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THE OUTBURSTS OF SYMBIOTIC NOVAE[1]

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ABSTRACT

We discuss possible conditions under which thermonuclear burning episodes in the hydrogen-rich envelopes of accreting white dwarfs give rise to outbursts similar in nature to those observed in the symbiotic stars AG Peg, RT Ser, RR Tel, AS 239, V1016 Cyg, V1329 Cyg, and HM Sge. In principle, thermonuclear runaways involving low-luminosity white dwarfs accreting matter at low rates produce configurations that evolve into A–F supergiants at maximum visual light and which resemble the outbursts of RR Tel, RT Ser, and AG Peg. Very weak, nondegenerate hydrogen shell flashes on white dwarfs accreting matter at high rates ($\dot{M} \gtrsim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$) do not produce cool supergiants at maximum, and may explain the outbursts in V1016 Cyg, V1329 Cyg, and HM Sge. The low accretion rates demanded for systems developing strong hydrogen shell flashes on low-luminosity white dwarfs are not compatible with observations of "normal" quiescent symbiotic stars. The extremely slow outbursts of symbiotic novae appear to be typical of accreting white dwarfs in wide binaries, which suggests that the outbursts of classical novae may be accelerated by the interaction of the expanding white dwarf envelope with its close binary companion.

Subject headings: stars: accretion — stars: combination spectra — stars: novae — stars: white dwarfs

I. INTRODUCTION

Our aim in this paper is to identify and to distinguish a restricted class of objects, variously classified elsewhere either as classical novae or as symbiotic stars, and to elaborate a model for this collection of objects which can explain their appearances and behaviors, both in outburst and at quiescence. The specific systems in question are the classical novae RT Serpentis 1909 and RR Telescopii 1946 and the symbiotic stars AG Pegasi, AS 239, V1016 Cygni, V1329 Cygni, and HM Sagittae; throughout this paper, we refer to these systems collectively as "symbiotic novae". Properties common to these seemingly diverse systems include: (*i*) their association with (relatively) long period binary systems; (*ii*) the presence of a normal M giant; and (*iii*) outbursts which may extend over many decades. We note, in this regard, that RT Ser and RR Tel are distinguished by the fact that they are the two slowest classical novae (Payne-Gaposchkin 1957).

Allen (1980) has previously called attention to the similarities exhibited by this group of objects and reviewed in depth their observed properties. He suggested that hydrogen shell flashes on white dwarfs accreting gas from the late-type components provide an attractive explanation of the phenomena observed in these systems. In view of the facts that hydrogen-fueled thermonuclear runaways provide a very satisfactory explanation of classical nova outbursts generally and that RT Ser and RR Tel represent limiting cases of such events, this seems both reasonable and straightforward. On the other hand, we might ask why it is that the development of these systems in outburst is so extremely slow: Is it a consequence of the long period character of the binary system, of the fact that the companion is a seemingly normal M giant, of the mass of the white dwarf component, or perhaps of some other yet unidentified physical parameter? These questions as well will be addressed in our subsequent discussions.

We thus wish to examine in detail both the underlying physical properties of and the observational consequences of nuclear powered outbursts, associated with accretion onto white dwarfs, which are capable of explaining the "symbiotic novae" we are considering. In § II of this paper, we briefly review and comment upon the properties of these systems which serve to distinguish them with respect to other cataclysmic variable and symbiotic systems (see Allen 1980). In § III, we present the results of hydrodynamic calculations of the progress of thermonuclear runaways, occurring in hydrogen shells on white dwarfs, which yield outbursts exhibiting time scale and light curve behaviors compatible with these very slow nova-like events. The characteristics of these runaways and resulting outbursts are compared with those associated with hydrogen shell flashes on white dwarfs under nondegenerate conditions (Paczyński and Zytkow 1978; Paczyński and Rudak 1980; Iben 1982) in § IV, and consideration is given to which of these models might be most appropriate to one or another of the systems we are studying. Section V contains a discussion of our results and conclusions.

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II. DISTINGUISHING PROPERTIES OF SYMBIOTIC NOVAE

The canonical model for a cataclysmic variable is a short period binary ($P < 1$ day) consisting of a white dwarf and a red dwarf. The red dwarf fills its Roche lobe and transfers matter to its companion via an accretion disk (Warner 1976). As material is accreted, a degenerate, hydrogen-rich envelope is formed at the white dwarf's surface. When the pressure at the base of this envelope reaches a critical value, the matter ignites explosively and is accelerated outward. Under a variety of conditions (Starrfield, Truran, and Sparks 1978; Sparks, Starrfield, and Truran 1978; Nariai, Nomoto and Sugimoto 1979; Fujimoto 1982*a*, *b*; MacDonald 1983), the thermonuclear runaway generates sufficient energy to unbind a substantial fraction of the accreted envelope. This is observed as a classical nova outburst, which can be a rather spectacular event. In the space of a few days (sometimes hours!), a typical nova increases in brightness by ~ 14 mag to $M_v \sim -7$. After this abrupt rise to maximum, a nova fades to relative insignificance over a period of months. The rate of this decline determines the *speed class* of a nova; typically *fast novae* fade within a few weeks, while *slow* novae decline over a period of months (cf. Payne-Gaposchkin 1957; Gallagher and Starrfield 1978).

For a small subset of classical novae, the outburst is a comparatively leisurely event. Payne-Gaposchkin (1957) lists two such systems (RT Ser and RR Tel), while Allen (1980) has identified five additional "very slow novae" (AG Peg, AS 239, V1016 Cyg, V1329 Cyg, and HM Sge). All are characterized by 2–7 mag eruptions followed by a 20–200 year decline. At maximum, their spectra resemble those of either F supergiants (e.g., RT Ser and RR Tel) or planetary nebulae (e.g., V1016 Cyg and HM Sge). After maximum, their spectra *all* evolve to higher excitation, suggesting that the outbursting star may be becoming hotter (Allen 1980). Additionally, low excitation features (e.g., Fe II and [Fe II] emission; Na I and TiO absorption) also strengthen during the decline (cf. Merrill 1951; Thackerary 1977; Andrillat, Ciatti, and Swings 1982). The combination of TiO bands and Fe II emission suggests that a late-type giant is present in these systems. In support of this view, 2.3 μm CO absorption has been detected in all seven very slow novae (Allen 1980; Puetter *et al.* 1978). This feature is typical of M type giants and Mira variables, and thus these slow novae appear to be related to the symbiotic stars (cf. Boyarchuk 1969; Allen 1979) in that they display high excitation nebular emission superposed on a late-type absorption spectrum.

The ~ 150 known symbiotic stars are a rather heterogeneous group of objects, including both very low excitation binaries such as EG And and extremely high excitation systems such as AS 295B (Allen 1979; Sahade 1982; Boyarchuk 1981). Roughly 20 of these have been observed to undergo an outburst, and this phase of symbiotic evolution displays a wide variety of features as well. The majority of the symbiotics have A–F supergiant spectra at visual maximum, as the high excitation emission lines fade during the rise in optical brightness. The nebular lines return during the decline, which may last from months to decades. Typical examples of this group are CI Cyg (Belyakina 1979) and RR Tel (Thackeray 1977). Other systems merely increase in excitation and optical luminosity, in an outburst which overwhelms the M type absorption spectrum. These absorption features gradually return as the optical luminosity fades over months to decades. Typical examples of this type of outburst are V1016 Cyg (Andrillat, Ciatti, and Swings 1982) and the most recent brightening in AG Dra (J. Kaler 1982, private communication).

Two distinct mechanisms have been proposed for the outbursts of symbiotic stars: accretion onto main-sequence or white dwarf stars (Bath 1977) and nuclear shell burning on the surface of a white dwarf (Tutukov and Yungel'son 1976). Both models have been successful at reproducing outburst light curves. Bath and Pringle (1982), for example, found that a burst of accretion onto a main sequence star ($\dot{M} \sim 10^{-3}\ M_\odot$ yr^{-1}) could explain the 1975 outburst of CI Cyg. Paczyński and Zytkow (1978) first investigated nuclear burning models for symbiotic stars; their models produced very luminous objects ($L \gtrsim 10^4\ L_\odot$), but they were not allowed to evolve to the low effective temperatures typical of F supergiants. Iben (1982) has recently evolved a number of accreting white dwarfs, again using a quasi-static code. Some of his models evolve to hot, luminous systems, while other sequences develop large extended envelopes with $T_{\rm eff} \lesssim 10^4$ K. In fact, the model light curve shown in his Figure 20 closely resembles that of RR Tel.

On the basis of the above discussion, it seems unlikely that the underlying nature of the symbiotic stars can be readily inferred merely from their outburst properties. Alternative means must be found. The advent of the *IUE* satellite has allowed direct observation of the continuum from the hot component. Kenyon and Webbink (1983, hereafter Paper I) have used the available *IUE* data to analyze a small group (~ 20) of symbiotic stars and have shown that this continuum is critically dependent on the nature of the hot component. They concluded that the vast majority of symbiotics are either accreting main sequence stars (e.g., CI Cyg and YY Her) or hot stellar sources (e.g., AG Peg and RW Hya). No obvious candidates for white dwarf accretors were identified, although some systems (e.g., RW Hya) might be accreting at low rates ($M \lesssim 10^{-8}$ $M_\odot$ yr^{-1}). In these latter cases, the intrinsic luminosity of the hot component would dominate the accretion luminosity.

As noted by Paczyński and Zytkow (1978) and Paczyński and Rudak (1980), two types of hydrogen flashes may occur on a white dwarf: degenerate flashes and nondegenerate flashes. Nondegenerate flashes occur when matter is accreted onto a luminous white dwarf ($L \approx 100\ L_\odot$). The systems identified as hot stellar systems in Paper I are likely observational counterparts for these objects. Each of these systems contains a luminous, compact star ($L \gtrsim 100\ L_\odot$, $R \lesssim 1\ R_\odot$) and an evolved red giant companion. In fact, the solution for RW Hya from Paper I ($L \approx 900\ L_\odot$, $T_{\rm eff} \approx 90{,}000$ K) places it on the cooling curve of a 0.7 $M_\odot$ white dwarf. Thus, systems such as RW Hya appear to be likely candidates for nondegenerate flashes, such as those studied by Paczyński and Zytkow (1978) and by Iben (1982 and references therein).

Degenerate hydrogen flashes occur when matter is accreted slowly onto a cool white dwarf (MacDonald 1983; Fujimoto 1982*a*, *b*). Such models have proved useful in understanding the classical nova outburst (Gallagher and Starrfield 1978; MacDonald 1983), and we will explore their applicability to symbiotic novae in the next section. It is unfortunate that observational counterparts for these systems in quiescence have not been detected among the symbiotic stars. However, it is possible that faint white dwarfs with low accretion rates ($L_{\rm WD} \lesssim 10^{-2}\ L_\odot$, $\dot{M} \lesssim 10^{-10}\ M_\odot\ {\rm yr}^{-1}$) would not be detected as symbiotic stars (see Paper I). An example of such an object may be the white dwarf companion to Mira, which is a low-temperature white dwarf ($T_{\rm eff} \approx 10{,}000$ K) accreting material from the wind ejected by Mira itself. We will show that, during outburst, such systems would not be readily distinguishable from those in which nondegenerate flashes occur.

III. RUNAWAY MODELS OF THE OUTBURSTS

We now present models of outbursts resulting from degenerate hydrogen flashes.

a) *Method of Calculation*

The calculations described in this section were performed on the University of Illinois Cyber 175 using an amended version of the computer code of Kutter and Sparks (1972; cf. Starrfield, Truran, and Sparks 1978). Two major changes have been made in the code for the studies presented in this paper. We have replaced the Sweigert (1973) fit to the Hubbard and Lampe (1969) conductive opacity with one developed by Iben (1975). The Iben interpolation formulae provide a much more accurate representation of the tabulated values and allow us better to determine the energy flow into the white dwarf core via electron conduction. This energy flow, which is usually found to be negligible for classical nova models, can be important for the very slow novae we discuss here. We have also incorporated the diffusion mixing algorithm suggested by Despain (1977). This tends to slow down the process of convective mixing and thus to slow the progress of the runaway.

b) *Description of the Evolution*

In the following discussions, we describe the evolution of two models for nova-like outbursts both of which involve 0.8 $M_\odot$ carbon-oxygen white dwarfs. The first (Model 1) has a $1.3 \times 10^{-4}\ M_\odot$ hydrogen rich envelope of roughly solar composition ($X = 0.7$, $Y = 0.27$, $Z = 0.03$). The carbon-oxygen core has been divided into 45 mass zones, while the envelope has 140 mesh points. Model 2 has a slightly smaller envelope ($1.06 \times 10^{-4}\ M_\odot$) which is assumed to have been enriched in abundances of CNO nuclei ($X = 0.53$, $Y = 0.27$, $Z = 0.20$). In both cases, the envelope represents roughly the minimum amount of hydrogen-rich material necessary to produce an outburst, for a given white dwarf mass and luminosity (cf. Starrfield *et al.* 1982). Generally, the envelope mass is $\sim$5%–10% more massive than the absolute minimum mass due to the finite grid size. Both envelopes begin the evolutionary sequence in hydrostatic equilibrium at a luminosity determined by the structure of the white dwarf core ($\sim 10^{-2}\ L_\odot$).

i) *Model 1*

The base of the hydrogen-rich envelope begins the evolutionary sequence at a temperature of 1.27×10^7 K and a density of 2500 g cm^{-3}. (Other initial conditions are as listed in Table 1.) Under these circumstances, the CNO cycle is the major source of energy, while electron conduction is the major energy transport mechanism. Since electron conduction is very efficient at carrying energy from the burning shell, the peak temperature characterizing the burning region ($T_{\rm ss}$) moves *outward* in mass from the base of the hydrogen-rich envelope. It takes zone 60 (at a mass of $1.13 \times 10^{-4}\ M_\odot$) $\sim 10^5$ years to reach a temperature of 3×10^7 K. The energy generation rate ($\epsilon_{\rm nuc}$) has increased to 8×10^7 ergs g^{-1} s^{-1}, and an exponential growth in the runaway begins. Another 1.4 years passes before $\epsilon_{\rm nuc}$ peaks at 4.2×10^{13} ergs g^{-1} s^{-1}, and this is followed by maximum $T_{\rm ss} = 1.37 \times 10^8$ K about 2 hours later. The hydrogen-rich envelope is completely convective *above* the zone where peak $T_{\rm ss}$ occurs. This serves to mix unburned ^{12}C nuclei into the shell source and maintain the runaway.

The luminosity and temperature profiles at the onset of runaway are shown in Figure 1. Electron conduction removes energy from the burning shell, and raises the temperature in the outer portions of the C-O core. The temperature increases abruptly near the base of the burning shell and then decreases adiabatically throughout the convective zone. The large flow of energy into the white dwarf core can be seen from the luminosity profile: At the outer edge of the C-O core the luminosity becomes negative.

Following peak $\epsilon_{\rm nuc}$, the luminosity and the effective temperature of the white dwarf increase dramatically. The initially rapid increase in luminosity follows a track

TABLE 1

INITIAL CONDITIONS OF DEGENERATE RUNAWAY MODELS

Parameter	Model 1	Model 2
Luminosity ($L_\odot$)	2.4×10^{-2}	9.2×10^{-3}
Log T_e (K)	4.33	4.23
Radius (km)	7993	7865
$M_{\rm env}$ ($M_\odot$)	1.30×10^{-4}	1.06×10^{-4}
$\epsilon_{\rm nuc}$ (ergs g^{-1} s^{-1})	367	58
$M_{\rm vis}$	11.0	11.5
$\tau_{\rm runaway}$ (yr)	9.5×10^4	1.2×10^6
$Z_{\rm CNO}$	0.03	0.20

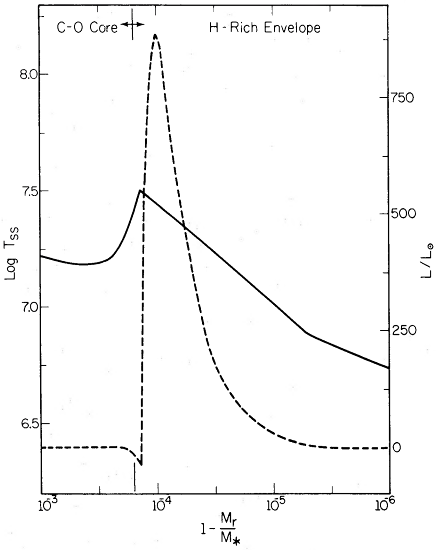

FIG. 1.—Temperature (*solid line*) and luminosity (*dashed line*) profiles in Model 1 at the onset of runaway.

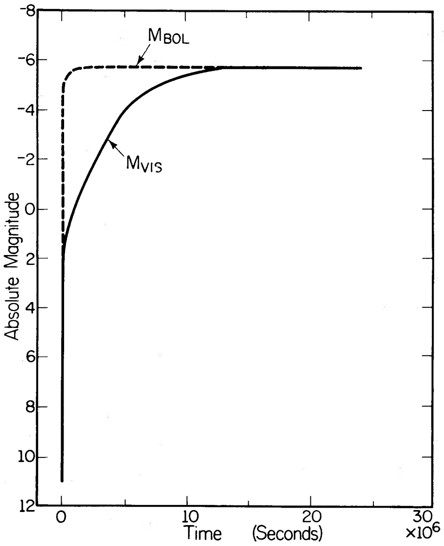

FIG. 3.—Visual and bolometric magnitudes as functions of the time since peak energy generation for Model 1.

of roughly constant radius in the H-R diagram as shown in Figure 2. Eventually, the large energy flux from the burning shell accelerates the envelope outward, and the evolutionary track proceeds toward lower effective temperatures in Figure 2. The bolometric luminosity peaks at $\sim 15{,}500\ L_{\odot}$ nearly 1 month after maximum $\epsilon_{\rm nuc}$ and remains roughly constant as the effective temperature decreases slowly.

The behaviors of the visual and bolometric magnitudes as functions of time are shown in Figure 3. With an average expansion velocity of ~ 5 km s^{-1}, it takes over 4 months for this model to reach visual maximum. The material in the envelope never reaches escape velocity, and thus no mass is ejected during the slow visual rise. During the next few months, the outer portion of the envelope becomes pulsationally unstable with a velocity amplitude of ~ 10 km s^{-1}. This behavior appears in the photosphere where hydrogen recombinations increase the opacity. This region of the envelope is not adequately resolved in our model, and thus the pulsations may be a numerical effect. The time-averaged light curve of this period is very nearly constant as shown in Figure 3.

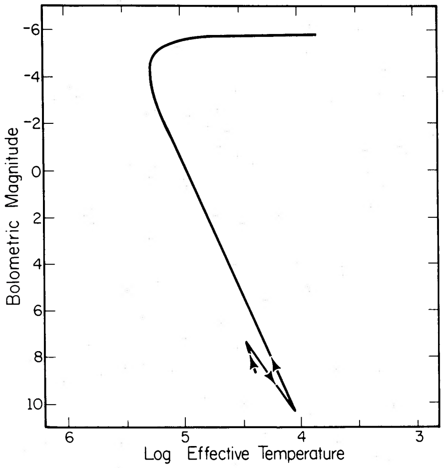

FIG. 2.—Evolutionary track of Model 1 in the H-R diagram. Peak energy generation is attained near the minimum in bolometric magnitude.

During the rise to visual maximum, the bolometric luminosity remains roughly constant at $\sim 16{,}000\ L_{\odot}$. The energy generation rate in the burning shell drops to $\sim 6 \times 10^{10}$ ergs g^{-1} s^{-1}, while $T_{\rm ss}$ stabilizes at 8.3×10^7 K. Energy continues to be transported from the shell source into the core, and this heats up the hydrogen-rich zones *below* the burning shell. These zones each flash to 8–9 $\times 10^7$ K, and the burning shell moves *inward* in mass. Eventually the last hydrogen-rich shell flashes to $\sim 9 \times 10^7$ K and begins to burn hydrogen very rapidly. The two outermost zones of the C-O core heat up to 8×10^7 K, but this temperature is not sufficient to ignite carbon.

After nearly 4 months at visual maximum, we terminated the evolutionary sequence since calculation of the further evolution would have required an enormous amount of computer time. The bolometric and visual luminosities are close to the local Eddington limit near the photosphere, but fall well below the local Eddington value beyond the photosphere where electron scattering opacity dominates. Thus, sustained mass loss via continuum radiation pressure cannot occur in our calculation. However, the conditions in the outer envelope of our model closely parallel those found in the Hubble-Sandage variables by Gallagher, Kenyon, and Hege (1981). These latter systems also resemble A–F supergiants and lose material at $\gtrsim 10^{-5}\ M_{\odot}$ yr^{-1}. A simple scaling of $\dot{M}$ with L/g (where g is the gravity) leads to a mass loss rate of 5–10 $\times 10^{-7}\ M_{\odot}$ yr^{-1} for our nova remnant. Over a period of ~ 100 yr, then,

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the envelope of this nova should be ejected. This serves to extinguish the burning shell and causes the model to retrace its path in the H-R diagram (Iben 1982; Truran 1982).

ii) *Model 2*

The base of the hydrogen-rich envelope at the start of this sequence is at a temperature of 1.07×10^7 K and a density of 2200 g cm^{-3}. Other initial conditions are listed in Table 1. These circumstances are such that the CNO reactions are not proceeding rapidly, and thus energy is initially generated solely by *p-p* reactions. Over the next 1.2×10^6 years, the CNO cycle becomes the dominant energy source as T_{ss} rises to 3×10^7 K. The energy generation rate has increased to 1.6×10^9 ergs g^{-1} s^{-1}, and a small convective zone feeds fresh ^{12}C nuclei into the shell source. This accelerates the runaway such that subsequently it takes only 23 days for T_{ss} to reach 10^8 K, when $\epsilon_{nuc} = 1.9 \times 10^{14}$ ergs g^{-1} s^{-1}. Note that this runaway is more violent than Model 1 due to the presence of greater abundances of the CNO nuclei. The maximum in ϵ_{nuc} of 4.75×10^{14} ergs g^{-1} s^{-1} is followed 312 s later by peak $T_{ss} = 1.29 \times 10^8$ K. The behavior of ϵ_{nuc} and T_{ss} during the peak of the runaway is shown in Figure 4.

At the point at which maximum energy generation is achieved, the hydrogen-rich envelope is completely convective. Soon after, a luminosity wave hits the surface, and M_{bol} decreases rapidly. This causes a rapid expansion of the outer envelope, and the top of the convective zone begins to recede from the surface. The gradual shrinking of the convective zone and the expansion of the envelope cause ϵ_{nuc} and T_{ss} to decrease rapidly as shown in Figure 4. They reach approximately constant values of 1.6×10^9 ergs g^{-1} s^{-1} and 5.2×10^7 K in a few hours.

The evolution of this model in the H-R diagram is very similar to that indicated in Figure 2 for Model 1. The model cools in the runaways early stages to $L \approx 3 \times 10^{-3} L_\odot$. After T_{ss} and ϵ_{nuc} reach their maximum values, the luminosity increases rapidly. It takes only ~ 100 s for M_{bol} to rise from $+11$ to -5, while T_{eff} has reached 210,000 K. Maximum luminosity of 17,000 $L_\odot$ occurs about 1 hour after peak ϵ_{nuc}. The initially rapid envelope expansion ($v_{exp} \approx 50$ km s^{-1}) resulting from the abrupt luminosity increase is followed by a re-adjustment in the envelope structure, and a brief decrease in luminosity when $T_{eff} \approx 100{,}000$ K. The luminosity then rises back to 17,000 $L_\odot$, once radiation pressure can support the outer envelope, and this luminosity is maintained until the end of the evolutionary sequence.

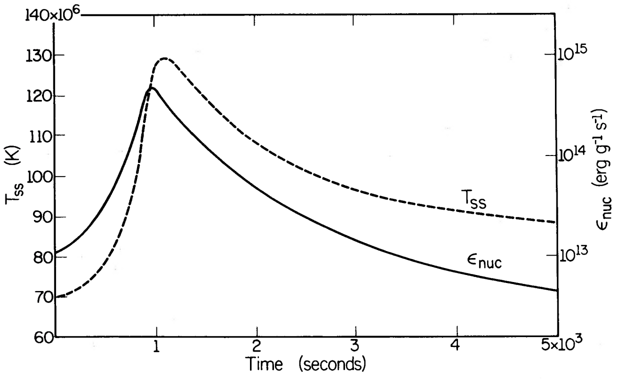

FIG. 4.—The behavior of the energy generation rate (ϵ_{nuc}) and the shell source temperature (T_{ss}) as functions of time for Model 2. Note that T_{ss} reaches maximum slightly after peak ϵ_{nuc}.

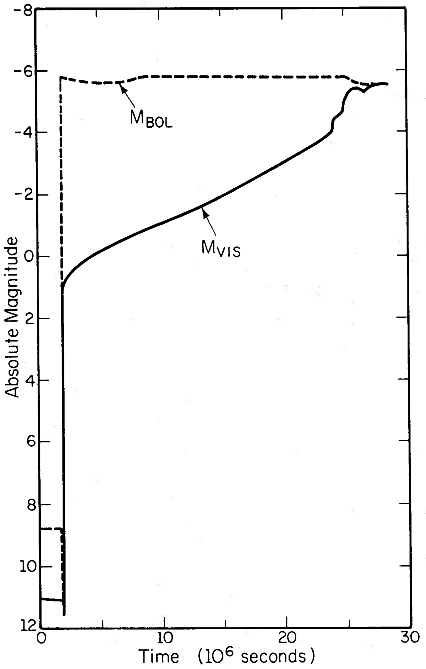

FIG. 5.—Visual and bolometric magnitudes as functions of time for Model 2. The time was defined to be zero at $T_{ss} = 30 \times 10^6$ K.

Once the luminosity peaks, a slow expansion ($v \approx 2.5$ km s^{-1}) phase begins, and M_{vis} begins to decline as shown in Figure 5. The reduced envelope mass of Model 2 results in a generaly slower expansion than in Model 1, and thus the rise to visual maximum occurs nearly a year after bolometric maximum, when $\sim 10^{-9} M_\odot$ of material has been ejected at $v \approx 50$ km s^{-1}. This matter was ejected during the rapid bolometric rise, while the remaining envelope pulsates with a velocity amplitude of 10–20 km s^{-1}. As in Model 1, radiation pressure should eject the remnant envelope on a time-scale of ~ 100 years, and the luminosity will fade.

IV. THERMONUCLEAR MODELS FOR SYMBIOTIC NOVAE

Paczyński and Zytkow (1978) investigated a wide range of accretion rates onto a white dwarf and suggested the outbursts of symbiotic stars resulted from hydrogen shell flashes. Since their original interest was cataclysmic binaries, most of their evolutionary sequences used a procedure which removed matter as it expanded past $R = 0.5 R_\odot$. Their sequence I follows a low-luminosity white dwarf accreting mass at $\sim 1.5 \times 10^{-11} M_\odot$ yr^{-1}. The evolution of this sequence during the flash closely parallels our Model 1 in the development of an extended atmosphere with $R \sim 100$ $R_\odot$ and $T_{\text{eff}} \sim 6300$ K. As in our models, peak bolometric luminosity is maintained for $\gtrsim 50$ years at the effective temperature of an F supergiant.

Recently, Iben (1982) has completed an extensive study of hot, accreting white dwarfs. Iben's calculations are similar in nature to those of Paczyński and Zytkow (1978), except the models can evolve to large radii. His results demonstrate a wide variety of shell flashes may occur on the surface of a white dwarf. As in Paczyński and Zytkow (1978), strong flashes occur at low accretion rates ($\dot{M} \lesssim 10^{-9}$ $M_\odot$ yr^{-1}). These expand to supergiant dimensions and maintain their large radii for $\gtrsim 25$ years before returning to minimum. The flashes grow weaker as the accretion rate increases until steady state nuclear burning is achieved at $\dot{M} \sim$ a few $\times$ 10^{-7} $M_\odot$ yr^{-1}. The models at higher $\dot{M}$ do not evolve to supergiant dimensions at low effective temperatures. Instead they remain very hot ($\sim 2 \times 10^5$ K) at bolometric maximum; this results in a rather small outburst in the visual ($M_{v,\max} \sim 0$ as opposed to $M_{v,\max} \sim -5$ for low $\dot{M}$).

The calculations discussed above show two types of hydrogen shell flashes occur on white dwarfs: (*i*) those that lead to expansion to A–F supergiants, and (*ii*) those for which the dwarfs remain at high effective temperatures. When a flash begins in a *degenerate* white dwarf envelope, it evolves from a relatively faint object to a luminous A–F supergiant. These systems remain at visual maximum for many decades and lose mass in a *low velocity wind* at maximum visual light. As these systems evolve toward higher effective temperatures, they develop high velocity winds as in classical novae. Paczyński and Rudak (1980) identified these as type II symbiotic stars. In their nomenclature type I symbiotic stars result from flashes in a nondegenerate envelope. The white dwarf expands only by a factor of 10 during the outburst and maintains a high bolometric luminosity for $\gtrsim 15$ years. In this circumstance, we expect a *high-velocity wind* as seen in O stars and the declining stages of novae (Cassinelli 1979; Gallagher and Starrfield 1978).

In a symbiotic binary, the giant component provides most of the optical continuum, while the hot star is usually considered the source of the emission lines (cf. Sahade 1982). Our model for symbiotic novae assumes this giant transfers matter to a white dwarf; some of this material is actually accreted by the dwarf, while the remainder forms a circumbinary nebula. The visibility of the nebula depends crucially on the accretion rate and intrinsic luminosity of the white dwarf (cf. Paper I): (*i*) If L_{WD} and $\dot{M}$ are low, nebular emission is weak, while (*ii*) if L_{WD} or $\dot{M}$ is high, nebular emission is strong. Thus, we might expect systems undergoing degenerate shell flashes (low $\dot{M}$, L_{WD}) to have weaker preoutburst nebular spectra than those systems currently in the midst of nondegenerate flashes (high $\dot{M}$ or L_{WD}). During an outburst, the giant component is not merely a spectator as it provides a *lower limit to the optical luminosity of the system.* In the early stages of a degenerate outburst, nebular emission increases as the white dwarf evolves up a line of constant radius in the H-R diagram (cf. Fig. 2). This phase is very short-lived ($\lesssim$ a few days) and is replaced by a longer period during which the white dwarf evolves to an A–F supergiant. The optical continuum of the giant (with $M_v \sim 0$ to -2) is completely overwhelmed by the F supergiant component ($M_v \sim -4$ to -7), although it may still dominate in the infrared. The nebular spectrum slowly returns as the outbursting white dwarf fades from visual maximum and increases in effective temperature (cf. Iben 1982, Fig. 21). After many years, the white dwarf returns to its pre-outburst state, presumably to begin the accretion process all over again.

The early evolution of a nondegenerate flash is identical to the degenerate flash discussed above. However, these objects never dominate the optical continuum since they remain at high effective temperatures in the H-R diagram (cf. Iben 1982, Fig. 8). The optical luminosity of this object is comparable to that of the giant, and it produces a large flux of hard UV photons. Should the binary possess a massive circumbinary nebula, nebular emission would dominate the optical spectrum with the hot star and the giant contributing equally to a weak underlying continuum.

The available observations of symbiotic novae suggest they can be understood in terms of one of the two types of hydrogen shell flashes. We believe the outbursts of stars such as RR Tel, RT Ser, and perhaps AG Peg were caused by degenerate flashes. These systems all exhibited B–F supergiant spectra at or near maximum and produced low velocity winds near maximum (Merrill 1916, 1929; Adams and Joy 1928; Thackeray 1977). Both AG Peg and RR Tel now show Wolf-Rayet features in their spectra (Hutchings, Cowley, and Redman 1975; Thackeray 1977) which is expected for a system evolving toward higher effective temperatures as it declines from visual maximum. Other symbiotic novae (e.g., V1016 Cyg, V1329 Cyg, and HM Sge) appear to have undergone nondegenerate flashes. None of these systems developed into F supergiants, and all have exhibited the intense nebular emission expected in such a flash (FitzGerald and Pilavaki 1974; Andrillat and Houziaux 1976; Dokuchaeva 1976). TiO and VO absorption bands are occasionally observed in these objects (Mammano and Ciatti 1971; Andrillat and Houziaux 1976; Andrillat, Ciatti, and Swings 1982), suggesting the M star contributes a significant fraction of optical light at unknown intervals. The existence of Mira variables in V1016 Cyg and HM Sge (Bregman 1982) tempts one to conclude the periodic appearances of TiO and VO are due to Mira-like variability, but additional observations are needed to test this hypothesis (Andrillat, Ciatti, and Swings 1982). High-velocity winds have also been observed in V1016 Cyg and HM Sge ($v \gtrsim 1000$ km s^{-1}; Wallerstein 1978; Andrillat, Ciatti, and Swings 1982), and these are expected only if the luminous blue star has a high effective temperature.

Recently, Allen (1981) has reported X-ray observations of three symbiotic novae (V1016 Cyg, HM Sge, and

RR Tel), whose spectra may be represented by a 10^6 K blackbody. For reasonable distances, the inferred surface areas of these X-ray sources are consistent with white dwarf stars. High temperatures are characteristic of hydrogen burning shells on white dwarfs, so these observations lend support to the thermonuclear runaway interpretation.

The behavior of symbiotic novae in the radio also upholds the runaway picture as discussed by Kwok (1982*a*, *b*). The radio intensity in V1329 Cyg has declined monotonically since its detection in 1973 and has recently disappeared below the VLA sensitivity limit (Kwok 1982*a* and references therein). This behavior is similar to the optically thin decline phase of classical novae (Hjellming *et al.* 1979). The radio emission in AG Peg has remained relatively constant since initial observations by Gregory, Kwok, and Seaquist (1977), and the available data suggest a windlike spectrum with a mass loss rate of $\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$. The behavior of the radio spectra of V1016 Cyg and HM Sge can also be understood in terms of wind-driven mass loss, although both the hot component and the Mira component in each of these systems appear to have lost substantial mass (Kwok 1982*a*, *b*).

Observations of symbiotic novae at minimum would be a very useful tool in interpreting their outbursts, but unfortunately such data are rare. RR Tel was discovered as a long period variable well before outburst, and Gaposchkin (1945) found the period to be 386.73 days. The Mira-like variations have continued throughout the outburst (Whitelock, Catchpole, and Feast 1982) and suggest the long period variable was not severely affected by the outburst. Preoutburst spectra of RR Tel are not available. V1016 Cyg was first observed as a very strong Hα source by Merrill and Burwell (1950) and was later detected as a red variable by Nassau and Cameron (1954). Although it is difficult to quantify Merrill and Burwell's observation, the combination of very strong Hα and an M star suggest V1016 Cyg was symbiotic *before* outburst. This agrees with our expectations: A very luminous white dwarf should undergo a nondegenerate type of flash, as is observed in V1016 Cyg. Only one preoutburst spectrum exists for V1329 Cyg as noted by Stienon, Chartrand, and Shao (1974), and it shows a middle M star with no emission lines. This is *not* what we would expect theoretically, since the outburst of V1329 Cyg is similar to the V1016 Cyg eruption. However, the spectrum of V1329 Cyg is of much lower excitation than that of V1016 Cyg (cf. Andrillat, Ciatti, and Swings 1982; Andrillat and Houziaux 1976), and it does not have a dusty, circumstellar shell (cf. Allen 1980, 1982). These observations suggest V1329 Cyg does not have an extensive circumbinary nebula, and thus we would not expect intense emission before outburst. Infrared observations at 10 μm would be useful to check for the silicate emission feature common to M stars with circumstellar shells. Of the other symbiotic novae, only HM Sge has a useful preoutburst observation: It is very red on the Palomar Sky Survey (Dokuchaeva 1976) and suggests an M type star was present in the system before outburst.

V. DISCUSSION

We have explored possible conditions under which thermonuclear burning episodes occurring in hydrogen shells atop degenerate (white dwarf) cores can give rise to outbursts compatible with those characterizing some symbiotic stars. The class of objects in question, that identified by Allen (1980), in fact includes both classical nova and symbiotic systems. Among the features suggestive of a thermonuclear burning event as the outburst mechanism for these systems are the extended time scale of the outbursts, the achievement of luminosities at maximum which are consistent with the core-mass-luminosity relation for degenerate cores (and approach the Eddington luminosity at large core masses), and the similarity of their outburst lightcurves to those of classical novae (slow novae). Models for such systems based upon the occurrence of nondegenerate shell flashes on hot accreting white dwarf stars have been proposed by Tutukov and Yungel'son (1976), Paczyński and Zytkow (1978), and Paczyński and Rudak (1980); more complete and detailed calculations have recently been presented by Iben (1982). Proceeding by analogy to the classical nova systems to which some symbiotic variables appear closely related, we have presented models of degenerate shell flashes which display many of the same outburst features. The results of our investigations are summarized briefly below.

1. Thermonuclear runaways involving low luminosity white dwarfs can in principle produce outbursts which resemble those of extremely slow novae (e.g., RT Ser and RR Tel) and some related symbiotic variables (e.g., AG Peg). For appropriate conditions—degenerate core mass and luminosity, and accretion rate—giving rise to runaway, a very slow rise to visual maximum will ensue, at which point the luminosity is approaching the Eddington value for a $\gtrsim M_\odot$ object. This can be followed by an even longer time scale decline from maximum, perhaps even approaching the nuclear time scale, depending upon whether some alternative mechanism for envelope depletion may be operating. We note here in particular that the conditions we have considered (and the models we have thus constructed and evolved) are consistent with those inferred from observations to be compatible with a thermonuclear event model for AG Peg (Gallagher *et al.* 1979).

2. In outburst, the observable characteristics of the models we have evolved are virtually indistinguishable from those of models of nuclear burning episodes on hot white dwarfs. In these latter models, a series of thermal pulses involving hydrogen burning or helium burning may be expected to occur (Paczyński and Zytkow 1978; Iben 1982). In both cases, the response of the star to the runaway includes a dramatic increase in bolometric luminosity, to a value $\lesssim L_{\mathrm{Edd}}$ and a steady increase in the visual luminosity, as the spectrum approaches that of an F type supergiant (at visual maximum) on a time scale dictated by the rather slow rate of envelope expansion. Under some circumstances, the occurrence of very weak, nondegenerate flashes on hot, luminous white dwarfs accreting matter at high rates,

may not give rise to F type supergiants at maximum. The special conditions required here are such that outbursts of this nature may not represent the typical events.

3. The appearances of the hot components of such systems in quiescence are clearly dependent upon the accretion rate and the intrinsic luminosity of the underlying white dwarf. If $L_{\mathrm{WD}} > L_{\mathrm{accretion}}$, the characteristic spectrum at minimum will be that of a hot star, while for $L_{\mathrm{accretion}} > L_{\mathrm{WD}}$ it should be that of an accretion disk. If extremely low values of $\dot{M}_{\mathrm{acc}}$ are demanded for systems giving rise to degenerate flashes, then it is possible that such models would not be compatible with observations of "typical" symbiotic systems at quiescence.

4. The initial composition of the envelope matter did not strongly influence the qualitative behaviors, which were found to be quite similar for the two models studied. We mention this point only because of the established role played by excess concentrations of CNO nuclei in distinguishing fast from slow classical novae (Gallagher and Starrfield 1978; Truran 1982). In the present study, involving a white dwarf configuration of 0.8 $M_{\odot}$, neither the rapid evolution of the visual light curve nor the shell ejection of matter nor the high velocities characteristic of very fast novae were realized.

These findings serve to shed light upon two broad questions regarding the nature of these symbiotic novae and their relationship to cataclysmic variable and other binary systems. The first of these questions involves the typical timescales of the outbursts: Why is it that the decline from maximum light is so very slow with respect, for example, to other classical novae? From the point of view of researchers working on thermonuclear runaway models of classical novae, it might appear that this question was posed in the wrong sense, since a major problem encountered in such studies is how to effect rapid termination of nuclear burning and return of the system to its preoutburst state. Certainly, evolution on a purely nuclear time scale (assuming no mass loss)

$$\tau_{\mathrm{nuc}} \approx 400 \text{ years} \frac{(M_{\mathrm{envelope}}/10^{-4} M_{\odot})}{(L/2 \times 10^{4} L_{\odot})}$$

is inconsistent with observations of these systems, and it has yet to be demonstrated that wind-driven mass loss will suffice to resolve the problem.

In this regard, the symbiotic nova systems may provide an important clue. These are systems in which the cool component is a normal M giant (or Mira variable) and for which the orbital periods are far greater than those characteristic of classical nova systems. The much larger Roche lobe radius ensures that, even when the dwarf component has expanded in outburst to F type supergiant dimensions, it will not engulf its M giant companion. The evolution following maximum thus proceeds, to first order, as if we were dealing rather with an isolated (single) star, and possible effects attributable to its binary nature do not strongly enter the picture. If this factor is indeed responsible in part for the very slow postmaximum development of these symbiotic novae, it then supports the view that the turnoff of classical novae may be accelerated by the interaction of the nova with its close binary companion (MacDonald 1980).

A further issue to be addressed is that concerning the evolutionary state of the hot components of symbiotic nova systems and therefore of the systems themselves. Our assumption of an intrinsic white dwarf luminosity $\sim 10^{-2} L_{\odot}$ implies an age for the dwarf and the system of order 3×10^{8} years; this is in fact a lower limit, with the assumption that significant accretion-induced heating of the white dwarf is not realized. It seems reasonable to suppose that some cooling of the white dwarf components of symbiotic nova systems has occurred prior to the onset of the accretion phase, although it is somewhat difficult to provide a realistic quantitative statement of the expected magnitude of such cooling. The relevance of the models based upon the occurrence of nondegenerate flashes or thermal pulses in steady state is thus strictly dependent upon the assumption that some reheating of the white dwarf core can be effected in the presence of accretion. A thorough study of this question is clearly demanded.

An alternative to the thermonuclear runaway model for symbiotic novae is Bath's (1977) supercritical accretion model. While many of the observed properties of the systems we have considered here can be equally well explained by Bath's mechanism (e.g., the development of optically thick winds), various observations appear to rule out supercritical accretion for many symbiotic novae. AG Peg underfills its Roche lobe by a substantial amount and cannot currently be transferring matter at a large rate (Keyes and Plavec 1980). V1016 Cyg, HM Sge, and RR Tel all appear to contain normal Mira variables, which would not lose mass at the rates necessary to power a supercritical accretion event providing they do *not* fill their Roche lobes. Calculations by Wood (1977; 1978, private communication) suggest a Mira-like star *filling* its Roche lobe loses mass steadily and does not pulsate. Thus it is likely these M type stars transfer mass to their white dwarf components via a wind. The existence of white dwarfs in each of these systems (Allen 1981) requires them to have very low masses if they are at the Eddington limit ($\sim$0.1–0.3 $M_{\odot}$ for distances of 2–5 kpc). These masses seem extremely low given the Mira-type companion; more reasonable masses ($\sim$0.6–0.8 $M_{\odot}$) are required for the thermonuclear runaway model. Little can be said about the remaining symbiotic novae (RT Ser, V1329 Cyg, and AS 239), since their cool components have not been as extensively observed as the other systems. However, their behavior resembles quite closely the behavior of other symbiotic novae, and it seems likely that all their outbursts were a result of thermonuclear runaways on the surfaces of white dwarf stars.

The above discussion does not preclude supercritical accretion events for other symbiotics, e.g., Z And, CI Cyg, and AX Per. The short recurrence time scales and the outburst behaviors of these systems are very difficult, if not impossible, to achieve with a thermonuclear model. We have not concerned ourselves with these systems in this paper; the interested reader is referred to Paper I and Bath and Pringle (1982) for a thorough discussion of the outbursts in these symbiotic stars.

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