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Deposited 08/23/2018

Citation of published version:

Townsley, D., Bildsten, L. (2002): Compressional Heating of Accreting White Dwarfs in CVs. *ASP Conference Series*, vol. 261. <http://adsabs.harvard.edu/abs/2002ASPC..261...31T>

Compressional heating of accreting white dwarfs in CVs

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Abstract. In recent years several Dwarf Novae (DN) systems have been observed in quiescence, when the accretion rate is low and the WD photosphere can be directly detected. The WDs are observed to cool after the DN outburst from high effective temperatures to lower effective temperatures (T_{eff}) thought to be indicative of the thermal state of the deep interior of the WD. Sion has argued that the most likely energy source for this quiescent luminosity is the gravitational compression of the WD interior, which rejuvenates an otherwise cold WD into a much hotter state. We are undertaking a theoretical study of the compressional heating of WD's, extending down to the very low time averaged accretion rates, $\langle \dot{M} \rangle \sim 10^{-11} M_{\odot} \text{ yr}^{-1}$, applicable to the post-turnaround CV's (the "TOADS"). Nuclear burning is unstable at these $\langle \dot{M} \rangle$'s, so we have incorporated the recurrent heating and cooling of the WD throughout the classical novae limit cycle. In addition to self-consistently finding the range of T_{eff} as a function of $\langle \dot{M} \rangle$ during the cycle, we also self-consistently find the ignition masses. Comparing these theoretical masses to the observed ejected masses will tell us whether the WD mass in CV's is secularly increasing or decreasing. We close by comparing our results to the accumulated observations of quiescent DN and making predictions for the colors of low $\langle \dot{M} \rangle$ CV's in quiescence that are applicable to searches for faint CVs in the field and galactic globular clusters.

1. Introduction

Dwarf Novae (DN) systems contain a white dwarf (WD) accreting matter at time-averaged rates $\langle \dot{M} \rangle < 10^{-9} M_{\odot} \text{ yr}^{-1}$ from a low-mass ($< 0.5 M_{\odot}$ typically) stellar companion. At these $\langle \dot{M} \rangle$'s, the accretion disk is subject to a thermal instability which 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 hours (below the period gap), but there are also DN above the period gap, > 3 hours (see Shafter 1992). The \dot{M} onto the WD can be low enough between outbursts that the optical/UV emission is dominated

by the internal luminosity of the WD, not the accretion disk. Recent *HST*/STIS spectroscopy has spectrally resolved the WD's contribution to the quiescent light and found effective temperatures $T_{\text{eff}} \sim 10\,000 - 40\,000$ K (see our Fig. 4 and Sion 1999).

The measured internal WD luminosity is larger than expected from an isolated WD of similar age (\approx Gyr), indicating that it has been heated by accretion (Sion 1985). Compressional heating (i.e. internal gravitational energy release) appears to be the main driver for this re-heating (Sion 1995). Sion's (1995) early estimate for 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 Sect. 2 that most energy is released 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, m_p is the baryon mass, and k is Boltzmann's constant. The theoretical challenge that we address in Sect. 3 is how to calculate the WD core temperature, T_c , as a function of $\langle\dot{M}\rangle$, and thus find T_{eff} . Because of the unstable nuclear burning and resulting classical novae cycle, the envelope mass changes with time. This allows 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 novae cycle) deep interior temperature of the accreting WD, T_c , as a function of $\langle\dot{M}\rangle$ and WD mass.

In Sect. 4, we compare our theoretical work to STIS observations and infer $\langle\dot{M}\rangle$ on the timescale of 10^6 years, critical to constraining CV evolutionary models. Figure 4 shows that DN above the period gap are hotter than those below the gap, and have $\langle\dot{M}\rangle$'s consistent with that expected from traditional 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 et. al. (2001) are correct. We also predict the minimum light (M_V) of $\langle\dot{M}\rangle < 10^{-10} M_{\odot} \text{ yr}^{-1}$ CVs in quiescence, allowing for discovery of the predicted large population of CVs with very low mass companions ($< 0.1 M_{\odot}$) that are near the period minimum (Howell, Rappaport, & Politano 1997). Observations already show that the WD fixes the quiescent colors of these CVs and our calculations are useful for surveys in the field that were discussed at this meeting (e.g. 2dF, SDSS, see in this volume Marsh et al., p. 200 and Szkody et al., p. 21 contributions here), as well as *HST* CV searches in globular clusters.

2. The basic physics of compressional heating

It is important to make clear what is meant by internal gravitational energy release or compressional heating *within the white dwarf*. Most are familiar with the energy released (GMm_p/R) when a baryon falls from a large distance to the stellar surface. This energy is deposited at, or near, the photosphere and is rapidly radiated away. This energy does not get taken into the star, as in the upper atmosphere (where $T \ll T_c$) the time it takes the fluid to move inward is always much longer (by a factor of at least T_c/T) than the time it takes for heat to escape. Thus, once accretion has shut off, or diminished (such as in DN quiescence), this energy release is no longer relevant. What is relevant is energy

release deep in the WD due to compression by the freshly accreted material and hydrostatic nuclear burning. That energy takes a long time to exit, will still be visible when accretion has halted, and sets T_{eff} in quiescence.

Let's start with the simplest view of compressional heating. In the non-degenerate outer atmosphere, the fluid is slowly falling down in the WD gravitational field, $g = GM/R^2$. A fluid element falls 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 scaling that appears in the formal viewpoint, which is to consider the heat equation

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

where ϵ_N is the nuclear burning rate, s is the entropy, and $\vec{v} = -\langle \dot{M} \rangle \hat{r}/4\pi r^2 \rho$ is the slow downward advection speed from accretion. In pressure units, and neglecting nuclear burning and the time-dependent piece, this becomes

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

The entropy decreases inward (i.e. the envelope and core are not convective), so this is an outward going L . The entropy profile is fixed by the temperature gradient needed to carry the luminosity outward and thus we simultaneously solve equation (2) (putting back in ϵ_N) with the heat transport equation, using opacities and conductivities from Iglesias & Rogers (1996) and Itoh et al. (1983). For an analytic understanding, we integrate through the non-degenerate envelope, where $s = k \ln(T^{3/2}/\rho)/\mu m_p$. Here, L is nearly constant, giving $T^{8.5} \propto P^2$. Integrating down to the isothermal core yields $L \approx 3kT_c \langle \dot{M} \rangle / \mu m_p$.

Now, let's turn to the degenerate carbon/oxygen core. For the $\langle \dot{M} \rangle$'s and typical $M = 0.6 M_\odot$ WD of interest here, all of 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 novae cycle, we don't 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 would only 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. Because of the mean molecular weight contrast, this is about a factor of five smaller than that released in the envelope. Thus, the entropy drop through the accreted layer is larger than that across the core, making the accreted layer the main source of compressional heating.

3. Finding the equilibrium core temperature

For our initial study, we dropped the time-dependent term in equation (1), and presumed that the C/O WD mass was constant throughout the classical nova

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

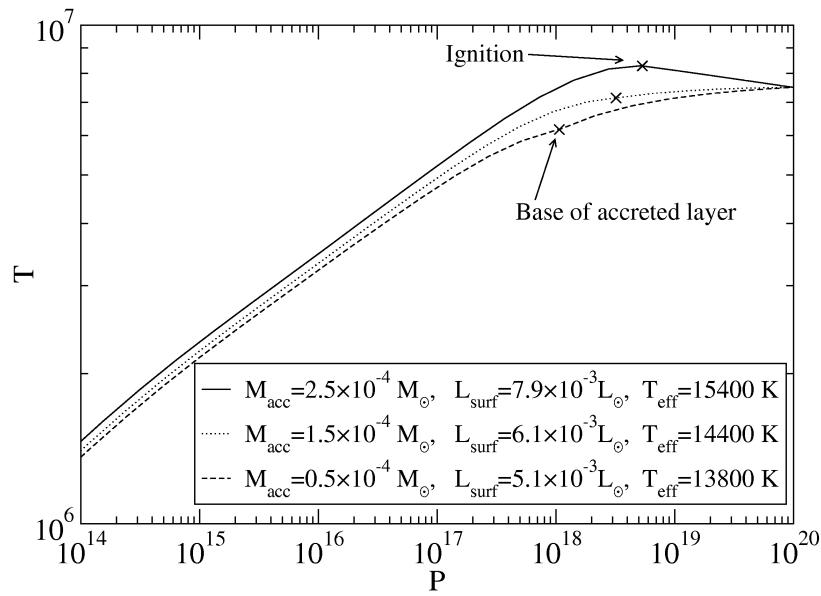


Figure 1. The hydrogen/helium envelope and outer core in temperature and pressure for three different values of accumulated mass, $M_{\text{acc}} = 0.5 \times 10^{-4} M_{\odot}$, $1.5 \times 10^{-4} M_{\odot}$ and $2.5 \times 10^{-4} M_{\odot}$ for $M = 0.6 M_{\odot}$ and $\langle \dot{M} \rangle = 10^{-10} M_{\odot}/\text{yr}$. The external surface luminosity of the WD and the corresponding T_{eff} is also listed. The part of the star off to the right of the figure ($P > 10^{20}$ dyne cm $^{-2}$) is the isothermal inner core.

cycle, thus only accounting for the compressional heating and ϵ_N in the H/He layer. This method improves on that of Iben et al. (1992) by allowing the accreted envelope mass to change through the 10^5 year 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. As 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 $\approx 10^8$ years. Since this time is usually shorter than the time over which $\langle \dot{M} \rangle$ changes, we construct such equilibrium accretors for a given M and $\langle \dot{M} \rangle$.

To do this, 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 outer boundary condition, we then integrate our structure equations with equation (1) to find the envelope state for an $\langle \dot{M} \rangle$ and accreted layer mass. See Fig. 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 a number of different accreted layer masses up to the unstable ignition. The ignition mass is found by comparing the T and ρ at the base of the accreted (hydrogen rich) layer with the analytic ignition curves in Fujimoto (1982).

We vary T_c to find an equilibrium model, where the “core luminosity” (L_{core}) averages to zero over the classical nova cycle as shown in Fig. 2. The quiescent T_{eff} which is expected for the same cycle is shown in Figure 3. At the nova out-

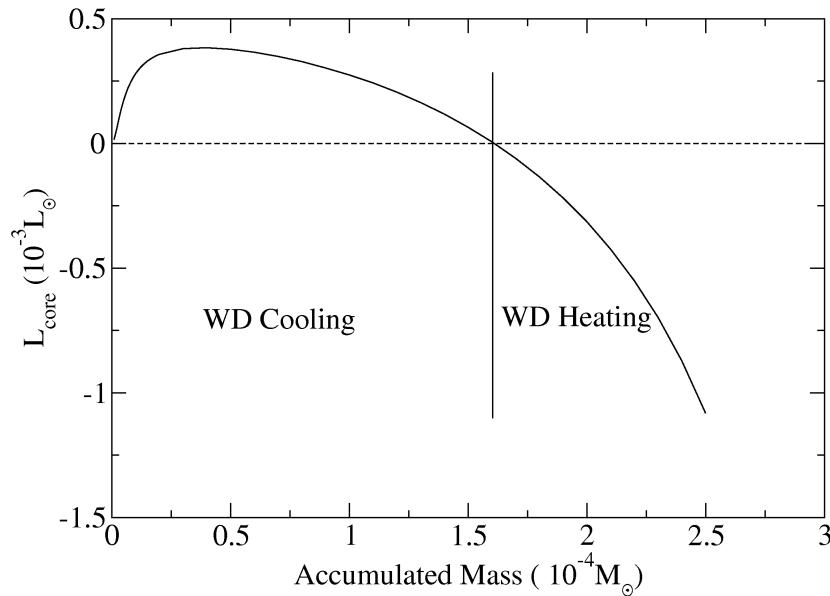


Figure 2. Luminosity at the outer edge of the core as a function of accumulated mass up to the classical nova ignition for the equilibrium model of Fig. 1. Positive is outgoing and epochs of core cooling and heating are indicated.

burst 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 $\langle \dot{M} \rangle = 10^{-10} M_{\odot}/\text{yr}$ are $T_c = 9 \times 10^6 \text{ K}, 7.5 \times 10^6 \text{ K}$ and $8.5 \times 10^6 \text{ K}$ for $M = 0.4, 0.6$ and $1.0 M_{\odot}$. The $M = 0.4 M_{\odot}$ star is hotter than the $M = 0.6 M_{\odot}$ 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 $T_c/10^6 \text{ K} = 4, 5.3, 12.2$ and 18.0 for $\langle \dot{M} \rangle / M_{\odot} \text{ yr}^{-1} = 10^{-11}, 3.2 \times 10^{-11}, 4.2 \times 10^{-10}$ and 10^{-9} . This also gives us the T_{eff} range during the classical nova cycle, which we now compare to observations.

4. Comparison with observations

In contrast to Sion's (1995) simulations which only directly addressed the immediate cooling after outburst, our work has focused on the release of heat from the deep interior. The long-timescale nature of heating in these deep layers allows a comparison between our results and the observed T_{eff} 's. For CVs in the field, the large set of STIS observations by Szkody et al. (2001) and previous observations (Urban et al. 2000) provide detailed spectra of quiescent WDs in DN. Fig. 4 shows the current T_{eff} measurements and compares them to our results. The measurements are made during deep quiescence when the accretion luminosity is negligible and are intended to be long enough after the outbursts that other emission mechanisms (e.g. Pringle's (1988) suggestion of radiative illumination of the WD) have faded. In that case, we are observing heat directly from the deep WD interior. The number of such systems will increase due to upcoming

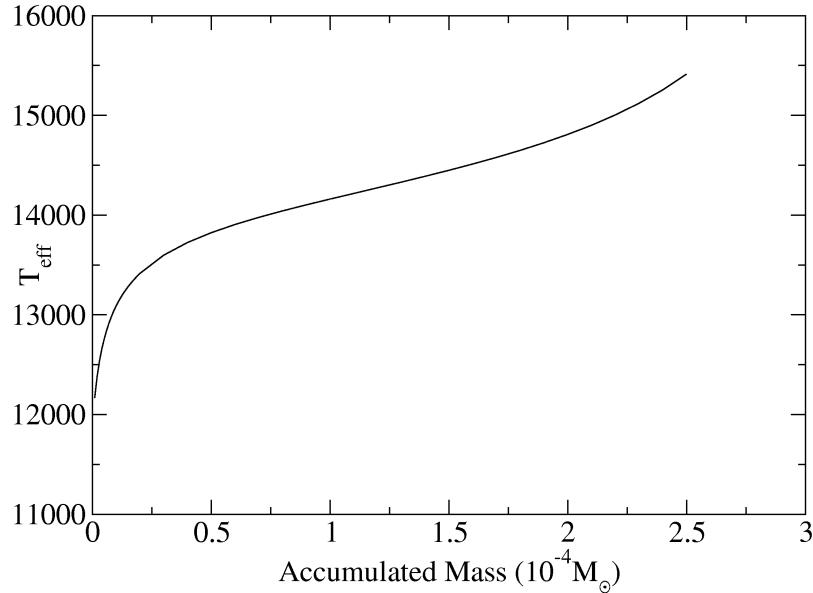


Figure 3. Effective temperature of the WD as a function of accumulated mass for equilibrium model of Fig. 1.

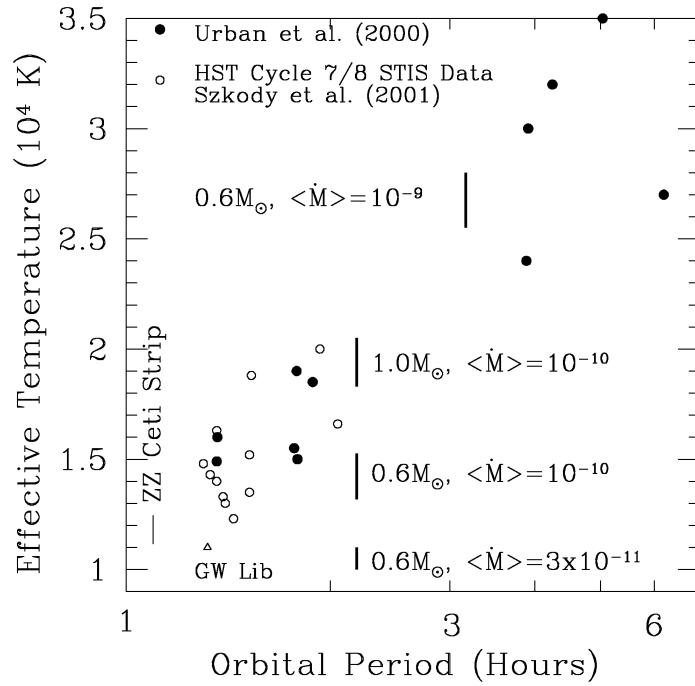


Figure 4. The quiescent WD T_{eff} 's in DN as a function of binary orbital period. The open circles are Cycle 7/8 STIS observations from Szkody et. al. (priv. commun.), while the solid circles are from the compilation of Urban et al. (2000). The single point for GW Lib is from Szkody, Desai, & Hoard (2000), which is cold enough ($T_{\text{eff}} \approx 11000$ K; Van Zyl 1998) to be a ZZ Ceti pulsator in quiescence. The thick vertical lines are our current predictions for the T_{eff} range for the stated masses and $\langle \dot{M} \rangle$'s. The thin solid line is the ZZ Ceti instability strip (Bergeron, Wesemael, & Beauchamp 1995).

all-sky surveys (such as SDSS and 2dF, see Marsh et al. 2001), and will push to lower $\langle \dot{M} \rangle$ systems with long quiescent intervals.

We can already give some general insight from the initial results shown. Our work indicates that below the period gap, $\langle \dot{M} \rangle \approx 10^{-10} M_{\odot} \text{ yr}^{-1}$ and the WD masses are in the range $0.6 - 1.0 M_{\odot}$. This agrees with the expectation from Kolb & Baraffe (1999), who find $\langle \dot{M} \rangle \approx 5 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$ at an orbital period of 2 hours presuming angular momentum losses from gravitational waves alone. Above the period gap, the T_{eff} is higher, and we estimate $\langle \dot{M} \rangle \approx 10^{-9} M_{\odot} \text{ yr}^{-1}$.

We predict that a $0.6 M_{\odot}$ WD above the gap has a core temperature of $1.8 \times 10^7 \text{ K}$ and, if in equilibrium below the gap, $T_c = 7.5 \times 10^6 \text{ K}$. An interesting question is whether the WD will have time to cool this much as it traverses the gap. If not, then the WD's below the period gap will be hotter than our calculation implies. We estimate this cooling time from the current WD cooling law (e.g. Chabrier et al. 2000) along with the heat capacity of the core,

$$L_{\text{cool}} \approx 10^{-2} L_{\odot} \left(\frac{T_c}{1.8 \times 10^7 \text{ K}} \right)^{2.5} = -\frac{d}{dt} \left[\frac{3k_B T}{\mu_i m_p} M \right], \quad (3)$$

which gives $\Delta t \approx 0.5 \text{ Gyr}$. 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 Gyrs after accretion halts, the WD will enter the ZZ Ceti instability strip!

These results also have bearing on the search for faint CVs in globular clusters. The expected population might well contain many low $\langle \dot{M} \rangle$ systems that spend much of their time in quiescence. These CVs 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, Grindlay et al. 2001b), and this method is fruitful. However, for the very-low $\langle \dot{M} \rangle$ systems, the disks can be very dim and the quiescent X-ray emission too faint even for *Chandra*. We now show that these systems (as well as CVs crossing the period gap or those “hibernating” post-novae, Shara et al. 1986) can 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 CV systems without dependence on the disk luminosity.

An excellent example is NGC 6397 (King et al. 1998; Taylor et al. 2001). Fig. 5 shows a CMD of NGC 6397 with our initial results that provide a relationship between T_{eff} and $\langle \dot{M} \rangle$. The lines were produced by superposing a WD with the maximum T_{eff} for the indicated $\langle \dot{M} \rangle$ with a MS star. Except for near the WD cooling line (dashed curve), where the WD becomes completely dominant, the I magnitude is set by the MS companion. The large dots along the $10^{-9} M_{\odot} \text{ yr}^{-1}$ and $10^{-10} M_{\odot} \text{ yr}^{-1}$ 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 $10^{-11} M_{\odot} \text{ yr}^{-1}$ line. This immediately provides a number of candidate systems (namely, those data residing in this part of the CMD).

The circled points are the “non-flickerers” (Cool et. al. 1998) recently reported by Taylor et al. (2001). The three at $I \approx 22.25$ are very strong H α 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

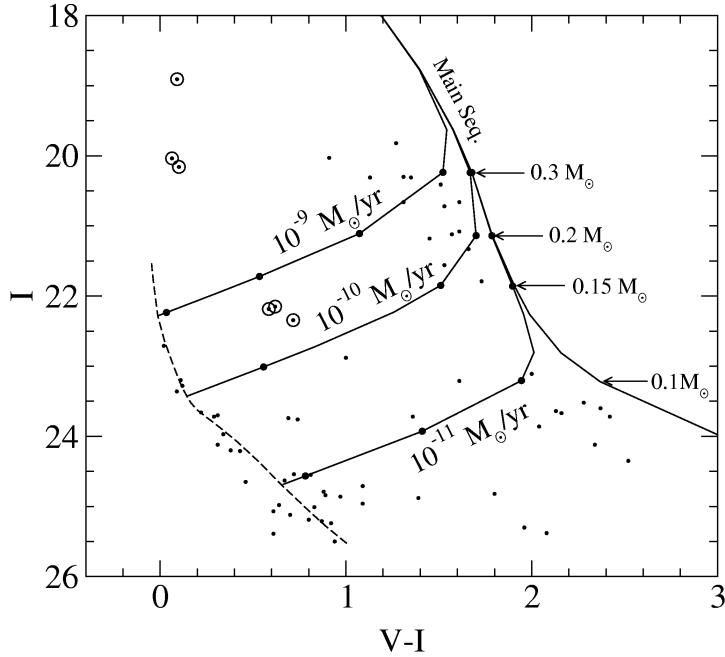


Figure 5. Color-Magnitude Diagram of NGC 6397. The dots are members of the cluster that are below the MS (*HST* observations by King et al. 1998) and the \odot 's are the “Non-Flickerers” from Taylor et al. (2001). The MS line is from Baraffe et al. (1997) for $[M/H] = -2.0$ and an age of 10 Gyr (actual cluster $[M/H] = -1.95$). The dashed line is from Bergeron et al. (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. 3). No disk has been included, which is a safe guess for the low $\langle \dot{M} \rangle$ systems. All curves have been put at the distance and reddening of the cluster, $(m - M)_I = 12.05$ and $E(V - I) = 0.288$.

WDs with millisecond pulsar companions, though, 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 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. The large number of data points below the $\langle \dot{M} \rangle = 10^{-11} M_{\odot} \text{ yr}^{-1}$ line could well be the long-sought post-turnaround systems with $\langle \dot{M} \rangle = 10^{-12} M_{\odot} \text{ yr}^{-1}$ and companion masses $< 0.09 M_{\odot}$ (Howell et al. 1997).

5. Conclusion and future directions

We have evaluated the action of compressional heating of accreting WD interiors. 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 which 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_{eff} of the WD throughout the classical nova cycle. Our models agree with the observations of Dwarf Novae in deep quiescence and imply $\langle \dot{M} \rangle \approx 10^{-10} M_{\odot} \text{ yr}^{-1}$ just below the period gap and $\langle \dot{M} \rangle \approx 10^{-9} M_{\odot} \text{ yr}^{-1}$ just above the period gap for WD masses in the range $0.6\text{--}1.0 M_{\odot}$.

Though our initial efforts have met with apparent success, there is still much to be done. First we need to investigate the relevant parameter ranges (e.g. M and $\langle \dot{M} \rangle$) within our initial scheme. The most critical parameter to vary is the metallicity of the accreted material, lowering to values relevant for globular cluster science. We must also survey our initial assumptions:

- WD excavation or accretion. The assumption that there was no net mass loss or gained by the WD through the classical nova cycle must be relaxed. This will allow for cooling of the WD due to adiabatic expansion after mass loss, or heating if it is increasing in mass. The large C/O fractions seen in some novae ejecta (Gehrz et al. 1998) might indicate that the WD is decreasing in mass at $\langle \dot{M} \rangle$.
- A self consistent accounting for the ignition masses, including varying the metallicity. Our initial work used Fujimoto's (1982) results for simplicity, but these are limited at low $\langle \dot{M} \rangle$'s. A careful comparison to more modern nova calculations (e.g. Prialnik & Kovetz 1995) must be carried out.
- Thermal evolution of the WD. We also need to concern ourselves with the secular change of $\langle \dot{M} \rangle$ due to the decreasing companion mass or changing angular momentum losses (such as a drop in magnetic braking at the period gap). When this occurs on a timescale comparable to the WD thermal time, it is possible that the WD will not reach the steady-state solution we have assumed. This memory of previous higher $\langle \dot{M} \rangle$ epochs could well allow the WD to be hotter than the equilibrium accretor.

While these steps are unlikely to change our understanding of the compressional heating mechanism, each is essential for applying our work to the observations. As assumptions are relaxed and investigated, much more will be learned about both the state of CV systems and their evolution.

Acknowledgments We thank Paula Szkody for sharing the most recent *HST* observations. This research was supported by NASA via grant NAG 5-8658 and by the NSF under Grants PHY99-07949 and AY97-31632. L. B. is a Cottrell Scholar of the Research Corporation.

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