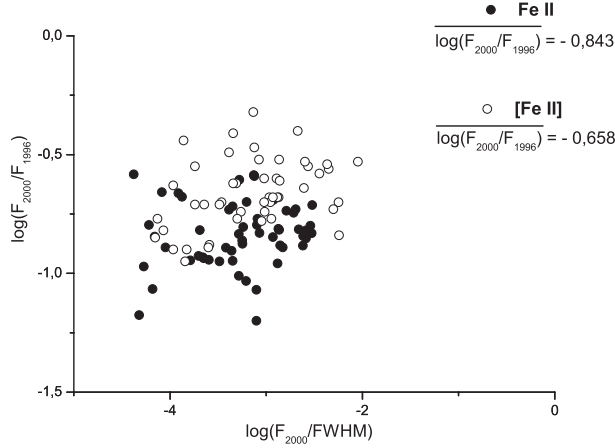
Fig. 3. Log (F_{2000}/F_{1996}) vs. log (F_{2000}/FWHM) for the Fe$^+$ lines. The values of log (F_{2000}/FWHM) in the abscissa give a measure of the line peak fluxes. F_{2000} and F_{1996} are emission line fluxes from the spectra taken 2000 and 1996, respectively, while FWHM refers to lines from the spectra taken in 2000.

Table 3. $\Delta E(B-V)$ for Fe$^+$ lines and for lines other than Fe$^+$ in four ionization potential ranges, as defined in figure 1.

	$\Delta E(B-V)$
IP I forb	-0.14 ± 0.21
IP I perm	0.30 ± 0.14
IP II forb	0.39 ± 0.12
IP II perm	-0.10 ± 0.09
IP III forb	0.04 ± 0.12
IP III perm	-0.07 ± 0.11
IP IV forb	0.41 ± 0.48
IP IV perm	0.40
Fe$^+$ forb	0.10 ± 0.10
Fe$^+$ perm	0.09 ± 0.07

4. Discussion

We only have emission line fluxes for two dates, one inside and one outside an obscuration event, so any interpretation is provisional. More observations are needed to confirm or invalidate what is seen here.

The graphs of log flux ratio against wavelength (figure 1) do not show any very clear sign of any correlation between these quantities. Within the errors the fits indicate an absence of a slope.

We have however studied the variation of the means and the standard deviations in the different ranges of ionization potential, which are indicated by horizontal bars (figure 2). The standard deviations are larger than for Fe$^+$ studied by itself (Kotnik-Karuza et al. 2006), and unlike for Fe$^+$ show no significant difference between permitted and forbidden lines. Whether this, like the larger standard deviations, found here, is at least due to a certain extent to different ions and atoms being studied together in the present investigation, is not clear. The different permitted line fluxes are of course affected by radiative transfer effects.

All of the mean log ratios are less than zero, so fading occurs for both permitted and forbidden lines in all ranges of the ionization potential. However, it appears to be largest in the lowest range of ionization potential.

This might indicate that optically thick clouds, whose existence in the Fe$^+$ regions was first suggested by Kotnik-Karuza et al. (2006) are also present in regions of formation of higher ionization lines. The clouds absorbing emission lines in the optical and ultraviolet ranges are further out from the cool component than the dust producing infrared absorption.

The latter region should then have a smaller covering factor. Selvelli et al. (2007), however, found apparently contradictory conclusions from the same HST / STIS data of 2000 October, which calibrate earlier spectra obtained with the Anglo-Australian telescope, studied by us. The relative fluxes of the He II Fowler series indicated a fairly low interstellar reddening

of $E(B-V)$ near 0.00, agreeing with what is expected from the interstellar hydrogen column density. However, gray absorption by optically thick clouds would not be detectable by a procedure that only compared the fluxes of lines at different wavelengths.

We have determined $\Delta E(B-V)$, i.e., the change of $E(B-V)$ in 2000 with respect to its value in 1996 separately for the forbidden and permitted lines of Fe$^+$ and for other ions in different ionization potential ranges, as shown in table 3.

In view of the errors, the values of $\Delta E(B-V)$, which are in some cases negative, are not significant. We may note that an increase of the photospheric temperature of the hot component, would lead to positive log flux ratios for the highest ionization lines, formed nearer that component, unlike what we have found. An alternative possibly more acceptable interpretation to that of the last paragraph would require the hot component to have moved to the cooling part of its track in the temperature luminosity diagram, following its increasing temperature in earlier decades, shown by the appearance with time of lines from ions with increasing ionization potential.

The 2000 spectrum of RR Tel still shows the previously known effect (see Thackeray 1977) that lines from more highly ionized atoms tend to be wider. This can clearly be seen in figure 4, where the mean FWHM is plotted against the ionization potential in the same ranges of ionization potential as in figure 2. It is also shown in figure 5, where the mean FWHM for each ion from table 2 is plotted against its ionization potential. Figure 5 shows the mean FWHM of individual ions; figure 4 shows averages over different ionization potential ranges, indicated by horizontal bars. The contribution of each ion to each ionization potential range has been weighted by the number of its measured lines.

Two discordant lines have been left out from the plot: the 6742 [Mn III] and the 6548[N II] line. The 6742 [Mn III] line is the only identified line of this ion in the 2000 spectrum, but not identified before. Its radial velocity shift is relatively large with respect to other lines in its neighborhood. Its flux is, moreover, quite low, and the large FWHM suggests that it is very weak. The 6548[N II] line is the only line of multiplet 1F identified in our spectrum. In the 1996 spectrum it was declared to be a blend, and had not been identified in the preceeding 1992 spectrum. This line, accompanied by the three-times stronger 6583[N II] line of the same multiplet, is a common feature of
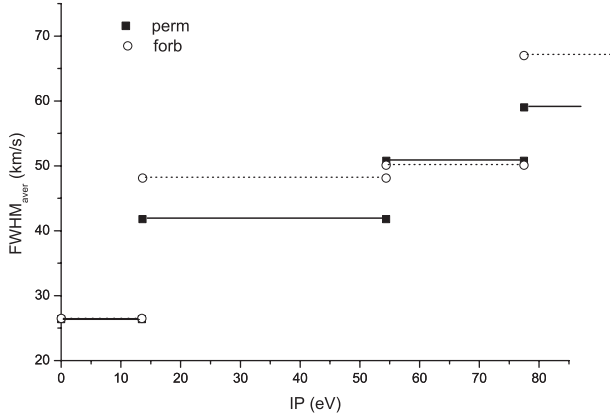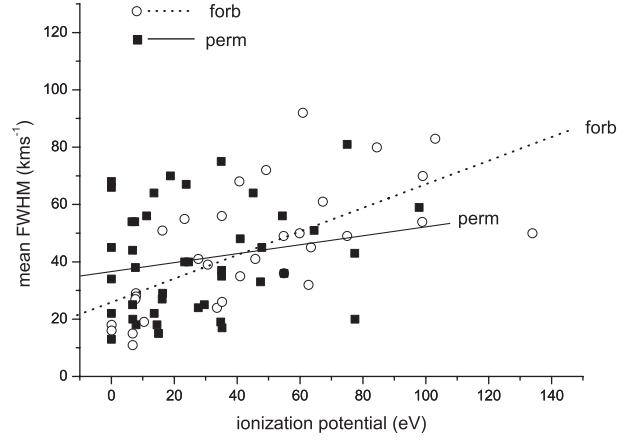
Fig. 4. FWHMs of the permitted and forbidden lines from the spectra taken in 2000 averaged over four ionization potential ranges: 1–13.5 eV; 13.598–54.4 eV; 54.416–77.472 eV; more than 77.5 eV. Note that the permitted and the forbidden lines overlap in the lowest ionization potential range. In the averaging procedure over different ionization potential ranges each ion was weighted by the number of its lines. The horizontal bars indicate ionization potential ranges.

Fig. 5. Mean FWHMs of lines belonging to individual ions from the spectra taken in 2000 as a function of ionization potential.

normal nebulae. The absence of the stronger 6583[N II] line in our 2000 spectrum indicates that identification of the weaker 6548[N II] line is probably wrong, and shows that the emission line regions of RR Tel are not like such nebulae.

According to Friedjung (1966), the FWHMs of the RR Tel emission lines of a given ionization stage tended to decrease with time. Data given in that paper for He II ($-$, $104\,\mathrm{km\,s^{-1}}$), [Fe V] ($92\,\mathrm{km\,s^{-1}}$, $81\,\mathrm{km\,s^{-1}}$), [Fe VI] ($182\,\mathrm{km\,s^{-1}}$, $-$), and [Fe VII] ($169\,\mathrm{km\,s^{-1}}$, $182\,\mathrm{km\,s^{-1}}$) refer to the spectra taken in 1960 and 1965 respectively. That data from photographic spectra at wavelengths below 5000 Å, with a quite approximate correction for instrumental broadening, are of lower quality than those of the present paper, and it is not easy to make a detailed comparison. However, by comparing the

non-instrumental broadening corrected FWHM_{2000} means of table 2 with the previously found values from 1960 and 1965 spectra, we can see that the mean FWHM decrease of the wider lines of highly ionized atoms seems to have continued.

The radii of the hot component photosphere of RR Tel at different dates, estimated by Mürset and Nussbaumer (1994), suggest that these velocities were considerably less than the hot component escape velocities, and therefore of a hot component wind. Let us in addition note that, as mentioned by Friedjung (1966), the Balmer lines near the beginning of the Balmer series, still tended to be wider in 2000, this being especially true for Hα.

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