MODELING RR TELERCOPII THROUGH THE EVOLUTION OF THE SPECTRA

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ABSTRACT

We investigate the evolution of RR Tel after the outburst by fitting the emission spectra in two epochs. The first one (1978) is characterized by large fluctuations in the light curve, and the second one (1993) by a slow fading trend. In the frame of a colliding wind model, two shocks are present: the reverse shock propagates in the direction of the white dwarf, while the other one expands toward or beyond the giant. The results of our modeling show that in 1993, the expanding shock has overcome the system and is propagating in the nearby ISM. The large fluctuations observed in the 1978 light curve result from line intensity rather than from continuum variation. These variations are explained by fragmentation of matter at the time of head-on collision of the winds from the two stars. A high-velocity (500 km s⁻¹) wind component is revealed from the fit of the SED of the continuum in the X-ray range in 1978, but is quite unobservable in the line profiles. The geometrical thickness of the emitting clumps is the critical parameter that can explain the short-timescale variabilities of the spectrum and the trend of slow line intensity decrease.

Subject headings: binaries: symbiotic — shock waves — stars: individual (RR Teleroequi) — white dwarfs

1. INTRODUCTION

RR Tel belongs to the group of symbiotic novae. They are distinguished from classic symbiotic stars by having undergone only one single major outburst and not yet recovered. The outburst of RR Tel started in 1944, when the system brightened by 7 mag. The light curve after the outburst shows a gradual fading, which is still in progress. In addition to the general decrease, the light curve is marked by periods of large fluctuations. The system is believed to be a binary, consisting of a nuclear-burning white dwarf (WD) and a late-type companion, with an emission nebula photoionized by the hot star. The cool component is a Mira-type variable, with a pulsation period of 387 days (Feast et al. 1983). Weak TiO absorption bands of spectral type about M5 were observed by Thackeray (1977). The system has been monitored in many different spectral regions, ranging from radio to X-rays, and was recently observed by the Hubble Space Telescope (HST). In spite of being extensively studied (Aller, Polidan, & Rhodes 1973; Thackeray 1977; Hayes & Nussbaumer 1986; etc.), many questions about RR Tel remain unsolved.

The emission-line spectra of symbiotic stars are usually calculated using a classical model in which the main excitation mechanism is photoionization from the hot star (Murset et al. 1991). However, in the last few years, the importance of the winds from both components in symbiotic systems and their collision has been addressed by many authors (e.g., Wallerstein et al. 1984; Girard & Willson 1987; Nussbaumer & Walder 1993; etc.).

Recently, a model has been successfully applied to the calculation of the line and continuum spectra of HM Sge (Formiggini, Contini, & Leibowitz 1995) and AG Peg (Contini 1997). This model is able to fit the high- and low-ionization emission lines by taking into account both the shock created by the winds and the photoionization flux from the hot star.

In this paper we investigate the evolution of RR Tel through the interpretation of both line and continuum spectra in different epochs. Both the photoionizing flux from the hot star and the collision of the winds are considered, so the calculation was performed with the SUMA code. SUMA (Contini 1997 and references therein) consistently accounts for both the radiation from the hot star and for the shock in a plane-parallel geometry. Dust reradiation is also consistently calculated.

In § 2 the evolution of the outburst is described. In § 3 the general model is presented. The spectra taken in 1978 and 1993 are discussed in § 4 and § 5, respectively. Model results for the two epochs 1978 and 1993 are compared in § 6, and conclusions follow in § 7.

2. THE EVOLUTION OF THE OUTBURST

Figure 1 shows the visual light curve of RR Tel between the years 1949 and 1995, obtained by collecting data from various sources (AAVSO circulars; Heck & Manfroid 1985; F. M. Bateson 1995, private communication). A period of 387 days was observed (Heck & Manfroid 1982) for the system after 1930, the same as observable in the infrared (Feast et al. 1983). It can be noted that a general decreasing trend started in 1949 and is still in progress. Above the fading trend, the curve displays a decrease of slightly larger than 0.5 mag in the years 1962–1963, and particularly large fluctuations in the years 1975–1982. During these years the cool companion remained quite stable, as shown by many observations collected at infrared wavelengths, where the cool star dominates. In fact, a periodicity of 387 days has been detected on JHKL photometric data during 1975–1981 by Feast et al. (1983). After these events the system recovered the general fading trend.

Penston et al. (1983) reported optical photometric variations from night to night and within a single night between 1975 and 1982. We recall that the line spectrum is very rich, and that some strong lines fall in the passbands of the broadband photometry. It is then likely that large fluctuations in the line intensities are the source of the strong variations in the visual light curve. However, the question of whether the variations in the continuum or in the line inten-

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sities are the cause of the photometric fluctuations is still open.

The outburst event led initially to an extended atmosphere around the white dwarf. The nebular phase emerged some years later, and is characterized by a wind with a terminal velocity increasing from 400 km s\(^{-1}\) in 1949 to 1300 km s\(^{-1}\) in 1960 (Thackeray 1977). However, when \(IUE\) became operational in 1978, Penston et al. (1983) measured a terminal velocity of about 75 km s\(^{-1}\), indicating that the wind had decelerated from initial velocities of thousands of km s\(^{-1}\) to less than 100 km s\(^{-1}\).

As the outburst evolved, emission lines from high-ionization levels appeared (Viotti 1988). The emission-line spectra of RR Tel were studied by Penston et al. (1983), Hayes & Nussbaumer (1986), Aufdenberg (1993), and others. Recently, Zuccolo, Selvelli, & Hack (1997; hereafter ZSH) retrieved all the available \(IUE\) spectra up to 1993, and after an accurate reduction and correction for spectral artifacts, saturation and other instrumental effects, a homogenous and complete list of the emission lines in the UV range was presented.

ZSH claim that the variations observed in the emission-line intensities from 1978 to 1993 show a rather strong correlation with the line ionization level. The decrease is by a factor of larger than 3 and up to 10 for low-ionization lines and between 2 and 3 for medium- and high-ionization lines. The fluxes for some representative lines from ZSH's Table 1 are plotted in Figure 2. Note that among the high-ionization level lines, only \([\text{Mg} \, \text{vi}]\) 1806 has increased between 1983 and 1993. It seems that the conditions of the system did not change significantly. Hayes & Nussbaumer (1986) already noticed a lack of periodic variation in the UV line fluxes over the period 1978–1984, finding only a slight decrease of the intensities. A modulation of the line intensities with orbital phase is observed in symbiotic stars (e.g., Kenyon et al. 1993 for AG Peg). The lack of periodicity of the RR Tel line intensities over a 15 yr span (1978–1993) can be explained either by the system being face-on or by a period longer than 15 yr. Orbital periods of symbiotic Miras are believed to be longer than 20 yr (Withelock 1988).

For the purpose of our modeling, we consider the system in two representative epochs, one in 1978, when the system underwent high variability in the visual light on small timescales, and the other in 1993, after it recovered the slow fading trend. We take advantage of the ZSH collection of data for the fitting of model calculations.

### 3. The General Model

A description of the colliding wind model is given by Girard & Willson (1987). Recall that the cool component of RR Tel is a Mira, characterized by a strong mass-loss rate that produces an extended atmosphere. The outburst is the starting point of the wind from the hot star. The winds from the two components approach from opposite directions, colliding head-on in the region between the stars and head-on-tail outside. It is plausible that fragmentation of matter in geometrically thin clumps results from turbulence caused by collision. The white dwarf (WD) ejecta propagate in the giant atmosphere toward higher densities. As a result of the collision two main shocks appear, the reverse shock and the expanding shock. The reverse shock propagates back into the WD ejecta facing the WD. Therefore, the photoionizing radiation flux from the WD reaches the very shock front. On the other hand, the secondary shock expanding toward the red giant propagates in a denser medium; therefore, its velocity is lower than that of the reverse shock. In this case, the radiation from the WD reaches the matter downstream, opposite to the shock front. A simple sketch of the model in different epochs is given in Figure 3.

The initially high velocity of the WD wind will produce high densities and temperatures behind the shock front, and hence hard X-ray emission would be expected. However, after propagating and sweeping up additional material, the shock decelerates. Lower shock velocities correspond to lower temperatures downstream, and the ionized region behind the shock front will become visible in the UV and optical spectra. In our model of RR Tel, two gas regions contribute to the emission spectra: downstream of the reverse shock and downstream of the expanding shock.

In this paper we consider the system in two epochs in 1978 and 1993. The input parameters for the calculation of
The stars indicate the WD and the filled circle the cool giant. Shock fronts are indicated by solid lines. Dotted and long-dashed lines indicate the geometrical thickness of the emitting clumps, \( d \), the dust-to-gas ratio by number. The models are matter bound, and the densities are constrained by the critical line ratios (Nussbaumer & Schild 1981) and the shock velocities by the FWHM of the line profiles. For all models, we adopt \( T_s = 1.4 \times 10^5 \) K (Murset et al. 1991) and \( B_0 = 10^{-3} \) Gauss, which is suitable to red giant atmospheres (Bohigas et al. 1989). Relative abundances are calculated phenomenologically within the range of values consistent with CV systems.

4. The spectra in 1978

The models that best fit the observation data are selected from a grid of model calculations. Note, however, that whenever different regions of emitting gas coexist in one object, the observed spectrum contains a contribution from all of them. Therefore, although some models better fit high-ionization lines and others low-ionization lines, the most probable model must consistently account for all the lines and the continuum.

4.1. The Line Spectrum in the Ultraviolet

In Table 1 the models are described, and in Table 2 the calculated line ratios (to \( C_{IV} \)) are compared with the observed data from ZSH. Arrows indicate that the multiplet is summed up.

The FWHM of line profiles from the observations are listed in column (2) of Table 2. Penston et al. (1983) measured in 1978 a terminal velocity of the wind of about 75 km s\(^{-1}\), indicating that the wind decelerated from initial velocities of thousands of km s\(^{-1}\) to less than 100 km s\(^{-1}\). Large features were actually not observed; however, wide feet of the high-level lines are not excluded by Nussbaumer & Dumm (1997) in later spectra.

Here we consider the most significant lines. The spectrum at 1978 contains lines from relatively high levels (\( O_{I} \)) down to neutral lines. As already noted by ZSH, the broader the line, the higher the level of the ion. The line widths range between 70 and 30 km s\(^{-1}\). The profiles are separated into two groups, one with FWHM ~ 40 km s\(^{-1}\), and the other with FWHM up to ~ 80 km s\(^{-1}\). It is known that broad and narrow profiles of single lines characterize most of the symbiotic spectra. In RR Tel, the two main widths are very close to each other and difficult to recognize.

Model REV1 (Table 1), with a shock velocity of 80 km s\(^{-1}\) and a density of \( 10^6 \) cm\(^{-3}\), represents the reverse shock. This model nicely fits high-ionization lines (from levels higher than \( \text{III} \)). \( N_{	ext{V}} \) at 1386 is overestimated by a factor of 4, while \( \text{Mg} \text{V} \) at 1324 is underestimated, but the identification of this line is doubtful (ZSH). An alternative model for the reverse shock is REV2, characterized by a lower density (\( 10^5 \) cm\(^{-3}\)), corresponding to a different location of the emitting clump in the system.

Model EXP represents the shock propagating toward the red giant, and is characterized by a velocity of 45 km s\(^{-1}\) and a density of \( 2 \times 10^6 \) cm\(^{-3}\), as indicated by the observations. The absolute intensity of \( \text{C} \text{IV} \) is extremely low for \( V_s < 50 \) km s\(^{-1}\) and \( U < 0.01 \); therefore, the line ratios to \( \text{C} \text{IV} / \text{C} \text{IV} \) = 100 are very high for this model. However, these are necessary conditions to obtain strong neutral lines. In fact, this model is constrained by the ratio of the \( \text{O} \text{I}/\text{C} \text{II} \) line intensities. The observed \( \text{O} \text{I} \) lines are relatively strong and show that the emitting clumps should contain a large region of cool recombined gas (see § 6).

In the last two columns of Table 2, the composite models SUM1 and SUM2 are listed. These result from the weighted sum of the contributions of the expanding shock (EXP) spectrum and that emitted by the reverse shocks REV1 and REV2, respectively. The relative weights adopted are given at the bottom of Table 1. The fit presented in Table 2 is...
other hand, the intensity of the dust radiation flux relative to bremsstrahlung emission depends on the dust-to-gas parameter, $d/g$.

The fit of model REV1 to the data in the IR yields $d/g = 5 \times 10^{-15}$, whereas for model EXP, $d/g = 10^{-14}$. Since model EXP represents a shock front closer to the giant, a higher $d/g$ implies a dustier atmosphere.

Figure 4 shows that the radiation flux calculated by model REV1 strongly prevails over that calculated by EXP, and that some absorption is present in the low-frequency domain.

As for the X-ray domain ($10^{16}$–$10^{18}$ Hz), the data show emission from a gas at a temperature between $10^6$ and $10^7$ K. Jordan et al. (1994) suggested that such a plasma could be produced by a fast wind, with velocity of $\sim 500$ km s$^{-1}$. This emission cannot be obtained either by the models that

### Table 1

| Parameter | REV1  | REV2  | EXP   | XX    | HN (1986)* |
|-----------|-------|-------|-------|-------|------------|
| $V_s$ (km s$^{-1}$) | 80    | 85    | 45    | 500   | ...        |
| $n_0$ (cm$^{-3}$)   | 1E6   | 1E5   | 1E5   | 1E6   | ...        |
| $B_0$ (Gauss)     | 1E-3  | 1E-3  | 1E-3  | 1E-3  | ...        |
| $T_e$ (K)         | 1.4E5 | 1.4E5 | 1.4E5 | 1.4E5 | 2E5        |
| $U$              | 0.2   | 0.2   | 2E-4  | 0.2   | ...        |
| $d$ (cm)          | 5.5E13| 8.15E14| 1E14  | <5.9E13| ...        |
| $d/g$            | 1E-14 | 5E-15 | 1E-14 | 5E-15 | ...        |
| C iv (ergs cm$^{-2}$ s$^{-1}$) | 9.4E3 | 1E3   | 5.9E-4| <0.016| ...        |
| He/H            | 0.1   | ...   | 0.1   | ...   | 0.2        |
| C/H             | 3.3E-4| ...   | 3.3E-4| ...   | 3.5E-4     |
| N/H             | 5.4E-4| ...   | 5.4E-4| ...   | 3E-4       |
| O/H             | 8.6E-4| ...   | 8.6E-4| ...   | 9E-4       |
| Mg/H            | 6.9E-4| ...   | 6.9E-4| ...   | 3E-5       |
| Si/H            | 5.3E-5| ...   | 5.3E-5| ...   | 3E-5       |
| W (SUM1)        | 1     | ...   | 1     | ...   | ...        |
| W (SUM2)        | ...   | 1     | 1     | ...   | ...        |

* Hayes & Nussbaumer 1986 model.

In Figure 4, model calculations are compared with the observations. The observed data are taken from Nussbaumer & Dum (1997) in the wavelength range between 1280 and 2600 Å, and from Kenyon, Fernendez-Castro, & Stencel (1986) in the IR. RR Tel was detected as an X-ray source in 1978 by Einstein (Kwok & Leahy 1984), and in 1992 by ROSAT (Jordan, Murset, & Werner 1994). The data in the X-ray are taken from Figure 3 of Kwok & Leahy (1984). The SED of the continua calculated by models REV1 and EXP are represented by solid and dotted lines, respectively. For each model, in addition to the curve representing bremsstrahlung emission from the gas, reradiation by dust is represented by the curve in the IR ($\nu < 10^{14}$ Hz). Generally, the temperature of the grains downstream follows the trend of the temperature of the gas (Viegas & Contini 1994, Fig. 3); therefore, the location of the dust reradiation peak depends on the shock velocity. On the other hand, the intensity of the dust radiation flux relative to bremsstrahlung emission depends on the dust-to-gas parameter, $d/g$. 

**Figure 4:** SED of the continuum in the year 1978. Filled squares represent the observations; curves represent model calculations (see text).
The high-velocity model XX \( V_v = 500 \text{ km s}^{-1} \) could explain the wide foot underneath the nebular emission of C IV, N v, and He II lines observed by Nussbaumer & Dumm (1997). However, since large FWHM are not observed in the line profiles, the contribution of the spectrum calculated by the high-velocity model to the line fluxes should be negligible. The line intensities calculated by model XX depend strongly on the geometrical thickness of the emitting clump \( d \). To obtain line intensities lower than those from model REV1, \( d \) should be lower than \( 6 \times 10^{-13} \text{ cm} \).

A high \( V_v \) is justified in a colliding scenario, since the wind collision yields to the disruption of the colliding matter and to the formations of clumps. The fast wind will propagate almost unaffected in the voids between the clumps.

An alternative scenario is represented by model X0 (Fig. 4, short-dashed lines), characterized by \( V_v = 500 \text{ km s}^{-1} \), but with a lower density (about \( 10^5 \text{ cm}^{-3} \)). The downstream region at high temperature in the clumps is rather extended \( (>5 \times 10^{14} \text{ cm}) \) and leads to emission that fits the high-frequency data and to the desired almost negligible line fluxes.

### Table 2

| Line       | FWHM (km s\(^{-1}\)) | Observed from (ZSH) | REV1 | REV2 | EXP | SUM1 | SUM2 |
|------------|-----------------------|---------------------|------|------|-----|------|------|
| 1199 [S v] | 47                    | 1.51?               | 0.45 | 0.4  | ... | 0.45 | 0.4  |
| 1206 Si iii| 55                    | 1.15                | 1.2  | 0.85 | 4.9E5 | 1.2  | 1.14 |
| 1218 O v]  | 59                    | 9.63                | 9.6  | 9.6  | ... | 9.6  | 9.6  |
| 1236 N v]  | 61                    | 27.14               | 31   | 32   | ... | 31   | 32   |
| 1242 N v]  | 51                    | 13.67               | ...  | ...  | ... | ...  | ...  |
| 1264 Si ii | 45                    | 0.08                | 0.016| 0.01 | 3.1E6 | 0.2  | 1.8  |
| 1302 O i]  | 51                    | 1.41                | ...  | ...  | ... | ...  | ...  |
| 1305 O i]  | 39                    | 0.30                | ...  | ...  | ... | ...  | ...  |
| 1324 [Mg v] | 48                  | 2.16                | ...  | ...  | ... | ...  | ...  |
| 1334 C ii | 40                    | 0.29                | 0.07 | 0.12 | 1.8E5 | 0.1  | 0.23 |
| 1335 C ii | 65                    | 0.45                | 0.03 | 0.02 | 7E6  | 0.45 | 4.1  |
| 1393 Si iv | 49                    | 6.64                | 11   | 10   | ... | 11   | 10   |
| 1398 S iv] | 43                    | ...                | 0.3  | 0.28 | ... | 0.3  | 0.28 |
| 1401 O iv] | 47                    | 8.37                | 7.8  | 6.9  | 1.1E4 | 7.8  | 6.9  |
| 1404 O iv] + S iv] | 47    | 4.73                | 4.6  | 4.0  | ... | 4.7  | 4.0  |
| 1407 O iv] | 53                    | 1.34                | 1.2  | 1.2  | ... | 1.2  | 1.2  |
| 1483 N iv] | 49                    | 0.41                | 0.56 | 0.5  | ... | 0.56 | 0.5  |
| 1486 N iv] | 42                    | 9.49                | 43   | 37   | ... | 43   | 37   |
| 1533 Si ii | 66                    | 0.24                | 0.012| 0.012| 7E5  | 0.06 | 0.42 |
| 1548 C iv | 52                    | 66.55               | 100  | 100  | 100  | 100  | 100  |
| 1551 C iv | 50                    | 34.40               | ...  | ...  | ... | ...  | ...  |
| 1574 [Ne v] | 61                  | 2.95                | 0.17 | 0.11 | ... | 0.17 | 0.11 |
| 1601 [Ne v] | 64                  | 1.88                | 2.3  | 2.3  | ... | 2.3  | 2.3  |
| 1604 He ii | 71                    | 30.70               | 32   | 36   | 1.6E7 | 32   | 45   |
| 1660 O iii] | 38                  | 2.57                | 5.1  | 6.8  | ... | 5.1  | 6.8  |
| 1666 O iii] | 36                  | 7.61                | ...  | ...  | ... | ...  | ...  |
| 1718 N iv] | 78                    | 0.27                | 0.25 | ...  | ... | 0.25 | ...  |
| 1746 N iii] | 48                  | 0.12                | ...  | ...  | ... | ...  | ...  |
| 1748 N iii] | 45                  | 0.43                | ...  | ...  | ... | ...  | ...  |
| 1749 N iii] | 41                  | 1.77                | 4.2  | 8    | 1.2E4 | 4.2  | 8    |
| 1752 N iii] | 48                  | 0.72                | ...  | ...  | ... | ...  | ...  |
| 1754 N iii] | 44                  | 0.37                | ...  | ...  | ... | ...  | ...  |
| 1806 [Mg vi] | ...                | ...                | 0.3  | 0.9  | ... | 0.3  | 0.9  |
| 1808 Si ii | 45                    | 0.05                | 0.3  | 0.07 | 2.1E6 | 0.18 | 1.3  |
| 1814 [Ne iii] | 43                 | 0.75                | 0.07 | 0.75 | 1.8E4 | 0.08 | 0.07 |
| 1882 Si iii | ...                 | 0.04                | ...  | ...  | ... | ...  | ...  |
| 1892 Si iii | 40                    | 5.10                | 6.6  | 5.5  | 1.5E6 | 6.7  | 6.4  |

Note.—Arrows indicate that the multiplet is summed up or down.
5.1. The UV Spectrum

In the 1993 UV spectrum, the high-ionization lines dominate, and the O I and C II lines are still present, although weakened. Therefore, a region of gas that emits low ionization level and neutral lines must still be present. This corresponds to a model with low $V_s$, low or even absent $U$, and a large zone of emitting gas at low temperature. Similar conditions were adopted to fit the 1978 spectrum (model EXP). In other words, the contribution of the expanding shock to the emitted spectrum is unavoidable. Note that the flux intensity of C IV has decreased by a factor of $>2$ with respect to the 1978 flux. In Table 4, line intensities relative to C IV = 100 are listed together with the FWHM from ZSH and the observed line ratios (cols. [2] and [3]). Two models for the reverse shock follow in columns (4) and (5), and three models representing the expanding shock are given in columns (6), (7), and (8). In the last three columns of Table 4, the composite models sum1, sum2, and sum3 (which better fit the observations) are presented. The relative weights of the single contributions in these models are listed in the bottom of Table 3.

The best fit to the 1993 high-level line spectrum, even if rough, is obtained by model rev1, which is characterized by a high $n_0$. In particular, the calculated intensity of the [Mg VI] 1806 line increased by a factor of 1.9 from 1978. This trend agrees with the data listed by ZSH (Fig. 2). The other parameters of model rev1 (Table 3) suggest that, compared to 1978, the shock velocity has slightly decreased, the densities are higher, and $U$ is lower than for model REV1 (see Table 1). A similar situation was found in the evolution of HM Sge (Formiggini et al. 1995).

On the other hand, comparing the FWHM of the low-ionization and neutral lines between 1978 and 1993, the expanding shock has maintained the same velocity, or even increased slightly. Three different models are considered, because depending on the location of the shock front, the preshock density can be very different. We have adopted the same velocity for all the low-level lines even if the FWHM of these lines (Table 5) show a wide range of values from 17 km s$^{-1}$ of [O I] 6300 to 83 km s$^{-1}$ of [N II] 6584.

Model exp1 represents the case in which the shock front is still near the giant star (Fig. 3b) and a high density charac-
The relative abundances are close to solar ones, because mixing is rather strong at those large distances. In this model the shock could have traveled in about 15 yr to a distance beyond $2.3 \times 10^{15}$ cm. The geometrical thickness of the emitting slab is large. The radiation flux from the hot star is not prevented from reaching the inner edge of the slab, but it is low.

Note that the three models exp1, exp2, and exp3 contribute only to low-level lines in the UV spectrum, which are few compared to the numerous high-level lines. Therefore, we will constrain the models by the fit of the optical spectrum, where the low-level lines are as numerous as the high-level ones. The consistent fit of line spectra in the different frequency ranges implies cross-checking until a fine-tuning of all of them is found.

### 5.2. The Spectrum in the Optical Range

In Table 5 observed line intensities in the optical range are compared with model calculations. These lines are those that are common to the observations of McKenna et al.
(1997) and the SUMA code. The lines in the optical range are given relative to Hβ = 1. For consistency, the same models used to fit the line in the UV are adopted. However, model rev2 is omitted.

Note that [O II] 3727, even if low, is present in the spectra. Considering that [O II] has a critical density for collisional deexcitation of \( \geq 3 \times 10^3 \) cm\(^{-3} \), the density in the emitting gas cannot be much higher. The electron density downstream decreases with recombination (§ 6); therefore, even preshock densities higher than the critical one can fit the [O II]/Hβ line ratio. On this basis, model exp3 is more acceptable than exp1 or exp2.

The calculated [O II] 4959 + 5007 is rather high compared with the observed line. A lower weight of model exp3 in the weighted sum (sum3) could improve the fit of [N II] 5754 Hβ and [O II]/Hβ, but would definitively spoil the fit of [O II]/Hβ.

Interestingly, a low \( R_{O\alpha} = [O III] 5007/[O II] 4363 \) ratio coexists with a relatively high [O II] 3727/Hβ ratio. Low \( R_{O\alpha} \) is generally due to either a high density or a high temperature of the emitting gas. High temperatures are excluded because the shock velocity is low. Therefore, high densities are indicated by \( R_{O\alpha} \) and low densities by [O II]/Hβ. This peculiarity of the spectrum strengthens the hypothesis of a composite model. In fact, the low [O III] 5007/[O II] 4363 ratio comes from the rev1 model, while the relatively high [O II] 3727/Hβ ratio comes from model exp3. The [O I] 6300/Hβ line ratio, even if not very high, indicates that a large zone of neutral oxygen is present and is consistent with the large \( d \approx 2 \times 10^{15} \) cm of model exp3. The relatively high [O I]/Hβ line ratio also appears in model sum2 if a weight of 100 (see Table 3) is adopted for model exp2. This is rather high, and definitively spoils the fit of most of the other line ratios. The composite model sum1 nicely fits most of the optical–near IR lines; however, [O I]/Hβ and [N II] 6584 + /Hβ are largely overestimated.

In the composite model sum3, model exp3 has been given a weight 3 times that of model rev1. This is acceptable, considering that the emission from the nebula between the components is certainly smaller than that from the nebula encircling the system.

Following the analysis of the optical spectrum, the composite model sum3 is selected. This model also fits the UV spectrum best, even if the O I 1304/C IV line ratio is underestimated (Table 4).

### 6. THE RR TEL SYSTEM IN THE EPOCHS 1978 AND 1993

After selecting the composite models that best fit the spectra observed in each of the epochs, a more quantitative description of the system can be given.

The results of model calculations give a rough physical picture of RR Tel in 1978. The distance \( r_{rs} \) of the reverse shock from the WD can be calculated from

\[
U_{nc} = N_{ph}(R_{wd}/r_{rs})^2, \tag{1}
\]

where \( N_{ph} \) is the Planck function corresponding to \( T_s = 1.4 \times 10^5 \) K and the WD radius \( R_{wd} = 10^{10} \) cm. Adapting the parameters of model REV1, \( N_{ph} = 3.4 \times 10^{46} \) photons cm\(^{-2} \) s\(^{-1} \), and considering the density \( n = n_{o} \) at the leading edge of the clumps due to the adiabatic jump, \( r_{rs} = 1.1 \times 10^{15} \) cm.

Applying equation (1) to the expanding shock (model EXP), the distance between the WD and the low-velocity slab \( r_{es} \) can be calculated. In this case, the density \( n \) is calculated after compression downstream \( (n = 3.2 \times 10^7 \) cm\(^{-3} \)) and the \( r_{es} \) that results is \( 1.37 \times 10^{15} \) cm. The expanding shock is very close to or even passing the red giant, considering the wide interbinary separation \( \approx 10^{15} \) cm.

In 1993, the reverse shock is at about the same distance from the WD as in 1978. On the other hand, from equation (1), the expanding shock represented by model exp3 has reached a distance of about \( 5 \times 10^{15} \) cm, corresponding to the outskirts of the system (§ 5.1).

As for the X-ray, the detection by ROSAT in 1992 (Jordan et al. 1994) indicates that the high-velocity wind (500 km s\(^{-1} \)) component is unchanged from 1978 (§ 4.2).

We now compare the physical conditions in the emitting gas at the two epochs.

### TABLE 5

**Optical Line Ratios to Hβ = 1 (1993)**

| Line       | FWHM (km s\(^{-1}\)) | Observed (from ZSH) | rev1 | exp1 | exp2 | exp3 | sum1 | sum2 | sum3 |
|------------|-----------------------|---------------------|------|------|------|------|------|------|------|
| 3710 S II  | 3.4E-3                | 9E-4                | 7E-4 | 0.26 | 1.2E-3 | 8.2E-4 | 0.015 | 0.001 |      |
| 3729b+ [O II] | 48.02               | ...                | 2E-3 | 0.22 | 1.2 | 8.2E-4 | 0.012 | 0.014 |      |
| 3759 Fe III | 69.09                | 0.84               | 2.7E-3 | 0.5 | 0.79 | 0.84 |      |      |      |
| 3869b+ [Ne III] | 43.07               | 0.79               | 3.1 | 2.5 | 0.23 | 0.55 | 0.42 |      |      |
| 4068+ [S II] | 46.02               | ...                | 0.33 | 0.6 | 1.7 | 0.13 | 0.03 | 0.02 |      |
| 4114 [Fe II] | 32.49E-3            | ...                | 0.16 | 0.36 | 0.08 | 8.8E-3 | 4.3E-3 |      |      |
| 4363 [O III] | 40.5               | 0.54               | 5 | 0.16 | 0.32 | 0.85 | 0.54 |      |      |
| 4625 [Ar v]  | 45.5E-3              | 0.019              | 3E-3 | 0.01 | 0.018 | 0.019 |      |      |      |
| 4686 He II  | 57.9                | 1.0                | ... | 0.02 | 0.37 | 0.6 | 0.94 | 0.99 |      |
| 4740 [Ar iv] | 67.013              | 7.2E-3             | 6E-3 | 4.2E-3 | 7.1E-3 | 7E-3 |      |      |      |
| 4893 [Fe v]  | 65.05               | 0.12               | ... | 0.07 | 0.11 | 0.12 |      |      |      |
| 4959+ [O II] | 59.035              | 0.6                | ... | 11 | 17.2 | 0.35 | 0.29 | 0.53 |      |
| 5076 [Fe vi] | 40.14E-3            | 0.09               | ... | 0.03 | 0.06 | 0.06 |      |      |      |
| 5754 [N II]  | 41.16E-3             | 2.3E-3             | 5.5 | 1.4E-3 | 0.3 | 0.06 |      |      |      |
| 5876 He I 1   | 41.9E-3              | 7.4E-3             | 7E-3 | 0.3 | 0.13 | 7.2E-3 | 0.02 | 9E-3 |      |
| 6300+ [O I]   | 17.4E-3              | 1.65               | ... | 0.13 | 0.67 | 0.7 | 7.2E-3 | 8E-3 |      |
| 6310+ [S II]  | 40.13E-3             | 1.5E-3             | 1.1E-3 | 0.42 | 1.8E-3 | 1.3E-3 | 0.024 | 1.5E-3 |      |
| 6584+ [N II]  | 83.5E-3              | 4E-4               | 0.54 | 1.44 | 3.8 | 0.2 | 0.08 | 0.01 |      |
The profiles of the fractional abundances of the most significant ions throughout the clumps in the two epochs are compared in Figures 6a (for 1978) and 6b (for 1993). In both figures, the WD is on the left. The diagrams on the left represent the clump downstream of the reverse shock, and the diagrams on the right the clump downstream of the expanding shock. Note that the blackbody radiation from the hot star reaches the very shock front edge in the reverse shocked clumps and the edge opposite to the shock front in the expanding ones. To better understand the physical conditions in the emitting regions, the profiles of the electron temperature, $T_e$, and of the electron density, $N_e$, in a logarithmic scale are also given at the top of the figures.

First, we focus on models REV1 and rev1 (left side of Figs. 6a and 6b), the spectra of which largely prevail in the weighted sums of both epochs. Note that He$^{++}$/He and C$^{++}$/C are very high throughout the clump geometrical width. The dotted vertical lines in Figures 6a and 6b show the actual geometrical thickness of matter-bound models. For comparison, the radiation-bound model results are also shown beyond these lines. The observational data show that C IV and He II line intensities prevail, and that N V/

C IV, He II/C IV, and (in a reduced way) also O V/C IV line ratios increase from 1978 to 1993 (see Tables 2, 4, and 5). In the same time, C IV absolute flux decreases by a factor of >2. The fit to these observations can be obtained by slightly reducing the shock velocity and the ionization parameter, and by increasing the preshock density, but in particular the geometrical thickness of the clump must be reduced by a factor larger than 2 (Tables 1 and 3).

Regarding the expanding shock, the physical conditions across the clumps in 1978 (model EXP) and 1993 (model exp3) are very different (Figs. 6a and 6b, diagrams on the right side of the figures). The clump is divided into two halves by the vertical solid line. The x-axis scale is logarithmic and symmetric, in order to have a comparable view of the two parts of the clump. The shock front is on the right, while the edge photoionized by the WD radiation is on the left. In 1993, the electron density never exceeds $10^5$ cm$^{-3}$. In 1978, the electron density never exceeds $10^5$ cm$^{-3}$. In 1978, the region corresponding to the O$^{++}$ ion prevails throughout the whole clump, while in 1993 it is reduced to the shock-dominated region.

In the previous sections we presented a model for RR Tel at two epochs. The first one (1978) is characterized by large fluctuations in the light curve and in the line intensities on very short timescales. In the second epoch (1993), the system recovered the fading trend. This epoch is considered with the aim of investigating the evolution of the system.

After the outburst, two shocks are present: the reverse shock propagates in the direction of the WD, and the other one expands toward or beyond the giant. A good fit of the observed emission line spectra and continuum in 1978 is provided by a composite model, in which the reverse shock is characterized by a velocity of $\sim 80$ km s$^{-1}$ and the expanding shock by a velocity of $\sim 45$ km s$^{-1}$. A high-velocity (500 km s$^{-1}$) wind component is revealed from the fit of the SED of the continuum in the X-ray range in 1978, but it is quite unobservable in the line profiles if the geometrical thickness of the clumps is lower than $6 \times 10^{13}$ cm.

The large fluctuations observed in the 1978 light curve result from line intensity rather than continuum variations. These variations are explained by the fragmentation of matter at the time of the head-on collision of the winds from the two stars.

The results of our modeling show that in 1993, the reverse shock velocity has slightly decreased (70–50 km s$^{-1}$), while the expanding shock with velocity between 50 and 100 km s$^{-1}$ has overcome the symbiotic system and is propagating in the nearby ISM. The decrease in the absolute flux of C IV is justified by the reduced shock velocity and ionization parameter. However, the geometrical thickness of the emitting clumps is the critical parameter that can explain the short-timescale variabilities of the spectrum and the trend of slow line intensity decrease.

Relative abundances of carbon, nitrogen, oxygen, and silicon to hydrogen calculated by the present model are in agreement with those assumed by the model of Hayes & Nussbaumer (1986).

Finally, although our modeling is rather simplistic, it shows that shock models can contribute to a better understanding of the outburst evolution of RR Tel.

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