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MULTIPLE HYDROGEN FLASHES ON ACCRETING LOW-MASS WHITE DWARFS: NOVAE AND DAO STARS

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ABSTRACT

We have computed 10 successive nova eruptions on two different mass white dwarfs as part of a study to determine the long-term evolution of cataclysmic binaries. The evolution of two low-mass white dwarfs, accreting hydrogen-rich matter at a rate of 10^{-9} $M_{\odot}$ yr^{-1}—typical of close binary systems—was calculated by means of a hydrodynamic code. The code includes algorithms for diffusion and mass-loss, and is capable of computing continuously several cycles, by adjusting the time steps to the prevailing evolutionary time scale.

A 0.6 $M_{\odot}$ white dwarf, composed of carbon and oxygen, and a 0.4 $M_{\odot}$ helium white dwarf are considered, both of low intrinsic luminosity. They are found to undergo periodic eruptions, which, for the CO white dwarf become regular only after about five cycles. The outbursts are similar in appearance to those of classical novae, although on a largely stretched time scale. The high-luminosity ("on") phase lasts for ∼200 yr for both stars. The accretion (the "off" phase) continues for 4×10^5 yr and 9×10^5 yr, for the 0.6 and 0.4 $M_{\odot}$ WDs, respectively. Both stars lose mass following the outburst. While the more massive white dwarf ejects the entire accreted mass, the smaller, He WD retains some of the accreted material which is added to the core after being burnt into helium. During the accretion phase these objects should look and behave like dwarf novae. During the several thousand years after mass ejection ends these stars should evolve in appearance from nitrogen-rich PG 1159 objects (like PG 1144+005) to DAO and perhaps DB-like stars.

Subject headings: accretion, accretion disks — binaries: close — diffusion — novae, cataclysmic variables — stars: white dwarfs

1. INTRODUCTION

Stellar evolution theory predicts that the mass spectrum of white dwarfs (WDs) should be double-peaked. The masses of helium WDs are concentrated around 0.4 $M_{\odot}$, the upper limit corresponding to the core mass required for a star to undergo a core helium flash. The masses of CO WDs, on the other hand, are concentrated at 0.6 $M_{\odot}$ with a declining frequency at higher values, as a result of the strong stellar wind during asymptotic giant branch evolution. The predicted distribution of CO WDs is in excellent agreement with that derived from observations of single stars (Bergeron, Saffer, & Liebert 1992). Although it is uncertain that He WDs can be formed by *single stars* in a Hubble time (Iben & Webbink 1989), helium WDs *can be formed in close binary systems.* Thus the calculated distribution of WD masses in zero-age cataclysmic binaries (Politano & Webbink 1990) has two components: systems containing He WDs, with masses ranging from 0.27 to 0.46 $M_{\odot}$, and systems containing CO WDs, whose masses range from 0.54 $M_{\odot}$ up to the Chandrasekhar mass, peaked around 0.6 $M_{\odot}$. The latter distribution is similar to that observed for single WDs.

The masses typical of WDs in novae, *as inferred from observations*, are found to be systematically higher than the calculated ones (and those of single WDs). This is due, however, to selection effects (Truran & Livio 1986; Politano et al. 1990; Ritter et al. 1991): essentially, nova outbursts are more frequent on massive WDs. But low-mass WDs in cataclysmic binaries have, in fact, been observed: several dwarf novae *are* known to have masses near 0.6 $M_{\odot}$ or less (Ritter 1990), and, according to Webbink (1990), of the small sample of WDs with determined masses in classical nova systems, a large fraction have masses near 0.7 $M_{\odot}$. Thus, low-mass WDs (0.4 $M_{\odot}$ helium WDs and 0.6 $M_{\odot}$ WDs) are still, probably, the most frequently occurring compact members of close binary systems. The evolution of accreting low-mass WDs has seldom been considered, although *massive* WDs (≥ 1 $M_{\odot}$), accreting hydrogen-rich matter from a companion, have been intensively studied. In the present paper we propose to fill this gap in our understanding of close binary system evolution.

WDs which accrete mass at a moderate rate (10^{-10}–10^{-8} $M_{\odot}$ yr^{-1}) are expected to undergo thermonuclear runaways (TNRs), when the accumulated mass surpasses a critical value. The intensity of the outburst, its duration (the length of the "on" phase) and the frequency of its occurrence (the length of the "off" phase)—for a given accretion rate—are determined mainly by the WDs mass (and, to a lesser degree, by its core temperature). Accretion of hydrogen-rich matter onto a 0.6 $M_{\odot}$ CO WD was found to lead, eventually, to a flash (e.g., Kovetz & Prialnik 1985), but the consequences were not studied. It has been argued that the mass of the accretor may be too low for a sufficiently high pressure to build up at the base of the accreted envelope, to ever permit a nova outburst (Fujimoto 1982). Moreover, even if low-mass WDs do undergo nova outbursts similar to those on massive WDs, they may be less interesting a priori, since the likelihood of observing them is orders of magnitudes lower (Ritter et al. 1991), as they erupt so much less frequently.

Accretion onto low mass CO WDs has been studied by Fujimoto & Sugimoto (1982) without, however, allowing for mass loss. As a result, hydrogen ignition led to the formation of a helium zone above the CO core, which underwent helium shell flashes typical of AGB stars. Finally, these WDs ended up as supernovae. Their work implies that the helium buffer zone grows continuously, at a high rate in the case of a high $\dot{M}$, and at a reduced rate in the case of a sufficiently low $\dot{M}$. The latter condition would have led to nova outbursts and mass ejection, but these phenomena have been suppressed. Instead, they assumed that ejection, if allowed to occur, would still leave some helium behind, which would accumulate over time. On this assumption, accretion of hydrogen rich material could be replaced by helium accretion when investigating the long-term evolution of WDs. This approach has been adopted by Taam (1980a, b) for CO WDs, and by Nomoto & Sugimoto (1977) and by Nariai, Nomoto, & Sugimoto (1980) for a low-mass helium WD. The main purpose of all these studies has been the explosive ignition of helium, rather than that of hydrogen. However, detailed studies of explosive hydrogen burning on the surface of (massive) WDs showed that the helium rich remnant at the end of a nova outburst is destroyed by mixing and ejection during the following outburst. Thus, even though a helium layer is formed, it is periodically destroyed and regenerated, and it does not grow (Prialnik 1986; Fijimoto & Iben 1992). The situation is unclear in the case of low-mass WDs. This prompted us to undertake the present study.

The light curve of a typical nova outburst has the general shape of the well-known McLaughlin curve (McLaughlin 1960), although the time scales may differ significantly from nova to nova. This same curve applies when the time scale is "stretched" from a few days (very fast and recurrent novae) to a few months or more (very slow novae). The time span between eruptions varies too: from a few tens of years (recurrent novae) to tens of thousands of years (classical novae). Since these differences are attributed to the mass of the accreting WD, the question is: could the time scale be stretched even further (and then to what extent), i.e., would the same light-curve still apply, when low-mass WDs are involved?

Numerical simulations of thermonuclear runaways resulting from accretion are generally confined to one outburst, sometimes followed by the full calculation of the decline phase and the return to minimum brightness, and very seldom continued through subsequent flashes. It is therefore implied that the initial conditions assumed are either realistic, or quickly forgotten, and that after the eruption the return to preoutburst conditions is completed long before the next eruption. This is supported by the calculations of two consecutive classical nova outbursts (Prialnik 1986), in which the second flash was found to be very similar to the first. Nevertheless, when steady-burning (quasi-static) calculations are performed (which are simpler and less time consuming, and hence cover longer evolutionary periods), it is found that only after the first few (less than two) cycles do the flashes reach an almost constant (slowly evolving) pattern (Iben 1982). The semi-analytic one-zone models of Paczyński (1983) also show that a full amplitude and a constant time interval between flashes are reached within two or three flash cycles.

Since computing facilities have improved significantly in recent years (workstations now provide almost unlimited CPU time), it is finally possible to follow the evolution of a number of consecutive flashes with full hydrodynamic calculations, testing the assumption that initial conditions affect the outcome only insignificantly. For this purpose, it is necessary to develop an algorithm that is capable of shifting from one evolutionary stage to another without outside intervention. Usually, the input parameters required for computing accretion are different from those required for simulating the TNR or mass loss, and hence a full cycle is computed in many separate runs.

The purpose of the present work is to follow the evolution of low-mass accreting WDs through several flashes. In § 2 we describe the method of computation; in §§ 3 and 4 we present the results of the evolution through ~ 10 consecutive flashes for two initial WD masses and compositions: in § 5 we compare our results with observations and in § 6 we summarize the main conclusions.

2. METHOD OF CALCULATION

The stellar evolution code used was that described in some detail by Prialnik (1986), with the outer boundary condition given by Kovetz, Prialnik, & Shara (1988). Diffusion was computed for all elements whose abundances (mass fractions) exceeded 10^{-5} at some point of the model; less abundant species were assumed to have vanishing diffusive velocities. The mass-loss algorithm was described by Prialnik & Kovetz (1992) and works as follows. The outward mass flux $\dot{m} = -4\pi r^2 \rho v$ (in standard notation) is set equal to its value at the base of the photosphere, provided that the outward velocity v exceed both the local sound speed and half the local escape speed, in accordance with optically thick wind models (e.g., Ruggles & Bath 1979).

Changes were introduced in the code in order to permit the computation of many cycles in a single, continuous, run (of ~ 50 CPU hours). The different stages of evolution of an accreting WD are characterized by radically different time scales: the accretion time scale is given by $\Delta m_{\rm acc}/\dot{M}_{\rm acc}$, which is of the order of 10^3–10^6 yr; the TNR time scale is determined by the half-life time of the CNO β-unstable isotopes, which is less than ~ 100 s; the dynamical time scale, $(G\rho)^{-1/2}$ is of the order of minutes to hours; the mass-loss time scale $\Delta m_{\rm acc}/\dot{M}_{\rm ej}$ is determined by the expansion velocities and ranges from days to months. Hence, by identifying numerically the evolutionary time scale—the time step required for physical parameters to change by a prescribed (small) fraction—the code was able to recognize the prevailing state of evolution and adjust the parameters which turn on and off different processes (such as accretion, mass loss, diffusion, etc.), accordingly.

Two evolutionary sequences were computed: a WD of 0.6 $M_\odot$ made of carbon and oxygen in equal mass fractions, and a pure helium WD of 0.4 $M_\odot$. The initial models were generated as follows: first, the core mass was divided into mass shells Δm that, in the outer part, decreased outward down to $\Delta m_{\rm min}$, and from there (still going outward) became constant. We chose $\Delta m_{\rm min}$ to be $\sim 1/150$ of the expected $m_{\rm acc}$. Next, a polytrope of index 2.5, homogeneous CO composition and ~ 1 $R_\odot$ was constructed with this mass distribution. This configuration was then evolved (excluding nuclear reactions, accretion and diffusion, but including neutrino emission) until it became a cooling, degenerate core with a central temperature of a few times 10^7 K. Now two outer mass shells of mass $\Delta m_{\rm min}$ and *solar* composition were added, and the new configuration evolved (with the same "input physics") down to a central

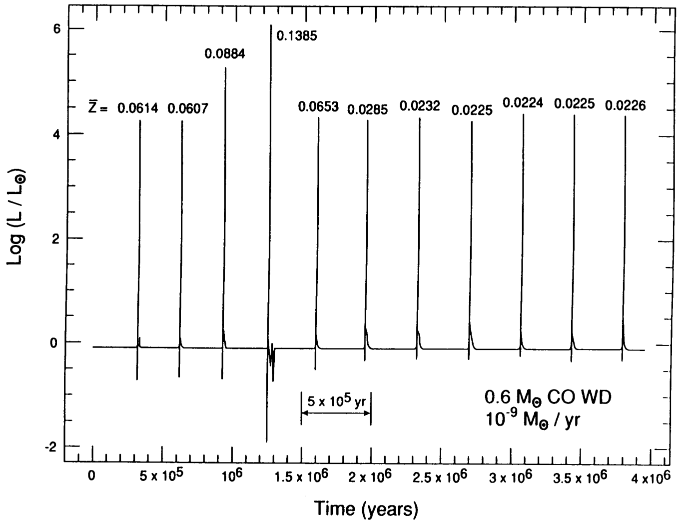

FIG. 1*a*

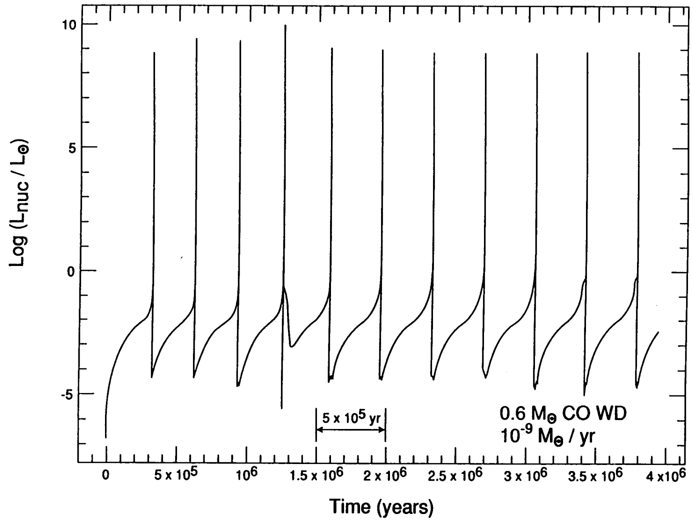

FIG. 1*b*

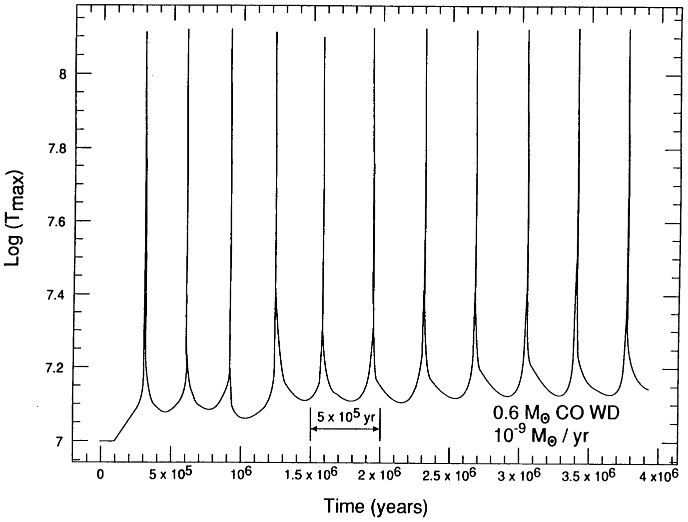

FIG. 1*c*

FIG. 1.—Evolution of a 0.6 $M_\odot$ carbon-oxygen WD, accreting hydrogen-rich matter at a rate of 10^{-9} $M_\odot$ yr^{-1}, through several cycles of accretion, outburst, and decline, spanning 4×10^6 yr. (*a*) Bolometric luminosity vs. time; at each flash; $\bar{Z}$ is the metal content of the envelope, resulting from diffusion and convection. (*b*) Nuclear luminosity vs. time. (*c*) Maximal temperature attained in the burning shell vs. time.

temperature of 10^7 K. The central densities were 3.33×10^6 g cm^{-3} for the CO WD and 9.24×10^5 g cm^{-3} for the He model. The

$$\dot{M} = 10^{-9}\ M_\odot\ \text{yr}^{-1}\ ,$$

typical of close binary systems, and the accreted matter was assumed to have solar composition. Accretional heating at the WD surface was taken to be (Regev & Shara 1989)

$$L_{\text{acc}} = 0.4 G M_{\text{WD}} \dot{M} / R_{\text{WD}}\ .$$

The properties of the two models are summarized in Table 1.

3. EVOLUTION OF AN ACCRETING 0.6 $M_\odot$ CO WD

The history of the 11 flashes calculated for this model is shown in Figure 1: (*a*) luminosity versus time, (*b*) nuclear energy generation rate versus time, and (*c*) maximal temperature attained versus time. The metal content of the envelope, resulting from diffusion and convection is indicated in Figure 1*a* for each outburst. The main conclusion that emerges from these figures is that a cyclic behavior eventually establishes, but the evolutionary pattern becomes regular (in fact, almost constant) only after the first five flashes. It is worth emphasizing that the first two flashes are rather similar; and both are quite different (in terms of ejected metal fraction) from the later (sixth through eleventh) "cyclically steady" flashes. The evolution of L, L_{nuc} and T_{max} through one full cycle (3.8×10^5 yr) is shown in Figures 2*a*–2*c*, respectively. Key points during the evolution through a full cycle, and the time elapsed between them are illustrated in the H-R diagram of Figure 3. During most of the accretion phase (A–B) the luminosity is almost constant and equal to the accretion luminosity which, for this model, exceeds significantly the intrinsic luminosity of the WD. The interesting feature that appears in Figures 2*a* and 3 is the rise in luminosity which occurs a few thousand years prior to the full development of the outburst. The peak of the outburst is given in more detail (on an enlarged time scale) in Figures 4*a*–4*c*. The imminent onset of the flash is marked by a brief drop in luminosity, caused by the adjustment of the hydrogen-rich shell structure to the convective regime that sets in, starting at the hottest point of the star and advancing toward the surface. This is followed by a sharp

TABLE 1

CHARACTERISTIC OF THE MODELS

PARAMETER	VALUES	
Mass ($M_\odot$)	0.6	0.4
Composition	CO	He
ρ_c (g cm^{-3})	3.3 (6)	9.2 (5)
T_c (K)	10^7	10^7
$\dot{M}_{\text{acc}}$ ($M_\odot$/yr^{-1}).....	10^{-9}	10^{-9}
m_{acc} ($M_\odot$)...........	3.7 (−4)	8.9 (−4)
T_{max} (K).............	1.33 (8)	1.04 (8)
$L_{\text{max}}/L_\odot$	1.3 (4)	6.6 (3)
P_{cycle} (yr)	3.7 (5)	9.0 (5)
$\dot{M}_{\text{wd}}$..................	−8 (−12)	9 (−11)

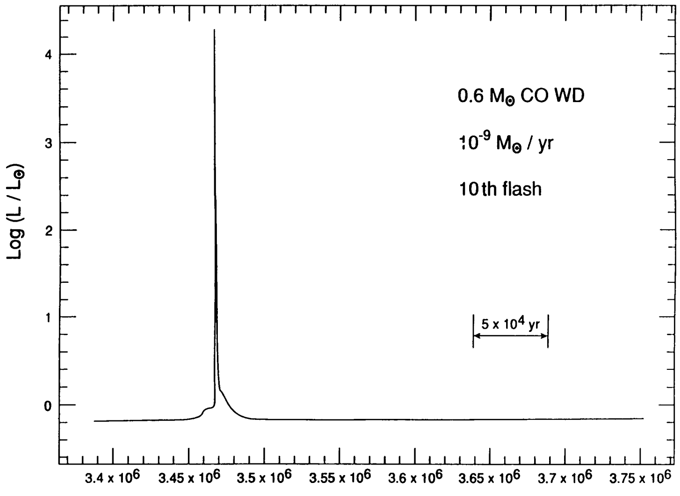

FIG. 2*a*

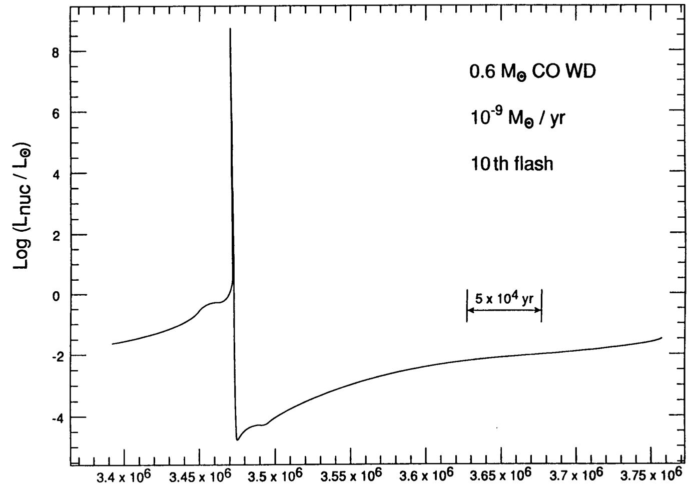

FIG. 2*b*

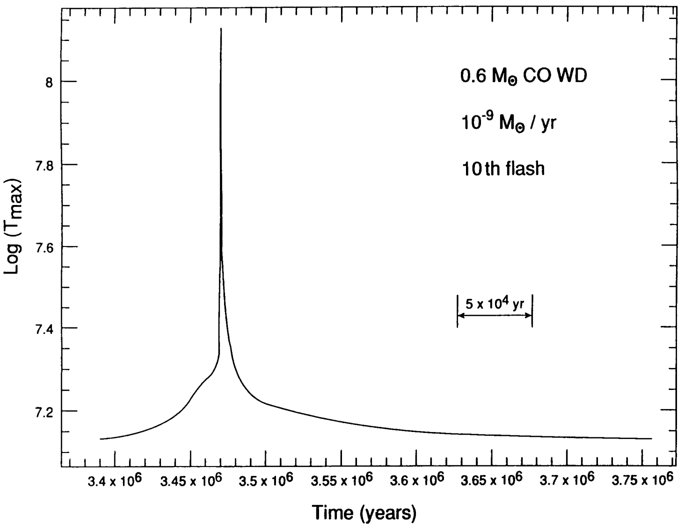

FIG. 2*c*

FIG. 2.—Evolution of the 0.6 $M_{\odot}$ WD model (accreting hydrogen-rich matter at a rate of 10^{-9} $M_{\odot}$ yr^{-1}) through one complete cycle of accretion, outburst and decline (the 10th cycle of Fig. 1). (*a*) Bolometric luminosity vs. time. (*b*) Nuclear luminosity vs. time. (*c*) Maximal temperature attained in the burning shell vs. time.

rise in luminosity, when the envelope has become fully convective. During a relatively brief period of time (near point D in Fig. 3) the effective temperature is $\sim 10^5$ K and the luminosity exceeds 10^3 $L_{\odot}$; the star would then appear as a source of extreme UV and even soft X-radiation. Eventually, a plateau luminosity in excess of 10^4 $L_{\odot}$—lower than the Eddington luminosity, but higher than the luminosity of a red giant with a 0.6 $M_{\odot}$ core (Paczyński's 1970 core-mass-luminosity relation)—is reached and maintained for ~ 160 yr. It would therefore be impossible (during a human lifetime) to observe the entire development of such an outburst. This is in marked contrast with the situation in classical novae, even the slowest among them. During the constant luminosity phase (the fluctuations see in Figures 4*a*–4*c* are of numerical origin, and result from mass rezoning at the surface) the star loses mass. Mass loss occurs in two stages: the first mass ejection episode ($\dot{M} \approx 0.0002$ $M_{\odot}$ yr^{-1}) follows the rapid expansion of the envelope. Then the inner layers of the envelope contract, raising the temperature, the outer layers expand, and the star again loses mass continuously via a stellar wind. The mass ejection rate declines gradually from ~ 0.001 $M_{\odot}$ yr^{-1} to zero. Typical expansion velocities are 100–200 km s^{-1}. There is no significant difference between the expansion velocities of the first and second ejection phases. The total mass lost $\Delta m_{\mathrm{ej}} = 3.75 \times 10^{-4}$ $M_{\odot}$, amounts to $\sim 90\%$ of the convective envelope's mass. This is slightly larger than the accreted mass Δm_{acc}. The difference is due to the small amount of core material, $\Delta m_c \approx 3 \times 10^{-6}$ $M_{\odot}$, which has been mixed into the envelope. Mass loss ceases when the envelope mass becomes too small to support its own pressure; a dynamic phase of contraction ensues. The white dwarf photospheric radius

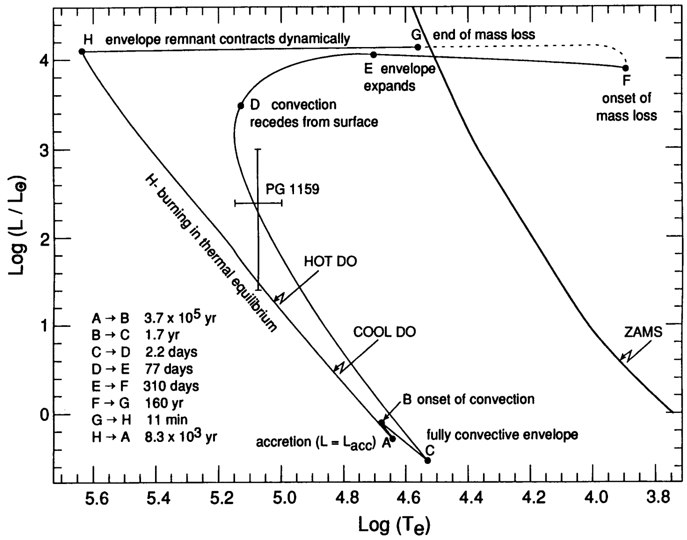

FIG. 3.—A full evolutionary cycle of an accreting 0.6 $M_{\odot}$ CO WD in the $L - T_e$ diagram. Important points are labeled A, B, ..., and the time elapsed between them is noted. The main sequence is labeled ZAMS. The approximate locations of PG 1159, and hot and cool DO stars are indicated.

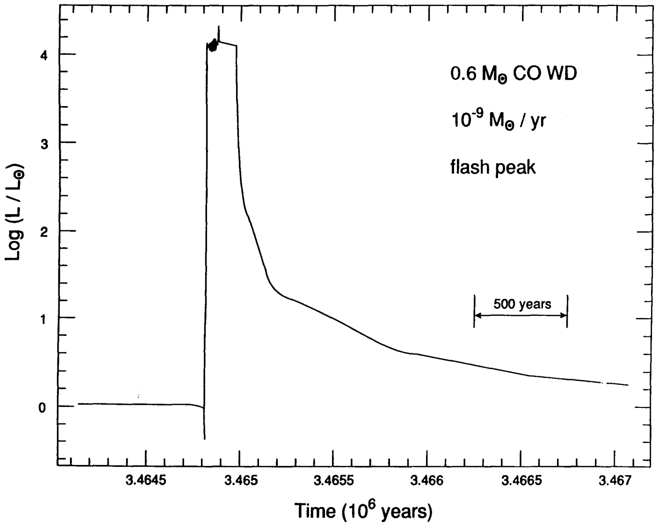

FIG. 4*a*

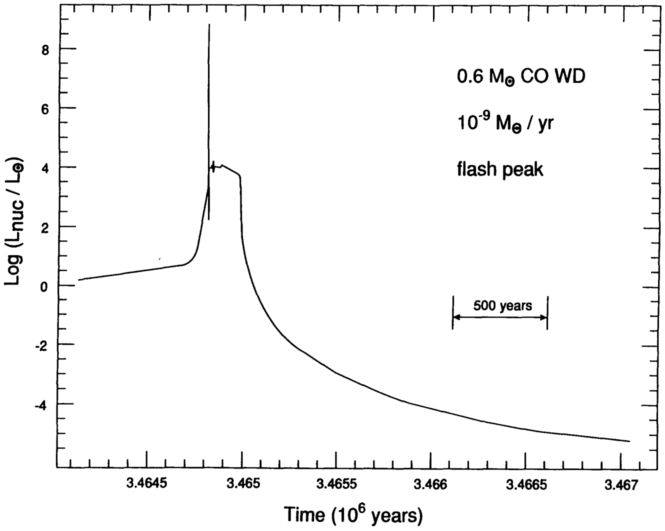

FIG. 4*b*

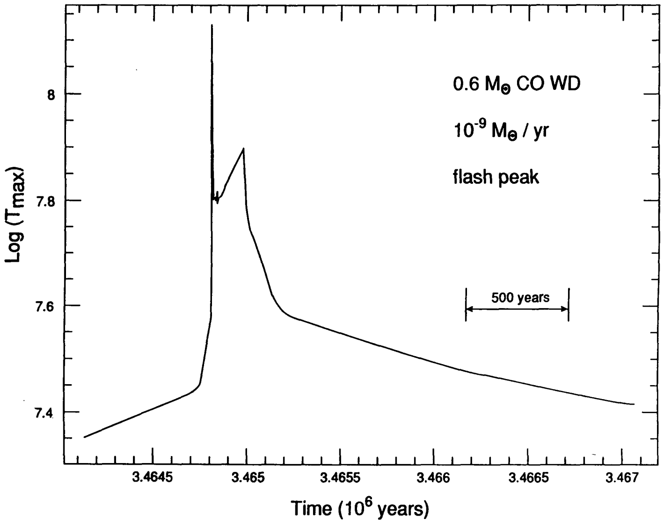

FIG. 4*c*

FIG. 4.—Evolution of the 0.6 $M_\odot$ WD model during the peak of a flash (from point B, through C, D ... to point A in Fig. 3). (*a*) Bolometric luminosity vs. time. (*b*) Nuclear luminosity vs. time. (*c*) Maximal temperature attained in the burning shell vs. time.

shrinks to $\sim 0.02\ R_\odot$. A relatively long period of decline of both bolometric and nuclear luminosities, which are now in balance, follows. The remnant hydrogen-rich material that is left on the WDs surface burns to helium, but the helium layer thus formed is only transient. It becomes mixed into the material which accretes, and ignites at the next outburst. Thus at each cycle the envelope contains hydrogen-rich accreted matter, helium-rich matter from the remnant and, when the flashes have settled into a regular pattern, a small amount of CO-rich material from the core. Fluctuations in $\bar{Z}$ during the first cycles are due to variations in the mass of the helium-rich buffer zone between the CO core and the accreted matter (starting from 0 at the first flash), increasing and then decreasing during subsequent cycles until it reaches a constant value. Then $\Delta m_{\mathrm{env}} = \Delta m_{\mathrm{acc}} + \Delta m_{\mathrm{rem}} + \Delta m_c = \Delta m_{\mathrm{ej}} + \Delta m_{\mathrm{rem}}$. On a long-term evolutionary scale the compact object loses mass at a rate

$$\dot{M}_{\mathrm{WD}} = -\frac{\Delta m_c}{\Delta m_{\mathrm{acc}}}\dot{M} \approx -8 \times 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}\ .$$

Over the ten flashes, the central temperature decreased by less than 0.1%. The evolution time was too short, and the change in temperature too small, to enable us to infer a meaningful rate of cooling for the WD. At any rate, the thermonuclear runaways did not lead to a secular heating of the center, in spite of their long duration (compared with those of classical novae).

Observed at random, this system would appear as a source of $\sim 0.8\ L_\odot$ with an effective temperature of 5.6×10^4 K. One out of ~ 2000 such systems would appear as a luminous object ($L \sim 10^4\ L_\odot$) with a surface temperature of $\sim 1.5 \times 10^4$ K.

4. EVOLUTION OF AN ACCRETING 0.4 $M_\odot$ He WD

The evolution of the lower mass, He WD has been followed for a period of ~ 8.5 million years, during which time it underwent nine flash cycles. It is described in Figures 5–8, which are the counterparts of Figures 1–4. The outbursts in this case are milder: the peak temperature barely reaches 10^8 K, and the maximum energy generation rate is about two orders of magnitude lower than in the previous case. The interflash period is ~ 3 times longer (so that the accreted mass prior to outburst is larger). Our results are consistent with those obtained by Nariai et al. (1980) for the first flash of a 0.4 $M_\odot$ He WD accreting at the rate of $10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. The high luminosity, although only about half the value obtained for the more massive WD, is maintained for more than 1000 yr. The main difference between the two models stems from the difference in the composition of the core (and to a lesser degree from the difference in mass). The only source of CNO nuclei in the 0.4 $M_\odot$ model is the accreted matter. Diffusion at the core-envelope interface is of no consequence; CNO enrichment does not occur. This is also the reason for the regularity of the flashes right from the beginning. The evolution through a full cycle is illustrated in Figure 7: the general behavior is similar to that of the more massive CO WD but, generally, the time scales are longer.

The significant feature of the cyclic evolution of this accreting WD is that a long-term trend is apparent. For example, the minimum temperature attained between flashes (see Fig. 5*c*) is

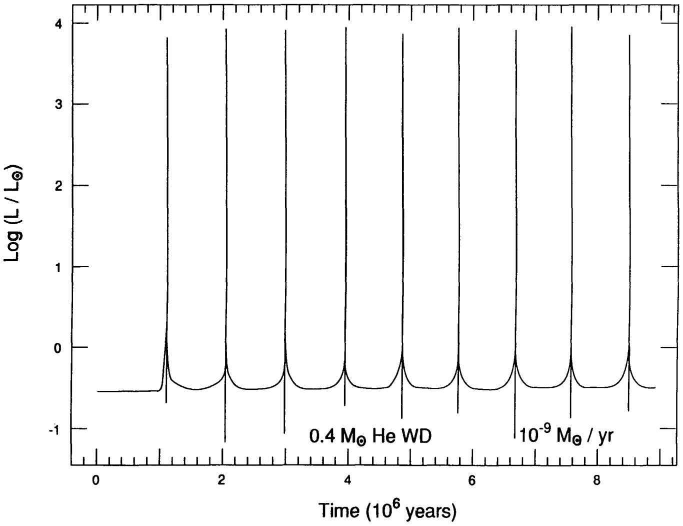

FIG. 5*a*

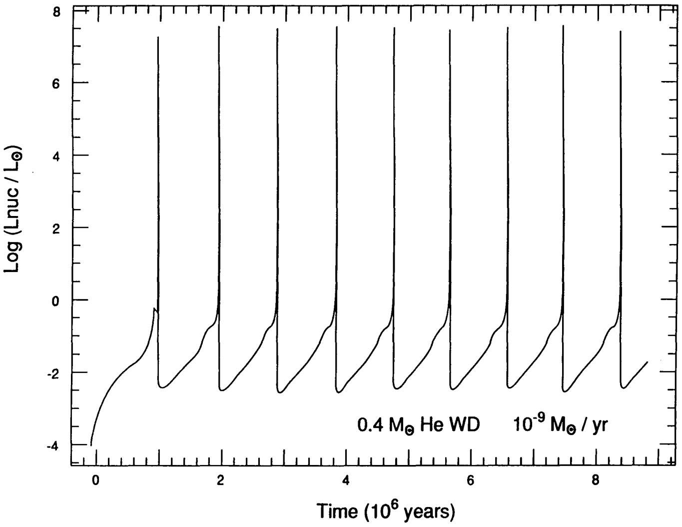

FIG. 5*b*

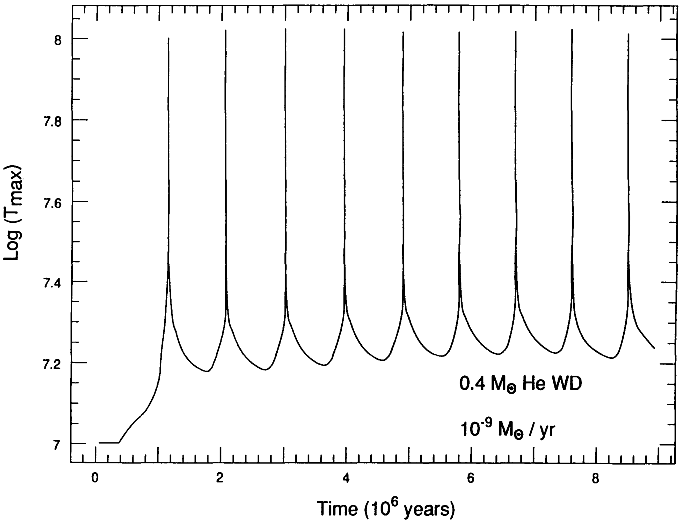

FIG. 5*c*

FIG. 5.—Evolution of a 0.4 $M_\odot$ helium WD, accreting hydrogen-rich matter at a rate of 10^{-9} $M_\odot$ yr^{-1} through several cycles of accretion, outburst, and decline, spanning 9×10^6 yr. (*a*) Bolometric luminosity vs. time. (*b*) Nuclear luminosity vs. time. (*c*) Maximal temperature attained in the burning shell vs. time.

very slowly, but steadily, increasing, implying that the outer layers of the core (at least) are gradually heated. Nevertheless, over the 10 flashes, the central temperature decreased by almost 1%. Another long-term evolutionary feature is the gradual growth in mass of the accreting WD. During each eruption the envelope expands to almost 100 $R_\odot$ and a wind develops. This results in the continuous ejection of most of the accreted matter, at velocities of a few tens km s^{-1}. In contrast to the previous model, there is only one mass-loss phase; the maximum temperature, the luminosity and the rate of nuclear energy generation remain nearly constant during the entire phase of mass loss. Near the end of this phase the star slowly contracts, and mass-loss ceases. Subsequently, nuclear burning continues in thermal equilibrium, at a declining rate. When the remaining hydrogen is consumed, the star cools off slowly and returns to its preoutburst state. Thus a remnant mass $\Delta m_{\rm rem} = {\sim}8 \times 10^{-5}$ $M_\odot$—about 10% of the accreted mass—is burnt into helium and hence added to the helium core. The WDs mass *grows* at an average rate

$$\dot{M}_{\rm WD} = \frac{\Delta m_{\rm rem}}{\Delta m_{\rm acc}} \dot{M} \approx 9 \times 10^{-11}\ M_\odot\ {\rm yr}^{-1} .$$

At this rate, the WD would double its mass during a time interval of the order of the solar system's age. However, if only 10% of the accreted mass is retained after each flash then at most ~0.1 $M_\odot$ from an initially 1 $M_\odot$ companion would be added to the He WD.

5. COMPARISON WITH OBSERVATIONS

The white dwarf masses we have studied in this paper (0.4 and 0.6 $M_\odot$) are common not only in single stars, but also in cataclysmic binaries. Ritter's (1990) catalog lists several systems (e.g., V2051 Oph with $M_{\rm wd} = 0.44$ $M_\odot$; LX Ser with $M_{\rm wd} = 0.41$ $M_\odot$; HT Cas with $M_{\rm wd} = 0.62$ $M_\odot$, and EM Cyg with $M_{\rm wd} = 0.57$ $M_\odot$) with white dwarf masses $M_{\rm wd}$ close to the above values. Our simulations suggestion that these systems, and others like them, erupt as exceptionally slow classical novae, at intervals of order 10^6 yr. Can such objects be found during the accretion, eruption, or remnant shell burning phases?

During the accretion phase (~95% of a system's life) we expect these objects to be indistinguishable from the dwarf nova or novalike variables population from which they are drawn. Only during the eruption or shell-burning episodes might we expect to be able to distinguish these low-mass objects.

An erupting system would appear as an extraordinarily slow nova, ejecting mass at very low velocity for 1–3 centuries. The CNO abundance in the ejecta should be roughly solar, with N and O enhanced and C depleted relative to solar. The long ejection time, and resultant low density of ejecta and long recombination time could lead to nova shells faintly visible for centuries after eruption, rather than decades (as is usually seen). The shell of the oldest recovered nova, CK Vul (Nova 1670; Shara, Moffat, & Webbink 1985) fulfils the above description. The central star, of this old nova, however, is too

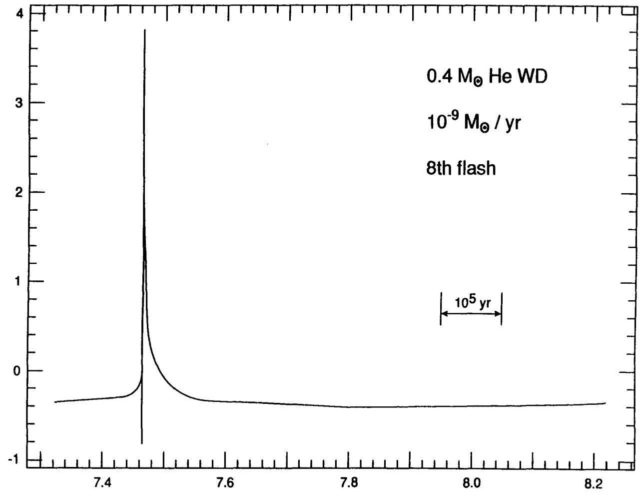

FIG. 6*a*

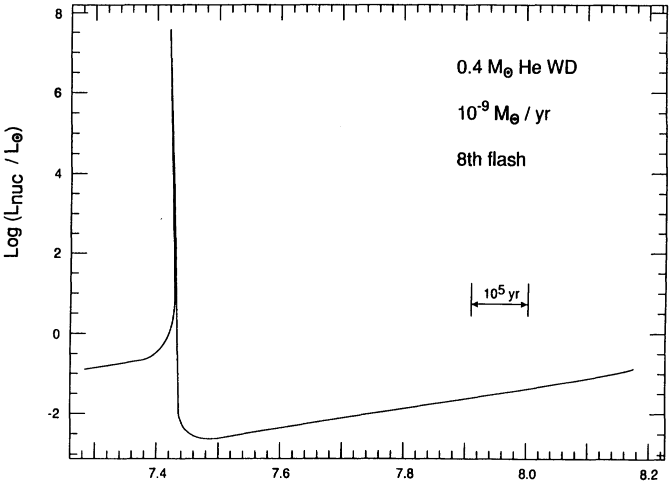

FIG. 6*b*

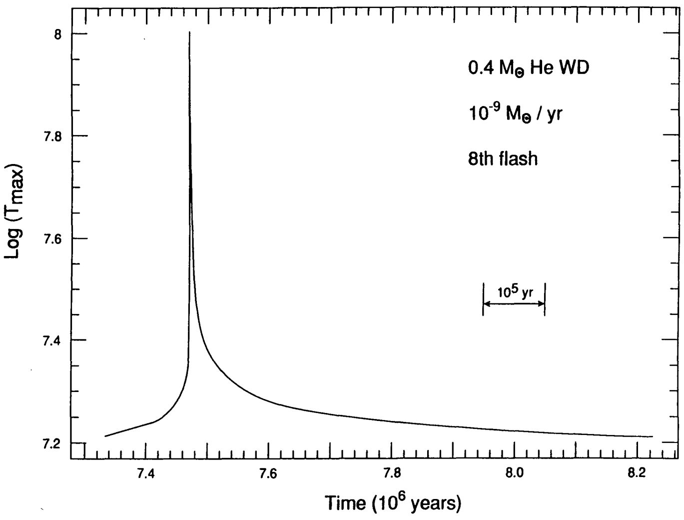

FIG. 6*c*

FIG. 6.—Evolution of the 0.4 $M_\odot$ WD model (accreting hydrogen-rich matter at a rate of 10^{-9} $M_\odot$ yr^{-1}) through one complete cycle of accretion, outburst and decline (the eighth cycle of Fig. 5). (*a*) Bolometric luminosity vs. time. (*b*) Nuclear luminosity vs. time. (*c*) Maximal temperature attained in the burning shell vs. time.

faint to resemble the postoutburst objects considered in this paper.

As there are less than 1000 known Galactic cataclysmic binaries, one expects to have to wait of order 1000 yr before a known system erupts in a manner similar to that detailed here. It is therefore not surprising that a nova, ejecting mass for a century or more, has not yet been seen.

During the 10^3–10^4 yr following the end of mass loss, these stars remain quite luminous ($L > L_\odot$) and extraordinarily hot ($T_{\rm eff} \sim 10^5$ K). A few such objects should now exist (10^3–10^4 yr × 10^3 objects per 10^6 yr) at distances d comparable to those of many of the objects in Ritter's (1989) catalog, i.e., $d \lesssim 1$ kpc. The *ROSAT* WFC and EUVE all-sky EUV surveys will be sensitive to these objects.

The large bolometric corrections (over 5 mag) associated with $T_{\rm eff} \sim 10^5$ K will reduce the distance out to which such objects can be detected in a magnitude-limited, visible band survey. Nevertheless, their extremely blue colors ($U - B \lesssim -1$) may have already lead to (one or more) such objects' detections in the Palomar Green, Kitt Peak Downes, or Montreal Cambridge Tololo surveys, as very hot white dwarfs.

The high effective temperatures and log $g \sim 7.5$–8 of our postejection models place them in the domain of the hottest white dwarfs: the PG 1159, DO, and DAO subclasses (see, e.g., Liebert 1986; Shipman 1989 for reviews). Typical locations of the former two subtypes are plotted in the H-R diagrams of Figures 3 and 7. We are not suggesting that these low mass, very slow novae (after the ejection phase) are the progenitors of most of the very hot white dwarfs. Rather, the high $T_{\rm eff}$ and log g of our postejection novae imply that such objects might masquerade as PG 1159/DAO/DO stars for up to $\sim 10^3$ yr after an eruption. Three simple diagnostics can suggest which hot white dwarfs might be low-mass postnovae.

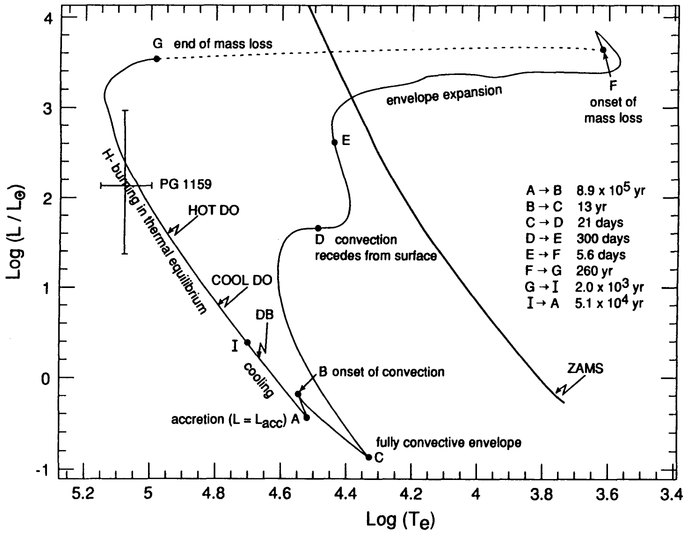

FIG. 7.—A full evolutionary cycle of an accreting 0.4 $M_\odot$ He WD in the $L - T_e$ diagram. Important points are labeled A, B, ..., and the time elapsed between them is noted. The main sequence is labeled ZAMS. The approximate positions of PG 1159, and hot and cool DO stars are indicated.

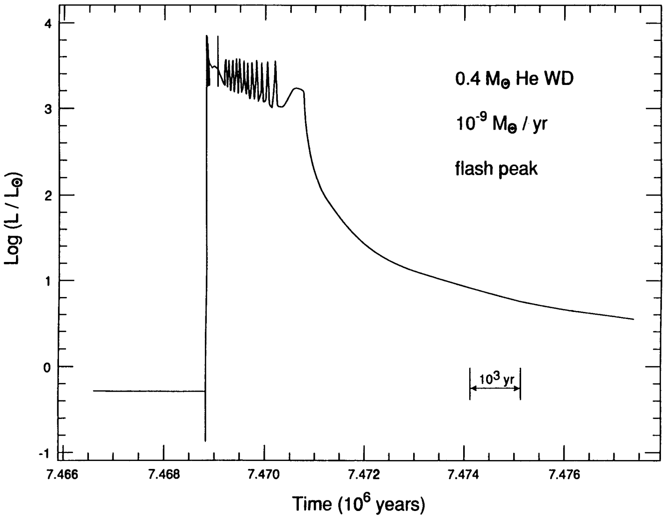

FIG. 8*a*

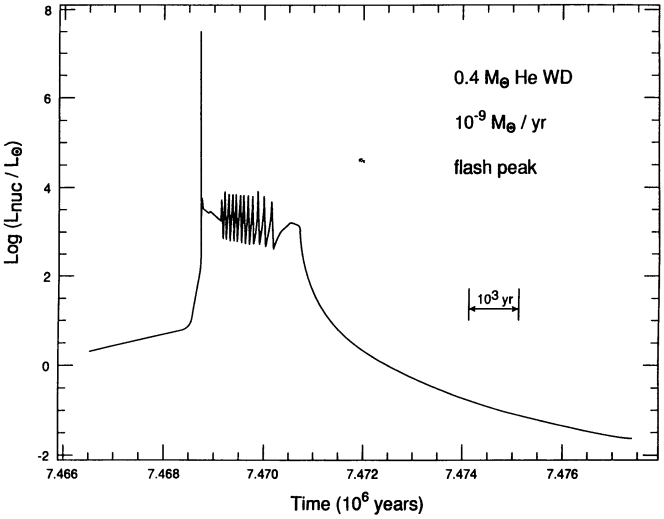

FIG. 8*b*

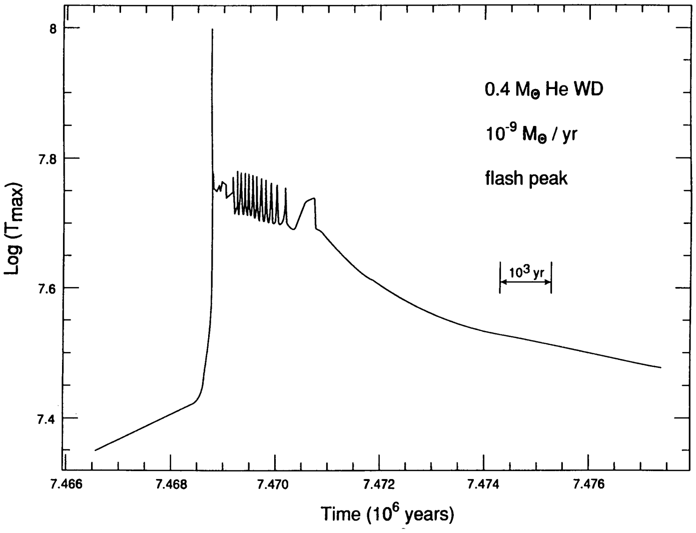

FIG. 8*c*

FIG. 8.—Evolution of the 0.4 $M_\odot$ WD model during the peak of a flash (from point B, through C, D ... to point I in Fig. 7). (*a*) Bolometric luminosity vs. time. (*b*) Nuclear luminosity vs. time. (*c*) Maximal temperature attained in the burning shell vs. time.

1. A hydrogen- and nitrogen-rich shell of $\sim 10^{-3}$ $M_\odot$ could be visible for centuries after the eruption. Carbon should be underabundant and neon roughly solar in the shell.

2. Nitrogen lines (e.g., N V $\lambda\lambda$4640) should be strong in the spectrum of the postnova star. This rules out most PG 1159 stars, whose spectra are dominated by lines of carbon. A notable exception is PG 1144+005. Werner, Heber, & Hunger's (1991) non–LTE analysis of this star suggest a high nitrogen abundance in its photosphere.

3. The low-mass, postnova spectra should show significant radial velocity variations with periods of a few hours, reflecting the orbital period of the underlying binary.

6. CONCLUSIONS

We can briefly summarize our results as follows:

1. We have numerically simulated 10 successive nova eruptions on low-luminosity white dwarfs of 0.6 $M_\odot$ (composed of CO) and 0.4 $M_\odot$ (pure He).

2. Both stars undergo periodic nova eruptions, which, for the CO white dwarf become regular only after ~5 cycles.

3. The outburst (and ejection) phases last several centuries, although they attain luminosities similar to more massive, classical novae.

4. The CO white dwarf ejects the entire accreted mass. The He white dwarf retains some of the accreted matter and grows montonically in mass.

5. After ejecting most of their envelopes, and burning the remnants these stars should resemble nitrogen-rich PG 1159, DAO or DO stars.

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