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Recurrent novae at quiescence: systems with giant secondaries

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Abstract. Spectroscopic and photometric behaviour of the class of recurrent novae with giant secondaries (T Coronae Borealis, RS Ophiuchi, V3890 Sagittarii and V745 Scorpii) at quiescence are presented in this study. The hot component in these systems is variable, with the variability manifesting as variability in the ultraviolet luminosity, the ultraviolet and optical emission line fluxes and in the UBV/visual magnitudes. The variations are uncorrelated with the binary orbital motion. The observed ultraviolet+optical spectral characteristics of the hot component in these systems can be explained by a white dwarf+accretion disc embedded in an envelope of wind from the M giant secondary. We suggest that the observed variations are a result of (a) fluctuations in the mass accretion rate; (b) changes in the column density of the absorbing wind envelope, which is optically thick.

Key words: stars: binaries: symbiotic – stars: novae, cataclysmic variables – stars: individual: T CrB, RS Oph, V3890 Sgr, V745 Sco

1. Introduction

The recurrent novae (RNe) form a small, but heterogeneous group of cataclysmic variable stars that undergo classical nova-like outbursts, reaching luminosities $M_V \leq -5.5$, at intervals of the order of decades. The nova outbursts are accompanied by the ejection of matter at velocities $V_{\rm exp} \geq 300$ km s^{-1}. Some RNe (U Scorpii, V394 Coronae Australis, LMC 1990 No. 2, T Pyxidis) are short period binaries similar to the classical novae and consist of a white dwarf and a dwarf secondary. In contrast, the other members of this group (RS Ophiuchi, T Coronae Borealis, V745 Scorpii, V3890 Sagittarii) are long period binaries, with periods of the order of several hundred days, and consist of a hot white dwarf and a red giant like the symbiotic binary systems. The nova outbursts in RNe is thought to be powered by a thermonuclear runaway (TNR) in the accreted layer formed on the white dwarf following accretion of mass from the companion (Starrfield et al. 1985; Kato 1990, 1991).

The outburst properties of the RNe with giant secondaries are quite homogeneous. They are fast novae with a rate of decline of ~ 0.3 mag/day. The outburst spectrum is characterized by broad emission lines ($V_{\rm exp} \sim 4000$ km s^{-1}), which narrow with time, the presence of intense coronal lines and other high excitation lines. The 1985 outburst of RS Oph was one of the best studied events, with the outburst being recorded from X-rays to radio wavelengths (see Rosino 1987 for a review on the outbursts of RS Oph). The coronal lines, X-ray and the radio emission arise in a region heated by the shock interaction of the fast moving dense nova ejecta with the pre-outburst slow moving red giant stellar wind. Some of the parameters of these systems are listed in Table 1.

At quiescence, the optical spectrum is dominated by that of the red giant with emission lines predominantly due to H I and He I. With the exception of T CrB, the other objects also have lines due to Fe II and Ca II. He II lines are either extremely weak or absent. Van Winckel et al. (1993) classify these systems as belonging to the symbiotic type S3, i.e. stars with a slow, very dense wind, leading to a deep central reversal of the Hα emission line.

Only T CrB and RS Oph have been observed in the ultraviolet (UV) using the International Ultraviolet Explorer (IUE). The UV spectra of T CrB show a complex structure with emission lines and shell-like absorption features superposed over a relatively hot continuum (Selvelli et al. 1992). The UV spectra of RS Oph show a flat continuum with a few weak emission lines like C III 3130, N III] 1750 and C IV 1550 (Dobrzycka et al. 1996a). The UV continuum as well as the emission line fluxes are variable in both the objects, and are strongly correlated. Variability in the UBV/visual magnitudes, and the optical emission lines has also been reported (e.g. Kenyon & Garcia 1986; Iijima 1990; Iijima et al. 1994; Anupama & Prabhu 1991; Anupama 1997; Dobrzycka et al. 1996a).

The binary nature of T CrB was first established by Sanford (1949), and later by Kraft (1958) who refined Sanford's period estimate to 227.6 days, derived a total mass of the system of 5 $M_\odot$, and a mass ratio of 1.4 with the giant being the more massive component. Kenyon & Garcia (1986) obtained new radial velocity data for the giant and combining with the data of Sanford and Kraft, obtained a new orbital solution and confirmed the previous estimates for the component masses. These results suggested the hot component has a mass exceeding the Chandrasekhar limit and hence must be a main sequence star, and posed a serious problem for the thermonuclear runaway model for the nova outbursts requiring a massive white dwarf.

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Table 1. Parameters of recurrent novae with giant secondaries

Name	$m_{\max}$	$m_{\min}$	t_3 days	$< t_{\rm rec} >$ yrs	$E(B-V)$	dist kpc	Giant	P days	Ref
T CrB	2.0	10.2	6.8	80	0.15	1.3	M3 III	227.67	1,2
RS Oph	5.0	11.5	9.5	22	0.70	1.6	M0/2 III	460	3,4
V3890 Sgr	8.2	17.0:	17.0	28	0.5	5.2	M5 III		5
V745 Sco	9.6	19.0:	14.9	52	1.1	4.6	M6 III		5

References: 1 Selvelli et al. (1992); 2 Belczyński & Mikołajewska (1998); 3 Cassatella et al. (1985); 4 Dobrzycka & Kenyon (1994); 5 Harrison et al. (1993).

Table 2. Details of observations from VBO

Date	JD*	Phase	m_{5500}	λ (Å)
T CrB[1]				
1990, Mar 24.9	47975	0.47	10.2	4200–7000
1990, Mar 30.9	47981	0.50	10.4	4200–7000
1990, Mar 31.9	47982	0.50	10.3	4200–7000
1990, Apr 1.9	47983	0.51	10.4	6000–8800
1990, Apr 2.9	47984	0.51	10.2	6000–8800
1995, Mar 15.9	49792	0.45	10.0	4200–7000
1995, Apr 13.8	49821	0.58	10.3	4200–7000
1996, Apr 6.9	50180	0.16	9.7	4200–7000
1997, Apr 20.8	50559	0.82	10.0	3600–8000
1997, May 18.9	50587	0.94	9.8	3600–8000
1998, Mar 20.9	50893	0.29	9.9	3600–9000
RS Oph[2]				
1990, Feb 21.0	47944	0.40	11.9	4300–7300
1990, Mar 31.7	47982	0.48	11.4	4500–8900
1991, Apr 15.8	48362	0.31	11.7	4400–9000
1992, Feb 14.0	48667	0.97	11.6	4100–7200
1992, Mar 13.9	48695	0.03	11.7	4100–7200
1993, Feb 15.0	49034	0.77	10.3	4200–7000
1993, Mar 28.0	49075	0.86	11.4	4000–7000
1995, Apr 13.9	49821	0.48	10.8	4500–7000
1996, Apr 6.9	50180	0.26	11.7	4200–7000
1997, Apr 20.9	50559	0.09	12.1	3600–8000
1997, May 18.8	50587	0.15	11.1	3600–8000
1998, Mar 19.4	50892	0.81	11.1	3600–9000
V3890 Sgr				
1997, Apr 20.9	50559		15.0	3600–8000
1998, Mar 21.0	50893		15.5	3600–8500
V745 Sco				
1998, Mar 20.9	50893		17.7	3600–8500

*: JD 2400000+
1: $T_0 = JD\,2431931.05 + 227.67\,E$
2: $T_0 = JD\,2444999.9 + 460\,E$

Recently, Belczyński & Mikołajewska (1998) have reanalyzed the photometric and radial velocity data and arrived at new parameters for the binary components. Their analysis shows that the mass ratio of T CrB $q \equiv M_{\rm g}/M_{\rm h} \approx 0.6$ with stellar masses $M_{\rm g} \sim 0.7\,M_\odot$ for the red giant and $M_{\rm h} \sim 1.2\,M_\odot$ for the hot companion, compatible with a white dwarf mass. This is also in agreement with the UV characteristics of the hot component which are easily explained by the presence of a white dwarf acceptor (Selvelli et al. 1992).

Garcia (1986) found that the radial velocity of the absorption features in the shell type profiles of the Fe II lines in RS Oph varied in a range from -30 km s^{-1} to -50 km s^{-1} with a period of about 230 days. Dobrzycka & Kenyon (1994) recently reanalyzed the orbital period for RS Oph and found the system has a spectroscopic orbit of period 460 days. Assuming the hot component to be a massive white dwarf, they estimated RS Oph to be a low mass system, with low inclination, quite similar to T CrB. The nature of the hot component in this system, however, still remains a bit of a mystery. Following the decline from the 1985 outburst, the temperature and luminosity of the central ionizing source as inferred from the optical and X-ray spectra (Anupama & Prabhu 1989; Mason et al. 1987), T$\sim 3.5\times10^5$ K; L$\sim 10^{37}$ erg s^{-1}, were consistent with the remnant residual hydrogen burning on top of a white dwarf with a thin atmosphere following the TNR outburst. The recent ROSAT detection of RS Oph at quiescence (Orio 1993) however, implies a soft X-ray luminosity $\sim 10^{31} - 10^{32}$. Recently, Dobrzycka et al. (1996a) analyzed the quiescent optical and UV spectra and estimated the hot star has a luminosity of $L_h \sim 100$–$600\,L_\odot$ and the spectrum mimics that of a B-type shell star. The absence of He II lines in the spectra together with the presence of He I lines led them to estimate the temperature of the source to be $\approx 5\times10^4$ K. They also found that although the hot component luminosity is consistent with the high accretion rate, $\sim 10^{-8}\,M_\odot\,{\rm yr}^{-1}$, needed for recurrent nova eruptions, the effective temperature and luminosity place the hot component far from standard massive white dwarf tracks in the HR diagram.

In this work, the behaviour of these systems at quiescence is studied. The observed spectral features of the hot component are interpreted in terms of an accreting white dwarf embedded in an envelope of wind from the giant secondary.

2. Observational data and results

All published photometric data of these objects at quiescence, as well as the visual magnitude observations from AAVSO and VSNET have been used in this study. Spectroscopic data are based on those published in the literature, as well as CCD spectra obtained from the Vainu Bappu Observatory (VBO) using both the 1.02m and the 2.3m telescopes. The VBO spectra were obtained during 1990–1998 at 10–12 Å resolution. The details of observations are given in Table 2. All spectra were reduced in the standard method, and brought to flux scale using spectrophotometric standards.

Table 3. T CrB: Emission line fluxes in 10^{-12} erg cm^{-2} s^{-1}

	JD 2400000+										
λ Å	47975	47981	47982	47983	47984	49792	49821	50180	50559	50587	50893
Hδ 4101									0.74	1.48	
Hγ 4340								1.48	0.94	1.52	
He II 4686									0.35	0.43	
Hβ 4861	0.68	1.28	1.06			0.92	0.14	3.08	2.34	3.75	0.59
He I 5876								1.02	0.86	1.22	
Hα 6563	2.36	5.20	5.00	5.91	6.46	5.07	1.21	13.78	6.36	8.60	3.71
He I 6678								1.24	0.58	1.19	
He I 7065									0.46		

Table 4. RS Oph: Emission line fluxes in 10^{-12} erg cm^{-2} s^{-1}

	JD 2400000+											
λ Å	47944	47982	48362	48667	48695	49034	49075	49821	50180	50559	50587	50892
Hδ 4101							0.19					0.03
Hγ 4340				0.15	0.33	0.48	0.37		0.14	0.12	0.32	0.04
Hβ 4861	0.76	1.18	0.87	0.36	0.81	2.75	1.09	1.73	0.86	0.81	1.50	0.46
Fe II 4924	0.19	0.23	0.13	0.06	0.10	0.27	0.13	0.16	0.14	0.10	0.13	0.06
Fe II 5018	0.13	0.30	0.14	0.04	0.13	0.45	0.13	0.24	0.22	0.27	0.23	0.09
Fe II 5169	0.16	0.11	0.21	0.12	0.16	0.63	0.32	0.16	0.15	0.14	0.45	0.09
Fe II 5235	0.12	0.15	0.08		0.06	0.15	0.07		0.13	0.05	0.14	0.04
Fe II 5276	0.04	0.23	0.13	0.05	0.14	0.74	0.30	0.42		0.18	0.29	
Fe II 5317	0.28	0.34	0.20	0.10	0.08	0.86	0.27	0.14	0.12	0.15	0.33	0.08
Fe II 5363	0.22	0.28	0.10		0.11	0.45	0.07	0.15	0.07	0.03	0.16	0.07
Fe II 5535	0.05	0.13			0.13	0.19	0.09	0.16	0.06	0.07	0.10	0.12
He I 5876	0.33	0.76	0.56	0.24	0.58	1.30	0.54	0.81	0.54	0.36	0.81	0.42
Fe II 5991	0.08	0.12	0.07		0.09	0.14			0.08	0.06	0.15	
Hα 6563	6.93	11.70	9.31	4.19	1.12	25.88	10.57	17.10	11.79	7.43	14.89	15.19
He I 6678	0.20	0.39	0.30	0.10	0.50	0.48	0.15	0.25	0.33	0.18	0.21	0.27
He I 7065	0.33	0.74	0.43	0.13	0.36					0.22	0.26	0.15
O I 7774			0.09							0.04		0.13
O I 8446		1.01	0.93									1.50
Ca II 8498		0.88	0.87									1.17
Ca II 8542		0.45	0.64									0.97
Ca II 8662		0.51	0.63									0.75

In Figs. 1–4 we show, respectively, the spectra of T CrB, RS Oph, V3890 Sgr and V745 Sco. The fluxes of selected emission lines are listed in Tables 3–6. The errors in the fluxes are $\sim$ 7–10% for the bright lines and $\sim$ 15–20% for the fainter features. The errors in some of the faint features in V745 Sco could be around 25%. The flux calibration is inaccurate beyond 8400 Å in the spectra of V3890 Sgr and V745 Sco obtained in 1998.

Table 5. V3890 Sgr: Emission line fluxes in 10^{-13} erg cm^{-2} s^{-1}

	JD 2400000+	
λ Å	50559	50893
Hγ 4340	0.37	0.26
He II4685	0.01	
Hβ 4861	1.48	0.88
Fe II 4924	0.24	0.14
Fe II 5018	0.56	
He I 5876	0.60	0.35
Hα 6563	12.21	5.87
He I 6678	0.27	0.12
He I 7065	0.25	0.08
O I 7774	0.22	0.03
O I 8446		1.45
Ca II 8498		0.12
Ca II 8542		0.11

3. Analysis

3.1. Variability

3.1.1. T Coronae Borealis

The UBV and J light curves of T CrB (Belczyński & Mikołajewska 1998 and references therein) show sinusoidal variations with half the orbital period caused by the orbital mo-

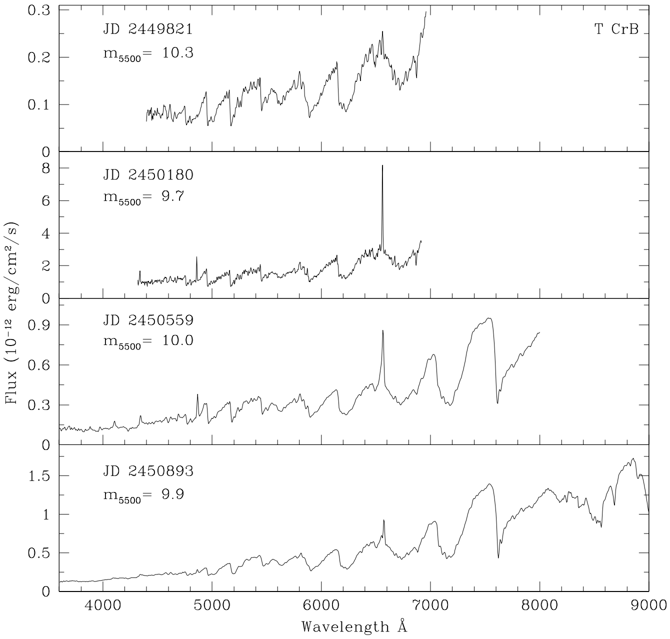

Fig. 1. Sample spectra of T CrB based on observations from VBO.

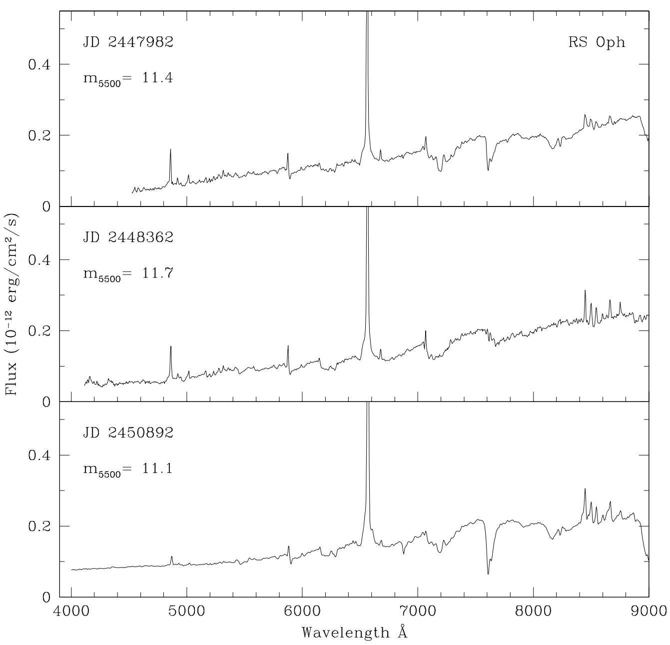

Fig. 2. Sample spectra of RS Oph obtained from VBO. The Hα line is truncated.

tion of the tidally distorted red giant. This effect is more pronounced in the V and J bands, while in the B and U bands it is superposed upon secular changes. The U light curve is dominated by the secular changes, as well as some erratic variations, which can be attributed to the hot component.

The optical emission line fluxes vary considerably during the period covered by our observations (Table 3). Similar variability has been previously observed (e.g. Andrillat & Houziaux 1982; Kenyon & Garcia 1986; Iijima 1990; Anupama & Prabhu 1991; Anupama 1997). Anupama (1997) also reports

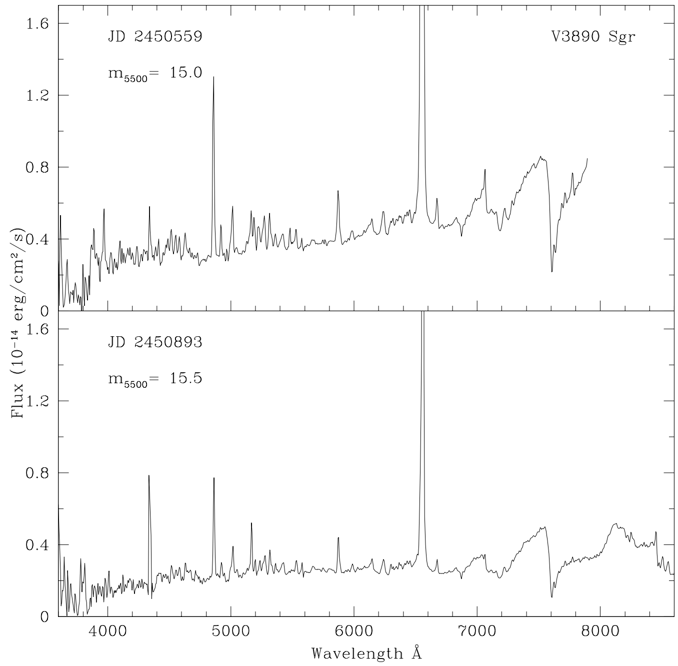

Fig. 3. Spectra of V3890 Sgr obtained from VBO. The Hα line is truncated.

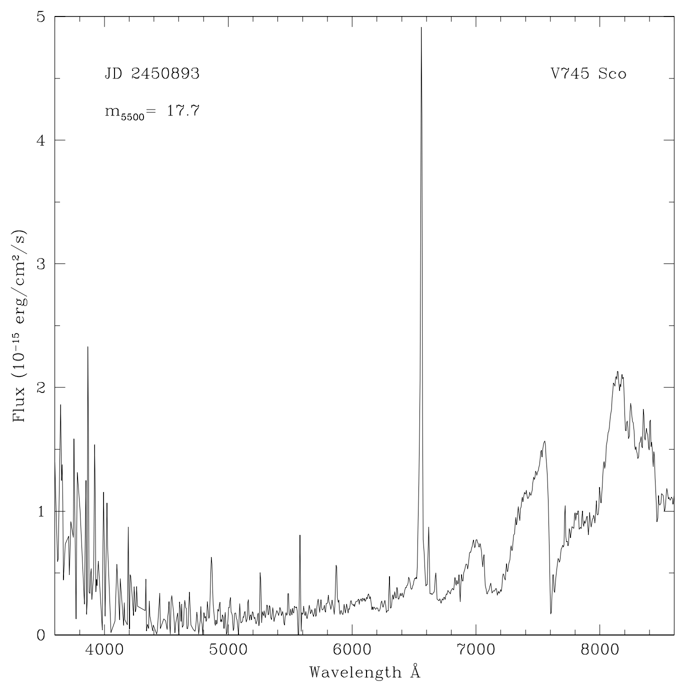

Fig. 4. Spectrum of V745 Sco.

long-term periodicities in the optical emission line variation. T CrB was in a high state in 1987 with the emission lines being very bright, followed by a low state in the early 1990's, when only the Balmer Hα and Hβ lines were weakly present. The emission line strengths increased once again in 1996, accompanied by significant brightening of the optical continuum.

Fig. 5 (top panel) shows our Hα and Hβ line fluxes together with those published plotted against the V magnitude. The cor-

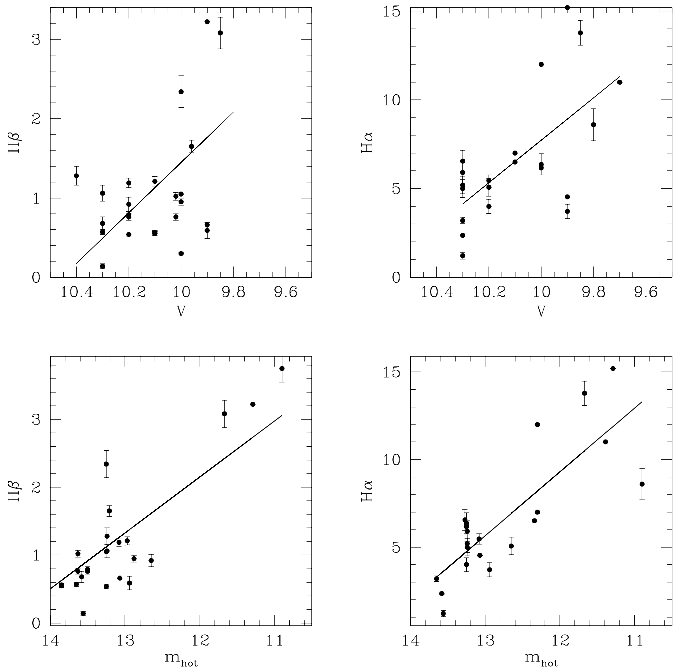

Fig. 5. Correlation of the Hβ and Hα emission line fluxes in T CrB with the V magnitude (*top panel*), and the V magnitude of the hot component $m_{\rm hot}$ (*bottom panel*). Fluxes are in 10^{-12} erg cm^{-2} s^{-1}.

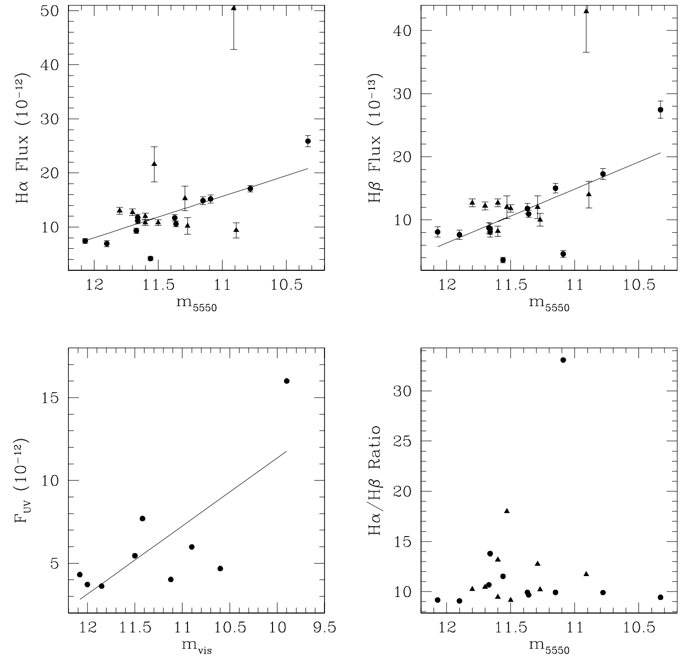

Fig. 6. *Top:* Correlation of the Hβ and Hα emission line fluxes in RS Oph with the monochromatic magnitude at 5500 Å. *Bottom:* Correlation of the total UV flux with visual magnitudes (*left*) and the observed Balmer line ratios as a function of m_{5500} (*right*). All fluxes are in erg cm^{-2} s^{-1}. Filled circles represent VBO data and filled triangles represent published data.

Table 6. V745 Sco: Emission line fluxes in 10^{-14} erg cm^{-2} s^{-1}

JD 2450893	
λ Å	Flux
Hβ 4861	1.89
Fe II 4924	0.27
Fe II 5018	0.32
Fe II 5169	0.35
Fe II 5317	0.20
Fe II 5363	0.19
He I 5876	1.15
Hα 6563	12.92
He I 6678	0.46
He I 7065	0.35

relation between the line strengths and the V magnitude is evident. Iijima (1990) found a similar behaviour of the Hβ flux with the B magnitude. The quiescent V light curve of T CrB is dominated by the ellipsoidal changes of the cool giant. To estimate the V magnitude of the hot component, $m_{\rm hot}$, we have subtracted the contribution of the M giant to the observed V magnitudes of T CrB using the synthetic ellipsoidal light curve for the M giant computed by Belczyński & Mikołajewska (1998). The strong correlation of the emission line fluxes with so estimated $m_{\rm hot}$ (bottom panel of Fig. 5) indicates that the hot component activity is responsible for the optical emission line changes.

The enhancement in the line fluxes in the optical is also correlated with the activity in the UV. For example, the fluxes in the UV and the optical emission lines were low in 1981 (Williams 1983, Blair et al. 1983, Selvelli et al. 1992), while the high state observed in the optical in 1987 coincides with the enhancement seen in the June 1987 UV spectrum. During the period 1982–1990, Luthardt (1992) found variations in the mean U brightness by more than 2.5 mag, while the variations in the B and V band were, respectively, about 1 mag and 0.3 mag. The variation in the U band is strongly correlated with the variation observed in the UV flux during the same period. It is thus quite evident that the optical enhancements seen in T CrB are associated with the hot component. We will discuss later as to the possible causes of the activity.

3.1.2. RS Ophiuchi

The visual magnitude of RS Ophiuchi is found to vary between 11–12 magnitude, with occasional rises to ~ 10 magnitude. The spectra presented in Fig. 2 and the fluxes listed in Table 4, indicate that the optical emission lines are also variable. Variability in the UV flux has also been reported (Dobrzycka et al. 1996a, Shore et al. 1996). Fig. 6 presents our Hβ and Hα flux estimates together with published data plotted against the continuum magnitude at 5500 Å, m_{5500}, dependence of the Balmer line ratios on m_{5500}, and the $F_{\rm UV}$ (from Shore et al. 1996) vs. $m_{\rm vis}$. The figure shows that the emission line flux variability is strongly correlated with the activity of the hot component as in the case of T CrB. Although the data available in the UV are few, there is also an indication of a correlation between the optical and UV flux.

Broad emission components in the emission lines of H I and He I were detected by Iijima et al. (1994) during 1991 and 1992. These broad components are present in the Hβ and Hα lines in some of our spectra (see Fig. 2) at velocities of the order of ~ 1000 km s^{-1}. The wavelength, profile and intensity of these components are found to be strongly variable with a time scale of days (Iijima et al. 1994). Iijima et al. also detect He II 4686 at an intensity of about 8% of Hβ on 1991 Oct. 2 and suggest the possibility of a relation between the presence of this line and the intensity of the broad components. They also suggest that the broad components arise in a region close to the surface of the hot component, a white dwarf.

3.1.3. V3890 Sagittari and V745 Scorpii

Similar to RS Oph and T CrB, V3890 Sgr also shows activity at quiescence, as depicted by the recent rise to ~ 14.6 mag in May 1997. The spectrum of 1997 (Fig. 3) was obtained when V3890 Sgr was in a high state at a visual magnitude of 15 mag. The emission lines are stronger in 1997 as compared to 1998 (Fig. 3; also Table 5). Comparing the spectra presented here with that of Williams (1983) obtained in 1981, it appears that this system was in a high state also in 1981. The emission lines were very strong and the ionization level was higher than that indicated by the 1997 and 1998 spectra. For example, He II 4686 Å was present with a strength $\sim$ 28% that of Hβ in 1981, while it is barely detected in 1997 and absent in 1998. It is interesting to note that the He II 4686 line was quite strong in the spectra presented by Williams et al. (1994) obtained 1–2 years after the 1990 outburst.

Fig. 4 shows the spectrum of V745 Sco obtained in March 1998. Although the blue region of the spectrum is very noisy, the lines due to Hβ, Fe II and He I 5876 can be easily identified. We are unable to say anything about activity in this nova owing to inadequate data. However, we expect its behaviour to be similar to that of the other members in the group.

3.2. Flickering activity

Rapid photometric variations with amplitudes of 0.01–1.0 magnitude over timescales of minutes have been observed in both T CrB and RS Oph. The amplitude of flickering in T CrB is maximum in the U band with $\Delta U \sim 0.1$–0.5 magnitude on timescales of minutes (Walker 1957; Ianna 1964; Lawrence et al. 1967; Bianchini & Middleditch 1976; Walker 1977; Bruch 1980; Oskanian 1983). The amplitude is smaller in B, $\Delta B \sim 0.1$–0.3 mag, and generally undetectable in the VRI bands (Raikova & Antov 1986; Lines et al. 1988; Bruch 1992; Mikołajewski et al. 1997). On some occasions, there is no flickering detected at all wavelengths (Bianchini & Middleditch 1976; Oskanian 1983; Dobrzycka et al. 1996b; Mikołajewski et al. 1997). The absence of flickering in the longer wavelength bands dominated by the flux from the cool component indicates that these rapid fluctuations are associated with the hot component.

We have looked for correlation of flickering with the activity of the hot component. Flickering is generally absent when the system is in a low state and usually present when the system is in a high state. In particular, T CrB was is in a relatively high state during most of the 1981–86 period (e.g. Fig. 1 of Belczyński & Mikołajewska 1998), when various observers detected flickering in the U, B and occasionally even in the V light (Oskanian 1983; Lines et al. 1988; Bruch 1992; Raikova & Antov 1986) with amplitudes up to 0.6 mag in U. The flickering activity however disappeared in June 1982, following a significant decline in UBV magnitudes ($\Delta U \sim 0.7$, $\Delta B \sim 0.6$ and $\Delta V \sim 0.5$). Similarly, the absence of flickering in June 1993 (Dobrzycka et al. 1996b) coincided with a general drop in the UBV as well as in the IUE fluxes after c. JD 2 447 000 (Luthardt 1992; Selvelli et al. 1992; Belczyński & Mikołajewska 1998). This low state prevailed until spring 1996; flickering reappeared in April 1996, when T CrB brightened significantly, and was generally present when the star remained blue ($B-V \lesssim 1.2$, $U-B \lesssim 0.3$; Fig. 1 of Mikołajewski et al. 1997). The presence or absence of flickering does not show any correlation with the orbital phase. It is however, evident that flickering is correlated with the activity of the hot component.

The observations of flickering activity in RS Oph are few. However, all observations show a consistent flickering activity with amplitudes of $\Delta U \sim 0.2$–0.3 and $\Delta B \sim 0.3$ (Walker 1957; Walker 1977; Bruch 1980, 1992; Dobrzycka et al. 1996b) over timescales of minutes. We must however note that all observations were made when the star was relatively bright ($V \lesssim 11.45$) and blue ($B-V \lesssim 1.1$).

The flickering activity detected in both T CrB and RS Oph is very similar to that observed in dwarf novae and other cataclysmic variables containing accreting white dwarfs, and provides very strong evidence for the presence of accreting white dwarfs in these recurrent nova systems also.

3.3. The cool component

Kenyon & Fernandez-Castro (1987) showed that the red TiO bands at 6180 Å and 7100 Å together the VO 7865 Å band and the Na I infrared doublet at 8190 Å provide good diagnostics for K-M stars. Thus, to estimate the spectral type and luminosity class of the giant secondary in our target systems, we have used the [TiO]$_{1,2}$, [VO] and [Na I] indices as defined by Kenyon & Fernandez-Castro. Our results are given in Table 7.

T CrB: Our spectra indicate a spectral type of M3-4 III for the M giant in T CrB consistent with previous estimates (Kenyon & Fernandez-Castro 1987, Webbink et al. 1987) based on optical spectra. The K band spectrum and the infrared colours are also consistent with this spectral classification (Harrison et al. 1993). The M giant does not show any pulsations.

RS Oph: Previous spectral classifications for the cool component in RS Oph range from G5–M2 III. Our spectra indicate a spectral type M0 $\pm$ 1, with the luminosity classification consis-

Table 7. Absorption indices and secondary spectral type

JD*	$[TiO]_1$	$[TiO]_2$	[VO]	[Na I]	Sp. type
T CrB					
50180	0.59				M4 III
50559	0.55	0.73			M3/4 III
50587	0.57	0.81			M4 III
50893	0.49	0.64	0.16	−0.03	M3 III
RS Oph					
47944	0.15	0.12			K5.3/K5.6
47982	0.13	0.17	−0.11	0.82	K5-M0 III
48362	0.22	0.31	0.02	0.98	M0-M1 III
48665	0.12				K5.3
48695	0.04				K4.7
49034	0.13				K5.4
49075	0.16				K5.7
49821	0.14	0.15			K5.6
50180	0.16				K5.7
50559	0.09	0.13			K5/K5.4
50587	0.16	0.29			K5.7/M1
50892	0.15	0.18	−0.18	0.18	K5.6-M0 III
V3890 Sgr					
50559	0.13	0.20			K5.5/M0
50893	0.15	0.36	0.27	−0.02	K5.6/M1.5/M5 III
V745 Sco					
50893	0.41	0.90	0.41	−0.31	M2/M5/M6 III

*: JD 2400000+

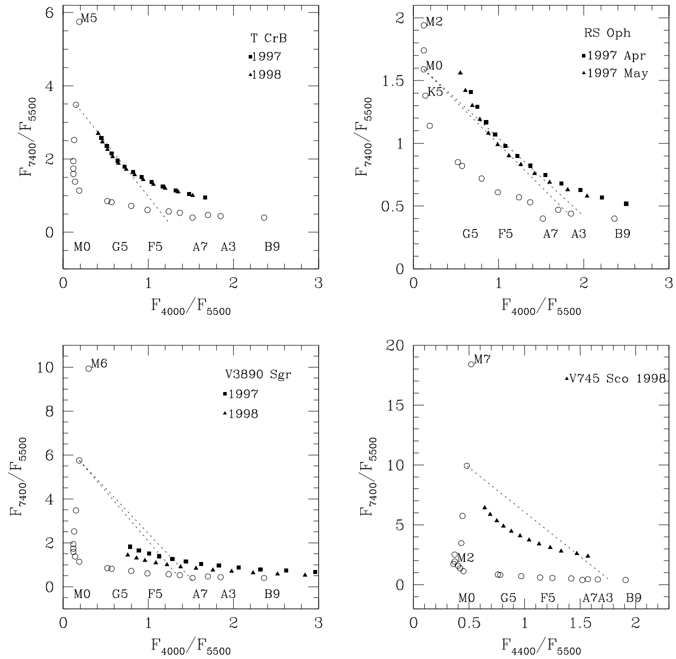

Fig. 7. The continuum flux ratio diagram. Open circles represent normal stars. The ratios for T CrB (*top left*), RS Oph (*top right*), V3890 Sgr (*bottom left*) and V745 Sco (*bottom right*) are plotted for different $E(B-V)$ ranging from 0.1 to 1.2, from top to bottom, in steps of 0.1. Also shown are the lines connecting the giant and the hot component spectral type for the adopted $E(B-V)$.

tent with that of a giant. The infrared K band spectra are also consistent with an M0 III star (Evans et al. 1988, Scott et al. 1994).

Our results (Table 7) show that the secondary spectral type varies between K4 and M1. Moreover, the $[TiO]_1$ index indicates an earlier spectral type compared to the $[TiO]_2$ index, indicating a presence of an additional blue continuum at shorter wavelengths. This blue continuum must be produced by the hot component, since the nebular continuum as predicted by the observed Hβ flux is too faint to produce any measurable effect. The dilution of the TiO indices due to the hot component contribution is clearly evident in the data presented by Dobrzycka et al. (1996a). In particular, the spectrum obtained 120 days after the 1985 outburst, when the hot component contribution to the optical/red continuum flux was negligible, indicates an M2 III spectral type, while spectra obtained during other periods indicate spectral type ranging between K5–M0 III, similar to our observations.

V3890 Sgr: Based on the TiO and VO features between 7000 Å and 8000 Å in the immediate post-1990 outburst, Williams et al. (1991) classify the secondary spectral type as M8 III. Comparing our spectra obtained in 1997 and 1998 with those presented by Williams et al., we find the strengths of the TiO bands have decreased.

Similar to RS Oph, the spectral type indicated by the longer wavelength indices is later (Table 7). The $[TiO]_1$ index implies a K5 type, while the [VO] and the [Na I] indices indicate a spectral type M5 III. The infrared colours of V3890 Sgr based on photometry in 1991 (Harrison et al. 1993) also indicate a spectral type M5 III.

V745 Sco: The secondary in V745 Sco has been classified as M6–8 III (Sekiguchi et al. 1990; Duerbeck & Seitter 1990; Williams et al. 1991). The infrared spectra and colours indicate a spectral type M4 III (Harrison et al. 1993). The absorption indices derived in this study indicate significant contribution from the hot component as in the case of both RS Oph and V3890 Sgr. In particular, the $[TiO]_2$ and [VO] indices indicate a spectral type M4–5 III, while the [Na I] index is consistent with an M6 giant.

3.4. Spectral decomposition

In the previous section we have found that the optical spectrum includes flux from the cool giant as well as significant (especially in the case of RS Oph, V3890 Sgr and V745 Sco) contribution from the hot component, while the nebular continuum is generally negligible. Our next goal is to determine the temperature and luminosity of the hot component from our optical data using simple spectral decomposition techniques.

Fig. 7 shows the observed flux ratio F_{7400}/F_{5500} plotted against the ratio F_{4000}/F_{5500} for all the four objects. The observed flux ratios are reddening corrected for a range of

Table 8. Results of spectral decomposition

JD*	SP_g	SP_h	f_h	V_h^0	V_g^0	$E(B-V)$
T CrB						
Average[1]	M4	F0/F3	0.20-0.25	10.9	9.7	0.15
RS Oph						
50559	M0/2	A2/A4	0.60	10.5	10.9	0.7
50587	M0/2	A2/A4	0.57	9.5	9.8	0.7
50892	M0/2	A0/B9	0.55	9.6	9.8	0.7
V3890 Sgr						
50559	M5	A7	0.84	13.6	15.4	0.5
50893	M5	F0	0.88	14.1	16.2	0.5
V745 Sco						
50893	M6	A1	0.75	14.6	15.8	1.1

*: JD 2400000+
1: Average of JD 2450559 and JD 2450587

$E(B-V) = 0.1$–1.2. Also plotted in the same figure are the standard flux ratios for normal stars. In the case of V745 Sco and RS Oph spectra obtained in 1998, we use the ratio F_{4400}/F_{5500} instead of F_{4000}/F_{5500} as the region around 4000 Å in these data is noisy and the fluxes inaccurate. Since the flux ratios for a composite system lie on a straight line connecting flux ratios for the individual components, the relative lengths of the line segments give the fractional contribution of each component at the common wavelength, 5500 Å (Wade 1982; Dobrzycka et al. 1996a). Table 8 lists results from our flux-ratio diagrams, the fractional contribution (f_h), spectral type (SP_h) and magnitude (V_h^0) of the hot component, and the magnitude of the giant (V_g^0), respectively, assuming the giant component of each system has the spectral type (SP_g) as estimated from the absorption indices (Sect. 3.3). The adopted reddening value is also listed in the table.

In the case of T CrB, we find that although the 7400/5500 ratio (Fig. 7, $E(B-V) = 0.15$) is consistent with that of an M3 giant, the 4000/5500 ratio is higher than a normal M3 giant. This indicates significant contribution from the hot component at lower wavelengths, consistent with the brightening observed in 1996–1997.

The results obtained for RS Oph (Table 8) suggest that on JD 2450559 the visual brightness of both the giant and the hot components was lower than usually. In fact, the [TiO] indices (Table 7) indicate a somewhat earlier spectral type for the giant than usually, possibly due to enhanced veiling by the hot component continuum, while the emission line fluxes (Table 4) are consistent with the rather low luminosity of the hot component. It seems that the giant was simply in a low state on that day. Low states of the M giant are also observed in the highly variable symbiotic system CH Cyg, whose giant however is much cooler ($\gtrsim$ M6) than the giant in RS Oph.

The hot component mimics the spectrum of an F0–F3 star in T CrB, a B9–A4 star in RS Oph (see also Dobrzycka et al. 1996a), A7–F0 in V3890 Sgr and A1 in V745 Sco. The optical spectral types combined with V_h magnitudes correspond to the hot component luminosity, $L_h \sim 50\,(d/1.3\,\mathrm{kpc})^2\ L_\odot$ for T CrB, $L_h \sim 190\,(d/1.5\,\mathrm{kpc})^2\ L_\odot$ for RS Oph, $L_h \sim 50$–$70\,(d/5\,\mathrm{kpc})^2\ L_\odot$ for V3890 Sgr, and $L_h \sim 25\,(d/5\,\mathrm{kpc})^2\ L_\odot$ for V745 Sco, respectively.

A check on the estimated temperature and luminosity of the hot component can be obtained from an estimate of the total luminosity of the source below the Lyman limit approximated as the sum of the H I, He I and He II Lyman continua inferred from the luminosities in Hβ, He I 5876 and He II 4686 emission lines (Kenyon et al. 1991):

$$L_{\rm EUV} \sim 50\,L({\rm H}\beta) + 105\,L({\rm He\,I}5876) + 110\,L({\rm He\,II}4686).$$

The observed line fluxes, corrected for the reddening values listed in Table 1, imply $L_{\rm EUV} \sim 35\,(d/1.3\,\mathrm{kpc})^2\ L_\odot$ in T CrB, $L_{\rm EUV} \sim 100$–$600\,(d/1.5\,\mathrm{kpc})^2\ L_\odot$ in RS Oph, $L_{\rm EUV} \sim 30\,(d/5\,\mathrm{kpc})^2\ L_\odot$ in V3890 Sgr and $L_{\rm EUV} \sim 40\,(d/5\,\mathrm{kpc})^2\ L_\odot$ in V745 Sco. In all cases, the EUV luminosities inferred from the emission line fluxes are much higher, an order of magnitude or so, than expected for normal stars with the spectral types derived from our spectral decomposition, and are comparable to the UV/optical flux from the hot component. Our results are similar to that obtained for RS Oph by Dobrzycka et al. (1996a).

3.5. The OI 8446 Å line

The O I 8446 Å line is observed in classical novae during the diffusion-enhanced and Orion phases. The flux of the O I 8446 line compared to that of other O I lines such as 6300 Å and 7774 Å indicates the line is enhanced by Lyβ fluorescence. Lyβ enhanced O I 8446 line has been detected in the outburst spectra of RS Oph, V3890 Sgr and V745 Sco. The line strength reaches a maximum during the coronal line phases and begins to decline thereafter as the density decreases (Anupama & Prabhu 1989; Williams et al. 1991). The line is absent during the nebular stages of the outburst. In RS Oph, the 8446 Å line appears once again in the spectrum during quiescence as seen in the data presented here as well as the spectra presented in Anupama & Prabhu (1990). On the other hand, the O I 7774 Å line is very weak or absent. O I 8446 line is also present in V3890 Sgr and could be weakly present in V745 Sco. The T CrB spectra presented here do not show this line. However, O I 1304 Å the third cascade line is seen in the IUE spectra (Selvelli et al. 1992), especially when the object has been in a high state. Unfortunately, our data during the recent high state of T CrB in 1996–1997 does not cover the 8446 Å region.

Kastner & Bhatia (1995) have recently calculated the fluorescent line intensities expected by Lyβ photoexcitation of the oxygen spectrum. The Fe II lines and the Ca II near infrared triplet lines in RS Oph imply an electron density of $\gtrsim 10^{11}$ cm^{-3} (see Sect. 4.1). Assuming the O I line arises in the same region, and comparing the observed ratio O I $8446/7774 \sim 10$ with Table 5 and Fig. 8 of Kastner & Bhatia, we estimate the photoexcitation rate to be in the range $R_p \sim 10^{-2} - 1$ s^{-1}. This rate corresponds to a mean Lyβ intensity of $J_{{\rm Ly}\beta} \gtrsim 1240$ erg cm^{-2} s^{-1}

sr^{-1}. Although the 8446 Å flux is inaccurate in V3890 Sgr, we can estimate a lower limit to the ratio as ~ 3, corresponding to $R_p \gtrsim 10^{-2}$, similar to RS Oph. This implies the existence of similar conditions in the line emitting regions as well as the ionizing source in both RS Oph and V3890 Sgr. The value of the Lyβ intensity obtained is a lower limit as the theoretical calculations are for the optically thin case while the line emitting region is optically thick as seen from the Balmer line ratios in these objects.

4. Discussion

4.1. The hot component

Although current thoughts favor a thermonuclear runaway on a massive white dwarf as the energy source for recurrent novae, there is a considerable debate in the literature about the nature of the hot component in T CrB. Basing on a rather controversial estimate of the hot component mass above the Chandrasekhar limit (Kraft 1958; Kenyon & Garcia 1986), Webbink et al. (1987) and Canizzo & Kenyon (1992) interpreted the nova-like outbursts of T CrB in terms of transient phenomena in a non-stationary accretion disc around a main sequence star. Unfortunately, as demonstrated by Selvelli et al. (1992) most observational data for T CrB are against the accretion model. In particular, they showed that the quiescent UV characteristics of T CrB provide direct observational evidence for the presence of a white dwarf accreting at rates $\dot{M}_{\rm acc} \approx 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. Moreover, recent analyses of the ellipsoidal variations of the M giant and the radial velocity data by Belczyński & Mikołajewska (1998) show that the system is a low mass binary system with stellar masses $\sim 0.7\ M_\odot$ for the giant and $\sim 1.2\ M_\odot$ for the hot component, and solve practically all controversies about the nature of the hot component and the physical causes of its eruptions.

The recent outbursts of RS Oph, V3890 Sgr and V745 Sco, respectively, in 1985, 1990 and 1989, indicate that the outburst luminosity was $\gtrsim L_{\rm Edd}$ for a 1.2 $M_\odot$ white dwarf as predicted by TNR outburst models. In general, various outburst phenomena in these systems can be easily explained by the TNR models (see e.g. Anupama 1995). The amplitude and timescales of the flickering detected during quiescence in T CrB and RS Oph, are very similar to the flickering found in other cataclysmic variables, and clearly point to the presence of an accreting white dwarf. The quiescent UV-optical spectrum of RS Oph on the other hand does not exhibit the high ionization lines generally seen in the spectra of cataclysmic variables, and occasionally also seen in T CrB. The high ionization emission lines are also absent in the optical spectra of T CrB, RS Oph, V3890 Sgr and V745 Sco analyzed in this paper.

The major problem for the TNR model is however the inconsistency of the hot component's luminosity and effective temperature (Sect. 3.4; also Dobrzycka et al. 1996a) with standard massive white dwarf tracks in the HR diagram. This seems to be an intrinsic feature of all four recurrent novae discussed in our paper. A possible explanation of this behaviour could be as follows.

The hot component in symbiotic systems is embedded in the red giant wind. In a majority of systems the hot component luminosity is high enough to ionize a significant portion of the red giant wind giving rise to both strong UV and strong optical emission lines. In particular, studies of samples of symbiotic systems in the radio and optical range (e.g. Seaquist & Taylor 1990; Mikołajewska et al. 1997), as well as numerical simulations of Raman scattered O VI emission lines (Schmid 1996) suggest that symbiotic systems have preferentially an ionization geometry with an *X*-parameter (as defined by Seaquist et al. 1984), $X \sim 1$, which means that the 'average shape' of the ionization front does not differ significantly from the plane between the two stellar components. However, in the case when the wind is very strong or/and the hot component luminosity is relatively low, only a small region of the wind around the hot companion is ionized and most of the emission emerging from this region can be absorbed in the enveloping neutral wind. Shore & Aufdenberg (1993), on the basis of an analysis of the ultraviolet spectra of several symbiotic systems, have shown that the emission lines could be severely affected by differential extinction due to absorption lines in the red giant wind produced by neutral and singly ionized iron peak elements. The effect of this "iron curtain" is to lower the ultraviolet continuum temperatures and also suppress the emission lines at sufficiently high column densities ($\geq 5 \times 10^{22}$ cm^{-2}). Shore & Aufdenberg also point out that the absence of emission lines does not rule out the existence of an accretion disc around the hot component.

Shore & Aufdenberg (1993) and Shore et al. (1996) have argued that the differential line absorption by the cool giant environment can account for the shape and variability of UV spectra of RS Oph and T CrB. The presence of Fe II emission lines in the optical region indicates that line blanketing by the "iron curtain" is indeed possible. The ratio of the Fe II and the Ca II infrared triplet lines in RS Oph is similar to the ratios observed in active galactic nuclei (Joly 1989), and indicate electron densities of $\sim 10^{11} - 10^{12}$ cm^{-3} and column density $\geq 10^{23}$ cm^{-2}. The Balmer line ratios indicate high optical depth in the line emitting region. The O I 8446/7774 line ratio in RS Oph and V3890 Sgr clearly indicate enhancement of the 8446 Å line by Lyβ fluorescence. Further, these ratios also imply a mean Lyβ radiation density $\gtrsim 1.2 \times 10^3$ erg cm^{-2} s^{-1} sr^{-1}. This implies the presence of a hot UV source hidden within the optically thick wind envelope. The EUV luminosity of the hot component estimated using the observed hydrogen and helium emission line fluxes is, as shown in Sect. 3.4, higher than the luminosities observed in normal stars of the estimated spectral type. This is consistent with the hot source being embedded within the wind envelope. The estimated spectral type of the hot component is hence not a true representation of the flux from the hot source and does not exclude the presence of a $\sim 10^5$ K white dwarf. Thus, the temperature and radius estimated by Dobrzycka et al. (1996a) for the hot component in RS Oph correspond to the pseudophotosphere of the wind envelope.

The absence of high ionization lines can be accounted for by the absorption and softening by reradiation of all direct photons from the white dwarf+accretion disc. It may be noted that the

He II 4686 Å line has been clearly detected in RS Oph in the spectrum of 1991 October (Iijima et al. 1994), indicating the presence of a 10^5 K ionizing source. It is interesting to note that the visual magnitude was low (~ 11.8 mag) during this period. We will return to this problem in the next section. The 4686 Å line was also clearly present in the spectra of both V3890 Sgr and V745 Sco obtained 1–2 years after the outburst. The strength of this line decreased with time, with the re-establishment of the envelope from the giant wind. We would like to point out here that the optical depths and electron densities and also the O I line ratios in these systems, as indicated by their quiescence spectra, are quite similar to what is observed in "Fe II" novae during the early phases of their outburst when the He II 4686 Å line is absent (Anupama et al. 1992; Kamath et al. 1997).

Finally, the absorption by the cool giant wind enveloping the hot component can also account for the low quiescent X-ray luminosity of T CrB and RS Oph (Selvelli et al. 1992; Orio 1993).

4.2. Causes of variability

The most striking behaviour in symbiotic RNe systems at quiescence is the variability of their hot radiation flux, manifested as variability in the UV and optical flux, and also in the fluxes of the emission lines. Selvelli et al. (1992) interpret the UV continuum and emission line variations in T CrB as being due to changes in the photoionization source as a result of variable mass transfer from the red giant. Shore & Aufdenberg (1993) on the other hand interpret the variations as effects of the environmental absorption. The lack of eclipses and absence of substantial changes in the spectrum of RS Oph rules out the brightening as being due to changes in the amount of intervening wind material.

The flickering detected in both T CrB and RS Oph can in principle provide some information about fluctuations in the mass transfer/accretion rate. In T CrB, the flickering is usually absent when the system is in a low state and present during the high state (see Sect. 3.2). This indicates an increase in the mass accretion rate during the optical brightening (the high state). The existing data on RS Oph do not show any such variations, but as we note above (Sect. 3.2), the observations are few and were all made when the star was relatively bright and blue. We therefore cannot exclude fluctuations in the mass transfer and consequently in the mass accretion rate also in this system. The flickering activity in T CrB was also investigated by Zamanov & Bruch (1998). They identify the vicinity of a white dwarf as the site of the flickering, and find that the ratio of the flux of the flickering light source and the quiet part of the primary remains constant while the U band flux varies considerably over long time scales. The latter result suggests that in T CrB the mass is transferred at the same rate from the secondary through the accretion disk (a steady state configuration), and it seems to rule out disk instabilities as the cause of the flickering.

As demonstrated by Shore & Aufdenberg (1993), the changes in the UV spectrum from an absorption spectrum to an emission line spectrum with no change in the total UV flux are due to changes in the line-of-sight column density through the wind envelope. In particular, they found that $N_{\rm H} \sim 10^{22} - 10^{23}\,{\rm cm^{-2}}$ is necessary to produce shell features in the UV spectrum and for the emission lines to be suppressed. Since in both T CrB and RS Oph the appearance of the shell features and the lack of strong emission lines is generally not correlated with the binary motion, to produce $N_{\rm H} \gtrsim 10^{22}\,{\rm cm^{-2}}$, $\dot{M}_{\rm g}/v_{\rm g} \sim$ a few $\times\, 10^{-8}\,{\rm M_\odot\,yr^{-1}/km\,s^{-1}}$ is required for an average $L_{\rm h} \sim 100\,L_\odot$. It is interesting that this is roughly consistent with the accretion rate necessary to power the quiescent hot component luminosity in T CrB and RS Oph, and to produce nova eruptions with the observed frequency.

Shore & Aufdenberg (1993) also found that the mean column density through the surrounding medium must be less than $5 \times 10^{21}{\rm cm^{-2}}$ to observe strong emission lines. It is interesting that the only detection of the optical He II 4686 emission line in RS Oph coincided with notable decline in the visual magnitude. This coincidence can be qualitatively explained as follows. The decrease in the giant mass loss rate, and in $N_{\rm H}$, results in disappearance of the absorbing species from the line of sight, so the emission is less affected; while the temporary decline in the mass accretion rate results in a decrease of the hot component luminosity.

Summarizing, we suggest that the changes in the UV spectrum during constant $F_{\rm UV}$ phases, such as seen in T CrB, are due to absorption effects, while the high and low states with corresponding changes in the luminosity are due to fluctuations in the mass accretion rates possibly caused by a variable mass loss from the red giant. The increase in the accretion rate during the high states also gives rise to flickering. Fluctuation in mass accretion rate can also cause variations in the absorption column density. The observed variability in these systems is thus more likely a combination of both effects, i.e. fluctuations in the mass accretion rate as well as change in the absorption column density.

Finally, the quiescent symbiotic recurrent novae show striking similarities with CH Cyg, a highly variable symbiotic system. The hot component luminosity in CH Cyg varies by a factor of 10^4, between ~ 0.1 and $\sim 300\,L_\odot$ (Mikołajewska 1994). The brightening of the hot component is associated with the appearance of flickering (e.g. Mikołajewski et al. 1990; Mikołajewski & Leedjaerv 1998), which suggests that the system is accretion-powered. The optical/UV spectrum of CH Cyg during bright phases resembles the spectra of the symbiotic recurrent novae, in particular the shell-absorption emerges, accompanied by H I, He I and Fe II emission lines while the UV emission lines are weak or absent (Mikołajewska et al. 1988). The accreting component in this system is a white dwarf (Mürset et al. 1997; Ezuka et al. 1998).

5. Summary

We present in this paper the behaviour of RNe with giant secondaries at quiescence. Variability is detected in the emission line fluxes in correlation with the continuum variations. The total UV flux is also found to be variable in both RS Oph and T CrB. All these variations, which are related to the radiation flux from the ionizing source, are caused by fluctuations in the mass accretion rates.

It is concluded that the hot source in these systems is an accreting white dwarf embedded in an optically thick envelope of wind from the giant. This envelope absorbs the direct photons from the white dwarf. This picture can explain the observed UV spectra, the X-ray luminosity, and the lack of high excitation lines in these systems.

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