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

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ABSTRACT
Using the disc instability model we investigate the stability of accretion discs in long–period binary systems. We simulate outbursts due to the thermal-viscous instabilities for two symbiotic systems, RS Ophiuchi and Z Andromedae. The outbursts properties deduced from our simulations suggest that although the recurrent nova events observed in RS Oph are due to a 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 onto the white dwarf at rates comparable to or larger than the mass-transfer rate. If the mass transfer rate is in the range $10^{-8}$ – $10^{-7}$ $M_\odot$/yr, 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, barely visible in the optical, but easily detectable in 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 outbursts properties, making them significant only for very high mass transfer rates, of the order of $10^{-6}$ $M_\odot$/yr, much higher than the expected secular mean in this system. It is thus likely that the so-called “combination nova” (Sokoloski et al. 2006b) outburst observed in years 2000-2002 was triggered not by a dwarf-nova instability but by a mass–transfer enhancement from the giant companion, leading to an increase of nuclear burning at the accreting white-dwarf surface.

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

1 INTRODUCTION
Symbiotic stars are interacting binary systems in which a primary hot star accretes 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 been also observed. These binary systems show several types of outbursts. A small subset is observed as “slow novae” whose outbursts last for decades; another subset is formed by recurrent nova (RN) whose outbursts repeat on timescales from several to several tens of years. Both types of nova outburst are known to result from thermonuclear runaways 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 of outbursts is known under the name of Classical Symbiotic Outbursts (hereafter CSO) and their origin is still a subject of debate (see e.g. Sokoloski et al. 2006b, hereafter S2006, and references therein).

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

Orbital periods of symbiotic stars range from years to decades which correspond to binary separations ranging from $10^{13}$cm to $10^{15}$cm, so that accretion discs (if present)

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2 THE MODEL

We use the version of the DIM described in Hameury et al. (1998) with added heating due to steam impact and the dissipation by the tidal torques as described in Buat-Ménard et al. (2001). Throughout this paper, unless otherwise noted (model RSB-A, see sect. 3), we take for the Shakura-Sunyaev viscosity parameters \( \alpha_c = 0.02 \) for a cold neutral disc and \( \alpha_n = 0.1 \) when the disc is hot and ionized.

2.1 Disc irradiation

For irradiated discs we use the version of the code (iDIM) described in Dubus et al. (1999); Hameury et al. (1999); Dubus et al. (2001); Lasota et al. (2008).

The flux \( F_{\text{irr}} \) of the outer disc regions is written as

\[
F_{\text{irr}} \equiv \sigma_{\text{SB}} T_\text{eff}^4 = C \frac{L}{4 \pi R^2},
\]

where \( \sigma_{\text{SB}} \) 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. 2018). In this case

\[
L = L_\text{acc} = \eta \dot{M} C \, \frac{R_c^2}{R_s^2},
\]

where \( R_s = 2GM/c^2 \) is the Schwarzschild radius and

\[
F_{\text{acc}} \equiv \sigma_{\text{SB}} T_\text{eff}^4 \approx 3GM \frac{\dot{M}}{8 \pi R_s^2}.
\]

For \( C \sim 10^{-3} \) and \( \eta \sim 0.1 \), used in models of X-ray transients (Dubus et al. 2001), \( F_{\text{irr}}/F_{\text{acc}} \sim 10^{-4} \) and \( T_{\text{irr}} > T_{\text{eff}} \) for \( R > 10^5 R_s \). However, for white dwarfs \( \eta \sim 10^{-2} \), and even for very large discs, self-irradiation of the outer disc is never in practice important since it would require disc radii \( R > 10^6 - 10^8 R_s \sim 4 \times 10^{14} - 10^{13} \) cm. Only for massive white dwarfs and \( C \sim 10^{-2} \) self-irradiation of its outer region could play a role in the disc structure and evolution (see below the discussion in the case of RS Oph).

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

\[
\frac{F_{\text{irr}}}{F_{\text{acc}}} \approx \frac{2}{3} \frac{C L_s}{G M/M/R_s R_c} \approx 0.5 \left( \frac{M_c}{M} \right) \left( \frac{R}{10^9 \text{cm}} \right) \left( \frac{C L_s}{10^{33} \text{erg s}^{-1}} \right) \left( \frac{10^{19} \text{g s}^{-1}}{M} \right),
\]

where \( R_c \) is the white dwarf radius. In the symbiotic star Z And, for example, the steady luminosity of thermonuclear burning is \( \sim 10^{11} L_\odot \) which shows that even for very high accretion rates the outer disc surface temperature will
be dominated by irradiation from the central source. Since constant irradiation is in the accretion rate, it impacts the whole disc outburst cycle because, contrary to the accretion-self-irradiation case, it is also present during quiescence. Notice that in Eq. (4), contrary to Eq. (2), the ratio $F_{irr,P}/F_{acc}$ depends on the accretion rate and decreases with increasing $M$.

One should note, however, that it is not clear in what conditions Eq. (1) applies to discs around white dwarfs, 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 is $C \sim 5 \times 10^{-2}$ (Dubus et al. 1999). Note that $C$ used here differs from the $C$ as defined in Dubus et al. (1999) in that it does not include the efficiency parameter $\eta$.

Eq. (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 by (see e.g., Hameury et al. 1999)

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

where the subscript $*$ refers to quantities measured at the white dwarf surface; $\rho = R_t/R_t$. At large distances, $F_{irr,S}$ as given by Eq. (5) varies as $R^{-3}$ and is much smaller than what one would get using Eq. (1); conversely, close to the white dwarf, Eq. (1) underestimates the irradiation flux.

In what follows, when the ratio of the disc scale-height to stellar radius $H/R_*$ is larger than 1, we use Eq. (1) to describe irradiation, whereas in the opposing case $H/R_*$ is much smaller than 1, Eq. (5) is used.

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 $\kappa P_\nu = 2/3 g_z$, is replaced by (Hameury et al. 2009)

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

where $\kappa$ is the Rosseland mean opacity, $g_z$ is the vertical component of gravity, $\rho$ the density, $P_\nu$ and $P_{rad}$ are the gas and radiation pressure respectively.

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

$$R_{mag} = 5.13 \times 10^{3} \mu_{30}^{4/7} m^{-1/7} \left( \frac{M_{acc}}{10^{15} \text{ g/s}} \right)^{-2/7} \text{ cm}, \quad (7)$$

where $m$ is the accretor mass in solar units, $M_{acc}$ is the accretion rate onto the white dwarf, which differs from $M_{nuc}$ if the system is not accreting, and $\mu_{30}$ is the white dwarf magnetic moment in units of $10^{30}$ G cm$^3$ (Frank et al. 2002).

2.3 S-curves

On the $\Sigma - T_{eff}$ plane, accretion disc’s steady-states at a given radius, form celebrated “S-curves”. Figure 1 shows examples of such S-curves we obtain 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 $10^8 - 10^{12}$ cm and for $C$ in the range $10^{-4} - 1$. As can be seen, 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. Note also that the extent of the unstable branch is largely 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 et al. 2003). For the shell burning sources we model their emission as that of a black-body with the shell luminosity $L_{nuc}$. The contribution of the red giant is important, and more difficult to evaluate in particular because it may or may not fill its Roche lobe. Specific details for RS Oph and Z And are given in the corresponding sections.

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

3 RS OPHIUCHI

3.1 Observations

RS Oph is a symbiotic RN with a recurrence time $\sim 20$ yr. The binary has an orbital period of $\sim 453.6$ days, the
mass ratio $q \equiv M_2/M_1 = 0.6$, and the eccentricity $e = 0$ (Brandi et al. 2009). The low-mass ejecta to the Chandrasekhar limit (see e.g. Yaron et al. 2005, for a study of the dependence of the ejecta characteristics upon the system parameters). Also other arguments point towards a high-mass primary (Mikołajewska & Shara 2017). Therefore the mass of the K7 giant ($\mu$ursel & Schmid 1999) companion can be estimated to be $M_2 \approx 0.8 M_\odot$; the inclination is $\approx 50^\circ$, and orbital separation $a \approx 2.2 \times 10^{13}$ cm.

The visual magnitude varies from 12.5 in quiescence to 4.8 at maximum (https://www.aavso.org/vsots_rsoph). During weeks 6 to 10 of the last, 2006 outburst, RS Oph was a supersoft X-ray source with a luminosity in the 0.2–1.0 keV range close to the Eddington luminosity, with a temperature of the white dwarf photosphere $\sim 8 \times 10^4$ 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 resulting 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 vary from $10^{-5} M_\odot$/yr (Iijima 2008) to $10^{-8} M_\odot$/yr (Evans et al. 2007). Recent estimates by Booth et al. (2016) give $5 \times 10^{-7} M_\odot$/yr.

The distance of $\sim 1.6$ kpc to RS Oph based on Bode (1987) is usually assumed but distances as low as 540 pc (Monnier et al. 2006) and as high as 2.45 kpc (Rupen et al. 2008) have been claimed. The quiescent accretion rate is variable. At day 241 after the 2006 outburst, when optical flickering had resumed indicating re-formation of an accretion disc, the accretion rate was estimated to be within $\sim 10^{-10} M_\odot$/yr and $\sim 10^{-9} M_\odot$/yr, depending on the assumed model of mass-loss from the secondary (Worters et al. 2007). However, on days 537 and 744 X-ray observations suggested accretion rates between $7 \times 10^{-11} M_\odot$/yr and $5 \times 10^{-9} M_\odot$/yr, depending on the emission model and assuming a 1.6 kpc distance (Nelson et al. 2011). At a distance of 2.45 kpc the accretion rates would be respectively $2 \times 10^{-9} M_\odot$/yr and $1.2 \times 10^{-8} M_\odot$/yr. The presence of an absorbed optical thick boundary layer would allow accretion rates up to $3.2 \times 10^{-8} M_\odot$/yr (for a 1.6 kpc distance; Nelson et al. 2011). However, observations by ROSAT PSPC of RS Oph six and seven years after the 1985 outburst implied quiescent accretion rates in the range $10^{-12}$ to few $10^{-11} M_\odot$/yr (Orio 1993; Orio et al. 2001). Similar results were obtained by Mukai (2008) in 1997. Such low accretion rates have been considered as “completely at odds with the short nova outburst recurrence time ($\sim 20$ years)” (Nelson et al. 2011).

The reason is that a thermonuclear–runaway recurrence time of 20 yr, for a white dwarf close to the Chandrasekhar limit requires an average accretion rate of $\approx 10^{-8} M_\odot$/yr (Yaron et al. 2005). Therefore the highest estimates of both the companion mass-loss and the accretion rate on the white dwarf are consistent with a nova outburst occurring every $\sim 20$ years. 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 whose presence 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 studying if this instability gives rise to large scale outbursts and if these outbursts, if occurring, can drop enough mass onto the white dwarf to trigger a thermonuclear runaway while having, according to the DIM, very low quiescent accretion rates.

### 3.2 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 AGNs, even when unstable, do not show large-scale outbursts for reasons explained in Hameury et al. (2009). It is therefore not obvious a priori what will be the response of a very large disc to a thermal-viscous instability. To study this problem we calculated a series of models whose parameters are given in Table 2.

#### 3.2.1 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 $10^{-6}$, $10^{-7}$ and $10^{-8} M_\odot$ yr$^{-1}$. To these three models we add RSB-A which is the closest we could get to the model considered in Alexander et al. (2011).

In all models the mass of the white dwarf is $m = 1.35$ (see e.g. Hachisu et al. 2007) and the assumed distance is 1.6 kpc. 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 $2 \times 10^{30}$ G cm$^3$. Truncation of the inner disc is necessary 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 just numerical nuisance.

Since the giant companion of RS Oph is not supposed to fill its Roche lobe, it is not clear what the structure of the accretion flow in this system is, in particular what is the size.

#### Table 2. Models of RS Oph dwarf-nova outbursts

| Model  | $R_{in}$(qsc) | $R_O$ | $M_e$ |
|--------|---------------|-------|-------|
| 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| $10^{-6}$ |

$R_{in}$(qsc) is the inner disc radius during quiescence, $M_e$ is the mass-transfer rate from the secondary and $R_O$ is the outer disc radius. * – model closest to Alexander et al. (2011).
of the accretion disc that apparently is present during quiescence. For the assumed binary parameters the circularisation radius for the Roche-lobe filling case is \( R_{\text{circ}}^{\text{tid}} = 2.37 \times 10^{12} \text{cm} \) (Lubow & Shu 1975), while in the case of wind accretion it is \( R_{\text{circ}}^{\text{wind}} < 2.2 \times 10^{11} \lambda(a)^{-4} \text{cm} \), where \( \lambda \sim 1 \) (Frank et al. 2002). In our code the average outer disc radius is determined by the tidal torque

\[
T_{\text{tid}} = c_{\text{tid}} \Omega_{\text{orb}} r_D \Sigma \left( \frac{r}{a} \right)^5,
\]

where \( \nu \) is the kinematic viscosity coefficient, \( c_{\text{tid}} \) is a numerical coefficient which 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 a value of \( c_{\text{tid}} = 3.0 \times 10^9 \) such that \( R_D \) is of the order of \( 10^{12} \) cm.

We also simulate the RS Oph system using the same parameters as in 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 the previous values, but, in order to have the same circularisation radius, \( R_c \approx 1.74 \times 10^{12} \text{ cm} \) and disc size (~\( R_c \)) as theirs, we consider the orbital period to be 287.5 days. As in Alexander et al. (2011), the disc is truncated at a fixed inner radius of \( \sim 10^{10} \) cm. We also use \( \alpha_c = 0.01 \) as in their model.

Figure 2 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, heating fronts reach the disc outer edge, and the outer radius of the disc does not vary during the outbursts contrary to what is seen in smaller discs. During quiescence the typical accretion rate onto the white dwarf \( \dot{M}_w \gtrsim 10^{-12} M_\odot \text{ yr}^{-1} \). The larger the mass-transfer rates, the larger the peak value of \( \dot{M}_w \) during an outburst. Figure 3 shows the time variations of the visual magnitude, the mass accretion rate, and the total disc mass for model RSB-6, which has the longest recurrence time. The small intermediate outbursts are not detectable in visible light, but could be marginally detectable in X-rays.

As the peak values of \( \dot{M}_w \) listed in Table 3 are more than three orders of magnitude larger than the quiescent values, most of the mass is accreted onto 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: ~ 2 vs ~ 6.5 mag. Also, the recurrence times of the outbursts for models RSB-6, RSB-7, RSB-8 is much shorter than the observed 20 yr (0.5 to 1.5 yr). Therefore the DIM as such cannot account for these outbursts.

We final consider model RSB-A. Our results differ widely from those of Alexander et al. (2011): the recurrence time we obtain is smaller than the value they get for a mass transfer rate of \( 10^{-6} M_\odot /\text{yr} \) by a factor four and their outburst duration is longer, as a consequence, the mass accreted onto the white dwarf in a single outburst is an order of magnitude larger than the value \( 3 \times 10^{-6} M_\odot \) we obtain for model RSB-A. These differences may be attributed to the way the 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, the effective temperatures are computed using a relation which only holds for large optical depths (they use \( T_{\text{eff}} = T_\text{e} \tau^{-1/4} \)), which is inconsistent with their estimate for the cooling term. In our models, we fully solve the vertical structure. For comparison, we plot the S-curves for RS Oph in Fig. 1 which we computed using the same parameters as in Alexander et al. (2011). The effective temperatures at the critical surface densities are smaller by factors 3-4 in their model as compared to ours. This significa-

Table 3. Disc outbursts properties for RS Oph models.

| Model | \( \dot{M}_w \) (qsc) \((M_\odot \text{ yr}^{-1})\) | \( \dot{M}_w \) (peak) \((M_\odot \text{ yr}^{-1})\) | \( M_V \) (qsc) | \( M_V \) (peak) | \( \Delta M \) / outburst \((M_\odot)\) | \( \tau_{\text{rec}} \) (days) | \( \tau_{\text{obs}} \) (days) | \( R_{\text{max}} \) (10^{10} cm) |
|-------|--------------------------|--------------------------|----------------|----------------|------------------------------|----------------|----------------|----------------|
| RSB-6 | \( 3.8 \times 10^{-12} \) | \( 4.15 \times 10^{-6} \) | 11.03 | 9.08 | \( 10^{-6} \) | 556 | 238 | 56 |
| RSB-7 | \( 3.8 \times 10^{-12} \) | \( 6.3 \times 10^{-7} \) | 11.03 | 10.48 | \( 6.8 \times 10^{-8} \) | 335 | 115 | 27 |
| RSB-8 | \( 3.8 \times 10^{-12} \) | \( 9.3 \times 10^{-8} \) | 11.03 | 10.9 | \( 4.5 \times 10^{-9} \) | 205 | 50 | 12.7 |
| RSB-A | \( 4.5 \times 10^{-12} \) | \( 9.6 \times 10^{-6} \) | 11.03 | 8.25 | \( 3.35 \times 10^{-6} \) | 1190 | 260 | 70 |

The first column lists the model reference, the second and third ones give the minimum quiescent and outburst peak value of the mass accretion rate. The fourth and fifth columns give the absolute visual magnitude during quiescence and outburst peak respectively. The sixth column gives an estimate of the amount of mass accreted onto the white dwarf during the 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 2. Optical light curves for the models RSB-6, RSB-7, RSB-8.](image-url)
cantly alters the results. One should also note that truncating the disc at $10^{10}$ cm is rather excessive. Magnetic truncation would imply a magnetic moment larger than $3 \times 10^{33}$ Gcm$^3$, i.e., large enough for pulsations at the spin period to be observed.

3.3 “Combination recurrent-nova” outbursts of RS Oph

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

We have considered this possibility for our three typical models.

- RSB6: In this model the mass accreted by the white dwarf during a single outburst $\Delta M \approx 10^{-6} M_\odot$ is larger than $M_{\text{ign}}$, so that one dwarf-nova outburst could, in principle, trigger a nova event. The mass $M_{\text{ign}}$ is accumulated during the first 90 days of the disc outburst; but, by the time this critical mass has been accreted, $M_\text{in}$ exceeds the stable nuclear burning limit, which is $M_{\text{stable}} = 6 \times 10^{-8} M_\odot$/yr (Wolf et al. 2013). $M_{\text{in}}$ also exceeds the limit $M_{\text{RG}} = 3 M_{\text{stable}}$ above which hydrogen can be burnt as quickly as it is accreted, so that the hydrogen mass increases; a thermonuclear runaway occurs as soon as the accretion rate falls below $M_{\text{stable}}$, which occurs at day 140 after the outburst has been triggered. The early phases of the outburst, corresponding to a $\sim 2$ change in visual magnitude could be visible in the optical (Adamakis et al. 2011) but would be easy to detect in X-rays since the accretion rate increases by five orders of magnitude. Of course, for such a scenario to work, the rate at which mass is transferred to the disc must be $\sim 10^{-6} M_\odot$/yr which implies that most of the mass lost by the companion must end up in the accretion disc. This is far for being guaranteed but this tight requirement could be loosened if disc self-irradiation were taken into account allowing higher mass accreted with lower accretion rate (see below). 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 during the 20 years between observed RS Oph nova outbursts one would expect about 13 dwarf-nova outbursts, each triggering a TNR. Which clearly is not the case.

- RSB-7: For this model $M_{\text{ign}}$ is accumulated during $\sim 6$ dwarf-nova outbursts in about 5 years. The quiescent accretion rate is the same as in RSB-6, because of the same disc truncation. During “quiescence”, the accretion rate would increase due to dwarf-nova outbursts that, in this case, does not trigger TNRs. They would be invisible in optical but could be detected in X-rays. The mass transferred to the disc is very reasonable, assuming a mass-loss from the companion of few times $10^{-7}$.

We conclude that a model with an accretion rate between those of RSB-7 and RSB-8 can explain most of the properties of RS Oph recurrent nova outbursts. The mass necessary for a TNR is accumulated during 20 years in a series of 15-20 dwarf nova outbursts. Such a scenario naturally explains the discrepant X-ray observations and different quiescent epochs of RS Oph outburst cycle: low values correspond to quiescent disc phase, while high X-ray luminosities to one of the dwarf nova outbursts.

On the other hand, also a more conventional scenario could explain RS Oph recurrent nova outbursts. A steady accretion rate of $\sim 2 \times 10^{-8} M_\odot$/yr is sufficient to accumulate the mass $M_{\text{ign}}$ corresponding to RS Oph parameters. A disc in a system with RS Oph binary parameters will be stable if the rate of mass at which it is fed satisfies the inequality $M_\text{in} > M_\text{crit}$, where the stable hot-disc minimal accretion rate is (Eq. A5)

$$M^+ = 1.44 \times 10^{-10} \alpha_{\text{h}}^{-0.008} m_{\text{wd}}^{-0.88} R_{\text{D,10}}^{-2.47} M_\odot \text{yr}^{-1};$$

where $m_{\text{wd}}$ is the white-dwarf mass in solar units, and $R_{\text{D,10}}$ the outer disc radius in units of $10^{16}$cm. For $M_\text{in} > 2 \times 10^{-8} M_\odot$/yr an accretion disc with an outer radius $R_D < 7.4 \times 10^{10}$cm will be stable with respect to the thermal-tidal instability. This is however 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 values of the accretion rate deduced from ROSAT and ASCA observations and one would be left with speculations of type presented in Mukai (2008), who suggested that RS Oph might be a fast rotator with essentially no boundary layer. Note that this is inconsistent with our assumption of a significant magnetic field.
4.1 Observations

Z And is classical symbiotic star consisting of a $M_1 = 0.65 \pm 0.28 \, M_\odot$ (Schmid & Schild 1997) white dwarf, and a giant secondary with mass ratio $M_2/M_1 \sim 2.0$. Its orbital period is 759 days (Formiggini & Leibowitz 1994), the inclination is $59^\circ.5$ (Skopal & Shagatova 2012). The distance to Z And is estimated to be $1.2 \pm 0.5$ kpc (Kenny 1995). The presence of magnetized ($\sim 10^4 - 10^5$ G) primary is deduced from observations of persistent optical pulsations at a period of 28 minutes (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 $\sim 10^3 \, L_\odot$ attributed to thermonuclear shell burning of hydrogen at rate of few times $10^{-8} \, M_\odot \, yr^{-1}$ (see, e.g., S2006). Symbiotic stars undergo outbursts, the most common of which are classical symbiotic outbursts whose origin is unknown, but whose high peak luminosities exclude dwarf-nova type outbursts but whose high repetition frequency rules out thermonuclear runaways of the recurrent-nova type. Contrary to the recurrent novae, white dwarfs in these symbiotic systems have low masses, precluding short recurrence times.

In 1997, the Z And light-curve showed a low amplitude
(≤ 1 mag) outburst in the V-light, with ≤ 20 days rise-time followed by a ~200 days decay. The asymmetric outburst shape prompted S2006 to suggest that the 1997 outburst was due to a dwarf-nova–type instability of the outside-in type, i.e. 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 – 2002, when after a rise similar to the 1997 event the brightness kept increasing to reach a 2 optical mag amplitude, corresponding to a bolometric luminosity ~ 10^6 L⊙. If accretion–powered, this high-state would correspond to an accretion rate $\dot{M} \gtrsim 10^{-5} M_{\odot}/yr$. Such high accretion rate would have to be sustained for a full year during which the system maintained a luminosity close to the maximum one (S2006). Since this seems unlikely, S2006 proposed that this event was a “combination nova” outburst in which a dwarf-nova outburst triggered an increased shell nuclear burning. In order to test the S2006 hypotheses we will calculate models of disc outbursts in Z And using our DDM code, adapted to the physical properties of this system.

### 4.2 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, to which corresponds a circularization radius $R_{\text{circ}} = 2.085 \times 10^{12}$ cm. In the case of wind accretion the circularization radius would be $1.34 \times 10^{10}$ cm, assuming that the wind speed is equal to the escape speed from the giant ($\alpha(a) \approx 1$).

Since the critical accretion rate at $R_{\text{circ}}$ is (Eq. (A5)) $2.95 \times 10^{-4} M_{\odot}yr^{-1}$, a non-irradiated disc in Z And will be thermally and viscously unstable for all realistic ($< 10^{-4} M_{\odot}yr^{-1}$) 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 – $R_D \approx 1.4 \times 10^{12}$ cm (S2006) – is one or two orders of magnitude larger than that in dwarf-novae which, as already noticed by Duschl (1986b), can have dramatic effects on heating and cooling front propagation (see e.g., Menou et al. 2000; Dubus et al. 2001).

Second, the disc is irradiated by a constant white dwarf surface luminosity of ~ 10^9 L⊙, 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 will 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.

Third, 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 interpreted as dwarf-nova outburst (Smak 1984). One should note, however, that “fast-rise – slow-decay” light-curves can be also produced by outbursts starting near the inner disc radius. This happens e.g., 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 as (Lasota 2001)

$$\dot{M}_{tr} \gtrsim \frac{0.5 \sqrt{\dot{M}_{tr}}}{\sqrt{3}} \dot{M}_{\text{crit}},$$

(10)

where $\delta < 2$, and

$$\dot{M}_{\text{crit}} = 1.15 \times 10^{-5} \alpha_c^{-0.02} M_{\odot}0.88 R_D^{6.5} M_{\odot}yr^{-1}$$

(11)

is the critical (maximal) accretion rate for a cold and stable accretion disc (Eq. A6). $R_D$ is the disc radius in 10^{12} cm units. For the Z And parameters Eq. (10) implies rather unrealistically high mass-transfer rates $\gtrsim 10^{-5} M_{\odot}yr^{-1}$.

#### 4.2.1 Non-irradiated disc

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 an non-irradiated disc. We assume a white dwarf magnetic moment of $5.12 \times 10^{35}$ G cm\(^2\), which corresponds to a magnetic field of ~ 10^8 G. Our results do not depend significantly on the value of the accretor magnetic moment.

In calculating the visual light-curves we include the contribution of the giant companion in a different way from Schreiber et al. (2003) which is well-adapted to a Roche-lobe filling low-mass companion but not applicable to the case of Z And. We considered each of the 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 secondary luminosity changes in response to irradiation in a maximum way. This would be 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 value for the 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 $110 R_\odot$, i.e. the secondary fills 57% of its Roche lobe.

We found that the two prescriptions produce very similar light-curves and in what follows we will 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 $\dot{M}_{tr} = 10^{-8}$, $10^{-7}$ and $10^{-6} M_{\odot}yr^{-1}$. We assume $\alpha_c = 0.02$ and $\alpha_h = 0.1$, and choose $c_{\text{tid}}$ such as the outer disk radius is $R_D = 2.37 \times 10^{12}$ cm. Following S2006 we assume a distance of 1.2 kpc.

The properties of these three models are presented in Table 5. One can see that only model ZAB-6 produces a visual amplitude ~ 1 mag; however, the shape of the outburst light-curve is markedly different from that observed in 1997 in Z And. The rise-time (~ 70 days) is three times longer, while the decay-time (~ 118 days) is roughly half the observed one. The light-curve shown in Fig. 5 is typical

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\(^1\) Model outbursts for LMXB parameters are always of the inside-out type (Dubus et al. 2001)
of a inside-out outburst, i.e. of an outburst starting in the inner disc region. Indeed, the inner disc radius during quiescence, given by Eq. (7) with \( \mu_{0} = 51.2 \) and \( \dot{M}_{\text{acc}} = 3.3 \times 10^{-11} \text{M}_{\odot}\text{yr}^{-1} \) is equal to \( R_{\text{in}} = 0.82 \times 10^{10} \text{cm} \) whereas the heating front starts propagating at \( R_{\text{trig}} = 4.05 \times 10^{10} \text{cm} \). While the inner disc edge reaches the white dwarf surface, this front propagates out up to \( R_{\text{max}} = 40 \times 10^{10} \text{cm} \), 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 \( \sim 10^{5} \) in the case of model ZAB-6 (see Fig. 6). At maximum the inner edge is squeezed by accretion on to the white dwarf surface (the white dwarf radius \( R_{\text{WD}} = 8.56 \times 10^{6} \text{cm} \)) and for this model the corresponding accretion luminosity reaches \( \sim 2600 \text{L}_{\odot} \), which should be emitted mostly in EUV. This is consistent with the observed increase of the white dwarf temperature from 150 000K to 180 000K during the 1997 outburst. The mass dropped onto the white dwarf during a ZAB-6 outburst is \( 5.6 \times 10^{-7} \text{M}_{\odot} \).

Since models ZAB-7 and ZAB-8 produce neither the shape nor the amplitude of 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 \( 10^{-7} \text{M}_{\odot} \), 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 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 et al. (2000) and Smak (2008).

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

4.2.2 Irradiated discs

4.2.2.1 Fully irradiated discs

We first consider the case where 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 subsection 2.1, when the disc scale-heights \( H \) is such that \( H/R_{\text{WD}} < 1 \) we use the extended source formula given by Eq. (5), with \( T_{\text{irr}, \text{WS}} = T_{\text{eff}}^4 + T_{\text{irr}, \text{eff}}^4 \) (Hameury et al. 1999). For \( H/R_{\text{WD}} > 1 \) we use Eq. (1) with \( L = L_{\text{r}} + L_{\text{acc}} \).

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 \( C = 0.001 \).
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Table 6. Outburst properties of Z And irradiated disc models. I– fully irradiated discs.

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

Figure 7. Column density profiles ($\Sigma(R)$) 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 Eq. 1, with parameters $C = 0.002$; $\alpha = 0.1$. The accretion rates from bottom to top are $10^{16}$, $10^{17}$, $10^{18}$, and $10^{19}$ g/s. Dashed lines represent non-irradiated discs, full lines correspond to disc irradiated by a constant luminosity. The position of the critical column densities $\Sigma^+$ and $\Sigma^-$ are marked by two green lines intersecting on the diagram at $r = 5 \times 10^{10}$ cm, $\Sigma = 100$ g/cm$^2$.

Since we do not have direct (or even indirect) information about disc irradiation in Z And or similar systems we are using parameters similar to those used in modelling dwarf-novae and X-ray transient sources, at least as far as the main properties of the light-curves are concerned.

Contrary to the case of soft X-ray transients the cooling fronts never reach the inner disc radius shown by dashed lines. This is a major difference with ZAB-6 in which the cooling front can propagate to the disc inner edge, and bring the full disc into quiescence. Due to 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.

Outbursts in a disc irradiated by a constant luminosity source (which dominates except at maximum in 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 radii $R_{\text{f,min}}$ and $R_{\text{f,max}}$. This is shown in Fig. 8, 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 dashed lines. The optical light is dominated by the secondary and one is thus able to define the same parameters $\tau_{\text{rec}}$, $\tau_{\text{rise}}$, $\tau_{\text{dec}}$ describing the outbursts properties as previously.

The resulting visual light-curves (see Table 6 and Fig. 5

\textbf{Figure 8.} Time evolution of the heating/cooling front positions during outbursts (solid lines) as compared to the inner disc radius (dashed lines) for the models ZAB-6 (red), ZAB-6-I (blue) and ZAB-6-II (green). The point at which the instability is triggered $R_{\text{trig}}$ is shown for model ZAB-6. ($R_{\text{f,min}}$ and $R_{\text{f,max}}$ are indicated for model ZAB-6-II.)
Table 7. Outburst properties of Z And irradiated disc models. II – inner irradiation only.

| Model      | $M_{\text{in}}$ (qsc) $(\text{M}_\odot\text{yr}^{-1})$ | $M_{\text{in}}$ (peak) $(\text{M}_\odot\text{yr}^{-1})$ | $\Delta M_V$ | $\Delta M/\text{outb} (\text{M}_\odot)$ | $R_{\text{in, qsc}} 10^{10} (\text{cm})$ | $R_{\text{trig}} 10^{10} (\text{cm})$ | $R_{\text{max}} 10^{10} (\text{cm})$ | $\tau_{\text{rise}}$ (days) | $\tau_{\text{dec}}$ (days) | $\tau_{\text{rec}}$ (days) |
|------------|-------------------------------------------------|-------------------------------------------------|--------------|---------------------------------------|-----------------------------------|-----------------------------------|----------------------------------|-----------------|-----------------|-----------------|
| ZAB-6-II-ES| $7.0 \times 10^{-11}$                           | $3.63 \times 10^{-6}$                           | 0.84         | $5.9 \times 10^{-7}$                  | 0.67                              | 4.17                              | 40.2                             | 64              | 108             | 352             |
| ZAB-7-II-ES| $7.0 \times 10^{-11}$                           | $5.45 \times 10^{-7}$                           | 0.22         | $4.17 \times 10^{-8}$                 | 0.66                              | 2.28                              | 18.8                             | 28              | 44              | 212             |
| ZAB-8-II-ES| $7.0 \times 10^{-11}$                           | $8.11 \times 10^{-8}$                           | 0.52         | $2.76 \times 10^{-9}$                 | 0.66                              | 0.87                              | 8.8                              | 13              | 17              | 139             |

the highest mass transfer rate case, $\dot{M}_t = 10^{-6} \text{M}_\odot\text{yr}^{-1}$ 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 onto the white dwarf. The shape of the visual light-curve is even less similar 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, to obtain the correct amplitude, the mass-transfer rate has to be increased by two orders of magnitude.

4.2.2.2 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 the outer disc is irradiated (Tuchman et al. 1990; Dubus et al. 1999), even if observations clearly show it is (see e.g., van Paradijs & McClintock 1995). Second, in LMXBs the illuminating radiation is much harder than it is the case in Z And. One could therefore argue that in the case of symbiotics the effect of outer disc irradiation is negligible. This is why we have made another test of the hypothesis that some of symbiotic outbursts, those of Z And in particular, are dwarf nova outbursts, or are triggered by them with a different assumption for the irradiation effects. We now assume that irradiation is given by Eq. (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 $1 - \beta = 0.01$ but since the results are almost undistinguishable 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 with the fully irradiated case, the cooling fronts are able to propagate to the inner disc radius; this is due to the fact that during decay, the inner disc radius becomes large and the irradiation flux, when calculated using Eq. 5 becomes small. This does not, however, lead to outbursts which differ in a very significant way from those obtained previously.

For the highest value of the accretion rate ($10^{-6} \text{M}_\odot\text{yr}^{-1}$) the model light-curves are very similar to that calculated for non-irradiated discs as can be seen in Figs. 5 and 6. 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, of 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 the observed ones.

4.3 Combination-nova outbursts of Z And

As mentioned before, S2006 suggest that the 2000 – 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. Indeed, this event seems to begin like the 1997 outburst, but reaching a luminosity close to $10^{4} \text{ L}_\odot$ and lasting more than a year. In addition, observation of the ejection of an optically thick shell of material exclude a dwarf-nova outburst and points to a milder version of a nova event. S2006 call such a disc-instability triggered thermonuclear eruption “combination nova”. They estimate from observations that the mass dropped onto the white dwarf during the 1997 outburst was $\sim 10^{-7} \text{M}_\odot$. The mass of the burning shell being $\sim 2 \times 10^{-6} \text{M}_\odot$ and S2006 consider that adding $\sim 0.01 – 0.1$ of the shell mass should be sufficient to trigger a shell thermonuclear flash.

We do not address here the problems that such 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 $\gtrsim 10^{-7} \text{M}_\odot$ only if the mass-transfer rate is close to $10^{-6} \text{M}_\odot\text{yr}^{-1}$. Therefore such an outburst must precede by an increase of the mass-transfer rate by two orders of magnitude, since the long-term value is supposed to be $10^{-8} \text{M}_\odot\text{yr}^{-1}$. However, although such outbursts would provide the mass-increase necessary to trigger 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 to get the right energetics require increasing the mass-supply to the disc suggests that such an increase could be sufficient to trigger the outbursts of Z And, as indeed proposed by Leibowitz & Formiggini (2008).

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. These binary systems harbour large accretion discs ($\gtrsim 10^{12}$ cm) which
are prone to thermal-viscous instabilities, unless the mass-transfer rates are greater than $10^{-6} M_\odot/yr$, and dwarf nova type outbursts are expected.

**RS Oph**

We have considered three models corresponding to three different mass-transfer rates - $10^{-6}$, $10^{-7}$ and $10^{-8} M_\odot/yr$. None of these models reproduce the observed recurrence time and brightness amplitude of the recurrent novae outbursts. This rules out the possibility that these outbursts are in fact dwarf-novae type outbursts, contrary to the suggestion by Alexander et al. (2011).

We also considered the possibility that the disc instability outbursts can trigger a thermonuclear runaway on the white dwarf surface; as was proposed by S2006 in the case of Z And. The mass of unburnt hydrogen accreted in a single outburst when the accretion rate is as high as $10^{-6} M_\odot/yr$ is sufficient to trigger a thermonuclear runaway, but the outbursts occur much more frequently than once every 20 yrs. For lower accretion rates, the mass accreted during a single outburst is less than the ignition mass, but this can be accreted over a few dwarf nova outbursts. For mass-transfer rates between $10^{-8}$ and $10^{-7} M_\odot/yr$, the disc instability outbursts can trigger a thermonuclear runaway every 20 yrs approximately. This might explain the pre-outburst luminosity increase observed in the light curves of RS Oph outbursts (Adamakis et al. 2011).

We have also considered the effect of irradiation due to accretion onto the white dwarf. We found that despite significant changes in the outbursts properties as compared to the unirradiated case, the same conclusion that for mass-transfer rates between $10^{-7}$ and $10^{-8} M_\odot/yr$, RS Oph nova outbursts are triggered every ~20 yr during one of the dwarf nova outbursts holds, the main difference being that the dwarf nova outbursts last longer, are brighter and have longer recurrence times, so that a smaller number of dwarf nova outbursts are needed for a thermonuclear runaway to occur.

**Z And**

The brightness amplitude of the disc instability outburst for a mass transfer rate of $10^{-6} M_\odot/yr$ both in the non-irradiated and irradiated case is close to 1 mag in the V band, very similar to the amplitude of the 1997 outburst. But both the non-irradiated and irradiated models fail to reproduce the observed shape of this outburst, because the rise-time is far too long, and the outburst duration is too short. For lower mass transfer rates, the outbursts are much fainter than observed.

We also considered the possibility that the 2000-2002 outburst in Z And was the combination of a dwarf nova and a nova type outburst, as suggested by S2006. The required mass range for nuclear burning enhancement is estimated to be within $10^{-7} - 10^{-6} M_\odot$ in S2006. Our results both in the irradiated and non-irradiated case show that approximately $2 \times 10^{-9} - 5.6 \times 10^{-7} M_\odot$ can be added to the white dwarf envelope during a single disc instability outburst, which implies that dwarf nova outbursts can result in enhanced nuclear burning on the white dwarf provided the mass-transfer rates are in the range $10^{-6} - 10^{-7} M_\odot yr^{-1}$, so this mechanism requires substantial mass-transfer enhancement. Since in addition dwarf-nova outbursts would have light-curve shapes different from those observed, one can conclude that they are not a component of the proposed “combination-nova” event. It is more likely that that this component is an abrupt enhancement of mass-transfer rate, such as proposed by Bath & Pringle (1982) for explaining the outbursts of the symbiotic binary CI Cyg, and which could be due e.g. to the magnetic activity on the surface of the companion as proposed by Leibowitz & Formiggini (2008).
APPENDIX A: CRITICAL VALUES OF EFFECTIVE TEMPERATURE, COLUMN DENSITY AND ACCRETION RATE

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

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

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

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

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

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

These fits are on the average accurate to 1.5% (\(T_{\text{eff}}^+\)), 3.5% (\(T_{\text{eff}}^-\)), 6.9% (\(\Sigma^+\)), and 10.3% (\(\Sigma^-\)), for \(10^{-2} < R_{10} < 100\) and \(10^{-4} < \alpha < 1\) with maximum errors of 10, 12, 40 and 35% respectively.

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