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Disc instabilities and nova eruptions in symbiotic systems: RS Ophiuchi and Z Andromedae

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ABSTRACT

Using the disc instability model for dwarf novae and soft X-ray transients, we investigate the stability of accretion discs in long-period binary systems. We simulate outbursts resulting from this thermal-viscous instability for two symbiotic systems, RS Ophiuchi and Z Andromedae. The outburst properties deduced from our simulations suggest that, although the recurrent nova events observed in RS Oph are caused by thermonuclear runaway at the white dwarf surface, these runaways are triggered by accretion disc instabilities. In quiescence, the disc builds up its mass, and it is only during the disc-instability outburst that mass is accreted on to the white dwarf at rates comparable to or larger than the mass-transfer rate. For a mass-transfer rate in the range 10^{-8} to $10^{-7} M_{\odot} \text{ yr}^{-1}$, the accretion rate and the mass accreted are sufficient to lead to a thermonuclear runaway during one of a series of a few dwarf nova outbursts, which are barely visible in the optical but easily detectable in the X-rays. In the case of Z And, persistent irradiation of the disc by the very hot white dwarf surface strongly modifies the dwarf nova outburst properties, making them significant only for very high mass-transfer rates, of the order of $10^{-6} M_{\odot} \text{ yr}^{-1}$, much higher than the expected secular mean in this system. It is thus likely that the so-called ‘combination nova’ outburst observed in the years 2000 to 2002 was triggered not by a dwarf-nova instability but by a mass-transfer enhancement from the giant companion, leading to an increase in nuclear burning at the accreting white dwarf surface.

Key words: accretion, accretion discs – binaries: symbiotic – stars: dwarf novae – stars: individual: RS Oph – stars: individual: Z And.

1 INTRODUCTION

Symbiotic stars are interacting binary systems in which a hot primary star accretes the matter lost by an evolved-giant, secondary star. In most known cases the primary is a white dwarf, but several systems with a neutron star primary have also been observed. These binary systems show several types of outburst. A small subset comprises objects observed as ‘slow novae’, whose outbursts last for decades; another subset is formed by recurrent novae, whose outbursts repeat on time-scales from several to several tens of years. Both types of nova outburst are known to result from thermonuclear runaway in the hydrogen-rich layer accumulated by accretion on the white dwarf surface. Table 1 lists the properties of Galactic recurrent novae, which have long orbital periods. The third type is that of classical symbiotic outbursts (hereinafter CSOs), and their

origin is still the subject of debate (see e.g. Sokoloski et al. 2006b, hereinafter S2006, and references therein).

In most cases, the companion giant star underfills its Roche lobe, and accretion on to the primary star occurs through stellar wind capture, which does not guarantee the presence of an extended disc. Despite that, dwarf-nova-type outbursts involving discs have been invoked as a possible source of, or a contributor to, CSOs (Duschl 1986a,b; Mikolajewska et al. 2002; Sokoloski et al. 2006b), and even as an explanation of the outbursts of one of the recurrent novae, RS Oph (King & Pringle 2009; Alexander et al. 2011).

The orbital periods of symbiotic stars range from years to decades, corresponding to binary separations ranging from 10^{13} to 10^{15} cm. Thus the accretion discs (if present) in such wide binary systems are subject to the thermal-viscous instability even for huge mass-transfer rates, since the critical accretion rate, below which the disc is unstable, increases with a 2.4 to 2.6 power of the disc radius (Lasota, Dubus & Kruk 2008).

The typical size of the accretion disc in a dwarf nova ranges from about 10^{10} to 10^{11} cm. Outbursts in such systems have been very well

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Table 1. Galactic recurrent novae with long binary orbital periods.

Object	Outburst year	P_{rec} [yr]	P_{orb} [d]	M_{WD} [M_{\odot}]	m_{min} [mag]	m_{max} [mag]
T CrB	1866, 1946	<80	228	$\gtrsim 1.35$	2.5	9.8
RS Oph	1898, 1907, 1933, 1945, 1958, 1967, 1985, 2006	<22	453.6	~ 1.35	4.8	11
V745 Sco	1937, 1989, 2014	<52	510	$\gtrsim 1.35$	9.4	18.6
V3890 Sgr	1962, 1990	<27	519.7	$\gtrsim 1.35$	8.1	15.5

The table lists the basic parameters of a few Galactic recurrent novae. The years in which outbursts were observed and the recurrence period of the outburst are given in the second and third columns. The next two columns shows the binary orbital period and mass of the white dwarf, and the final two columns give the brightness in the V band measured during the outburst peak and quiescence. References: Schaefer (2010); Anupama (2013).

modelled by the disc instability model (DIM; see Lasota 2001, for a review of the model). There have not been many attempts to apply the DIM to the description of the large discs of symbiotic stars (SBs), with the notable exceptions of the work of Duschl (1986a,b) and Alexander et al. (2011). In two papers, Duschl (1986a,b) studied the stationary and time-dependent behaviour of accretion discs around a main-sequence star and suggested that the light-curves of SBs can be explained by disc instabilities. Since the accreting primary was a main-sequence star and the transition fronts were approximated as quasi-stationary, these models are not directly applicable to the study of outbursts in SBs as known at present (Sokoloski et al. 2017). The simplified code used by Alexander et al. (2011) in their study of RS Oph outbursts requires serious improvements in order to be able to describe the physics of accretion disc outbursts (Graham Wynn, private communication; see also Section 3.1.1). The DIM code developed by Hameury et al. (1998) and Dubus et al. (1999) has been used to describe outbursts of irradiated low-mass X-ray binary (LMXB) discs extending up to radii of a few times 10^{11} cm (Dubus 1998; Dubus, Hameury & Lasota 2001), but larger configurations have not yet been explored.

In this article we use our DIM code to test two hypotheses involving disc instabilities in the context of SBs. First, inspired by King & Pringle (2009) and Alexander et al. (2011), we examine the role of dwarf-nova-type instabilities in the 2006 outburst of the recurrent nova RS Oph. In particular, we test the hypothesis (Alexander et al. 2011; John Cannizzo, private communication) that the thermonuclear runaway in this and other similar systems could be triggered by a single dwarf-nova instability. Secondly, we address the ‘combination nova’ scenario (S2006), according to which a CSO observed in the prototypical SB Z And is caused by an increase of thermonuclear shell-burning triggered by accretion disc instability. We also study the possibility of ‘pure’ dwarf nova outbursts in shell-burning SBs. A direct comparison of the light-curves generated by the DIM code with the observational data is not appropriate because this would require the DIM code to be coupled with a code describing the thermonuclear runaway at the white dwarf surface. Instead, for each model we consider, we compare the model predictions of the general outburst characteristics (outburst duration and amplitude, recurrence time) with the observed values.

2 THE MODEL

We use the version of the DIM described by Hameury et al. (1998), with added heating due to stream impact and the dissipation by the tidal torques as described by Buat-Ménard, Hameury & Lasota (2001). The code we have developed solves the standard disc equations in the radial dimension (mass, angular momentum and energy conservation, see e.g. Lasota 2001) of a geometrically thin, opti-

cally thick disc in order to follow its thermal and viscous evolution. Since the disc is assumed to be geometrically thin, the radial and vertical dimensions decouple, and the viscous-heating as well as the radiative-cooling terms can be calculated as a function of local quantities (surface density, central disc temperature, radius) only. The code is implicit and uses an adaptive grid so that the heating and cooling fronts are well resolved; the inner and outer edges of the disc are allowed to vary in time (see below). Time derivatives are calculated using a Lagrangian scheme. The non-linear equations are solved using a generalized Newton–Raphson method.

The heating and cooling terms are calculated by solving the vertical structure of the accretion disc, assuming hydrostatic and thermal equilibrium. The equations are very similar to those used for the stellar structure. The main difference is the heating term, which is the result of viscous rather than nuclear processes. This enables us to determine the temperature profile, and in particular the central and effective temperature as a function of the local surface density Σ and radius, for a given viscosity parameter α . The disc is not necessarily in thermal equilibrium though. As noted by Hameury et al. (1998), this introduces an additional term into the heat transport equation, which is supposed to have the same behaviour as the viscous heating term; that is, it is proportional to pressure. The disc vertical structure can then be determined for any position and Σ when the disc is not in thermal equilibrium, but α is no longer given; the central temperature then becomes a free parameter. In order to speed up the resolution of the radial time-dependent equations, effective temperatures are pre-calculated on a grid in radius, Σ and central temperature, and trilinear interpolation is performed on this grid.

Throughout this paper, unless otherwise noted (model RSB-A, see Section 3), we take the Shakura–Sunyaev viscosity parameters to be $\alpha_c = 0.02$ for a cold neutral disc and $\alpha_h = 0.1$ when the disc is hot and ionized.

2.1 Disc irradiation

For irradiated discs we use the version of the code (IDIM) described by Dubus et al. (1999, 2001); Lasota et al. (2008) in the context of LMXBs and Hameury, Lasota & Dubus (1999) in the slightly different context of cataclysmic variables. Irradiation does not affect the time-dependent radial equations, but only modifies the vertical structure of the disc by changing the relationship $F_z = \sigma T_{\text{eff}}^4$ into $F_z + F_{\text{irr}} = \sigma T_{\text{eff}}^4$.

The flux F_{irr} irradiating the outer disc regions is written as

$$F_{\text{irr}} \equiv \sigma_{\text{SB}} T_{\text{irr}}^4 = C \frac{L}{4\pi R^2}, \quad (1)$$

where R is the radial coordinate, σ_{SB} is the Stefan–Boltzmann constant, and $C < 1$ is a constant encapsulating the irradiation geometry, albedo etc. This very simple description of disc irradiation gives satisfactory results when describing outer-disc irradiation in X-ray binaries, in particular in transient systems (Dubus et al. 2001; Tetarenko et al. 2018a). In this case, $L = L_{\text{acc}} = \eta \dot{M} c^2$, where η is the accretion radiation efficiency. The ratio of irradiation to accretion (‘viscous’) flux is, in the steady-state case,

$$\frac{F_{\text{irr}}}{F_{\text{acc}}} = \frac{4}{3} C \eta \frac{R}{R_{\text{S}} F}, \quad (2)$$

where $R_{\text{S}} = 2GM_1/c^2$ is the Schwarzschild radius, M_1 being the primary mass, and

$$F_{\text{acc}} \equiv \sigma_{\text{SB}} T_{\text{eff}}^4 = \frac{3GM_1 \dot{M}}{8\pi R^3}. \quad (3)$$

For $C \approx 10^{-3}$ and $\eta \approx 0.1$, used in models of X-ray transients (Dubus et al. 2001), $F_{\text{irr}}/F_{\text{acc}} \approx 10^{-4} R/R_{\text{S}}$ and $T_{\text{irr}} > T_{\text{eff}}$ for $R > 10^4 R_{\text{S}}$. However, for white dwarfs $\eta \approx 10^{-5}$ to 10^{-3} , and even for very large discs, self-irradiation of the outer disc is never in practice important because it would require disc radii $R > 10^6$ to $10^8 R_{\text{S}} \approx 4 \times 10^{11}$ to 10^{13} cm. It is only for massive white dwarfs and $C \approx 10^{-2}$ that self-irradiation of the outer region could play a role in the disc structure and evolution (see the discussion below in the case of RS Oph).

In some systems such as symbiotic stars and supersoft X-ray sources, however, the steady thermonuclear burning of matter accumulated at the white dwarf surface can be important and even dominate accretion disc irradiation. In this case,

$$\begin{aligned} \frac{F_{\text{irr},*}}{F_{\text{acc}}} &\approx \frac{2}{3} \frac{CL_*}{GM_1 \dot{M}/R_*} \frac{R}{R_*} \\ &\approx 0.5 \left(\frac{M_{\odot}}{M_1} \right) \left(\frac{R}{10^8 \text{cm}} \right) \left(\frac{CL_*}{10^{37} \text{erg s}^{-1}} \right) \left(\frac{10^{19} \text{g s}^{-1}}{\dot{M}} \right), \end{aligned} \quad (4)$$

where R_* is the white dwarf radius. In the symbiotic star Z And, for example, the steady luminosity of thermonuclear burning is about $10^3 L_{\odot}$. So even for very high accretion rates, the outer-disc surface temperature is dominated by irradiation from the central source. Since constant irradiation is independent of the accretion rate, it impacts the whole disc outburst cycle because, in contrast to the accretion–self-irradiation case, irradiation is also present during quiescence. Notice that in equation (4), in contrast to equation (2), the ratio $F_{\text{irr},*}/F_{\text{acc}}$ depends on the accretion rate and *decreases* with increasing \dot{M} .

It should be noted, however, that it is not clear under what conditions equation (1) applies to discs around white dwarfs, and in particular what value of C should be used. In X-ray binaries, for which there is direct evidence of outer-disc irradiation, a ‘reasonable’ value for C is about a few times 10^{-3} (Dubus et al. 1999; Coriat, Fender & Dubus 2012; see, however, Tetarenko et al. 2018b). Note that the C used here differs from the C as defined by Dubus et al. (1999) in that it does not include the efficiency parameter η .

Equation (1) assumes that the disc is irradiated by a point source. This assumption is no longer true close to the white dwarf, and irradiation has to be described (see e.g. Hameury et al. 1999) by

$$F_{\text{irr},*} \equiv \sigma_{\text{SB}} T_{\text{irr},*}^4 = (1 - \beta) \left[\sin^{-1} \rho - \rho \sqrt{1 - \rho^2} \right] \frac{T_*^4}{\pi}, \quad (5)$$

where the subscript * refers to quantities measured at the white dwarf surface and $\rho = R/R_*$.

At large distances, $F_{\text{irr},*}$ as given by equation (5) varies as R^{-3} and is much smaller than the value that would be obtained using

equation (1); conversely, close to the white dwarf, equation (1) underestimates the irradiation flux.

In what follows, when the ratio of the disc scale-height to the stellar radius $H/R_* > 1$, we use equation (1) to describe irradiation, whereas in the opposite case, $H/R_* < 1$, we use equation (5).

2.2 Boundary conditions

Since radiation pressure can be dominant during outbursts, and gravity could potentially vary within the extended disc photosphere, the usual photospheric boundary condition $\kappa P_{\text{g}} = 2/3 g_z$ is replaced (Hameury, Viallet & Lasota 2009) with

$$\kappa \left(P_{\text{g}} + \frac{1}{2} P_{\text{rad}} \right) = \frac{2}{3} g_z \left(1 + \frac{1}{\kappa \rho z} \right), \quad (6)$$

where κ is the Rosseland mean opacity, g_z is the vertical component of gravity, ρ is the density, and P_{g} and P_{rad} are the gas and radiation pressure respectively.

In all models, the disc is truncated at a magnetospheric radius given by

$$R_{\text{mag}} = 5.13 \times 10^8 \mu_{30}^{4/7} \left(\frac{M_1}{M_{\odot}} \right)^{-1/7} \left(\frac{\dot{M}_{\text{acc}}}{10^{16} \text{g s}^{-1}} \right)^{-2/7} \text{cm}, \quad (7)$$

where M_1 is the accretor mass in solar units, \dot{M}_{acc} is the accretion rate on to the white dwarf, which differs from \dot{M}_{tr} if the system is not steady, and μ_{30} is the white dwarf magnetic moment in units of 10^{30}G cm^3 (Frank, King & Raine 2002).

2.3 S-curves

On the Σ – T_{eff} plane, accretion disc steady-states, at a given radius, form the well-known ‘S-curves’. The upper and lower branches are stable; the intermediate branch is thermally and viscously unstable. As noted earlier, these S-curves are calculated by solving the disc vertical structure. The bends in the S-curves define the critical values of the parameters at which the stability properties of a local disc ring are changing. The numerical fits to these values can be found in Appendix A.

Fig. 1 shows examples of such S-curves obtained for various radii. Fits to the critical surface densities, effective temperatures and corresponding accretion rates are given in Appendix A. These fits are valid for radii in the range 10^8 to 10^{12} cm and for α in the range 10^{-4} to 1. As can be seen, the S-curves do not look very different from those found for smaller discs; the extension to large radii does not change the overall shape of the S-curves, but merely increases typical surface densities and slightly decreases the corresponding effective temperatures. They do, however, differ quite significantly from those used by Alexander et al. (2011), as can be seen from a comparison with their fig. 1. We return to this point in Section 3.1.1. Note also that the extent of the unstable branch is dominated by the jump in the viscosity parameter (Hameury et al. 1998).

2.4 Light-curves

When calculating the light-curves, we include the contributions from the thermal emission of the white dwarf, the (irradiated) secondary star and the hot-spot where the mass-transfer stream hits the disc (see Schreiber, Hameury & Lasota 2003). For the shell-burning sources, we model their emission as that of a black-body with shell luminosity L_{nuc} . The contribution of the red giant is important and more difficult to evaluate, particularly because it may or may not

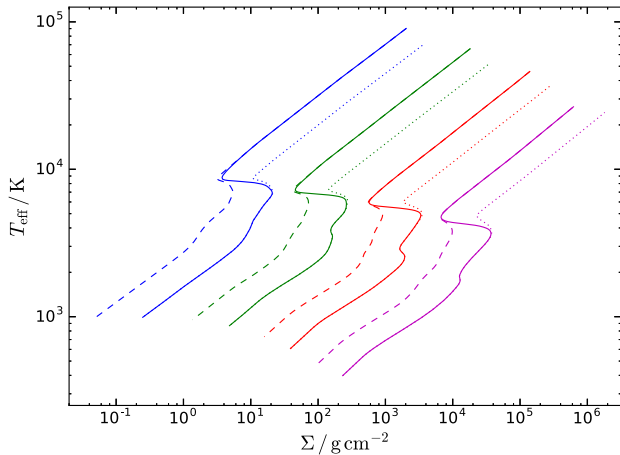


Figure 1. $\Sigma - T_{\text{eff}}$ S-curves computed for a $1.35 M_{\odot}$ white dwarf are plotted for various radii. The four sets of curves (each set includes a dashed, a solid and a dotted), from left to right, represent the S-curves at radii $r = 10^9, 10^{10}, 10^{11}$ and 10^{12} cm, respectively. Solid lines represent the S-curves attained from temperature-dependent α . Dashed and dotted lines represent S-curves for fixed $\alpha = 0.1$ and $\alpha = 0.01$ respectively (we use these values for a direct comparison with fig. 1 of Alexander et al. 2011; see Section 3).

fill its Roche lobe. Specific details for RS Oph and Z And are given in the corresponding sections below.

We also account for interstellar reddening, which decreases the observed optical fluxes; the visual extinction is $A_V = 3.1E(B - V)$, where $E(B - V)$ is the colour excess. For RS Oph, we take $E(B - V) = 0.73$ (Sniijders 1987). For Z And, we consider the minimum $E(B - V) = 0.27$, as did S2006; values for $E(B - V)$ found in the literature are in the range of 0.27 to 0.35.

3 RS OPHIUCHI

RS Oph is a symbiotic recurrent nova with a recurrence time of about 20 yr. The binary has an orbital period of 453.6 d, a mass ratio $q \equiv M_2/M_1 = 0.6$, and an eccentricity $e = 0$ (Brandi et al. 2009). The low mass of the ejecta of the 2006 outburst (approximately in the range 10^{-7} to $10^{-6} M_{\odot}$; Sokoloski et al. 2006a) and their high velocity (4000 km s^{-1} ; Das, Banerjee & Ashok 2006; Anupama 2008) suggest a white dwarf mass close to the Chandrasekhar limit (see e.g. Yaron et al. 2005, for a study of the dependence of the ejecta characteristics on the system parameters). Other arguments also point towards a high-mass primary (Mikołajewska & Shara

2017). Therefore the mass of the K7 giant (Mürset & Schmid 1999) companion can be estimated to be $M_2 \approx 0.8 M_{\odot}$, the inclination is about 50° , and the orbital separation is $a \approx 2.2 \times 10^{13}$ cm.

Fig. 2 shows the long-term light-curve of RS Oph in the visual over the period 1982 to 2017, obtained using AAVSO data. The visual magnitude varies from 11–12 in quiescence to 4.8 at maximum. During weeks 6 to 10 of the last, 2006 outburst, RS Oph was a supersoft X-ray source with luminosity in the range 0.2 to 1.0 keV, close to the Eddington luminosity, and a temperature of the white dwarf photosphere close to 8×10^5 K (Nelson et al. 2008). Nuclear burning ended around day 69 after outburst. The nova shell ejected by RS Oph was asymmetrical and contained a jet-like structure. Although this feature of the outburst motivated King & Pringle (2009) to assert that it was not thermonuclear but resulted from a dwarf-nova instability, the clear signature of nuclear burning observed in RS Oph during the supersoft state makes such a possibility highly improbable.

The giant companion star is probably close to filling its Roche lobe. Estimates of the mass-loss rate vary from about $10^{-8} M_{\odot} \text{ yr}^{-1}$ (Iijima 2008) to $10^{-6} M_{\odot} \text{ yr}^{-1}$ (Evans et al. 2007). Recent estimates by Booth, Mohamed & Podsiadlowski (2016) give $5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$.

Until *Gaia* determined the parallax of RS Oph, which corresponds to a distance of 2.26 ± 0.27 kpc (Gaia Collaboration et al. 2018), the distance of 1.6 kpc to RS Oph based on Bode (1987) had usually been assumed, although distances as low as 540 pc (Monnier et al. 2006) and as high as 2.45 kpc (Rupen, Mioduszewski & Sokoloski 2008) had been claimed. For comparison with previous studies, we use here the value of 1.6 kpc, and discuss at the end of this section the impact of the updated distance. The quiescent accretion rate is variable. At day 241 after the 2006 outburst, when optical flickering had resumed, indicating the re-formation of an accretion disc, the accretion rate was estimated to be within 10^{-10} and $10^{-9} M_{\odot} \text{ yr}^{-1}$, depending on the assumed model of mass-loss rate from the secondary (Worters et al. 2007). However, on days 537 and 744, X-ray observations suggest accretion rates between 7×10^{-11} and $5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$, depending on the emission model and assuming a distance of 1.6 kpc (Nelson et al. 2011). At the true *Gaia* distance of 2.26 kpc, the accretion rates would be respectively 1.4×10^{-10} and $1.0 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. The presence of an absorbed optically thick boundary layer would allow accretion rates up to $3.2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ (for a distance of 1.6 kpc; Nelson et al. 2011). However, observations by ROSAT PSPC of RS Oph 6 and 7 yr after the 1985 outburst implied quiescent accretion rates in the range of 10^{-12} to a few $10^{-11} M_{\odot} \text{ yr}^{-1}$ (Orio 1993; Orio, Covington & Ögelman 2001). Similar results were obtained by Mukai (2008) in 1997. Such low accretion rates have been considered as ‘completely

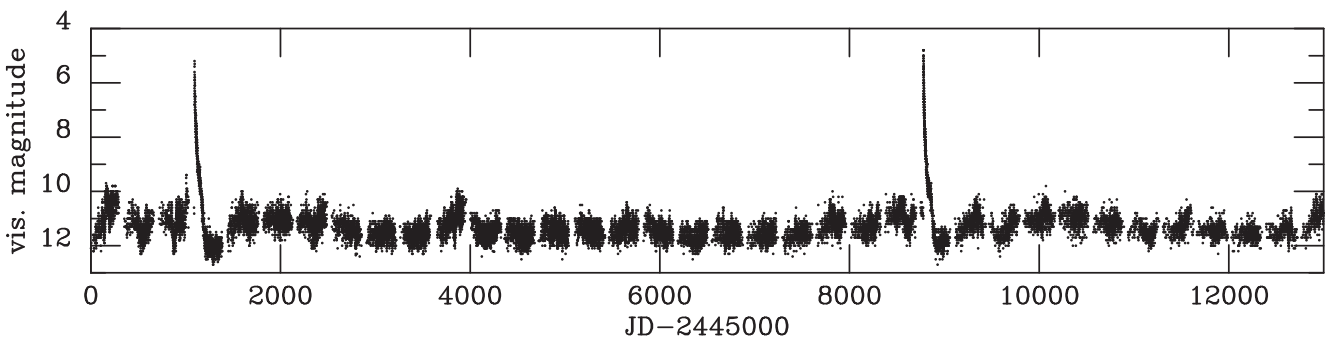


Figure 2. RS Oph visual light-curve (data from AAVSO).

Table 2. Models of RS Oph dwarf nova outbursts.

Model	$R_{\text{in}}(\text{qsc})$ [10^{10} cm]	R_{D} [10^{10} cm]	\dot{M}_{tr} [$M_{\odot} \text{yr}^{-1}$]
RSB-6	0.215	256.25	10^{-6}
RSB-7	0.215	256.25	10^{-7}
RSB-8	0.215	256.25	10^{-8}
RSB-A*	1.0	253.56	10^{-6}

$R_{\text{in}}(\text{qsc})$ is the inner disc radius during quiescence, R_{D} is the outer disc radius, and \dot{M}_{tr} is the mass-transfer rate from the secondary. * Model closest to Alexander et al. (2011).

at odds with the short nova outburst recurrence time (~ 20 years) (Nelson et al. 2011).

The reason is that a thermonuclear runaway recurrence time of 20 yr requires, for a white dwarf close to the Chandrasekhar limit, an average accretion rate of about $10^{-8} M_{\odot} \text{yr}^{-1}$ (Yaron et al. 2005). Therefore the highest estimates of both the companion mass-loss rate and the accretion rate on the white dwarf are consistent with a nova outburst occurring every 20 yr. However, since these estimates are model- and distance-dependent, the consistency between the observed properties of RS Oph outbursts and the standard nova-outburst model cannot be assumed with certainty. Since the accretion disc, the presence of which seems to be confirmed by the observed optical flickering and by the necessity of a high accretion efficiency, may extend to a distance large enough to make it thermally and viscously unstable, it is worth investigating whether this instability gives rise to large-scale outbursts and whether these outbursts, if they occur, can drop enough mass on to the white dwarf to trigger a thermonuclear runaway while having, according to the DIM, very low quiescent accretion rates. We also want to test the claim by Alexander et al. (2011) that RS Oph outbursts do not have their origin in thermonuclear runaway but are caused by stable hydrogen-burning at the white dwarf surface, with the burning triggered by dwarf nova outbursts recurring every 20 yr.

3.1 Dwarf nova outbursts of RS Oph

It is not always realized that the presence of a thermally and viscous unstable disc is only a necessary condition for the occurrence of dwarf-nova-type outbursts. For example, accretion discs in active galactic nuclei, even when unstable, do not show large-scale outbursts, for reasons explained by Hameury et al. (2009). It is therefore not obvious a priori what the response of a very large disc to a thermal-viscous instability will be. To study this problem, we calculated a series of models, the parameters of which are given in Table 2.

3.1.1 Unirradiated discs

First, we consider three models for a system with parameters appropriate for RS Oph (RSB-6, RSB-7, RSB-8), corresponding to three different mass-transfer rates from the secondary of 10^{-6} , 10^{-7} and $10^{-8} M_{\odot} \text{yr}^{-1}$. To these three models we add RSB-A, which is the closest we could come to the model considered by Alexander et al. (2011).

In all models the mass of the white dwarf is $1.35 M_{\odot}$ (see e.g. Hachisu, Kato & Luna 2007) and the assumed distance is 1.6 kpc. In order to be compatible with Alexander et al. (2011), we assume the secondary's temperature to be 3500 K (Schaefer 2009). In order to have a truncated disc, we assume arbitrarily a white dwarf magnetic moment of $2 \times 10^{30} \text{ G cm}^3$. Truncation of the inner disc is necessary

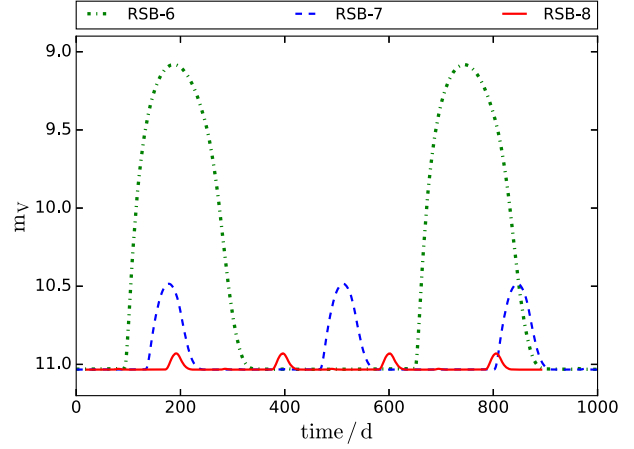


Figure 3. Optical light-curves for the models RSB-6 (dash-dotted green curve), RSB-7 (dashed blue curve) and RSB-8 (solid red curve).

to avoid multiple small outbursts, which are inevitable when the inner disc radius is as small as that of a $1.35 M_{\odot}$ white dwarf radius and are a numerical nuisance.

Since the giant companion to RS Oph is not supposed to fill its Roche lobe, the structure of the accretion flow in this system is not clear. In particular, what is the size of the accretion disc that apparently is present during quiescence? For the assumed binary parameters the circularization radius for the Roche-lobe-filling case is $R_{\text{circ}}^{\text{RL}} = 2.37 \times 10^{12}$ cm (Lubow & Shu 1975), while in the case of wind accretion it is $R_{\text{circ}}^{\text{W}} < 2.2 \times 10^{11} \lambda(a)^{-4}$ cm, where $\lambda \approx 1$ (Frank et al. 2002). In our code, the average outer disc radius is determined by the tidal torque

$$\mathcal{T}_{\text{tid}} = c_{\text{tid}} \Omega_{\text{orb}} r \nu \Sigma \left(\frac{r}{a} \right)^5, \quad (8)$$

where ν is the kinematic viscosity coefficient and c_{tid} is a numerical coefficient that modulates the tidal truncation radius and provides an average value of the disc outer radius, R_{D} , when the disc is steady. Here we use $c_{\text{tid}} = 3.0 \times 10^9$ such that R_{D} is of the order of 10^{12} cm, which is appropriate for both cases of mass transfer from the giant companion.

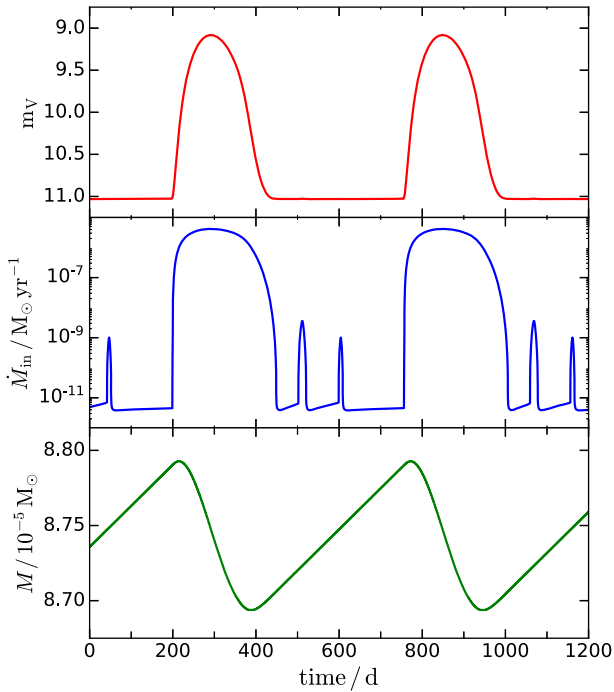
We also simulate the RS Oph system using the same parameters as Alexander et al. (2011), referred to as model RSB-A in Table 2. The masses of the white dwarf and of the secondary are identical to those in RSB-6, -7 and -8, but, in order to have the same circularization radius, $R_{\text{c}} \approx 1.74 \times 10^{12}$ cm, and disc size (slightly larger than R_{c}) as in their work, we assume the orbital period to be 287.5 d. As in Alexander et al. (2011), the disc is truncated at a fixed inner radius of 10^{10} cm. We also use $\alpha_{\text{c}} = 0.01$ as in their model.

Fig. 3 shows the light-curves obtained for the three models considered here, and Table 3 provides the main outburst characteristics for the RS Oph dwarf nova outbursts. As the mass-transfer rate increases, the recurrence time between outbursts increases and the outbursts last longer too. In none of the models do heating fronts reach the disc outer edge, and the outer radius of the disc does not vary during the outbursts, in contrast to what is seen in smaller discs. During quiescence the typical accretion rate on to the white dwarf is $\dot{M}_{\text{in}} \gtrsim 10^{-12} M_{\odot} \text{yr}^{-1}$. The larger the mass-transfer rate, the larger the peak value of \dot{M}_{in} of an outburst. Fig. 4 shows the time variations of the visual magnitude, the mass accretion rate (a proxy for the X-ray emission), and the total disc mass for model RSB-6, which has the longest recurrence time. The small intermediate

Table 3. Disc outburst properties for RS Oph models.

Model	\dot{M}_{in} (qsc) [$M_{\odot}\text{yr}^{-1}$]	\dot{M}_{in} (peak) [$M_{\odot}\text{yr}^{-1}$]	m_V (qsc)	m_V (peak)	ΔM [M_{\odot}]	τ_{rec} [d]	τ_{ob} [d]	$R_{\text{f,max}}$ [10^{10} cm]
RSB-6	3.8×10^{-12}	4.15×10^{-6}	11.03	9.08	10^{-6}	556	258	56
RSB-7	3.8×10^{-12}	6.3×10^{-7}	11.03	10.48	6.8×10^{-8}	335	115	27
RSB-8	3.8×10^{-12}	9.3×10^{-8}	11.03	10.9	4.5×10^{-9}	205	50	12.7
RSB-A	4.5×10^{-12}	9.6×10^{-6}	11.03	8.25	3.35×10^{-6}	1190	260	70

The first column lists the model reference, the second and third ones give the minimum quiescent and outburst peak of the mass accretion rate. The fourth and fifth columns give the apparent visual magnitude during quiescence and outburst peak respectively. The sixth column gives an estimate of the amount of mass accreted on to the white dwarf during one outburst. The next two columns denote the recurrence time for the outburst and the outburst duration, respectively. The last column gives the largest distance reached by the heating fronts.


Figure 4. From top to bottom: visual magnitude, accretion rate on to the white dwarf, and disc mass for model RSB-6.

outbursts are not detectable in visible light, but could be marginally detectable in the X-rays.

Since the peaks of \dot{M}_{in} , listed in Table 3, are more than three orders of magnitude larger than in quiescence, most of the mass is accreted on to the white dwarf during outbursts only. Table 3 also shows that the visual amplitude of the outbursts is much smaller than the amplitude observed in RS Oph: less than 2 versus 6.5 mag. Furthermore, the recurrence times of the outbursts for models RSB-6, RSB-7 and RSB-8 (from 0.5 to 1.5 yr) are much shorter than the observed 20 yr. Therefore, contrary to the suggestion of King & Pringle (2009), the DIM as such cannot account for the recurrent outbursts of RS Oph.

Finally, we comment on model RSB-A. Our results are very different from those of Alexander et al. (2011): the recurrence time we obtain is shorter than what they obtained for a mass-transfer rate of $10^{-6} M_{\odot} \text{yr}^{-1}$ by a factor of 4, and their outburst duration is longer; as a consequence, in their case the mass accreted on to the white dwarf in a single outburst is an order of magnitude larger than the value of $3 \times 10^{-6} M_{\odot}$ that we obtain for model RSB-A. These differences may be attributed to the way the disc’s vertical structure is treated. Alexander et al. (2011) assume that the disc

is vertically isothermal, and the cooling rates are computed using a one-zone approximation. This approximation is no longer valid if the opacities vary significantly with height in the disc, which is the case during outbursts. Moreover, their effective temperatures are computed with a relationship that holds only for large optical depths (they use $T_{\text{eff}} = T_c \tau^{-1/4}$), which is inconsistent with their estimate for the cooling term. In our models, we fully solve the vertical structure. A comparison of our Fig. 1, where we plot the S-curves for RS Oph computed using the same parameters as Alexander et al. (2011), with their fig. 1 illustrates the substantial differences between the two approaches. For example, the Alexander et al. (2011) effective temperatures at the critical surface densities are lower than ours by factors of 3 to 4. This significantly alters the results. It should also be noted that truncating the disc at 10^{10} cm is rather excessive. Magnetic truncation would imply a magnetic moment larger than $3 \times 10^{33} \text{ G cm}^3$, that is, large enough for pulsations at the spin period to be observed.

3.2 ‘Combination recurrent nova’ outbursts of RS Oph

One should still examine the possibility that, by dropping enough mass on the white dwarf surface, dwarf nova outburst(s) trigger a nova outburst. To start a thermonuclear runaway (TNR) in a system with RS Oph parameters, it is necessary to accumulate a mass of $M_{\text{ign}} \approx 4 \times 10^{-7} M_{\odot}$ on the white dwarf surface (Wolf et al. 2013).

We considered this possibility for our three typical models.

RSB-6: In this model, the mass accreted by the white dwarf during a single outburst, $\Delta M \approx 10^{-6} M_{\odot}$, is larger than M_{ign} , so that one dwarf nova outburst could, in principle, trigger a nova event. The mass M_{ign} is accumulated during the first 90 d of the disc outburst but, by the time this critical mass has been accreted, \dot{M}_{in} exceeds the stable nuclear burning limit, which is $\dot{M}_{\text{stable}} = 6 \times 10^{-8} M_{\odot} \text{yr}^{-1}$ (Wolf et al. 2013). \dot{M}_{in} also exceeds the limit $\dot{M}_{\text{RG}} = 3\dot{M}_{\text{stable}}$ above which hydrogen can be burned as quickly as it is accreted, so that the hydrogen mass increases; therefore, a TNR can occur only during the decay from the outburst maximum, as soon as the accretion rate falls below \dot{M}_{stable} , which happens at day 140 after the outburst is triggered. The early phases of the outburst, corresponding to a change in visual magnitude of about 2, could be just visible in the optical (Adamakis et al. 2011) but would be easy to detect in the X-rays because the accretion rate increases by six orders of magnitude. Of course, for such a scenario to work, the rate at which mass is transferred to the disc must be of the order of $10^{-6} M_{\odot} \text{yr}^{-1}$, which implies that most of the mass lost by the companion must end up in the accretion disc. This is far from being guaranteed, but this tight requirement could be relaxed if disc self-irradiation were taken into account, allowing more mass to be accreted with a lower accretion rate (see below).

Table 4. Disc outburst properties for RS Oph irradiated models.

Model	\dot{M}_{in} (qsc) [$M_{\odot}\text{yr}^{-1}$]	\dot{M}_{in} (peak) [$M_{\odot}\text{yr}^{-1}$]	m_{V} (qsc)	m_{V} (peak)	ΔM [M_{\odot}]	τ_{rec} [d]	τ_{ob} [d]	$R_{\text{f,max}}$ [10^{10} cm]
RSB-6-I	1.25×10^{-12}	4.05×10^{-6}	11.03	9.09	5.08×10^{-6}	1340	538	72.7
RSB-7-I	1.45×10^{-12}	1.17×10^{-6}	11.03	10.15	3.9×10^{-7}	1530	305	43
RSB-8-I	1.44×10^{-12}	$1.1\text{--}2.4 \times 10^{-7}$	11.03	10.85	$1.5\text{--}3.9 \times 10^{-8}$	935-1335	135-140	16.8-22.5

Columns are the same as in Table 3

The quiescent accretion rate corresponds to 1991, 1992 *ROSAT* PSPC and 1997 *ROSAT* post-1985 outburst observations. The higher post-2006 accretion rates observed by *Chandra* and *XMM-Newton* could coincide with ‘mini-outbursts’ observed in the model light-curve. The main problem with this scenario is that, because each dwarf nova outburst is able to trigger a TNR, the recurrence time is very short, of the order of 1.5 yr, which is more than an order of magnitude shorter than observed.

RSB-7: For this model, M_{ign} is accumulated during six dwarf nova outbursts in about 5 yr. The quiescent accretion rate is the same as in RSB-6, because of the same disc truncation. Between thermonuclear eruptions, the accretion rate would increase due to dwarf nova outbursts that, in this case, are unable to trigger TNRs. They would be invisible in the optical but could be detected in the X-rays.

RSB-8: For this model, M_{ign} is accumulated during 80 dwarf nova outbursts during a period of around 45 yr. As for the preceding model, these disc outbursts would be unobservable in the optical, but the increased accretion rate could be detected through X-ray observations during most of the 50 d of activity.

We conclude that a model with an accretion rate between those of RSB-7 and RSB-8 (a mass-loss rate from the companion of a few times $10^{-8} M_{\odot} \text{yr}^{-1}$) can explain most of the properties of the RS Oph recurrent nova outbursts. The mass necessary for a TNR is accumulated during 20 yr in a series of 15 to 20 dwarf nova outbursts. Such a scenario has the advantage of naturally explaining the discrepant X-ray observations at different quiescent epochs of the RS Oph outburst cycle: low values correspond to the quiescent disc phase, while high X-ray luminosities correspond to one of the dwarf nova outbursts.

3.3 Self-irradiated discs

We note from the results of the previous section that the accretion rate at the inner edge becomes quite high during outbursts, and can therefore lead to significant irradiation effects in the outer parts of the accretion disc (see equation 2), because the white dwarf is massive. Here we consider irradiation using equation (1) for the entire disc. This is appropriate because irradiation effects are important only in the outer disc. We consider models similar to the three that we discussed above – RSB-6-I, RSB-7-I, RSB-8-I – with the irradiation coefficient $\mathcal{C} = 0.005$. The results are shown in Table 4, and the light-curves (V magnitude) are shown in Fig. 5.

RSB-6-I: \dot{M}_{in} at maximum is almost the same as in the unirradiated case, but the outburst lasts longer and the mass deposited on the white dwarf during an outburst is five times larger. The recurrence time is 2.5 times longer than for RSB-6, but this is still not consistent with the observations; roughly five outbursts are expected to occur in a 20-yr span, and each outburst can trigger a TNR. As before, one can therefore reject this model.

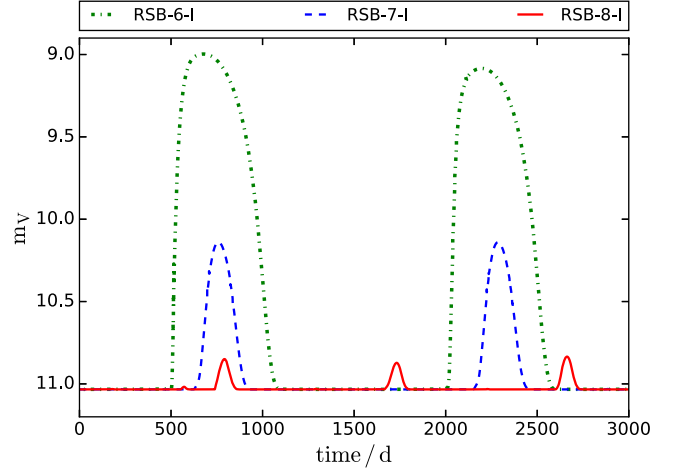


Figure 5. Optical light-curves for irradiated models of RS Oph: RSB-6-I (dash-dotted green curve), RSB-7-I (dashed blue curve) and RSB-8-I (solid red curve).

RSB-7-I: Irradiation has a significant impact in this model. The \dot{M}_{in} peak is roughly 1.85 times that obtained for RSB-7. The mass deposited on the white dwarf during an outburst is very close to M_{ign} and could trigger a recurrent nova, in contrast to RSB-7 for which at least six outbursts were required to accrete the same mass. The recurrence time is 4.5 times longer than for RSB-7, but because of the increased accumulated mass during a single outburst, roughly four to five outbursts are expected to occur in a 20-yr span. Each outburst can again trigger a TNR. For this reason, this model also conflicts with the observations.

RSB-8-I: Irradiation effects are the strongest of the three models we considered. Here, we obtain a cycle of slightly different outbursts – hence the range given in Table 4 for this model. These outburst properties, however, do not vary by more than a factor of 2. Both the peak accretion rate and the mass accreted during an outburst are an order of magnitude larger than in the case of RSB-8, but the mass accreted during a single outburst is clearly less than the ignition mass. Now 18 outbursts are required to accrete the ignition mass, and a recurrent nova can be triggered once every 55 yr. Although more mass is accreted when irradiation is taken into account, the recurrence time is also significantly increased, and the time required to trigger a recurrent nova is similar to in the RSB-8 case.

We therefore conclude that, as for the unirradiated case, if dwarf nova outbursts are to be recurrent nova triggers, the mass-transfer rate must lie in the range from 10^{-7} to $10^{-8} M_{\odot} \text{yr}^{-1}$. This is therefore a general conclusion, independent of the magnitude of the irradiation effect.

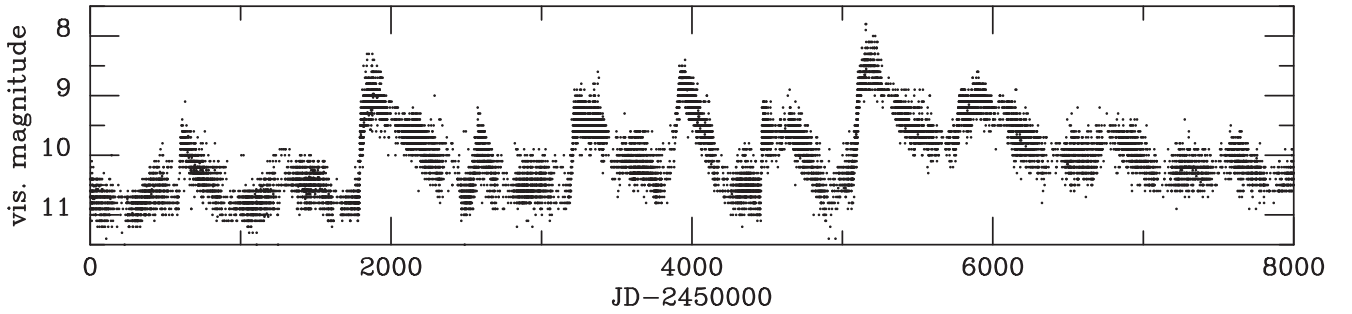


Figure 6. Z And visual light-curve (data from AAVSO).

3.4 Are dwarf novae needed to trigger RS Oph TNR outbursts?

Finally, we should check whether a more conventional scenario, not involving dwarf nova outbursts, can explain the RS Oph recurrent nova outbursts. A steady accretion rate of $2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ is sufficient to accumulate the mass M_{ign} corresponding to the RS Oph parameters. A disc in a system with RS Oph binary parameters is stable if the rate at which it is fed mass satisfies the inequality $\dot{M}_{\text{tr}} > \dot{M}_{\text{crit}}^+$, where the stable hot-disc minimal accretion rate is (equation A5)

$$\dot{M}^+ = 1.44 \times 10^{-10} \alpha_{\text{h}}^{-0.008} m_{\text{wd}}^{-0.88} R_{\text{D},10}^{2.67} M_{\odot} \text{ yr}^{-1}; \quad (9)$$

m_{wd} is the white dwarf mass in solar units, and $R_{\text{D},10}$ is the outer disc radius in units of 10^{10} cm. For $\dot{M}_{\text{tr}} > 2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$, an accretion disc with an outer radius $R_{\text{D}} < 7.4 \times 10^{10}$ cm is stable with respect to the thermal-tidal instability. This is quite small, but marginally possible if accretion occurs via a wind (the circularization radius must be smaller than the disc size). In such a scenario there would be no direct explanation for the low accretion rate deduced from *ROSAT* and *ASCA* observations, and one would be left with speculations of the type presented by Mukai (2008), who suggested that RS Oph might be a fast rotator with essentially no boundary layer. Note that this scenario is inconsistent with our assumption of a significant magnetic field.

3.5 Gaia revised distance

We finally comment on the recently updated distance of $2.26 \pm .27$ kpc by *Gaia* (Gaia Collaboration et al. 2018), a 40 per cent increase with respect to the distance we have used here. With this new distance, the optical magnitude of the entire light-curve would increase by 0.7 mag, all model parameters being kept at their previous values. In order to still account for the observed quiescent luminosity, the secondary temperature has to be increased to 3800 K; the outburst amplitude is then reduced by a factor of less than 2, all other parameters being unaltered. The (undetected) dwarf nova outbursts of RS Oph would thus be slightly fainter, but the total mass accreted on to the white dwarf surface as well as the sequence of dwarf nova outbursts and nova eruptions remain exactly the same as previously and our conclusions for RS Oph remain unaltered.

4 Z ANDROMEDAE

Z And is a classical symbiotic star consisting of an $M_1 = 0.65 \pm 0.28 M_{\odot}$ (Schmid & Schild 1997) white dwarf and a giant secondary with mass ratio $M_2/M_1 \approx 2.0$. Its orbital period is 759 d (Formigini & Leibowitz 1994) and the inclination is $59_{-2}^{+1} \circ$

(Skopal & Shagatova 2012). Until recently, the distance to Z And was estimated to be 1.2 ± 0.5 kpc (Kenny 1995), but the recent parallax measured by *Gaia* (Gaia Collaboration et al. 2018) puts Z And at a distance of 1.95 ± 0.078 kpc. As for RS Oph, we use here the old value of 1.2 kpc for comparison with previous studies, and comment at the end of this section on the impact of increasing the distance by 70 per cent. The presence of a magnetized (10^4 to 10^6 G) primary is deduced from observations of persistent optical pulsations at a period of 28 min (Sokoloski & Bildsten 1999).

As in most classical symbiotic stars, the white dwarf in Z And (the hot component) exhibits a quasi-steady luminosity component of about $10^3 L_{\odot}$ attributed to thermonuclear shell-burning of hydrogen at a rate of a few times $10^{-8} M_{\odot} \text{ yr}^{-1}$ (see e.g. S2006). Symbiotic stars undergo outbursts, the most common of which are *classical symbiotic outbursts*, whose origin is unknown. Their high peak luminosities exclude dwarf-nova-type outbursts, while their high repetition frequency rules out TNRs of the recurrent-nova type. In contrast to recurrent novae, white dwarfs in these symbiotic systems have low masses, precluding short recurrence times.

Fig. 6 shows the visual light-curve of Z And from 1995 to 2017, obtained using AAVSO data. The light-curve is complex and displays a variety of outbursts of different amplitudes and durations, which are not necessarily caused by the same mechanism.

In 1997, the Z And light-curve showed a low-amplitude (about 1 mag) outburst in the *V* light, with a rise-time shorter than about 20 d followed by a decay lasting about 200 d (first outburst in Fig. 6). The asymmetric outburst shape prompted S2006 to suggest that the 1997 outburst was caused by a dwarf-nova-type instability of the outside-in type; that is, with an outburst starting in the outer disc regions (see e.g. Buat-Ménard et al. 2001). A more powerful outburst was observed in 2000 to 2002, when after a rise similar to the 1997 event the brightness kept increasing to reach a 2 mag amplitude in optical, corresponding to a bolometric luminosity of about $10^4 L_{\odot}$ (second outburst in Fig. 6, starting at $\text{JD} \approx 2451800$). If accretion-powered, this high-state would correspond to an accretion rate of $\dot{M} \gtrsim 10^{-5} M_{\odot} \text{ yr}^{-1}$. Such a high accretion rate would have to be sustained for a full year during which the system maintained a luminosity close to its maximum (S2006). Since this seems unlikely, S2006 proposed that this event is a ‘combination nova’ outburst, in which a dwarf nova outburst triggered increased shell nuclear burning. In order to test S2006’s hypothesis we calculate models of disc outbursts in Z And using our DIM code, adapted to the physical properties of this system.

4.1 Dwarf nova outbursts of Z And

As in the case of RS Oph, it is not clear how in Z And the mass lost by the giant companion forms an accretion disc around the white

dwarf. The orbital separation of Z And is $a = 3.053 \times 10^{13}$ cm, which corresponds to a circularization radius of $R_{\text{circ}} = 2.085 \times 10^{12}$ cm. In the case of wind accretion, the circularization radius would be 1.34×10^{10} cm, assuming that the wind speed is equal to the escape speed from the giant, $\lambda(a) \approx 1$.

Since the critical accretion rate at R_{circ} is (equation A5) $2.95 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, a non-irradiated disc in Z And is thermally and viscously unstable for all realistic (less than $10^{-4} M_{\odot} \text{ yr}^{-1}$) mass-transfer rates. However, outbursts of Z And should differ in several aspects from those observed in normal dwarf novae.

First, the presumed radius of the accretion disc in Z And, $R_{\text{D}} \approx 1.4\text{--}2.8 \times 10^{12}$ cm (S2006), is one or two orders of magnitude larger than that in dwarf novae, which, as noted by Duschl (1986b), can have dramatic effects on the heating and cooling front propagation (see e.g. Menou et al. 2000; Dubus et al. 2001, and Section 3.1 about RS Oph).

Secondly, the disc is irradiated by a constant white dwarf surface luminosity of about $10^3 L_{\odot}$, corresponding to an effective temperature of 150 000 K, while temperatures of white dwarfs in dwarf novae are an order of magnitude lower (see e.g. Urban et al. 2000). Finally, the observed visual light-curves have a major contribution from the giant companion (Duschl 1986b; Kenyon 1986), and the duration of the outbursts is shorter than the orbital period, which might provide an additional source of variability.

Thirdly, according to S2006, the asymmetric shape of the 1997 outburst light-curve suggests an *outside-in* event (i.e. an outburst in which the heating front propagates inwards from the outer disc regions) if it is interpreted as a dwarf nova outburst (Smak 1984). It should be noted, however, that ‘fast-rise–slow-decay’ light-curves can also be produced by outbursts starting near the inner disc radius. This happens, for example, in the case of truncated and/or irradiated discs. In addition, outside-in outbursts are unlikely to occur in very large discs.¹ The criterion for an outside-in outburst can be written (Lasota 2001) as

$$\dot{M}_{\text{tr}} \gtrsim \frac{0.5}{\sqrt{\delta}} \dot{M}_{\text{crit}}^{-}, \quad (10)$$

where $1 < \delta \lesssim 2$,

$$\dot{M}_{\text{crit}}^{-} = 1.15 \times 10^{-5} \alpha_{\text{c}}^{-0.02} \left(\frac{M_1}{M_{\odot}} \right)^{-0.88} R_{\text{D},12}^{2.65} M_{\odot} \text{ yr}^{-1} \quad (11)$$

is the critical (maximal) accretion rate for a cold and stable accretion disc (equation A6), and $R_{\text{D},12}$ is the disc radius in units of 10^{12} cm. For the Z And parameters, equation (10) implies rather unrealistically high mass-transfer rates, larger than about $10^{-5} M_{\odot} \text{ yr}^{-1}$.

4.1.1 Non-irradiated disc

We will first check the S2006 suggestion that the disc instability model can explain the asymmetrical, 1-mag feature observed in 1997 in the visual light-curve of Z And. In order to separate and evaluate the various components contributing to the light-curve of a hypothetical dwarf-nova-type outburst of Z And, we first consider the case of a non-irradiated disc. We assume a white dwarf magnetic moment of 5.12×10^{31} G cm³, which corresponds to a magnetic field close to 10^5 G. Our results do not depend significantly on the accretor’s magnetic moment.

¹Model outbursts for LMXB parameters are always of the inside-out type (Dubus et al. 2001).

In calculating the visual light-curves, we include the contribution of the giant companion in a different way from Schreiber et al. (2003). Their approach is well suited to a Roche-lobe-filling, low-mass companion but it is not applicable to the case of Z And. We considered separately the following two extreme simplified assumptions:

(a) The secondary luminosity does not change in response to irradiation. This is appropriate if for example the irradiated side is not facing the observer. The secondary contribution is fixed to be 10.8 mag.

(b) The response of the secondary luminosity to irradiation is maximal. This is appropriate if the irradiated side of the secondary is facing the observer, and if the secondary radius is as large as possible. In this case, we use the minimum acceptable secondary effective temperature, which we take to be 2900 K, and estimate the radius that would correspond to the Z And quiescent visual magnitude (10.5 mag); the secondary radius is then found to be $110 R_{\odot}$, so the secondary fills 57 per cent of its Roche lobe.

We found that the two prescriptions produce very similar light-curves, and in what follows we present light-curves calculated using assumption (b) only.

We consider outburst models for three mass-transfer rates: ZAB-8, ZAB-7 and ZAB-6 for respectively $\dot{M}_{\text{tr}} = 10^{-8}, 10^{-7}$ and $10^{-6} M_{\odot} \text{ yr}^{-1}$. We assume $\alpha_{\text{c}} = 0.02$ and $\alpha_{\text{h}} = 0.1$, and choose c_{tid} so that the outer disc radius is $R_{\text{D}} = 2.37 \times 10^{12}$ cm. Following S2006, we assume a distance of 1.2 kpc, for the purpose of comparing our results with their work, although we shall later comment on the recently updated distances by *Gaia*.

The properties of these three models are presented in Table 5. It can be seen that only model ZAB-6 produces a visual amplitude not too different from 1 mag; however, the shape of the outburst light-curve is markedly different from that observed in 1997 in Z And. The rise-time (73 d) is three times longer than that observed, while the decay-time (118 d) is roughly half that observed. The light-curve shown in Fig. 7 is typical of an inside-out outburst, namely of an outburst starting in the inner disc region. Indeed, the inner disc radius during quiescence, given by equation (7) with $\mu_{30} = 51.2$ and $\dot{M}_{\text{acc}} = 3.3 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$, is equal to $R_{\text{in}} = 0.82 \times 10^{10}$ cm, whereas the heating front starts propagating at $R_{\text{trig}} = 4.05 \times 10^{10}$ cm. While the inner disc edge reaches the white dwarf surface, this front propagates out to $R_{\text{f,max}} = 40 \times 10^{10}$ cm, far from the outer disc rim. The outermost disc regions are not affected by the fronts, and the outer disc radius remains fixed because the amount of angular momentum deposited by the outburst is too small to affect it in a significant way.

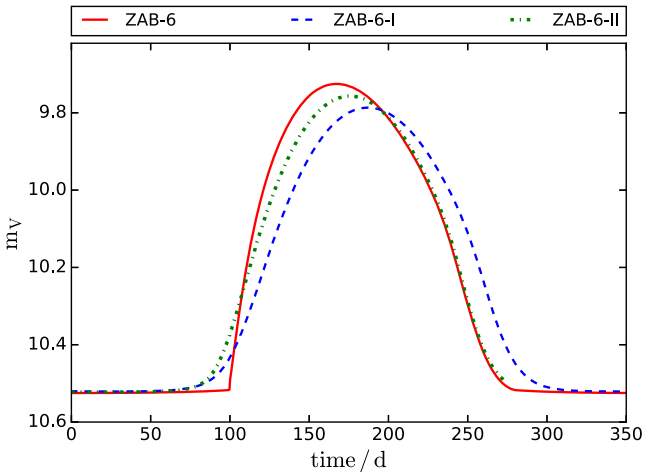
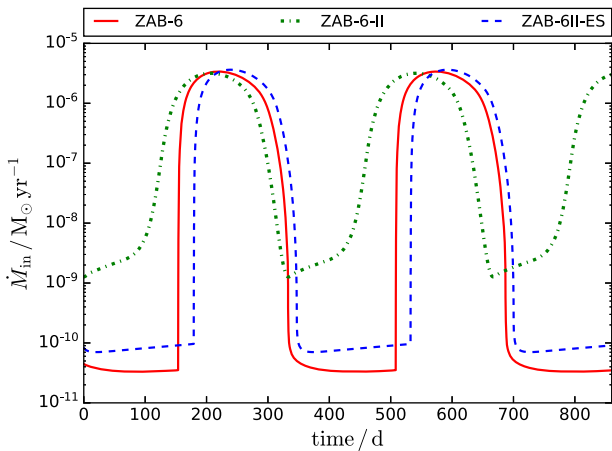
Although the visual amplitude is small, the accretion rate at the inner edge increases by several orders of magnitude, by a factor of about 10^5 in the case of model ZAB-6 (see Fig. 8). At maximum, the inner edge is squeezed by accretion on to the white dwarf surface (the white dwarf radius $R_{\text{WD}} = 8.56 \times 10^8$ cm), and for this model the corresponding accretion luminosity reaches $2600 L_{\odot}$, which should be emitted mostly in the extreme ultraviolet. This is consistent with the observed increase of the white dwarf temperature from 150 000 to 180 000 K during the 1997 outburst. The mass dropped on to the white dwarf during a ZAB-6 outburst is $5.6 \times 10^{-7} M_{\odot}$.

Since models ZAB-7 and ZAB-8 reproduce neither the shape nor the amplitude observed during the 1997 outburst, the only potential candidate for a model explanation of this event is ZAB-6, corresponding to an accretion rate of $10^{-6} M_{\odot}$, which is two to three orders of magnitude larger than the mass-transfer rate considered to be typical of systems such as Z And (S2006). Therefore the 1997

Table 5. Outburst properties of Z And non-irradiated disc models.

Model	\dot{M}_{in} (qsc) [$M_{\odot} \text{ yr}^{-1}$]	$\dot{M}_{\text{in}}(\text{peak})$ [$M_{\odot} \text{ yr}^{-1}$]	Δm_V	ΔM [M_{\odot}]	R_{trig} [10^{10} cm]	$R_{\text{f,max}}$ [10^{10} cm]	τ_{rise} [d]	τ_{dec} [d]	τ_{rec} [d]
ZAB-6	3.3×10^{-11}	3.4×10^{-6}	0.8	5.6×10^{-7}	4.05	40	73	118	355
ZAB-7	3.3×10^{-11}	5.2×10^{-7}	0.2	4.0×10^{-8}	2.15	19	30	46	208
ZAB-8	3.3×10^{-11}	8.4×10^{-8}	0.05	3.1×10^{-9}	1.5	10	14	18	143

The first column lists the models, the second column gives the value of the accretion rate during quiescence, the third column gives the accretion rate attained during the peak of the outburst. The fourth column gives the outburst amplitude in visual magnitudes. The next column contains an estimate of the amount of mass accreted on to the white dwarf during the outburst. The following two columns provide respectively the radii at which the heating front starts and finishes its propagation. The next two columns give the outburst rise and decay times observed in V . The final column gives the recurrence time between outbursts.


Figure 7. Visual light-curve of dwarf nova outbursts for the models ZAB-6 (solid red curve), ZAB-6-I (dashed blue curve) and ZAB-6-II (dash-dotted green curve). The properties of the light-curves are given in Tables 5 and 6.

Figure 8. Accretion rate at the inner disc edge during outburst for models ZAB-6 (solid red curve), ZAB-6-II (dash-dotted green curve) and ZAB-6II-ES (dashed blue curve).

outburst would have to be related to an increase in the mass-transfer rate and could not be a pure dwarf nova outburst. It would be similar to dwarf nova *superoutbursts* according to the interpretation of Hameury, Lasota & Warner (2000) and Smak (2008).

The Z And accretion disc is irradiated, however, and its structure can be substantially affected by irradiation. We discuss the impact of irradiation in the next subsection.

4.1.2 Irradiated discs

In this section we consider irradiation, under two different assumptions for the irradiation efficiency at the outer disc.

4.1.2.1. Fully irradiated discs. We first consider the case in which irradiation by both nuclear burning at the white dwarf surface and accretion modify the structure of the entire disc (i.e. both inner and outer regions). As mentioned in Section 2.1, when the disc scale-height H is such that $H/R_{\text{WD}} < 1$, we use the extended source formula given by equation (5), with $T_{\text{irr,S}}^4 = T_*^4 + T_{\text{eff}}^4$ (Hameury et al. 1999). For $H/R_{\text{WD}} > 1$ we use equation (1) with $L = L_* + L_{\text{acc}}$.

We consider the same three mass-transfer rates as before, but with two sets of irradiation parameters: a strong irradiation case, ZAB-6-I, ZAB-7-I and ZAB-8-I with $1 - \beta = 0.03$ and $C = 0.002$; and a weaker irradiation case, ZAB-6-II, ZAB-7-II and ZAB-8-II with $1 - \beta = 0.01$ and $C = 0.001$. Since we do not have direct (or even indirect) information about disc irradiation in Z And or similar systems we use parameters similar to those used in modelling dwarf novae and X-ray transient systems. There is no guarantee that this choice is adequate, but, as we shall see, the results are fairly insensitive to irradiation parameters, at least as far as the main properties of the light-curves are concerned.

Constant irradiation of the outer disc has a different effect on disc stability from accretion self-irradiation, the luminosity of which is proportional to the accretion rate. A comparison of Fig. 9 with figures 8 and 9 of Dubus et al. (1999) shows that in both cases irradiation extends the radius of the hot stable portion of the disc, but in the case of constant irradiation this effect increases with decreasing accretion rate so that discs with accretion rates lower than about 10^{17} g s^{-1} are fully *thermally* stable. Our model ZAB-8-I (corresponding to an accretion rate of $6.3 \times 10^{17} \text{ g s}^{-1}$) is locally unstable, but because of the stabilizing effects of the radial terms in the time-dependent energy-conservation equation (the term proportional to J in equation 7 of Dubus et al. 2001) no outburst is produced.

Outbursts in a disc irradiated by a constant-luminosity source (which dominates except at maximum in the ZAB-6 models) are different from those occurring in non-irradiated discs or in self-irradiated discs of soft X-ray transient sources. They consist of reflections of heating and cooling fronts travelling between two radii defined as $R_{\text{f,min}}$ and $R_{\text{f,max}}$. This can be seen in Fig. 10, for ZAB-6-I and ZAB-6-II, where the fronts propagate between $R_{\text{f,max}}$ and $R_{\text{f,min}}$, so that the cooling fronts never reach the inner disc radius shown by the dashed lines. This is a major difference from ZAB-6, in which the cooling front can propagate to the disc inner edge and bring the full disc into quiescence. As a result of the irradiation, the inner disc is kept hot during the whole outburst cycle, which produces cooling-front reflections, whereas, as in the non-irradiated case, the heating front is stopped well before reaching the disc outer rim. In contrast to the case of soft X-ray transients (Dubus et al. 2001),

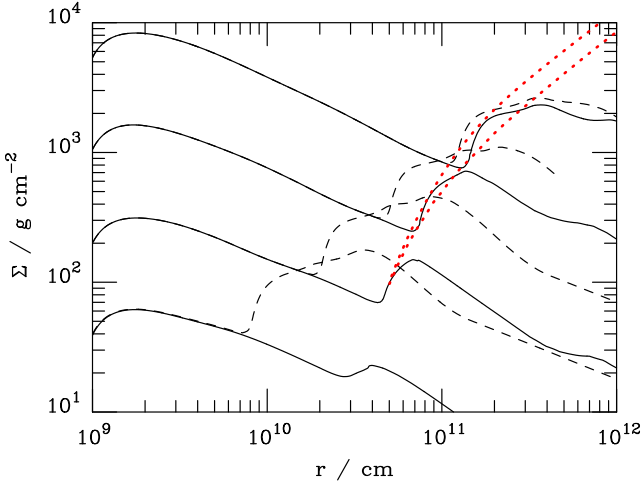


Figure 9. Column density ($\Sigma(R)$) profiles of stationary discs around a $0.65 M_{\odot}$ white dwarf irradiated by a constant luminosity $L = 4 \times 10^{36} \text{ erg s}^{-1}$. Disc irradiation is described by equation (1), with parameters $\mathcal{C} = 0.002$ and $\alpha = 0.1$. The accretion rates from bottom to top are 10^{16} , 10^{17} , 10^{18} and 10^{19} g s^{-1} . Dashed lines represent non-irradiated discs; full lines correspond to discs irradiated by a constant luminosity. The position of the critical column densities Σ^+ and Σ^- are marked by two dotted red lines intersecting at $r = 5 \times 10^{10} \text{ cm}$, $\Sigma = 100 \text{ g cm}^{-2}$.

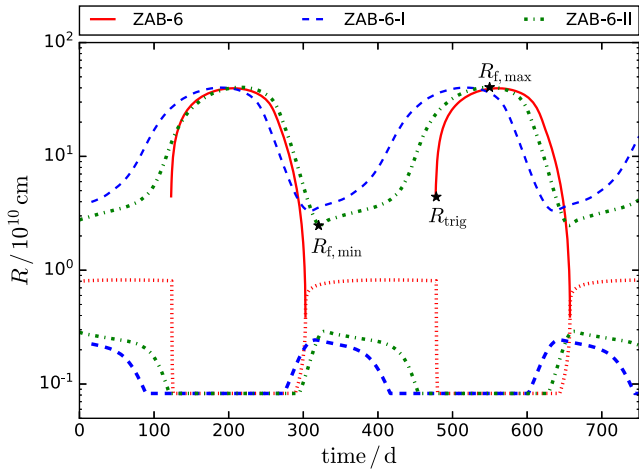


Figure 10. Position of heating/cooling fronts during outbursts for models ZAB-6, ZAB-6-I and ZAB-6-II (top red solid, blue dashed and green dash-dotted curves, respectively). The positions of the inner disc radius during the outburst for these models are also shown (bottom curves), using the same line-styles except for the ZAB-6 model (red dotted curve). The radius at which the instability is triggered, R_{trig} , is marked for the second of the ZAB-6 outbursts. Similarly, the maximum radius $R_{f,\text{max}}$ reached by the heating front and the minimum radius $R_{f,\text{min}}$ reached by the cooling front are indicated for the second of the ZAB-6-II outbursts.

disc truncation does not suppress reflares because the irradiation is dominated by its constant component, independent of the accretion rate. Although the disc never fully enters into quiescence, the light-curve shows clear, well-separated outbursts, with quiescent intervals during which the optical light is dominated by the secondary, and it is thus possible to define the same parameters τ_{rec} , τ_{rise} , τ_{dec} describing the outburst properties as previously.

The resulting visual light-curves (see Fig. 7 and Table 6 for the outburst parameters) for the case of the highest mass-transfer rate, $\dot{M}_{\text{tr}} = 10^{-6} M_{\odot} \text{ yr}^{-1}$, are similar to those obtained in the non-irradiated case, but more symmetric. Since the heating fronts reach similar radii, the peak accretion rate is roughly the same as for non-irradiated discs, and a comparable amount of mass is dropped by an outburst on to the white dwarf. The shape of the visual light-curves is even more unlike to that observed during the 1997 outburst of Z And. For lower mass-transfer rates, the outbursts we obtain are weaker than in the non-irradiated case and cannot really be qualified as outbursts. As before, in order to obtain the correct amplitude, the mass-transfer rate has to be increased by two orders of magnitude.

4.1.2.2. Inner disc irradiation only. One could reasonably argue that describing outer disc irradiation in Z And using the LMXB formalism adapted to the symbiotic case does not make much sense. First, even in the case of LMXBs it is not clear how and why their outer discs are irradiated (Tuchman, Mineshige & Wheeler 1990; Dubus et al. 1999; Tetarenko et al. 2018b), even if observations clearly show that they are (see e.g. van Paradijs & McClintock 1995). Secondly, in LMXBs the illuminating radiation is much harder than it is in the case of Z And. One could therefore argue that in the case of symbiotic systems the effect of outer disc irradiation is negligible. This is why we have made another test of the hypothesis that some symbiotic outbursts, those of Z And in particular, are dwarf nova outbursts or are triggered by them, using a different assumption about the irradiation effects. We now assume that irradiation is given by equation (5) throughout the disc, whatever the value of H/R_* , so that irradiation becomes very small for large radii. The irradiation flux now varies as R^{-3} for large values of R .

As before, we tried two cases: ‘I’, with $1 - \beta = 0.03$; and ‘II’, with $1 - \beta = 0.01$. However, since the results are almost indistinguishable we present in Table 7 results only for ZAB-6-II-ES, ZAB-7-II-ES and ZAB-8-II-ES, where ‘ES’ means that only inner disc irradiation is taken into account.

In contrast to the fully irradiated case, the cooling fronts are able to propagate to the inner disc radius; this is because, during decay, the inner disc radius becomes large and the irradiation flux, when calculated using equation (5), becomes small. This does not, however, lead to outbursts that differ in a very significant way from those obtained previously.

For the highest accretion rate ($10^{-6} M_{\odot} \text{ yr}^{-1}$), the model light-curves are very similar to that calculated for non-irradiated discs, as can be seen in Figs 7 and 8. They are also not much different from the light-curves obtained for a fully irradiated disc. This is not surprising, because the importance of constant irradiation diminishes with increasing accretion rate and because, owing to the low white dwarf accretion efficiency, self-irradiation is (almost) never dominant.

Differences in light-curves are more prominent for lower accretion rates, but these produce neither amplitudes nor shapes comparable to these observed.

4.2 Combination-nova outbursts of Z And

As noted above, S2006 suggest that the 2000 to 2002 eruption of Z And was powered by an increase in nuclear shell-burning on the white dwarf surface triggered by mass influx added by a dwarf nova outburst. They noticed that this event seems to begin like the 1997 outburst (which they assume to be a dwarf nova outburst), but

Table 6. Outburst properties of Z And irradiated disc models. I - fully irradiated discs.

Model	$\dot{M}_{\text{in}}(\text{qsc})$ [$M_{\odot} \text{ yr}^{-1}$]	$\dot{M}_{\text{in}}(\text{peak})$ [$M_{\odot} \text{ yr}^{-1}$]	Δm_V	ΔM [M_{\odot}]	$R_{\text{in,qsc}}$ [10^{10} cm]	$R_{\text{f,min}}$ [10^{10} cm]	$R_{\text{f,max}}$ [10^{10} cm]	τ_{rise} [d]	τ_{dec} [d]	τ_{rec} [d]
ZAB-6-I	2.96×10^{-9}	2.98×10^{-6}	0.7	4.63×10^{-7}	0.24	3.3	40.2	122	123	335
ZAB-7-I	3.04×10^{-9}	2.65×10^{-7}	0.13	1.51×10^{-8}	0.23	3.6	16.1	65	57	129
ZAB-8-I	–	–	–	–	–	–	–	–	–	–
ZAB-6-II	2.02×10^{-9}	3.16×10^{-6}	0.76	4.98×10^{-7}	0.29	2.5	40.5	110	116	335
ZAB-7-II	1.61×10^{-9}	3.44×10^{-7}	0.16	2.11×10^{-8}	0.29	2.5	17.0	55	52	142
ZAB-8-II	2.05×10^{-9}	2.17×10^{-8}	0.0017	4.02×10^{-10}	0.25	2.9	6.7	20	20	44

Columns are the same as in Table 5.

Table 7. Outburst properties of Z And irradiated disc models. II – inner irradiation only.

Model	$\dot{M}_{\text{in}}(\text{qsc})$ [$M_{\odot} \text{ yr}^{-1}$]	$\dot{M}_{\text{in}}(\text{peak})$ [$M_{\odot} \text{ yr}^{-1}$]	Δm_V	ΔM [M_{\odot}]	$R_{\text{in,qsc}}$ [10^{10} cm]	R_{trig} [10^{10} cm]	$R_{\text{f,max}}$ [10^{10} cm]	τ_{rise} [d]	τ_{dec} [d]	τ_{rec} [d]
ZAB-6-II-ES	7.0×10^{-11}	3.63×10^{-6}	0.84	5.9×10^{-7}	0.67	4.17	40.2	64	108	352
ZAB-7-II-ES	7.0×10^{-11}	5.45×10^{-7}	0.22	4.17×10^{-8}	0.66	2.28	18.8	28	44	212
ZAB-8-II-ES	7.0×10^{-11}	8.11×10^{-8}	0.52	2.76×10^{-9}	0.66	0.87	8.8	13	17	139

Columns are the same as in Table 5

reaches a luminosity close to $10^4 L_{\odot}$ and lasts for more than a year. In addition, observation of the ejection of an optically thick shell of material excludes a dwarf nova outburst and points to a milder version of a nova event. S2006 proposed that this was a disc-instability-triggered thermonuclear eruption and called it a ‘combination nova’. They estimated from observations that the mass dropped on to the white dwarf during the 1997 outburst was approximately $10^{-7} M_{\odot}$. The mass of the burning shell was about $2 \times 10^{-5} M_{\odot}$, and S2006 consider that adding 1 to 10 per cent of the shell mass should be sufficient to trigger a shell thermonuclear flash.

We do not address here the problems that such an interpretation poses for models of nuclear burning on the surface of a white dwarf mentioned by S2006 but consider only the viability of the dwarf nova component of the combination nova. As we have shown above, a dwarf nova outburst of a disc with Z And parameters can provide more than about $10^{-7} M_{\odot}$ only if the mass-transfer rate is close to $10^{-6} M_{\odot} \text{ yr}^{-1}$. Therefore such an outburst must be preceded by an increase of the mass-transfer rate by 2 orders of magnitude, because the long-term rate is supposed to be $10^{-8} M_{\odot} \text{ yr}^{-1}$. However, although such outbursts would provide the mass increase necessary to trigger an enhanced thermonuclear burning shell on the white dwarf surface, the shape of their visual light-curves does not correspond well to observations. Therefore the hypothesis that the combination of dwarf nova and nova outbursts is an explanation of Z And symbiotic outbursts is not confirmed by model calculations of disc thermal-viscous instabilities. The fact that an increase in the mass supply to the disc is required to obtain the right energetics suggests that such an increase could be sufficient to trigger the outbursts of Z And, as proposed by Leibowitz & Formigini (2008).

Use of the updated distance from *Gaia* supports this argument. With this new distance, the secondary has to be hotter than 3200 K for the quiescence magnitude to be around $V = 10.5$, assuming that the secondary still fills 57 per cent of its Roche lobe. The outburst amplitude is then reduced from 0.8 to 0.4 mag. If, on the other hand, we assume that the temperature is 2900 K as before, then

the secondary must entirely fill its Roche lobe, and the outburst amplitude is about 0.6 mag. In both cases, the dwarf nova outbursts cannot explain the observed Z And outbursts, pointing towards other possibilities such as mass-transfer enhancement, as mentioned above.

5 CONCLUSIONS

We have studied the stability of accretion discs in symbiotic stars, which usually have long orbital periods, with particular emphasis on two systems, RS Oph and Z And. For the expected mass-transfer rates lower than $10^{-4} M_{\odot} \text{ yr}^{-1}$, their presumably large accretion discs (larger than 10^{12} cm) are prone to thermal-viscous instabilities and are thus expected to exhibit outbursts of the type observed in dwarf nova stars.

RS Oph

We have considered three models corresponding to three different mass-transfer rates, 10^{-6} , 10^{-7} and $10^{-8} M_{\odot} \text{ yr}^{-1}$. None of these models reproduces the observed recurrence time and brightness amplitude of the recurrent nova outbursts. This rules out the possibility that these outbursts are in fact dwarf-nova-type outbursts, contrary to the suggestion by King & Pringle (2009), even in the case where their luminosity is increased as a result of steady hydrogen burning (Alexander et al. 2011). Note also that the peak accretion rate found by Alexander et al. (2011) exceeds the limit $\dot{M}_{\text{RG}} = 3\dot{M}_{\text{stable}}$ above which hydrogen can be burned as quickly as it is accreted; their outburst luminosity is therefore largely overestimated and TNRs are unavoidable.

We also considered the possibility that the disc instability outbursts can trigger a TNR on the white dwarf surface; as was proposed by S2006 in the case of Z And. For a mass-transfer rate of $10^{-6} M_{\odot} \text{ yr}^{-1}$, we found that the mass of unburnt hydrogen accreted in a single outburst is sufficient to trigger a TNR, but the outbursts would then occur every 1.5 to 4 yr, instead of the observed 20 yr.

We found, however, that for mass-transfer rates of a few times $10^{-8} M_{\odot} \text{ yr}^{-1}$, the ignition mass can be accumulated on the white dwarf surface within roughly 20 yr. In this case, a series of dwarf nova outbursts can trigger the recurrent nova eruptions observed in RS Oph. This model might explain the pre-outburst luminosity increase observed in the light-curves of RS Oph outbursts (Adamakis et al. 2011) and explain the varying X-ray flux observed at different epochs of RS Oph quiescence. A recurrent-nova model not involving dwarf nova triggers requires a very small disc and does not explain the quiescent and pre-outburst observations. This suggests that RS Oph outbursts are recurrent ‘combination nova events’.

Z And

We studied the possibility that, as suggested by S2006, some features of the complex Z And light-curve can be explained by dwarf nova outbursts. We found that for a mass-transfer rate of $10^{-6} M_{\odot} \text{ yr}^{-1}$ the brightness amplitude of the disc instability outburst is close to 1 mag in the V band, which is very close to the amplitude of the 1997 outburst. However, the disc instability model totally fails to reproduce the observed shape of this outburst: the rise-time is far too long, and the outburst duration is too short. For lower mass-transfer rates, in addition to being the wrong shape, the outbursts are much fainter than observed.

Although we have shown that the 1997 feature was not caused by a dwarf nova outburst, we explored the possibility that the 2000-to-2002 outburst of Z And was, as suggested by S2006, a combination of a dwarf nova and nova outburst. We found that a single dwarf nova outburst can enhance nuclear burning on the white dwarf provided that the mass-transfer rates are close to $10^{-6} M_{\odot} \text{ yr}^{-1}$. Such steady high mass-transfer rates are most unlikely in this system. Reaching such a value requires a large (factor 10 at least) mass-transfer enhancement, which would in itself generate a significant brightening of the disc. Whether this enhancement leads to a disc instability or not is of little importance, and we therefore conclude that the initial component of the proposed ‘combination nova’ scenario is most likely the abrupt enhancement of the mass-transfer rate. Such an enhancement has been proposed by Bath & Pringle (1982) for explaining the outbursts of the symbiotic binary CI Cyg, and could be attributed for example to the magnetic activity at the surface of the companion, as suggested by Leibowitz & Formigini (2008).

Dwarf nova outbursts may play a role in triggering RS Oph recurrent outbursts but are, most probably, of no importance in the case of Z And.

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APPENDIX A: CRITICAL VALUES OF EFFECTIVE TEMPERATURE, COLUMN DENSITY AND ACCRETION RATE

$$T_{\text{eff}}^+ = 7122 \alpha^{-0.002} m^{0.03} R_{10}^{-0.082} \text{ K} \quad (\text{A1})$$

$$T_{\text{eff}}^- = 5665 \alpha^{-0.005} m^{0.03} R_{10}^{-0.087} \text{ K} \quad (\text{A2})$$

$$\Sigma^+ = 7.983 \alpha^{-0.784} m^{0.374} R_{10}^{1.122} \text{ g cm}^{-2} \quad (\text{A3})$$

$$\Sigma^- = 12.16 \alpha^{-0.835} m^{0.371} R_{10}^{1.113} \text{ g cm}^{-2} \quad (\text{A4})$$

$$\dot{M}^+ = 9.16 \times 10^{15} \alpha^{-0.008} m^{-0.88} R_{10}^{2.67} \text{ g s}^{-1} \quad (\text{A5})$$

$$\dot{M}^- = 3.67 \times 10^{15} \alpha^{-0.02} m^{-0.88} R_{10}^{2.65} \text{ g s}^{-1} \quad (\text{A6})$$

The ‘+’ and ‘−’ superscripts distinguish between the critical values for the upper and lower branch respectively. These fits are on average accurate to 1.5 per cent (T_{eff}^+), 3.5 per cent (T_{eff}^-), 6.9 per cent (Σ^+) and 10.3 per cent (Σ^-), for $10^{-2} < R_{10} < 100$ and $10^{-4} < \alpha < 1$ with maximum errors of 10, 12, 40 and 35 per cent respectively.

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