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FAINT CATACLYSMIC VARIABLES IN QUIESCENCE: GLOBULAR CLUSTER AND FIELD SURVEYS

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ABSTRACT

Current evolutionary models imply that most cataclysmic variables (CVs) have $P_{\rm orb} < 2$ hr and are dwarf nova (DN) systems that are quiescent most of the time. Observations of nearby quiescent DNs find that the UV spectrum is dominated by the hot white dwarf (WD), indicating that it provides a significant fraction of the optical light in addition to the quiescent disk and main-sequence companion. Hence, identifying a faint, quiescent CV in either the field or a globular cluster (GC) from broadband colors depends on our ability to predict the WD contribution in quiescence. We are undertaking a theoretical study of the compressional heating of WDs, extending down to very low time-averaged accretion rates, $\langle \dot{M} \rangle \sim 10^{-11}\ M_\odot\ {\rm yr}^{-1}$, which allows us to self-consistently find the $T_{\rm eff}$ of the WD. We demonstrate here that most of the compressional heating occurs in the freshly accreted envelope and that the WD core temperature reaches a fixed value on a timescale of less than typical evolutionary times. Since nuclear burning is unstable at these $\langle \dot{M} \rangle$'s, we have incorporated the recurrent heating and cooling of the WD core throughout the classical novae limit cycle in order to find the $T_{\rm eff}$-$\langle \dot{M} \rangle$ relations. Comparing with observations of field DNs confirms the $\langle \dot{M} \rangle$-$P_{\rm orb}$ relation of disrupted magnetic braking. We also predict broadband colors of a quiescent CV as a function of $\langle \dot{M} \rangle$ and companion mass and show that this leads to the identification of what may be many CVs in deep *Hubble Space Telescope* images of GCs.

Subject headings: binaries: close — globular clusters: general — novae, cataclysmic variables — white dwarfs

1. INTRODUCTION

Dwarf nova (DN) systems contain a white dwarf (WD) accreting matter at time-averaged rates $\langle \dot{M} \rangle < 10^{-9}\ M_\odot\ {\rm yr}^{-1}$ from a low-mass (<0.5 $M_\odot$ typically) stellar companion (see Osaki 1996 for an overview). At these $\langle \dot{M} \rangle$'s, the accretion disk is subject to a thermal instability that causes it to rapidly transfer matter onto the WD (at $\dot{M} \gg \langle \dot{M} \rangle$) for a few days to a week once every month to year. The orbital periods of these binaries are usually less than 2 hr (below the period gap), but there are also DNs above the period gap (>3 hr; see Shafter 1992). The $\dot{M}$ onto the WD is often low enough between outbursts that the UV emission is dominated by the internal luminosity of the WD. Indeed, recent spectroscopy has resolved the WD's contribution to the quiescent light and found effective temperatures $T_{\rm eff} \sim$ 10,000–40,000 K (see Sion 1999).

The measured internal WD luminosity is larger than expected from an isolated WD of similar age (≈1 Gyr), indicating that it has been heated by accretion (Sion 1985). Compressional heating (i.e., the internal gravitational energy release) appears to be the main driver for this reheating (Sion 1995). Sion's (1995) estimate for the internal gravitational energy release within the WD (of mass M and radius R) was $L \approx 0.15GM\langle \dot{M} \rangle/R$. However, we show in § 2 that the energy release actually depends on the thermal state of the WD interior and that the dominant energy release is in the accreted outer envelope, giving $L \approx 3kT_c\langle \dot{M} \rangle/\mu m_p$, where $\mu \approx 0.6$ is the mean molecular weight of the accreted material, T_c is the WD core temperature, m_p is the baryon mass, and k is Boltzmann's constant.

The theoretical challenge that we address in § 3 is how to calculate T_c as a function of $\langle \dot{M} \rangle$ and thus find $T_{\rm eff}$. Because of unstable nuclear burning and the resulting classical nova cycle, the H/He envelope mass changes with time, allowing the core to cool at low accumulated masses and be heated prior to unstable ignition. We use nova ignition to determine the maximum mass of the overlying freshly accreted shell and find the steady state (i.e., cooling equals heating throughout the classical nova cycle) core temperature, T_c, as a function of $\langle \dot{M} \rangle$ and M.

We compare our calculations to *Hubble Space Telescope* (*HST*)/Space Telescope Imaging Spectrograph (STIS) observations and infer $\langle \dot{M} \rangle$ on the timescale of 10^6 yr. We find that DNs above the period gap have $\langle \dot{M} \rangle \approx 10^{-9}\ M_\odot\ {\rm yr}^{-1}$, while those below have $\langle \dot{M} \rangle \approx 10^{-10}\ M_\odot\ {\rm yr}^{-1}$, consistent with that expected from traditional cataclysmic variable (CV) evolution (e.g., Howell, Nelson, & Rappaport 2001), even those that involve some "hibernation" (Shara et al. 1986; Kolb et al. 2001). The result is more surprising if the much weaker magnetic braking laws of Andronov, Pinsonneault, & Sills (2001) are correct. We also predict the minimum light (M_V) of CVs in quiescence for a range of $\langle \dot{M} \rangle$, WD mass, and companion mass. This assists the search for the predicted large population of CVs with very low mass companions (<0.1 $M_\odot$) that are near, or past, the period minimum (Howell, Rappaport, & Politano 1997). Observations already show that the WD fixes the quiescent colors of these CVs and that our calculations are useful for CV surveys in the field (e.g., the 2 degree Field [2dF] Survey and the Sloan Digital Sky Survey [SDSS]; see Marsh et al. 2001 and Szkody et al. 2002) and globular clusters (GCs).

2. COMPRESSIONAL HEATING: CORE-ENVELOPE CONTRAST

Compressional heating is the energy released by fluid elements as they are compressed by further accretion. The important feature of this heating mechanism is that the heat is released in the WD *interior* and thus is radiated on a timescale that is longer than the time between DN outbursts. Contrast this to the gravitational potential energy released by the infalling matter, (GMm_p/R per baryon) that is deposited at, or near, the photosphere and is rapidly radiated away. Such infall energy does not get taken into the star because in the upper atmosphere (where $T \ll T_c$), the time it takes the fluid to move inward is much longer (by at least T_c/T) than the time it takes for heat to escape. This means infall energy is not important for setting the internal thermal state of the WD; it simply has no influence there. Also, once accretion has diminished for longer than the time to radiate the infall energy away (such as in DN quiescence), it is no longer relevant to the observed luminosity.

An additional energy source in the WD interior is slow nuclear burning near the base of the accreted H/He layer. This is significant when the accreted layer becomes thick, eventually becoming thermally unstable and leading to a classical nova. The nova energy is assumed to be radiated away in the explosion, but we have found that slow burning before that point contributes an amount of energy to the WD interior comparable to the energy released by compression. Our calculations take account of both compressional heating and slow nuclear burning to determine the WD's thermal state.

We now sketch how compressional heating is included in our stellar model, demonstrate that heating in the envelope dominates that in the core, and estimate its magnitude. This is a discussion specific to DNs with low $\langle \dot{M} \rangle$, and the reader should consult Nomoto (1982) for a complete account. The simplest estimate of the compressional energy release is the gravitational energy liberated as a fluid element moves down in the WD gravitational field, $g = GM/R^2$. In the nondegenerate outer atmosphere, a fluid element moves a distance of order the scale height, $h = kT/\mu m_p g$, in the time it takes to replace it by accretion, giving $L \sim \langle \dot{M} \rangle gh \sim \langle \dot{M} \rangle kT/\mu m_p$. This exhibits the correct scaling, notably the dependence on μ that is a contrasting parameter between the accreted H/He envelope and the C/O core.

To calculate the actual heat release, we consider the local heat equation

$$T\frac{ds}{dt} = T\frac{\partial s}{\partial t} + T\boldsymbol{v}\cdot\boldsymbol{\nabla}s = -\frac{\partial L}{\partial M_r} + \epsilon_N, \qquad (1)$$

where ϵ_N is the nuclear-burning rate, s is the entropy, and $\boldsymbol{v} = -\langle \dot{M} \rangle \hat{r}/4\pi r^2 \rho$ is the slow downward advection speed from accretion. The entropy profile is fixed by the temperature gradient needed to carry the luminosity outward, and thus we simultaneously solve equation (1) with the heat transport equation, using opacities and conductivities from Iglesias & Rogers (1996) and Itoh et al. (1983) to find the thermal structure of the accreted envelope and the outer edge of the C/O core. For an analytic understanding, we neglect nuclear burning and $\partial/\partial t$ and use hydrostatic balance to recast equation (1) into

$$L = -\langle \dot{M} \rangle \int_0^P T\frac{\partial s}{\partial P}\, dP. \qquad (2)$$

Entropy decreases inward (i.e., the envelope and core are not convective), so this is an outward L. In the nondegenerate envelope, where $s = k \ln (T^{3/2}/\rho)/\mu m_p$, one more approximation is necessary to obtain an analytic form. For an atmosphere in which L is constant with depth, the envelope satisfies $T^{8.5} \propto P^2$. Although L is not constant here, we use this to get an estimate, integrating down to the isothermal core and finding $L \approx 3kT_c\langle \dot{M} \rangle/\mu m_p$.

Now consider the degenerate C/O core. For the $\langle \dot{M} \rangle$'s and typical $M = 0.6\ M_\odot$ WDs of interest here, the entropy is in the liquid ions at $T_c \approx 10^7$ K. The time it takes to transport heat through the interior is $\sim 10^7$ yr $\ll M/\langle \dot{M} \rangle$, so the core is isothermal, and any compression is far from adiabatic.[1] Due to uncertainty from the classical nova cycle, we do not know whether the C/O core is secularly increasing in mass, but if it were, almost all of the work of compression goes into increasing the electron Fermi energy. The integrated heat release in the core would then be $L \approx 15kT_c\langle \dot{M} \rangle/\mu_i m_p$ (Nomoto 1982) for a 0.6 $M_\odot$ C/O WD, where $\mu_i \approx 14$ is the ion mean molecular weight.

Due to the mean molecular weight contrast between the accreted envelope and the core, the energy release in the core is about a factor of 5 smaller than that in the envelope. Thus, for a given amount of compression of the star, the entropy drop for material in the accreted layer is much larger than for material in the core. *Despite its comparatively small mass, the accreted layer is the main source of compressional heating.*

3. FINDING THE EQUILIBRIUM CORE TEMPERATURE

For this initial study, we dropped the time-dependent term in equation (1) and presumed that the C/O core mass was constant throughout the classical nova cycle, thus only accounting for the compressional heating and ϵ_N in the accreted layer. This method improves on that of Iben et al. (1992) by allowing the accreted envelope mass to change through the 10^5 yr classical nova cycle. Early in the cycle, the mass of the accreted layer is small, compressional heating is small, and the WD cools. Later in the cycle, the accreted layer becomes thick enough that compressional heating, along with slow hydrogen burning, releases a sufficient amount of energy to heat the core. Since the WD has a large heat capacity, reaching the equilibrium T_c where the heat exchanged between the envelope and core averages to zero over a single classical nova cycle takes $\approx 10^8$ yr. Since this time is shorter than the time over which $\langle \dot{M} \rangle$ changes because of the changing orbital period, we construct such equilibrium accretors for a given M and $\langle \dot{M} \rangle$.

To do this construction, we first fix T_c at the outer edge of the C/O core at a pressure high enough so that the changing accumulated mass has little direct effect. With a radiative-zero outer boundary condition, we integrate our structure equations with equation (1) to find the thermal state for an $\langle \dot{M} \rangle$ and accreted layer mass. See Figure 1 for examples of the resulting *T-P* relations. We then evaluate the luminosity across the chosen location (the right edge of the plot in Fig. 1) for different accreted layer masses, up to the unstable ignition that is found by comparing the T and ρ at the base of the accreted layer with analytic ignition curves (Fujimoto 1982).

We vary T_c to find an equilibrium model, where the "core luminosity" ($L_{\rm core}$) averages to zero over the classical nova cycle as shown in Figure 2. The quiescent $T_{\rm eff}$ for the same cycle is also shown in Figure 2. At the nova outburst, we assume that the accreted shell is expelled and that, due to the rapidity of this event, it does not appreciably heat the WD. The resulting equilibrium core temperatures for $\langle \dot{M} \rangle = 10^{-10}\ M_\odot\ {\rm yr}^{-1}$ are $T_c/10^6$ K = 9, 7.5, and 8.5 for $M = 0.4$, 0.6, and 1.0 $M_\odot$. The 0.4 $M_\odot$ star is hotter than the 0.6 $M_\odot$ star because it has a larger maximum accumulated mass that leads to a longer period of core heating. For a 0.6 $M_\odot$ WD, the core temperatures are $T_c/10^6$ K = 4, 5.3, 12.2, and 18.0 for $\langle \dot{M} \rangle/M_\odot\ {\rm yr}^{-1} = 10^{-11}$, 3.2×10^{-11}, 4.2×10^{-10}, and 10^{-9}.

The $T_{\rm eff}$ during the classical nova cycle varies over a relatively

[1] This is in contrast to the rapid accretion rates $\langle \dot{M} \rangle \gg 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ considered for more massive Type Ia progenitors, where the interior undergoes nearly adiabatic compression (see Bravo et al. 1996).

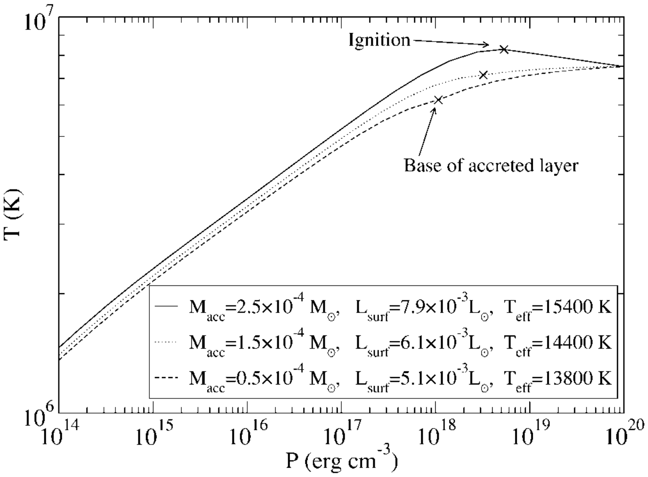

FIG. 1.—H/He envelope and outer core in temperature and pressure for three different values of accumulated mass: $M_{acc}/10^{-4}\ M_\odot = 0.5$, 1.5, and 2.5 for $M = 0.6\ M_\odot$ and $\langle \dot{M} \rangle = 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. The external surface luminosity of the WD and the corresponding T_{eff} are also listed. The part of the star off to the right of the figure ($P > 10^{20}$ ergs cm^{-3}) is the isothermal inner core.

narrow range that allows us to compare with observations. For field CVs, the large set of STIS observations by Szkody et al. (2001) and previous observations (Urban et al. 2000) provide spectra of quiescent WDs in DNs. These measurements are made during deep quiescence when the accretion luminosity is negligible and are long enough after the outbursts that other emission mechanisms (e.g., Pringle's 1988 suggestion of radiative illumination of the WD) have faded. The observed T_{eff}'s thus measure the heat directly from the WD interior. This comparison with observations indicates that below the period gap, $\langle \dot{M} \rangle \approx 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ and the WD masses are in the range of 0.6–1.0 $M_\odot$. This agrees with the expectation from Kolb & Baraffe (1999), who find $\langle \dot{M} \rangle \approx 5 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ at an orbital period of 2 hr, presuming angular momentum losses from gravitational waves alone. Above the period gap, the T_{eff} is higher, and we estimate $\langle \dot{M} \rangle \approx 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$. For a graphical comparison, see Townsley & Bildsten (2001). This general agreement with data from field WDs in which the internal luminosity is directly visible gives us confidence that our calculations can be applied to other quiescent DN systems.

We predict that a 0.6 $M_\odot$ WD above the gap has $T_c = 1.8 \times 10^7$ K, and if in equilibrium below the gap, it has $T_c = 7.5 \times 10^6$ K. However, if the WD does not have time to cool as it traverses the gap, it will be hotter than our calculation implies. We estimate this cooling time from the current WD cooling law (e.g., Chabrier et al. 2000), $L_{cool} \approx 10^{-2}\ L_\odot \times (T_c/1.8 \times 10^7\ \mathrm{K})^{2.5}$, along with the heat capacity of the core, $M3k_B/\mu_i m_p$, giving $\Delta t \approx 0.5$ Gyr. Since this is comparable to the estimated time spent in the gap (Howell et al. 2001), our equilibrium assumption below the gap is likely safe. However, note that about 0.2 Gyr after accretion halts, the WD will enter the ZZ Ceti instability strip!

4. APPLICATION TO GLOBULAR CLUSTER POPULATIONS

Due to the high frequency of stellar interactions in GCs, an abundant population of CVs is expected to be found there, especially at low $\langle \dot{M} \rangle$. CVs in GCs are commonly searched for via the presence of hydrogen emission lines or X-ray emission (as recent *Chandra* observations have found; Grindlay et al. 2001a, 2001b), and this method is fruitful. We show that these systems (as well as CVs crossing the period gap or those "hibernating" postnovae; Shara et al. 1986) can also be identified by their position in a color-magnitude diagram (CMD). By using our theory of the thermal state of the WD, it is possible to predict the broadband colors of quiescent CVs.

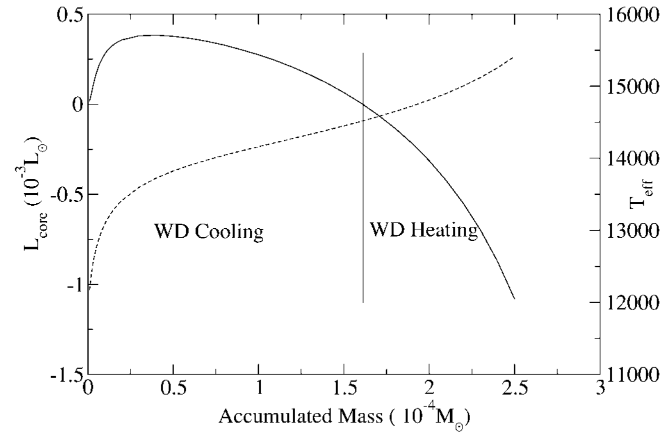

FIG. 2.—Luminosity at the outer edge of the core (*solid line*) and surface effective temperature of the WD (*dashed line*), both as a function of accumulated mass up to the classical nova ignition for the equilibrium model of Fig. 1, $M = 0.6\ M_\odot$ and $\langle \dot{M} \rangle = 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. The positive luminosity is outgoing, and the epochs of core cooling and heating are indicated.

An excellent example is NGC 6397 (King et al. 1998; Taylor et al. 2001). Figure 3 shows a CMD of NGC 6397 with our initial results. The data points are objects that meet the proper-motion criteria for cluster membership and are below the main sequence (MS). The lines were produced by superposing a WD with the maximum T_{eff} for the indicated $\langle \dot{M} \rangle$ with an MS star. Due to uncertainty in the theory of quiescent disks (Menou 2000), no disk contribution has been added. Note, however, that a constant $T \sim 5000$ K disk like those indicated in eclipse

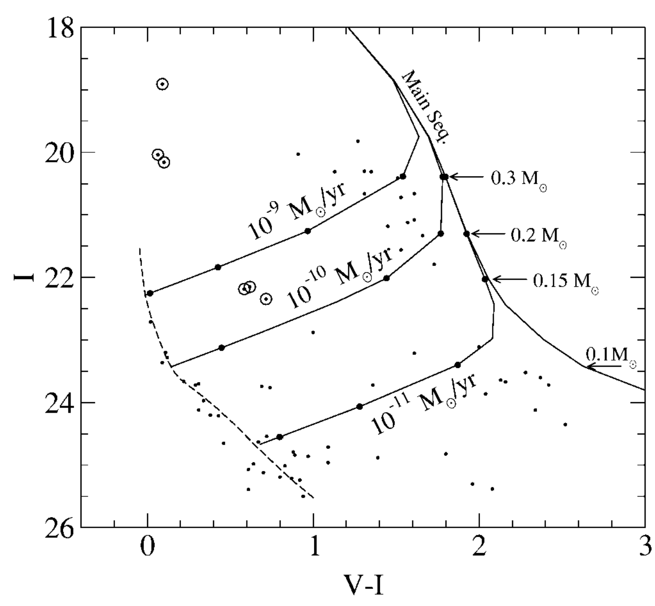

FIG. 3.—CMD of NGC 6397. The filled circles are plausible cluster members that are below the MS (*HST* observations by King et al. 1998), and the encircled points are the nonflickerers from Taylor et al. (2001). The MS line is from Baraffe et al. (1997) for the cluster [M/H] of −1.5 and an age of 10 Gyr. The dashed line is from Bergeron, Wesemael, & Beuchamp (1995) for DA WDs with $\log g = 8$. The lines connecting the MS to the WD sequence are our current calculations of the WD + MS binary at the specified $\langle \dot{M} \rangle$. The highest T_{eff} during the classical nova cycle has been used for the WD in each case (see Fig. 2). No disk has been included. All curves have been put at the distance and reddening of the cluster, $(m-M)_I = 12.05$ and $E(V-I) = 0.288$.

maps (Wood & Crawford 1986) would have a $V-I$ color of 1.24, including the cluster reddening. Except for near the WD cooling line (Fig. 3, *dashed curve*), where the WD dominates, the I magnitude is set by the MS companion. The large filled circles along the 10^{-9} and 10^{-10} $M_\odot$ yr^{-1} lines indicate where the MS companion is 0.3, 0.2, 0.15, and 0.1 $M_\odot$, and two additional points at 0.09 and 0.085 $M_\odot$ are indicated on the 10^{-11} $M_\odot$ yr^{-1} line. This immediately provides a number of candidate systems (namely, data in this part of the CMD).

The encircled points are the "nonflickerers" (Cool et al. 1998) recently reported by Taylor et al. (2001). The three at $I \approx 22.25$ are very strong Hα absorbers (consistent with a DA WD) and were not detected by *Chandra* (Grindlay et al. 2001b). These authors had discussed these systems as possible helium WDs with millisecond pulsar companions, although, given our work, we would claim that these are hot WDs with $\approx$0.15 $M_\odot$ MS companions. In addition, the population of data points in this diagram with respect to our theoretical curves will eventually constrain CV evolutionary scenarios. If we assume that many of the data points are CVs, we already see that most systems with high $\langle \dot{M} \rangle$ have 0.15–0.3 $M_\odot$ companions. If confirmed as members of the cluster, the stars below the $\langle \dot{M} \rangle = 10^{-11}$ $M_\odot$ yr^{-1} line could well be the long-sought post-turnaround systems with $\langle \dot{M} \rangle = 10^{-12}$ $M_\odot$ yr^{-1} and companion masses of less than 0.09 $M_\odot$ (Howell et al. 1997).

5. CONCLUSIONS AND DISCUSSION

We have evaluated the action of compressional heating on accreting WD interiors and have shown that most of the compressional energy release takes place in the accreted envelope and is thermally communicated to the core. The maximum envelope mass is set by the unstable nuclear burning that causes a classical nova runaway and most likely expels the accreted mass. We have constructed equilibrium accretors that have constant core temperatures such that the heat lost from the core when the envelope is thin (i.e., right after the classical nova) is balanced by that regained when the envelope is thick. This equilibrium determines the $T_{\rm eff}$ of the WD throughout the classical nova cycle. Our models agree with the observations of DNs in deep quiescence and imply $\langle \dot{M} \rangle \approx 10^{-10}$ $M_\odot$ yr^{-1} just below the period gap and $\langle \dot{M} \rangle \approx 10^{-9}$ $M_\odot$ yr^{-1} just above the period gap for WD masses in the range of 0.6–1.0 $M_\odot$.

Our $T_{\rm eff}$ calculations provide a prediction of the colors of quiescent DNs. Using MS stellar models, we have predicted where a DN should appear in a CMD as a function of $\langle \dot{M} \rangle$ and the mass of its companion. Many unidentified objects appear in the relevant regions of the detailed CMDs that have been obtained for GCs by the *HST*. The number of such systems in the field will increase due to upcoming surveys (such as the SDSS and the 2dF Survey; see Marsh et al. 2001) and will push to lower $\langle \dot{M} \rangle$ systems.

Although our initial efforts have met with apparent success, there is still much to be done. We need to vary the metallicity of the accreted material, lowering to values appropriate for GC science. This could change our results at large $\langle \dot{M} \rangle$, but at low $\langle \dot{M} \rangle$, the ignition mass is set by *p-p* burning and will likely not change too much. We also need to relax our initial assumptions, e.g., by including WD excavation or accretion and accounting for the thermal evolution of the WD.

The internal thermal state of the WD has been a long-standing uncertainty in classical nova work, as has the question of how much mass is ejected in the explosion (Gehrz et al. 1998). Our work provides the first calculation of the internal thermal state of a WD undergoing a classical nova cycle and will eventually lead to self-consistent calculations for ignition masses, including variations of the metallicity. This will be an improvement on previous work (e.g., Prialnik & Kovetz 1995) that treated T_c and $\langle \dot{M} \rangle$ as two independent parameters.

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