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HYDROGEN SHELL FLASHES IN MASSIVE ACCRETING WHITE DWARFS*

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ABSTRACT

The long-term evolution of massive ($M > 1.1\ M_\odot$) accreting white dwarfs in close binary systems is discussed in the context of several astrophysical problems. The evolution of massive white dwarfs was followed with model calculations. The models have ^{12}C–^{16}O cores and envelopes with composition $X = 0.7$, $Z = 0.03$. The accreted hydrogen-rich matter was assumed to have the same composition as the stellar envelope. A 1.2 $M_\odot$ white dwarf accreting at the rate $1.03 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ gives rise to repetitive hydrogen shell flashes with an interflash period of 17 years. A 1.2 $M_\odot$ white dwarf accreting at the rate $1.03 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ has an interflash period of approximately 630 years. A 1.3 $M_\odot$ white dwarf accreting at the rate $2.71 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ undergoes stable hydrogen burning in a steady state with accretion.

The possible relationship of our models to understanding the underlying variability of the blue component of symbiotic variables is discussed. The application of our models to X-ray sources containing massive degenerate dwarfs undergoing rapid accretion is considered.

Subject headings: stars: accretion — stars: binaries — stars: combination spectra — stars: interiors — stars: white dwarfs

I. INTRODUCTION

Thermonuclear instabilities in mass-accreting degenerate dwarfs have been the subject of numerous hydrostatic and hydrodynamic accretion studies (see Giannone and Weigert 1967; Rose 1968; Starrfield 1971; Starrfield, Sparks, and Truran 1974*a*, *b*; Sparks, Starrfield, and Truran 1976, and references therein). The mechanism for the classical nova outburst is now understood on the basis of well-studied thermal runaways in the envelopes of accreting white-dwarf binary components. Mass ejection and the gross features of both the fast and slow novae outbursts have been obtained by Starrfield, Truran, and Sparks (1978) and Sparks, Starrfield, and Truran (1979).

The longer-term evolutionary behavior of mass-accreting degenerate dwarfs, however, has not been so well studied. Recently, Webbink, Truran, and Gallagher (1978) have discussed the long-term evolution of a nova binary system, during which it is expected that helium runaways will sometimes be responsible for nova outbursts. A hydrostatic study by Paczyński and Żytkow (1978, hereafter PZ) has explored the occurrence of hydrogen shell flashes during the long-term evolution of a nova-like binary. PZ studied the evolution of a 0.8 $M_\odot$ white dwarf with initial luminosity $L = 1\ L_\odot$. For accretion rates in the range $1.46 \times 10^{-7} \leq \dot{M} \leq 1.067 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, repetitive hydrogen shell flashes were found with interflash periods in the range 12×10^4 years to 170 years, respectively. For $\dot{M} > 2.7 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, envelope expansion to a red-giant structure occurred, while stable hydrogen burning was found in the narrow range $1.1 \times 10^{-7} \leq \dot{M} \leq 2.7 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. A clear accretion rate–interflash period relation was indicated.

The long-term evolution may have an important bearing on physical processes in a variety of eruptive or posteruptive close binary systems. Among these processes we mention the following: (1) the behavior of postnovae (novae appear very similar before and after their eruptions); (2) sustained stable burning at high luminosity as a source of soft X-ray/EUV radiation (see Shara, Prialnik, and Shaviv 1978); (3) repetitive hydrogen shell flashes as a mechanism for the long-term variability of symbiotic and related stars (see PZ); (4) the possibility (although remote) that the so-called supermaxima in SU Ursae Majoris–type systems may have thermonuclear origin; (5) the Webbink *et al.* investigation, cited earlier, of helium runaway nova outbursts; and (6) the Whelan and Iben (1973) scenario for the origin of Type I supernovae. Recently Bond (1978) has pointed out that the nova-like system CD −42°14462 may be a dwarf nova in a permanent state of outburst! The possibility of this system being in the high state of a thermonuclear shell flash episode cannot be easily ruled out.

The objective of the present study is to follow the evolution of massive high-luminosity degenerate dwarfs ($M > 1.1\ M_\odot$) as they accrete matter in a steady state with nuclear burning. Our choice of massive models may be more appropriate for close binaries containing white dwarfs and late-type companions (Warner 1973), although Warner's conclusions have been questioned by Ritter (1976). Massive models are required for Type I supernova models, as discussed by Whelan and Iben (1973). Moreover, arguing by

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analogy with the degenerate core mass–interflash period relation for helium shell flashes (Paczyński 1975), interflash periods should be inversely proportional to the mass of the white dwarf. The shortest interflash period found by PZ was 175 years for a 0.8 $M_\odot$ white dwarf accreting at the rate 1.067×10^{-7} $M_\odot$ yr^{-1}. Shorter interflash periods than those found by PZ, we believe, would have greater interest for the long-term variability of symbiotic stars. If burning in massive models can be stable at high luminosities, sustained nuclear burning in X-ray sources such as Sco X-1 (Kylafis and Lamb 1979) would be permitted. For these reasons we feel that computations of massive accreting white dwarfs have considerable importance for the aforementioned problems.

In § II we describe the details of our model calculation and in § III we present our results. Section IV contains a summary of our conclusions.

II. CONSTRUCTION OF MODELS

The evolutionary program described by Vila (1967) was modified to follow the evolution of high-luminosity degenerate stars as they accrete matter. Our computational technique differed in two respects from that done in the study by PZ. (*a*) We did not tabulate and fit a static envelope but instead followed the evolutionary behavior of core and envelope together. Gravitational energy terms were included throughout our models. (*b*) The evolution during and between shell flashes was followed in detail without artificial addition or subtraction of mass or energy.

The effects of radiation pressure were fully included and the outer boundary condition utilized the relation $\frac{2}{3}(g - g_r) = \kappa P_g$ where g is the surface gravity, P_g is the gas pressure, κ is the opacity, and $g_r = \kappa(\sigma/c)T_e^4$ as defined in Unsöld (1955), with σ being the Stefan-Boltzmann constant, and c, the speed of light. The models were tested for convective stability by comparing the temperature gradient with the adiabatic gradient in the presence of radiation. Time-dependent mixing within convective zones was not included. Each model contained approximately 200 shells. New shells were interpolated automatically whenever necessary. The convergence criterion we adopted was that the maximum change in $\log T$ in the next iteration had to be smaller than 10^{-4}. Typically a model converged in four to six iterations. Convergence problems were usually encountered at the onset and peak of a shell flash but were always solved with either finer mass zoning or shorter time steps. The equation of state, opacities, and nuclear reaction rates are the same as those described in detail by Sion, Acierno, and Turnshek (1978) for static massive models. The CNO and proton-proton reaction rates were taken from Reeves (1965). We did not include a nuclear reaction network in our calculations.

After each time step, the mass of the model was increased by $\dot{M}\Delta t$ where $\dot{M}$ is the steady-state accretion rate. We ignored, for the purpose of these calculations, the kinetic energy flux of infall (see Sion *et al.*; PZ). The accreted material is assumed to be added at zero velocity with the same entropy as that at the stellar surface. Our time steps were normally chosen to be a fraction of the local Kelvin time of the nuclear burning shell. Thus at the beginning and peak of a shell flash episode the time steps became very small (on the order of hours). The initial models were obtained from the grid calculated by Sion *et al.* where the details of model construction are described. The initial models had ^{12}C–^{16}O cores and hydrogen-rich envelopes with composition $X = 0.70$ and $Z = 0.03$. The large masses of white-dwarf components determined by Robinson (1976) are more readily understood as carbon-oxygen white dwarfs than as pure helium white dwarfs. Starting transients in the initial models were minimized by evolving each model through several global Kelvin times and local Kelvin times holding the composition constant. Then evolution was allowed to proceed with mass accretion.

III. RESULTS

Three model sequences were evolved, corresponding to 1.2 $M_\odot$ with $\dot{M} = 1.03 \times 10^{-7}$ $M_\odot$ yr^{-1} (sequence A), 1.3 $M_\odot$ with $\dot{M} = 2.71 \times 10^{-7}$ $M_\odot$ yr^{-1} (sequence B), and 1.2 $M_\odot$ with $\dot{M} = 1.03 \times 10^{-8}$ $M_\odot$ yr^{-1} (sequence C). Sequence A required 2253 models, while for sequences B and C, 1184 models and 1558 models were needed, respectively. The properties of the initial model in each sequence is shown in Table 1. Quantities listed are the mass in solar masses, the luminosity in solar luminosities and the steady-state accretion rate in solar masses per year, effective temperature, radius,

TABLE 1

PROPERTIES OF INITIAL MODELS

PARAMETER	SEQUENCE A	SEQUENCE B	SEQUENCE C
$M/M_\odot$	1.2	1.3	1.2
$\log (L/L_\odot)/\dot{M}$	4.0 (1.03×10^{-7})	4.42 (2.71×10^{-7})	3.0 (1.03×10^{-8})
$\log T_e$	5.850	5.950	5.609
$\log R$	8.670	8.679	8.651
$\log T_{sh}$	7.898	7.981	7.734
$\log \rho_{sh}$	1.565	1.236	2.152
$\log P_{sh}$	17.707	17.656	18.043
M_e	5.799×10^{-7}	3.303×10^{-7}	1.315×10^{-6}

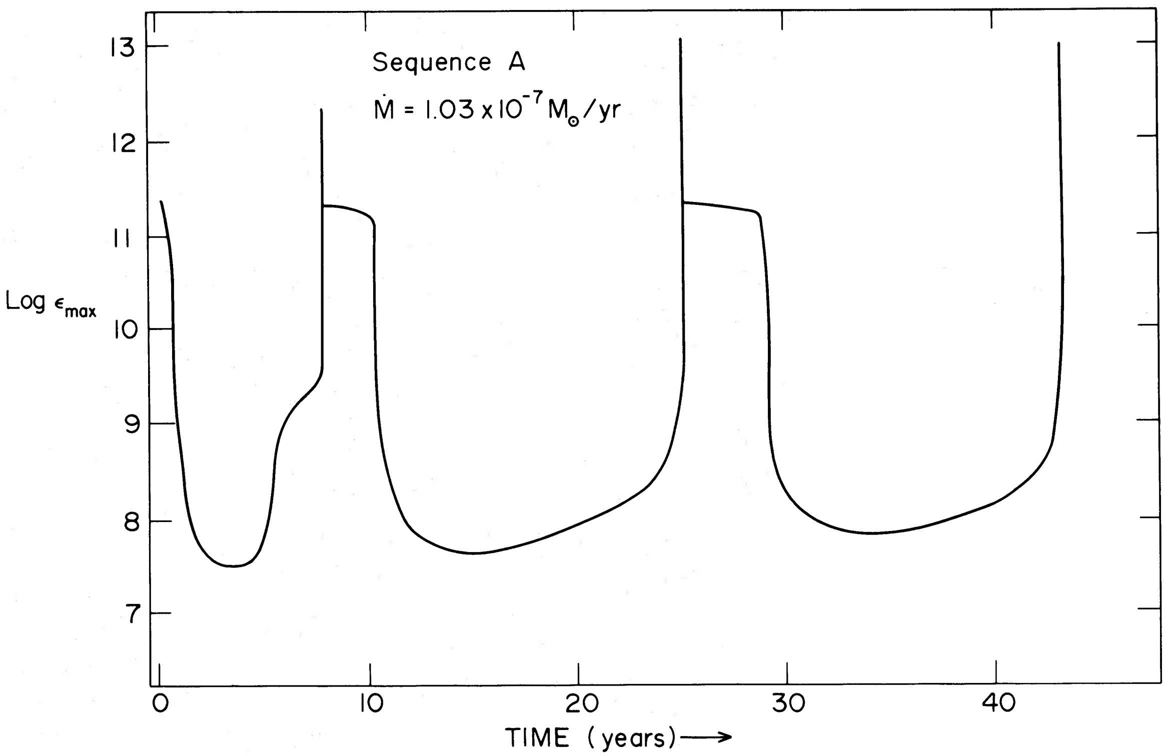

FIG. 1.—The maximum nuclear energy generation as a function of time due to hydrogen burning for evolutionary sequence A. The computation was stopped at the peak of the third shell flash episode.

temperature at the shell source, density at the shell source, pressure at the shell source, and the envelope mass in solar masses. Unless otherwise noted, all quantities listed are in cgs units.

Taam (1977) has shown that the depth of energy transport into the white-dwarf core increases with decreasing accretion rate. For our high accretion rates, thermonuclear shell flash instabilities occur at a low degree of electron degeneracy and the energy transport into the core beneath the shell source was small. Therefore we followed the thermal evolution of only part of the core but carefully monitored, during each sequence, the extent of downward energy diffusion.

The evolution of sequence A is shown in Figure 1 and Figure 2; during it, three hydrogen shell flashes occurred. Figure 1 displays the maximum nuclear energy generation as a function of time. The weaker flash strength of the first flash relative to the two succeeding flashes is due in part to the smaller envelope mass (lower shell pressure) and starting transients in the initial model. The following two shell flashes have approximately equal strength, and we stopped the calculation at the peak of the third shell flash. Sequence A had the highest accretion for which repetitive shell flashes occurred. The peak in surface luminosity always lagged the peak energy generation in the shell source as a thermal pulse ("luminosity wave") propagated toward the surface following each flash.

Sequence B was started with the 1.304 $M_\odot$ model listed in Table 1 with a steady-state accretion rate $\dot{M} = 2.71 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. An initial shell flash did not occur, which indicates the thermal stability of our starting model before evolution with accretion began. This initial model was tested for thermal stability in an earlier paper (Sion *et al.*), using both a linearized technique (Giannone and Weigert 1967) and a perturbation technique using the Henyey code. The stability analysis is confirmed by the actual evolutionary models with mass accretion. The early behavior of sequence B is shown in Figure 3. The accretion rate in this sequence almost exactly balances the rate of hydrogen burning. A stable, steady-state hydrogen-burning phase is obtained. We stopped the calculation after 5 years of stable burning in a steady state with accretion. If accretion continued indefinitely while in a steady state with burning, the model would reach 1.4 $M_\odot$ in 360,000 years.

The evolution of sequence C was followed through one flash only in order to determine an approximate interflash period for an accretion rate one order of magnitude lower than that of sequence A. Once the model settled into thermal equilibrium (i.e., the bolometric luminosity balanced the nuclear luminosity) following an initial weak flash, the surface luminosity declined to 5 $L_\odot$ while the star accreted at the rate $\dot{M} = 1.03 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. After 632 years an accretion-induced shell flash occurred and we stopped

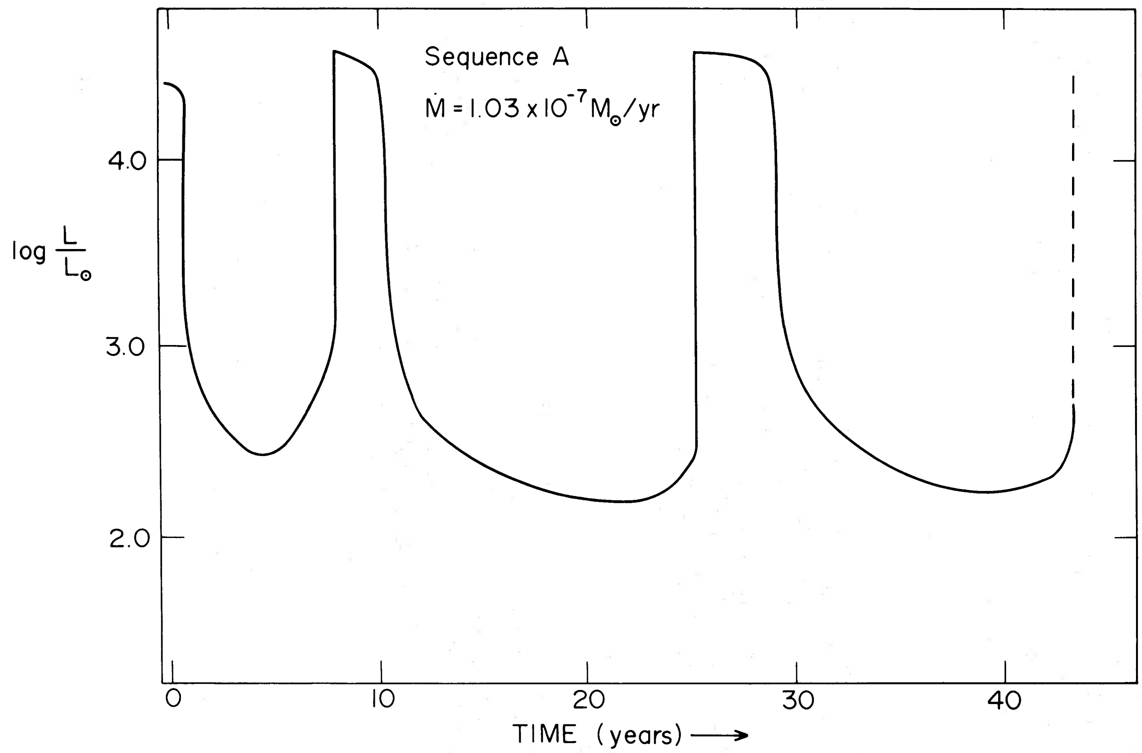

FIG. 2.—The surface luminosity as a function of time for evolutionary sequence A. The dashed line shows the value *L* would reach if the computation had continued beyond the peak nuclear luminosity of the third shell flash. Maximum surface luminosity always occurred later than the nuclear energy generation peak.

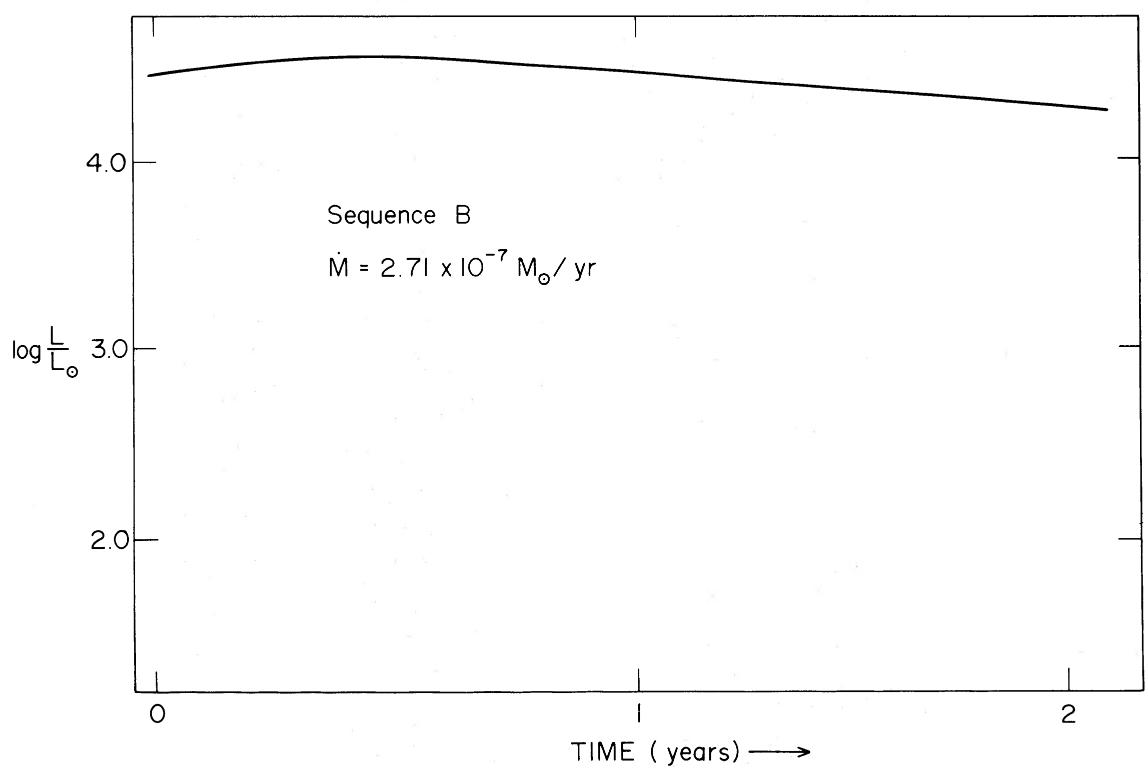

FIG. 3.—The surface luminosity as a function of time for evolutionary sequence B

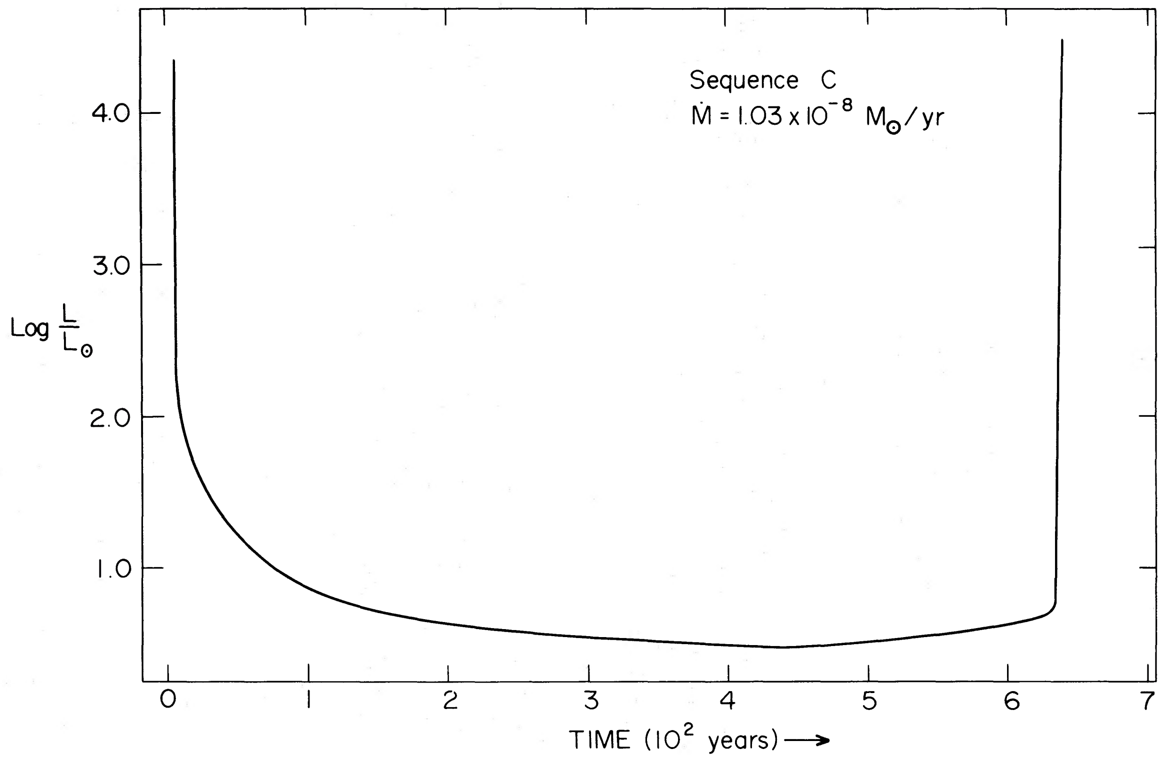

FIG. 4.—The surface luminosity as a function of time for evolutionary sequence C

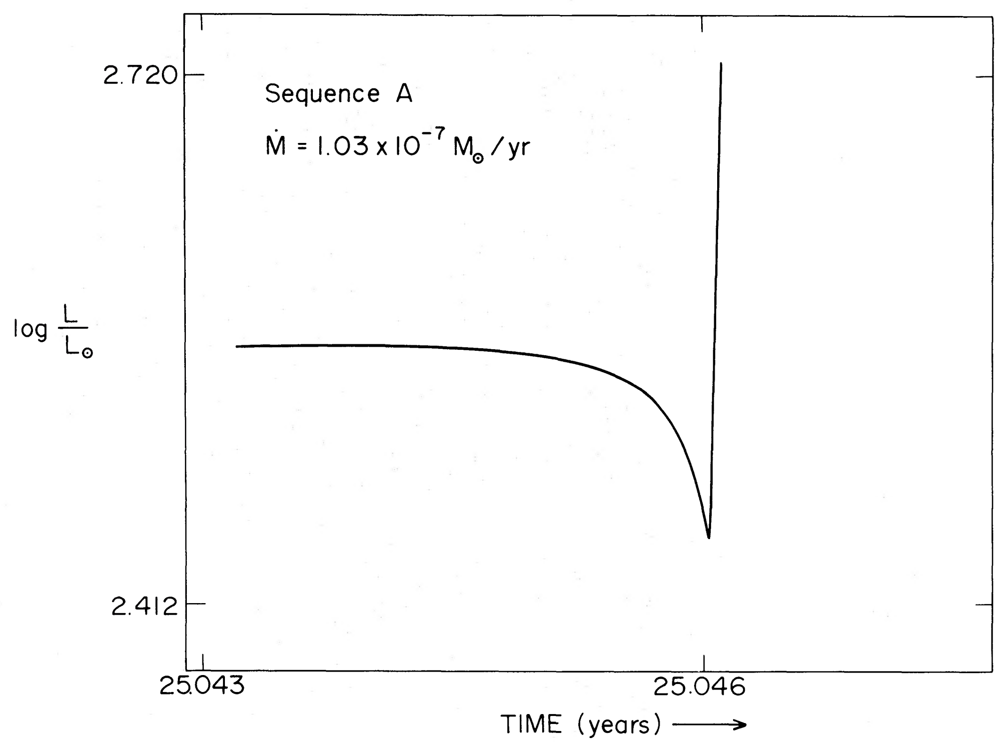

FIG. 5.—The surface luminosity as a function of time near the onset of the second shell flash in sequence A

our calculation at the peak of the flash. The behavior of this model sequence is shown in Figure 4. For sequences A and C, we found a small dip in surface luminosity just preceding the rise to flash peak. In Figure 5 we show a fine-resolution time plot of the surface luminosity just prior to the onset of the second shell flash in sequence A. This same dip in surface luminosity was found in all evolutionary sequences reported by PZ. The dip in luminosity was accompanied by an exactly coincident dip in effective temperature. The dip in luminosity and effective temperature was also reported by Truran *et al.* (1977). Following this dip, the effective temperature reached a peak and then decreased sharply as the surface luminosity rose to maximum. Following this sharp spike, the effective temperature resumed its gradual rise to maximum at the flash peak. The stellar radius decreased when the luminosity and effective temperature dipped at the onset of a shell flash.

Some properties of the evolutionary models are shown in Table 2. For each model sequence we have listed the evolution time t in years, the effective temperature T_e, the temperature in the hydrogen burning shell T_{sh}, and the pressure in the shell source P_{sh}. The shell source quantities are listed at the point where the mass abundance of hydrogen, $X = 0.35$.

IV. SUMMARY AND DISCUSSION

We have shown that very short interflash periods are obtained with massive white dwarfs accreting at high rates. We have assumed spherically symmetric accretion rather than disk accretion and our models have high surface luminosity. These two factors preclude their applicability to dwarf novae. Moreover, the shell flashes exhibited by our models are not strong enough to eject mass, as in classical novae. However, the repetitive hydrogen shell flashes found in sequence A with an interflash period of 17 years may be relevant to understanding the underlying variability of the blue component of symbiotic variables if the blue component is a white dwarf. According to this scenario the white dwarf is accreting cold stellar wind (with low angular momentum per unit mass) from the extended atmosphere of its red-giant companion star. Thus the accretion may be regarded as quasi-spherical without the formation of an accretion disk. Our 17 year interflash period is 10 times shorter than that found at the same accretion rate by PZ for 0.8 $M_{\odot}$. The bolometric luminosity range from interflash low state to flash peak in sequence A corresponds to a visual magnitude amplitude of 2–3 mag. The observed properties of the symbiotic variables are summarized by Boyarchuk (1969).

The interflash periods found for sequences A and C demonstrate the high sensitivity of the interflash period to the accretion rate. Our interflash periods at 1.2 $M_{\odot}$ are approximately 10 times smaller than the interflash periods found by PZ at 0.8 $M_{\odot}$. An estimate from their Table 1 (accretion rate–interflash period relation) yields an interflash period of approximately 6000 years for a 0.8 $M_{\odot}$ white dwarf accreting at 1.03×10^{-8} $M_{\odot}$ yr^{-1}. The shortest period they report is 175 years at 1.067×10^{-7} $M_{\odot}$ yr^{-1}, close to our sequence A accretion rate.

The stable burning found in sequence B may have an important bearing on detailed X-ray models of systems such as Sco X-1 reported recently (Kylafis and Lamb 1979). If steady nuclear burning occurs, the resulting soft X-ray blackbody radiation significantly increases Compton cooling in the emission region (Katz 1977). Kylafis and Lamb (1979) find the observed X-ray spectrum of Sco X-1 to be in agreement with a high-mass degenerate dwarf ($M \gtrsim 1.2$ $M_{\odot}$) accreting at a high to moderate rate. Moreover, if a degenerate dwarf X-ray source can undergo steady nuclear burning, these X-ray models are relieved of problems imposed by accretion-driven shell flashes during rapid mass accretion. To our knowledge, sequence B is the first reported case of stable burning of accreted material by a massive white dwarf at high luminosity. Our result is consistent with the stable burning range found by PZ at 0.8 $M_{\odot}$.

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TABLE 2

PROPERTIES OF EVOLUTIONARY MODELS

Sequence	$\dot{M}$	t (yr)	log T_e	log T_{sh}	log P_{sh}
A........	1.03×10^{-7}	5.01	5.499	7.636	18.179
		10.19	5.905	7.972	17.688
		19.00	5.447	7.649	18.358
		27.49	5.800	8.013	17.625
		38.25	5.444	7.619	18.239
B........	2.71×10^{-7}	0.50	5.953	8.012	17.731
		1.52	5.947	7.985	17.783
		3.08	5.947	7.984	17.773
C........	1.03×10^{-8}	213.0	5.052	7.380	18.440
		404.5	5.026	7.411	18.671
		633.9	5.429	8.037	17.674

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