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On the nova-like eruptions of symbiotic binaries

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SUMMARY

We discuss three popular explanations for the nova-like eruptions observed in symbiotic binary stars and compare model predictions with recent observations. Most outbursts occur when unstable hydrogen shell burning causes a hot white dwarf to expand to a radius of 1–100 $R_\odot$. This model predicts a long-duration, constant-luminosity phase following visual maximum, and observations of the symbiotic novae and several steady-burning sources confirm this feature of thermonuclear runaway calculations. At least two symbiotics erupt when the accretion rate from a circumstellar disc onto a solar-type central star increases by 1–2 orders of magnitude. Simple accretion models emit ~50 per cent of the gravitational energy in the disc and the remainder in a hot boundary layer between the disc and central star. Observations of CI Cyg and AX Per support this picture for accretion rates below $\sim 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, but boundary layer emission vanishes for higher accretion rates. Finally, we associate observations of extra reddening and the appearance of high-ionization emission lines in R Aqr with an increase in the Mira mass-loss rate initiated, perhaps, by a helium shell flash above the Mira's degenerate core.

Key words: accretion, accretion discs – binaries: symbiotic – stars: evolution – stars: individual: R Aqr.

1 INTRODUCTION

A. Cannon and P. Merrill discovered symbiotic binaries in the 1920s as red giant stars with unusually strong H I and He II emission lines. Most newly discovered symbiotics showed semiperiodic optical brightness variations of $\lesssim 1$ mag on time-scales of years, and several had undergone 2–4-mag eruptions in the previous 30 years. The optical spectrum changed dramatically in an eruption, as an A–F supergiant star appeared to replace the red giant at optical maximum and many high-ionization emission lines vanished. Both the red giant absorption spectrum and strong emission lines returned as the system declined from optical maximum.

Early binary models for symbiotic stars proposed that a hot companion to the red giant caused the eruptions (e.g., Berman 1932; Hogg 1934; Kuiper 1940; Payne-Gaposchkin 1957). Ultraviolet observations acquired with the *International Ultraviolet Explorer (IUE)* confirm the presence of a hot, compact star in many symbiotics, and these systems are now commonly accepted as interacting binaries similar to cataclysmic variable stars (see, for example, Mikołajewska, Selvelli & Hack 1988). The physical cause of the eruptions remains controversial, as both accretion-powered events and thermonuclear runaways in material accreted by a white dwarf can account for many observed features of a typical symbiotic outburst.

Our aim in this paper is to review popular explanations for the eruptions of symbiotic binaries and then to see if the available data support these models. We begin with a brief discussion of the theories in Section 2 and compare their predictions with observations in Section 3.

2 THEORIES FOR ERUPTIONS IN SYMBIOTIC BINARIES

2.1 Thermonuclear outbursts

Most models for symbiotic eruptions involve nuclear burning of material accreted by a white dwarf secondary (see, for example, Tutukov & Yungel'son 1976; Paczyński & Rudak 1980; Kenyon & Truran 1983; Sion & Starrfield 1986; Livio, Prialnik & Regev 1989; Sion & Ready 1992). An accreting white dwarf has three possible configurations, depending on the mass accretion rate $\dot{M}$. For a small range of $\dot{M}$, hydrogen burns in a stable shell as it is accreted (Paczyński & Żytkow 1978; Sion, Acierno & Tomczyk 1979; Fujimoto 1982b). The minimum accretion rate for steady burning is (Iben 1982):

$$\dot{M}_{\mathrm{steady,min}} \approx 1.32\times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}\ M_{\mathrm{wd}}^{3.57}, \quad (1)$$

where M_{wd} is the white dwarf mass in $M_\odot$. The maximum steady burning rate is set by the core mass–luminosity relation (Paczyński 1970; Üüs 1970):

$$\dot{M}_{\rm steady,\,max} \approx 8 \times 10^{-7}\, M_\odot\ {\rm yr}^{-1}\, (M_{\rm wd} - 0.522\, M_\odot). \qquad (2)$$

A white dwarf stably burning incoming hydrogen has a large luminosity – $L \sim 1\text{–}50 \times 10^3\ L_\odot$ – and a very high effective temperature – $T_{\rm eff} \sim 1\text{–}2 \times 10^5$ K.

If $\dot{M}$ exceeds $\dot{M}_{\rm steady,\,max}$, incoming material accumulates above the burning shell and expands to giant dimensions. Although the bolometric luminosity remains approximately constant during this evolution, the optical brightness increases by 1–2 orders of magnitude as the effective temperature decreases from $T_{\rm eff} \sim 1\text{–}2 \times 10^5$ to $\sim 10^4$ K. The optical eruption occurs on a thermal time-scale:

$$\tau_{\rm th} \sim 0.1 \left(\frac{M_{\rm env}}{10^{-4}\, M_\odot}\right) \left(\frac{L_{\rm h}}{10^4\, L_\odot}\right)^{-1} {\rm yr}, \qquad (3)$$

where $L_{\rm h}$ is the total luminosity and $M_{\rm env}$ is the envelope mass (Paczyński & Rudak 1980; Fujimoto 1982b; Iben 1982). Both $L_{\rm h}$ and $M_{\rm env}$ depend on the white dwarf mass: $M_{\rm env}$ decreases with increasing white dwarf mass, while $L_{\rm h}$ increases with increasing white dwarf mass. Published calculations suggest $\tau_{\rm th} \lesssim 1$ yr for $M_{\rm wd} > 1\ M_\odot$, so small increases in $\dot{M}$ above the steady burning limit can cause symbiotic eruptions only in systems with massive white dwarfs.

When $\dot{M}$ falls below $\dot{M}_{\rm steady,\,max}$, hydrogen burning depletes the envelope faster than accretion can replenish it. The lack of envelope material eventually extinguishes the burning shell, and material again begins to accumulate on the white dwarf's surface. When the pressure at the base of the envelope reaches a critical value, nuclear burning recommences in a 'hydrogen shell flash' (e.g. Fujimoto 1982a; Iben 1982; MacDonald 1983). If $\dot{M}$ is low enough, the shell flash occurs in a degenerate envelope and the envelope burns explosively. The accreted envelope is non-degenerate for higher $\dot{M}$s, and the hydrogen shell flash is milder.

The bolometric luminosity increases by a factor of $10\text{–}10^4$ over a rise time of ~ 1 yr in most hydrogen shell flashes. Unless mass loss reduces the envelope mass substantially, the white dwarf luminosity remains close to the core mass luminosity until the envelope is almost completely burned on the nuclear time-scale:

$$\tau_{\rm nuc} \sim 400 \left(\frac{M_{\rm env}}{10^{-4}\, M_\odot}\right) \left(\frac{L_{\rm h}}{2 \times 10^4\, L_\odot}\right)^{-1} {\rm yr}. \qquad (4)$$

Kenyon & Webbink (1984; see also Paczyński & Rudak 1980; Kenyon 1986) summarize the predicted photometric and spectroscopic evolution of thermonuclear symbiotic systems, and we review them briefly here. All accreting white dwarfs should be hot, luminous extreme-ultraviolet (EUV) and ultraviolet (UV) sources – $L_{\rm h} \sim 10\text{–}10^4\ L_\odot$ and $T_{\rm eff} \sim 0.5\text{–}2 \times 10^5$ K – and are identified as quiescent symbiotic binaries when they have a red giant companion.

If $\dot{M}$ should increase for a steadily burning white dwarf, the accreting star evolves into an A–F supergiant at constant luminosity. Thus, the optical luminosity rises while the EUV/UV luminosity declines. Emission from high-ionization emission lines – such as He II and C IV – decline in step with the EUV/UV luminosity, although lower ionization emission from H I and He I remains prominent. The solid curve in Fig. 1 summarizes the photometric evolution anticipated from a steadily burning white dwarf.

The photometric evolution expected from a hydrogen shell flash is substantially different. The rise to visual maximum during this event is characterized by a rapid increase in bolometric luminosity at nearly constant radius, followed by a slow expansion at constant bolometric luminosity. Thus, the EUV/UV continuum and high-ionization emission lines initially increase dramatically while the optical brightness remains nearly constant. Once the bolometric luminosity reaches maximum, the photometric and spectroscopic evolution follow the behaviour of a steadily burning white dwarf, as decreases in the UV continuum and high-ionization emission accompany an increase in optical brightness. The decline from an optical maximum should occur roughly on the nuclear time-scale, although wind-driven mass loss can shorten the length of this constant-luminosity phase below that predicted by equation (4).

The total increase in visual brightness depends on the strength of the shell flash. White dwarfs undergoing strong, degenerate flashes evolve into A–F supergiants and thus resemble classical novae at maximum visual light (Fig. 1). Objects experiencing weak, non-degenerate flashes remain at high effective temperatures throughout their evolution and more closely resemble the central stars of planetary nebulae at visual maximum (Paczyński & Rudak 1980; Iben 1982; Kenyon & Truran 1983).

2.2 Accretion-powered outbursts

Kuiper (1940, 1941) first proposed that the behaviour of β Lyr and other peculiar stars might be caused by tidal overflow in an interacting binary system. Matter lost by the lobe-filling primary star forms a disc around its companion to produce a blue continuum source and emission lines, and variations in the mass-flow rate result in optical outbursts. Accretion – energy derived by material falling into a potential well – rather than nuclear fusion powers the binary in this picture, and luminosity variations result from changes in the accretion rate, $\dot{M}$.

Two physical mechanisms can change $\dot{M}$ through an accretion disc, mass-transfer instabilities and disc instabilities. Disc instabilities occur when the mass-flow rate through the disc, $\dot{M}_{\rm d}$, is smaller than the mass-transfer rate into the disc, $\dot{M}_{\rm in}$ (see Duschl 1986a, b, and references therein). The disc mass increases in this situation until the surface density, Σ, reaches a critical value and the disc's surface temperature, $T_{\rm d}$, and luminosity increase abruptly. The total disc luminosity evolves roughly on the local sound traveltime:

$$\tau_{\rm s} \sim 0.3 \left(\frac{R_{\rm d}}{1\ {\rm AU}}\right) {\rm yr}, \qquad (5)$$

where $R_{\rm d}$ is the outer disc radius. If the mass-transfer rate set by the surface temperature – $\dot{M}_{\rm d} \propto T_{\rm d}^4$ – increases above $\dot{M}_{\rm in}$, the disc mass decreases until $\dot{M}_{\rm d} < \dot{M}_{\rm in}$ and the eruption ends. This decline occurs over several thermal time-scales, and then the disc can begin the instability cycle again.

Mass-transfer instabilities commence when the lobe-filling giant ejects an extra blob of gas through the L_1 point (Bath 1975; Webbink 1976). The increased disc mass results in a larger $\dot{M}$ – and hence larger luminosity – on the thermal time-scale (equation 5). Unlike the disc instability mechan-

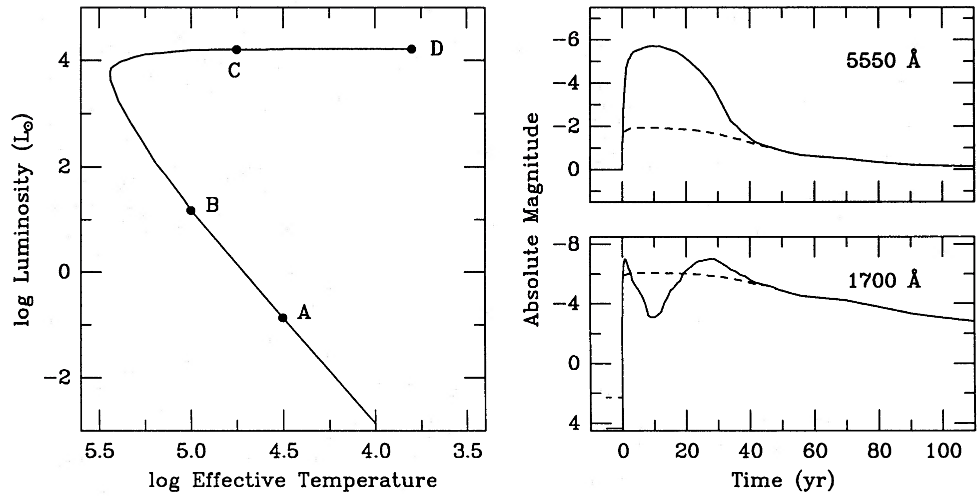

Figure 1. Predicted evolution of thermonuclear runaway models for symbiotic binary stars. The left panel shows the cooling curve of a low-mass white dwarf (adapted from Paczyński 1971). A white dwarf experiencing a degenerate shell flash evolves from point A to point D, while a system undergoing a non-degenerate flash evolves from point B to point C. The right-hand panels show the predicted evolution of optical and ultraviolet light curves during degenerate flashes (solid curves) and non-degenerate flashes (dotted curves).

ism, the decline from a mass-transfer instability occurs on the viscous time-scale, which is 10–100 times longer than the thermal time-scale.

The 2–7-mag optical eruptions place serious constraints on accretion-powered models for symbiotic stars. Bath & Pringle (1982) and Kenyon & Webbink (1984) showed that $\Delta V \gtrsim 2$ mag eruptions require main-sequence accretors unless $\dot{M}$ exceeds the Eddington limit (see also Webbink 1976). The evolution of a super-Eddington disc resembles a thermonuclear runaway (see Bath 1977; Kenyon & Webbink 1984), so accretion-powered eruptions can be identified only if $\dot{M}$ remains below the Eddington limit.

Accretion-powered outbursts distinguish themselves observationally from thermonuclear events by *an increase in the emitted flux at all wavelengths*, rather than the flux redistribution that characterizes the rise to optical maximum and early optical decline in the thermonuclear case. Main-sequence accretors develop A–F supergiant optical spectra at maxima as do degenerate thermonuclear events, but ultraviolet spectra more closely resemble late B or early A supergiants. This behaviour is caused by the radial temperature profile in the disc: $T_{\rm eff}$ decreases from ~ 20–30×10^3 K in the inner disc to ~ 5–10×10^3 K in the outer disc. During decline the systems qualitatively retrace this evolution, although the details depend on the cause of the increase in $\dot{M}$.

Most disc models predict that a boundary layer between the disc and central star radiates 50 per cent of the accretion energy if the central star rotates slowly (see Lynden-Bell & Pringle 1974). The boundary layer temperature exceeds 10^5 K for main-sequence accretors, so it emits most of its radiation in the EUV spectral range. This radiation photoionizes gas surrounding the disc – and perhaps material in the disc – to produce optical and UV emission lines such as H I, He II and N V. The fluxes in these lines provide a reasonably good estimate of the EUV luminosity produced by the boundary layer (Iijima 1981; Kenyon *et al.* 1991), so the evolution of the boundary layer can be determined with optical and ultraviolet spectra. A basic prediction of the disc model is that the EUV luminosity from the boundary layer should be comparable to the optical + UV luminosity from the disc. This behaviour is exactly opposite to that expected from the constant-luminosity phase of a thermonuclear runaway, where the emission-line intensities increase as the optical continuum fades.

Accretion-powered eruptions can mimic thermonuclear runaways in a red giant + white dwarf binary if the mass-transfer rate should exceed the Eddington limit, $\dot{M} \sim 10^{-5}$ $M_\odot$ yr^{-1} (e.g., Bath 1977). These ‘super-critical’ accretion events can produce an extended constant-luminosity phase that is hard to distinguish from the early decline from maximum during a thermonuclear runaway, but the core-mass luminosity for a typical 0.6-$M_\odot$ white dwarf, $L_{\rm core} \sim$ a few $\times 10^3$ $L_\odot$, is an order of magnitude smaller than the Eddington limit, $L_{\rm Edd} \sim$ a few $\times 10^4$ $L_\odot$. Thus, the bolometric luminosity at maximum serves to discriminate thermonuclear runaways from most super-critical accretion events. However, the core-mass luminosity roughly equals the Eddington luminosity for white dwarfs with masses exceeding 1 $M_\odot$, so the observed luminosity cannot help us to determine the source of an eruption in a symbiotic binary containing a massive white dwarf.

2.3 Ionization eruptions

Nussbaumer & Vogel (1987) proposed a new model for symbiotic binaries that relies on the red giant to produce an eruption. They envision a detached system composed of a hot, very luminous white dwarf accreting material from a red giant wind. In quiescence, the red giant loses material at a low rate – $\lesssim 10^{-7}$ $M_\odot$ yr^{-1} – and the white dwarf ionizes all gas it does not accrete from the wind. An outburst begins when the mass-loss rate of the giant increases to $\sim 10^{-5}$ $M_\odot$ yr^{-1}. Although the hot component's intrinsic luminosity does not increase substantially, emission from the ionized nebula increases dramatically from $M_V \sim +7$ to $\sim +2$ on a short time-scale.

Nussbaumer & Vogel claim that the $\Delta V \sim 5$ mag produced by their model can account for many symbiotic eruptions. Unfortunately, the total system brightness really changes very little, because a nebula with $M_V \sim +2$ is fainter than a typical red giant with $M_V \sim 0$. In addition, a wind with $\dot{M} \sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ produces a substantial local extinction. For a neutral wind with a normal gas-to-dust ratio (Savage & Mathis 1979), the local optical reddening is

$$A_V \sim 40 \left(\frac{\dot{M}}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right) \left(\frac{R_\mathrm{G}}{1\ \mathrm{AU}}\right)^{-1} \left(\frac{v_\mathrm{wind}}{100\ \mathrm{km\ s}^{-1}}\right)^{-1} \mathrm{mag}, \tag{6}$$

where R_G is the red giant's radius and v_wind is the wind velocity. The hot component does ionize some of the wind, but the portion of the wind occulted by the giant should be neutral and have large A_V. Thus, symbiotic stars experiencing this type of outburst should *decrease* in brightness until the giant's mass-loss rate relaxes to its quiescent level.

Nussbaumer & Vogel do not propose a mechanism for increasing a red giant's mass-loss rate on a short time-scale. One possibility is helium shell flashes, which are expected to recur with a period, P (in yr), given by:

$$\log P = 3.05 - 4.5(M_\mathrm{core} - 1.0\ M_\odot), \tag{7}$$

where M_core is the mass of the degenerate carbon–oxygen core (see Becker 1979). Although helium shell flashes do not change the photospheric properties of red giant models significantly, red giant mass-loss rates are sensitive to the stellar radius and luminosity (see Dupree 1986 and references therein). This mechanism for increasing $\dot{M}$ from a red giant has not been explored in much detail.

Photometric and spectroscopic observations can distinguish these 'ionization events' from the actual luminosity increases expected from accretion- or nuclear-powered eruptions. First, the large A_V expected from a high $\dot{M}$ should result in an overall decline in the red giant's optical and infrared luminosity. The emission lines should increase in overall intensity, provided that the hot component can ionize a large fraction of the stellar wind and is not occulted by the neutral portion of the wind. Most eruptive symbiotics do not display this type of behaviour, although some unusual systems may fit into this picture, as described in the next section.

3 DISCUSSION

We have shown that both accretion disc and thermonuclear runaway models can produce the A–F-type continuum observed during the eruptions of many symbiotic stars. The main distinguishing feature of accretion events versus thermonuclear runaways is the behaviour of the hot component's luminosity, L_h, and temperature, T_h, with time. In thermonuclear events, T_h increases at constant L_h as the visual brightness declines with time; both L_h and T_h decrease as the visual brightness declines in an accretion-powered outburst. Although accretion events do not naturally produce objects resembling the central star of planetary nebulae, thermonuclear runaways and increases in the red giant mass-loss rate can account for this smaller fraction of symbiotic eruptions. These two mechanisms can be distinguished simply by the visual light curve, as we expect the visual brightness to increase in a runaway and to decrease when the red giant mass-loss rate increases by 1–2 orders of magnitude.

We now consider how the observed behaviour of symbiotic stars fits these general predictions.

3.1 Thermonuclear outbursts

A small subset of symbiotic stars have undergone a single eruption of long duration. These eight very slow *symbiotic novae* – V1016 Cyg, V1329 Cyg, AG Peg, HM Sge, RT Ser, RR Tel, PU Vul and possibly AS 239 – rose from obscurity to bright visual maxima on a 1–2-yr time-scale and have remained luminous for many decades (see Allen 1980; Kenyon 1986; Viotti 1988; and references therein). Several – RT Ser, RR Tel, PU Vul and probably AG Peg – displayed A–F supergiant optical spectra at visual maximum and seem good candidates for the degenerate hydrogen shell flashes described above. The rest closely resemble the nuclei of planetary nebulae and probably underwent non-degenerate shell flashes.

Few pre-outburst observations exist for symbiotic novae. Three systems – V1016 Cyg, V1329 Cyg and PU Vul – appear as M giants on old objective prism plates; of these, only V1016 Cyg is known to have exhibited a strong Hα emission line prior to its eruption. Both V1016 Cyg and RR Tel displayed long-period brightness variations before outburst, and RR Tel's light curve identifies it as a Mira variable (Mayall 1952). The lack of quiescent observations for symbiotic novae makes it impossible to determine the bolometric amplitudes of their eruptions.

Following eruption, all symbiotic novae maintain a constant luminosity for several decades. For example, the bolometric brightness of AG Peg at optical maximum in 1871 – $M_\mathrm{bol}(\mathrm{hot}) \sim -3$ for an adopted A–F spectral type – agrees with the $M_\mathrm{bol}(\mathrm{hot}) \sim -2.5$ to -3 estimated from *OAO-2* and *IUE* observations acquired prior to 1980 (Gallagher *et al.* 1979; Mürset *et al.* 1991). Recent *IUE* data suggest a 1-mag decline in $M_\mathrm{bol}(\mathrm{hot})$ since 1980; this decline is hard to assess, because reliable model atmosphere calculations of the Wolf–Rayet-like hot component are not available. The optical luminosity in RR Tel remained constant at $M_V \sim -5$ during its 4-yr tenure as an A–F supergiant in 1946–50, which is close to the $M_\mathrm{bol}(\mathrm{hot}) \sim -4.5$ to -5 that Mürset *et al.* (1991) estimated from 1978–83 *IUE* spectra. The UV luminosities of V1016 Cyg and HM Sge have remained constant at the factor-of-two level for ~ 12 yr (Nussbaumer & Vogel 1990; Mürset *et al.* 1991), while PU Vul – aside from a very peculiar minimum in 1980 – has maintained a constant luminosity for at least 10 yr (Nussbaumer 1992).

The hot components in all symbiotic novae evolve towards higher effective temperatures, T_eff, as they decline from optical maxima (see Kenyon 1986). These increases in T_eff are substantial: Mürset *et al.* (1991) list $T_\mathrm{eff} > 10^5$ K for AG Peg and RR Tel at the present epoch, while $T_\mathrm{eff} \sim 7000$ K at visual maximum. Thus, these objects slowly contract at constant luminosity. This behaviour strongly suggests that they follow standard white dwarf cooling curves following optical maximum (see Fig. 1) and identifies the source of the eruption as a thermonuclear runaway on the surface of a white dwarf star.

The luminosities of several symbiotic novae – V1016 Cyg, HM Sge and PU Vul – are sufficiently close to the Eddington limit for 0.5–1.0-$M_\odot$ objects that their eruptions *might* be caused by super-critical accretion events rather than thermonuclear runaways. However, the time evolutions of these systems and those other symbiotics with much lower luminosities are so similar that we feel confident that thermonuclear runaways produce symbiotic novae.

The hot components in several other symbiotic stars also appear to maintain roughly constant bolometric luminosities, even though their effective temperatures vary on time-scales of years instead of decades. For example, the quiescent luminosity of BF Cyg – $L \sim 1\text{–}3 \times 10^3\ L_\odot$ – is close to the $L \sim 2700\ L_\odot$ estimated for the A–F shell source at visual maximum (Mikołajewska, Kenyon & Mikołajewski 1989). The same seems true for Z And. We estimate $L \sim 1700\ L_\odot$ for the A–F source that appeared in Z And in the 1930s and again in the late 1960s, while the hot component's quiescent luminosity is $L \sim 0.5\text{–}2 \times 10^3\ L_\odot$ (Kenyon & Webbink 1984; Fernández-Castro *et al.* 1988; Mürset *et al.* 1991). In both cases, an outburst appears to occur when the hot component expands in radius at roughly constant luminosity. Cassatella's (1984) estimate of $v_{\rm exp} \sim 100$ km s^{-1}, from Z And's P Cyg profiles in C IV and N V, suggests a slow expansion similar in nature to a slow nova eruption.

The 1–10-yr outburst time-scales for Z And and BF Cyg are more typical of thermal time-scales in white dwarf envelopes than of nuclear time-scales. Thus, we believe these eruptions are caused by small variations in $\dot{M}$ about the steady burning rate, $\dot{M}_{\rm steady}$. This interpretation has one major difficulty, because both Z And and BF Cyg appear to contain low-mass white dwarfs – $M_{\rm h} \sim 0.6\ M_\odot$ – as estimated from their low bolometric luminosities. Model calculations suggest short thermal time-scales occur only for massive white dwarfs with $M_{\rm h} \gtrsim 1\ M_\odot$ and $L \gtrsim 2 \times 10^4\ L_\odot$ (e.g., Paczyński & Rudak 1980; Iben 1982). However, Sion & Ready (1992) calculations of accretion onto a low-mass white dwarf showed surprisingly strong eruptions that warrant further investigation.

Several symbiotic binaries – EG And, V443 Her, RW Hya and SY Mus – contain luminous hot components but have yet to undergo an eruption. Kenyon & Fernández-Castro (1987) suggested that these symbiotics might be *pre-symbiotic novae*, systems that have not yet accumulated enough hydrogen to initiate a thermonuclear runaway. Iben's (1982) calculations suggest that pre-symbiotic novae should outnumber actual symbiotic novae by roughly 30:1 for typical accretion rates of $\sim 10^{-8}\ M_\odot$ yr^{-1}, which is reasonably close to the observed ratio of eight symbiotic novae per ~ 150 symbiotic stars (Kenyon 1986). Additional observations are needed to establish a better link between these systems and symbiotic novae, and to determine why these systems do not undergo eruptions like those observed in Z And and BF Cyg.

Table 1 summarizes available data concerning hot-component luminosities and orbital periods for symbiotic novae and related objects. If the hot components lie on the plateau portion of white dwarf cooling curves, their luminosities are directly related to their masses by the core mass–luminosity relation (Paczyński 1970; Üüs 1970). The white dwarf masses for shorter period systems are comparable to masses of single field white dwarfs (Schönberner 1983), while more massive hot components appear to inhabit binaries with longer orbital periods. Aside from R Aqr, EG And and CH Cyg – which probably do not lie on the plateau of white dwarf cooling curves – the apparent correlation between white dwarf mass and orbital period seems quite striking (Fig. 2). This relation must be confirmed with dynamical mass estimates derived from radial velocity measurements.

Table 1. Parameters for white dwarf symbiotic stars.

Star	Type	Period	L_h ($L_\odot$)	M_h ($M_\odot$)
TX CVn	WD	200 d	50-2000	
RW Hya	WD	372 d	200	0.52
EG And	WD	480 d	10	
AG Dra	WD	554 d	300	0.53
V443 Her	WD	597 d	1200	0.54
SY Mus	WD	627 d	1500	0.55
BF Cyg	WD	757 d	2000	0.56
Z And	WD	757 d	1000	0.54
AG Peg	SN	827 d	>1400	0.55
V1329 Cyg	SN	950 d	9500	0.68
R Aqr	WD	>10 yr	1-100	
V1016 Cyg	SN	>10 yr	35000	1.1
HM Sge	SN	>10 yr	21000	0.9
RR Tel	SN	>10 yr	11000	0.7
PU Vul	SN	>10 yr	25000	0.9
CH Cyg	WD	5700 d	0.05-500	1.0

Note: WD = accreting white dwarf; SN = symbiotic nova.

3.2 Main-sequence accretors

Two systems – CI Cygni ($P_{\rm orb} = 855$ d) and AX Persei ($P_{\rm orb} = 681$ d) – provide convincing evidence that accretion-powered eruptions occur in symbiotic binaries. The accreting secondary in both systems is a low-mass main-sequence star with $M_{\rm h} \sim 0.4\text{–}0.5\ M_\odot$ and $R_{\rm h} \sim 0.4\text{–}0.5\ R_\odot$; the red giant component fills its tidal lobe and has a mass of $M_{\rm g} \sim 1\text{–}1.5\ M_\odot$ (see Kenyon *et al.* 1991; Mikołajewska & Kenyon 1992).

In an eruption, the luminosity of the hot component increases from $L_{\rm h} \sim 1\text{–}2 \times 10^2$ to $\sim 5\text{–}10 \times 10^3\ L_\odot$ in several months and declines back to minimum in 1–2 orbital cycles. The optical colours at maximum in CI Cyg are not consistent with a single-temperature stellar photosphere: the apparent spectral type varies from B7 ($U-B$) through A5–A6 ($B-V$) to F0 ($V-I$ and $R-I$). The colour evolution of AX Per is not known well; however, an *IUE* spectrum acquired during the early decline from the 1979 eruption has a much earlier spectral type (A0) than the optical spectrum (F0).

The H I emission-line intensities increase during the rise to visual maximum – and decrease following visual maximum – in both systems, and this behaviour is opposite to that observed in symbiotic novae. The He II flux increases during the early portion of the rise to visual maximum, although these lines disappear close to maximum. In AX Per, Mikołajewska & Kenyon (1992) report strong He II λ4686 emission when the optical spectrum resembled an F0 supergiant, and the EUV luminosity estimated from the λ4686 flux –

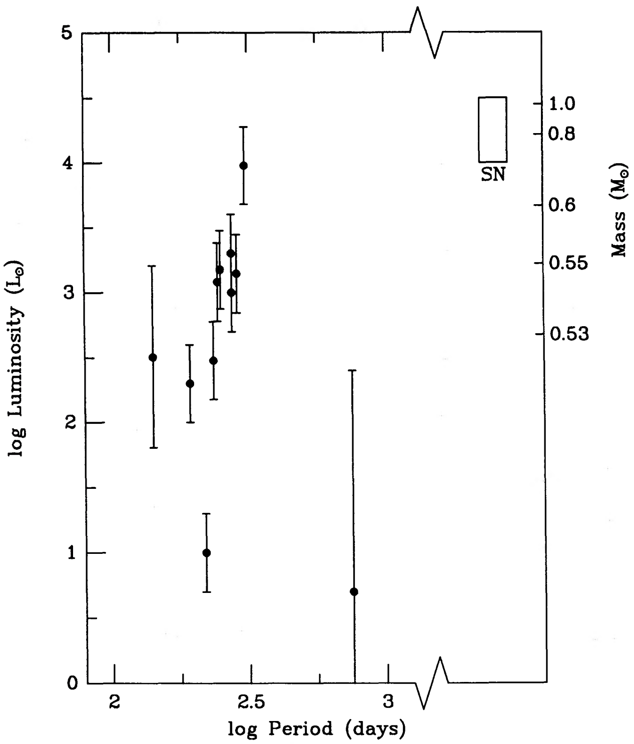

Figure 2. Relation between hot-component luminosity and orbital period for white dwarf symbiotics and symbiotic novae. We have adopted the Paczyński-Üüs core mass-luminosity relation to associate mass and luminosity on the right-hand axis of the figure. We have adopted periods from Kenyon (1986), Mikołajewski, Tomov & Mikołajewska (1987) and Taranova & Yudin (1987), and hot-component luminosities from Kenyon & Webbink (1984), Kenyon & Fernández-Castro (1987), Fernández-Castro *et al.* (1988), Mikołajewska, Selvelli & Hack (1988), Kenyon & Garcia (1989), Mürset *et al.* (1991), and this paper.

$L_{\rm EUV} \sim 600\ L_\odot$ – agrees with the optical luminosity of $L_{\rm opt} \approx 640\ L_\odot$.

In both CI Cyg and AX Per, strong high-ionization lines appear during declines from visual maxima with $L_{\rm EUV} \approx L_{\rm UV+opt}$ (Kenyon *et al.* 1991; Mikołajewska & Kenyon 1992). Kenyon & Webbink (1984) fit the UV continua at these epochs with optically thick, steady-disc models, and these models suggest that $\dot{M}$ declines with time (Kenyon *et al.* 1991). The EUV luminosity derived from strong H I, He I and He II emission lines follows the disc luminosity during this decline, with $L_{\rm EUV} \approx L_{\rm disc}$ (Kenyon *et al.* 1991; Mikołajewska & Kenyon 1992). In both systems, the size of the H II region in the orbital plane shrinks during outbursts (Mikołajewska 1985; Mikałajewska & Kenyon 1992), which indicates the presence of an optically (and geometrically) thick accretion disc that prevents ionization and excitation in the orbital plane. The He II lines are slightly blueshifted relative to the systemic velocity, as if a spherically symmetric He^{2+} region flowing away from the hot component were bisected by a circumstellar disc.

The red giant eclipses the hot component in both binaries, and the giant serves as a knife edge to estimate the outburst radius of the hot component in the orbital plane. For AX Per, the hot component's eclipse radius – $R_{\rm e} \sim 25\ R_\odot$ – exceeds the spherically symmetric radius inferred from the total luminosity – $R_{\rm e} \sim 12\ R_\odot$ – by a factor of 2. If the hot component in AX Per is an ellipsoid, then the radius of the major axis ($R \sim 25\ R_\odot$) exceeds the radius of the minor axis ($H \sim 6\ R_\odot$) by a factor of 4 (Mikołajewska & Kenyon 1992). Mikołajewska & Mikołajewski (1983) estimated $H/R \sim 0.2$–0.3 for CI Cyg's disc using data from maximum (1975) and during the decline (1980) of an eruption. The large values of H/R for the discs in CI Cyg and AX Per, $H/R \sim 0.2$–0.3, agree with Bath & Pringle's (1982) predictions for high-$\dot{M}$ discs surrounding main-sequence stars.

This outburst behaviour – an ellipsoidal hot component, the variation of spectral type with wavelength, and the similarity in EUV and optical/ultraviolet luminosities – points to an accretion-powered outburst with a main-sequence accretor. However, both systems display two deviations from the behaviour predicted by theory: EUV emission from the boundary layer disappears near optical maximum, and a large mechanically heated region develops during the decline from optical maximum. We associate the disappearance of boundary layer emission with changes in the physical structure of the inner disc as $\dot{M}$ approaches the Eddington limit (see also Kenyon *et al.* 1989). Shock-excited emission grows in intensity as the outer disc becomes optically thin. Kenyon *et al.* (1991) suggested a magnetic origin for this region, but this hypothesis needs to be tested.

3.3 Ionization outbursts

We described earlier that large increases in mass-loss rate from the red giant in a symbiotic system can be distinguished from other types of eruptive activity by an overall decline in the brightness of the cool giant – caused by local extinction – coupled with an increase in emission-line fluxes. Far-infrared and radio observations of the 'Mira symbiotics' demonstrate that mass-loss rates approaching $10^{-5}\ M_\odot\ {\rm yr}^{-1}$ characterize the D-type symbiotic binaries (e.g., Whitelock 1987; Seaquist & Taylor 1990), and the large infrared extinctions observed in these systems [$A_K \sim 1$–2 mag (Whitelock 1987; Kenyon, Fernández-Castro & Stencel 1988)] confirm the basic picture we outlined above. Some symbiotics also show 1–2 mag declines in infrared and optical brightness that last several years and are generally attributed to an obscuration of the Mira by dust (Whitelock 1987). However, increased emission-line fluxes were not associated with the obscuration events observed in HM Sge (Munari & Whitelock 1989) or V1016 Cyg (Munari 1988). Both of these systems contain very luminous hot components (see above) that can ionize gas lost by the Mira, so dust grains can condense only in the shadow cone of the Mira where gas is shielded from the hot component. Whitelock (1987) suggests that obscuration events in these symbiotic nova systems only occur when the shadow cone is directed toward the observer.

The best candidates for Nussbaumer & Vogel's eruption mechanism are RX Puppis and R Aquarii. Seaquist & Taylor (1987) noted increased radio emission during an infrared-faint phase in RX Pup, while Klutz & Swings (1981) recorded a strengthening of high-ionization emission lines. Whitelock (1988) interpreted these observations as a response of a hot companion to an increase in the Mira mass-loss rate. Unfortunately, *IUE* high-resolution spectra show the hot component's wind is also strongly variable in intensity and velocity (Kafatos, Michalitsianos & Hollis 1986; Allen & Wright 1988), which complicates any interpretation.

The Mira symbiotic R Aqr has experienced at least two dramatic changes in visual brightness separated by ~45 yr. In 1975–77, the Mira component faded by ~2 mag at V (0.55 μm) and ~1 mag at K (2.2 μm), and its infrared energy distribution became significantly redder than a normal Mira (Khozov & Khudyakova 1974; Khozov, Khudyakova & Larionova 1975; Khozov, Khudyakova & Nikitin 1976; Khozov *et al.* 1977, 1978; Catchpole *et al.* 1979; Whitelock *et al.* 1983). The optical extinction measured from hydrogen Balmer emission-line ratios increased from $A_V \sim 0$ to ~2 during this period and then declined back to $A_V \sim 0$ as the spectral energy distribution of the Mira returned to normal (Wallerstein & Greenstein 1980; Kaler 1981; Willson, Garnavich & Mattei 1981; Brugel *et al.* 1984). Nearly all reddening in R Aqr must be local, because interstellar extinction in this direction is negligible (Burstein & Heiles 1982).

In 1924–33, R Aqr's optical maxima were ~0.5 mag fainter than normal, while its minima were ~2 mag brighter (see Willson *et al.* 1981). The optical colour index decreased from $m_{pg} - m_v \sim 1.5$ to ~0.5 during this change, and the hot component developed broad emission lines from He II, N III and C III (Merrill 1940; Swings & Struve 1942; Beals 1951, and references therein). Although a complete spectral energy distribution is not available for this time, we estimate that an *unreddened* hot component with $V \sim 9$ and an extinction of $A_V \sim 1$ mag *towards the Mira component* can account for the observed visual light curve (see also Pettit & Nicholson 1933).

The hot component in R Aqr is usually quite faint, with $L_h \sim 1\ L_\odot$ estimated from the observed UV continuum and $V \gtrsim 12$ (Michalitsianos, Kafatos & Hobbs 1980; Johnson 1982; see also Kenyon 1986). For 1924–33, the overall hot-component luminosity increased to $L_h \gtrsim 10$–$100\ L_\odot$, while the appearance of strong P Cygni profiles in the H I lines suggests mass ejection at high velocities (see Beals 1951). The relatively small increase in luminosity and simultaneous presence of H I and high-ionization lines point to accretion rather than a thermonuclear runaway as the source of the eruption (see Sections 3.1 and 3.2). We suggest that an enhancement in the Mira wind produces a coordinated increase in optical/infrared extinction and total luminosity of the hot component. The hot component's luminosity as observed from Earth depends on the orientation of the orbit relative to our line of sight. If we adopt Whitelock's (1987) proposed geometry for V1016 Cyg and HM Sge, then the hot component would have been in front of the Mira's dust shell in 1924–33 and behind it in the 1970s.

Our interpretation of R Aqr's 'ionization events' requires an orbital period different from the 44-yr period proposed by Willson *et al.* (1981). We associate the 44-yr interval between events with occasional helium shell flashes above the degenerate core of the Mira primary. The 44-yr period implies a Mira core mass of $M_{core} \sim 1.3\ M_\odot$ (equation 7), which corresponds to a bolometric luminosity of $L_{Mira} \sim 4.5 \times 10^4\ L_\odot$ ($M_{bol} \sim -7$) using an appropriate core mass–luminosity relation (Paczyński 1970; Üüs 1970). The observed bolometric magnitudes [$M_{bol} \sim -5.5$ for $d = 260$ pc (Baade 1943) and $M_{bol} \sim -4.7$ using Feast's (1984) period–luminosity relation] are tolerably close to the predicted value, given the uncertainties in equation (7) and the observations.

The ionization events observed in R Aqr seem the best application of Nussbaumer & Vogel's (1987) idea to real symbiotic stars. Even so, the hot component's luminosity must change dramatically to explain the light curve, which is contrary to the behaviour Nussbaumer & Vogel expected.

Other symbiotic Miras do not experience the ionization events observed in R Aqr, although they do undergo periods of obscuration when the apparent extinction to the Mira increases dramatically. We suspect that R Aqr shows more dramatic events than other symbiotic Miras, because its mass-loss rate estimated from far-infrared and radio observations is much lower than for other systems (Whitelock 1987; Kenyon *et al.* 1988; Seaquist & Taylor 1990). The source of the increased mass loss in symbiotic Miras remains a mystery, but observations of other Mira binaries – such as Mira itself – might shed some light on this problem.

4 CONCLUDING REMARKS

To summarize, we have critically reviewed three popular eruption mechanisms for symbiotic binary systems and have identified good examples for each model.

Most eruptions appear associated with hydrogen shell burning on white dwarf stars. The available observations confirm the main prediction of this model – a long-duration phase of constant luminosity – but some low-mass systems appear to evolve on faster time-scales than predicted by published calculations.

Accretion powers the eruptions of at least two systems, CI Cyg and AX Per. The UV and optical observations suggest that the disc and boundary layer each emit ~50 per cent of the total luminosity for most of the outburst, which agrees with the predictions of simple disc models. However, boundary layer emission vanishes near visual maxima, and this behaviour probably reflects changing physical conditions at the disc's inner edge.

R Aqr's nova-like eruptions do not behave as predicted by either thermonuclear or accretion-powered models. We suggest that the hot component in R Aqr brightens when the mass-loss rate of its Mira companion increases during a helium shell flash. The wavelength coverage of the historical observations is not extensive enough to test the most basic predictions of this model (an increase in A_V and emission-line fluxes when $\dot{M}$ increases), but it accounts for published data in a fairly simple way.

One surprise of our study is the apparent correlation of hot-component luminosities and orbital periods for white dwarf systems (Fig. 2). This correlation implies a relation between white dwarf mass and orbital period if the hot components lie on the plateau portion of white dwarf cooling curves and follow a standard core mass–luminosity relation. The available data do not yet allow us to make a direct link between white dwarf mass and orbital period, because CH Cyg is the only system with a dynamical estimate for the hot-component mass ($M_h \sim 1\ M_\odot$; Mikołajewski, Tomov & Mikołajewska 1987). The long derived orbital period for CH Cyg – 5700 d – lends some support to the correlation, but more direct measurements of hot-component masses are needed.

Webbink (1988) has commented on the difficulty in forming red giant + white dwarf pairs in short-period binaries, because these systems must avoid common-envelope evolution after the original primary star fills its tidal surface as a red giant. [Both CI Cyg and AX Per seem poised to enter a common-envelope phase, as described by Mikołajewska & Kenyon (1992).] Common-envelope evolution can be avoided if the mass ratio, M_g/M_h, is small enough, and the binary enters a phase of quasi-conservative mass transfer instead. Webbink (1988) predicts a correlation between white dwarf mass and orbital period among the products of quasi-conservative evolution, and the observations in Fig. 2 provide some support for his evolutionary scenario.

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