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MEASURING WHITE DWARF ACCRETION RATES VIA THEIR EFFECTIVE TEMPERATURES

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ABSTRACT

Our previous theoretical study of the impact of an accreting envelope on the thermal state of an underlying white dwarf (WD) has yielded equilibrium core temperatures, classical nova ignition masses, and thermal luminosities for WDs accreting at time-averaged rates of $\langle\dot{M}\rangle = 10^{-11}$ to $10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. These $\langle\dot{M}\rangle$ values are appropriate to WDs in cataclysmic variables (CVs) of $P_{\mathrm{orb}} \lesssim 7$ hr, many of which accrete sporadically as dwarf novae. Approximately 30 nonmagnetic dwarf novae have been observed in quiescence, when the accretion rate is low enough for spectral detection of the WD photosphere and a measurement of T_{eff}. We use our theoretical work to translate the measured T_{eff} values into local time-averaged accretion rates, confirming the factor of 10 drop in $\langle\dot{M}\rangle$ predicted for CVs as they transit the period gap. For dwarf novae below the period gap, we show that if $\langle\dot{M}\rangle$ is that given by gravitational radiation losses alone, then the WD masses are greater than $0.8\ M_\odot$. An alternative conclusion is that the masses are closer to $0.6\ M_\odot$ and $\langle\dot{M}\rangle$ is 3–4 times larger than that expected from gravitational radiation losses. In either case, it is very plausible that a subset of CVs with $P_{\mathrm{orb}} < 2$ hr will have T_{eff} values low enough for them to become nonradial pulsators, as discovered by van Zyl and collaborators for GW Lib.

Subject headings: binaries: close — novae, cataclysmic variables — stars: dwarf novae — white dwarfs

1. INTRODUCTION

Cataclysmic variables (CVs; Warner 1995) are formed when the low-mass stellar companion of a white dwarf (WD), exposed during a common envelope event, finally (on timescales of 0.1–10 Gyr) fills the Roche lobe as a result of long-term angular momentum losses. The WD will cool during this time; a $0.20\ M_\odot$ He WD would have core temperature $T_c = 3.3 \times 10^6$ K at 4 Gyr (Althaus & Benvenuto 1997), whereas a $0.6\ M_\odot$ C/O WD would have $T_c = 2.5 \times 10^6$ K in 4 Gyr (Salaris et al. 2000). These WDs have effective temperatures $T_{\mathrm{eff}} \approx 4500$–$5000$ K just before mass transfer starts. However, once the Roche lobe is filled, the WD accretes material at $\langle\dot{M}\rangle \approx 10^{-11}$ to $10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ (e.g., Howell, Nelson, & Rappaport 2001) and can be reheated (Sion 1991) to higher T_{eff} values.

Dwarf novae (DNs) are the subset of CVs with low time-averaged rates $\langle\dot{M}\rangle < 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$ and thermally unstable accretion disks. The transfer of matter onto the WD occurs in outbursts that last a few days to a week once every month to year (or even longer in some systems). Most DNs have orbital periods $P_{\mathrm{orb}} < 2$ hr, below the "period gap," with fewer above the gap (see Shafter 1992). During accretion disk quiescence, the $\dot{M}$ onto the WD is often low enough that the system's UV (and sometimes optical) emission is dominated by light from the WD surface, allowing for a measurement of the WD T_{eff}, nearly all of which exceed 10,000 K (Sion 1999). Thus, the WD is hotter than expected for its age, providing evidence of the thermal impact of prolonged accretion on the WD (Sion 1995). Townsley & Bildsten (2003, hereafter TB) have calculated T_{eff} and its dependence on $\langle\dot{M}\rangle$, the WD mass, M, and core temperature, T_c. In this Letter we now use that work to constrain these parameters from the measured T_{eff} values.

The gravitational energy released when a particle falls from a large distance to the stellar surface (GM/R) is deposited near the photosphere and is rapidly radiated away. This energy does not penetrate inward with the inflowing material, as the time it takes the fluid to move inward is much longer than the time it takes for heat to escape. This eliminates the outer boundary condition and instead points to the importance of energy release deep in the accreting H/He envelope due to both gravitational energy release and a low level of nuclear "simmering" (TB). We begin in § 2 by reviewing our work and showing that the best-constrained quantity from a measured T_{eff} is $\langle\dot{m}\rangle \equiv \langle\dot{M}\rangle/4\pi R^2$. At very low $\langle\dot{M}\rangle$ values, T_{eff} also depends on T_c. However, in this regime, we can calculate T_c self-consistently (TB), removing it from consideration.

In § 3 the $\langle\dot{m}\rangle$ values implied by the available measurements are presented and compared to CV evolutionary scenarios. A detailed comparison is presented for DNs with $P_{\mathrm{orb}} \lesssim 2$ hr, showing that the observed T_{eff} values imply that either $M > 0.6\ M_\odot$ or $\langle\dot{M}\rangle$ is larger than implied by gravitational radiation losses alone. We close in § 4 with a discussion of future work, especially the seismology of accreting WDs.

2. THE RELATION OF T_{eff} TO $\langle\dot{M}\rangle$

The high-quality UV spectra of quiescent DNs from the STIS instrument on *Hubble Space Telescope*, e.g., Howell et al. (2002), Szkody et al. (2002b), and many of the references in the table appearing in Winter & Sion (2003), yield accurate measurements of T_{eff}. However, the lack of accurate distance information prohibits the measurement of the WD radius, and hence mass, motivating the identification of a physical parameter that is best constrained by T_{eff} alone. The intent of this section is to demonstrate that, without knowledge of R or M, the best-constrained parameter is the accretion rate per unit area, $\langle\dot{m}\rangle$.

Our previous work (TB) presented a detailed discussion of the impact of accretion onto the thermal structure of a WD.

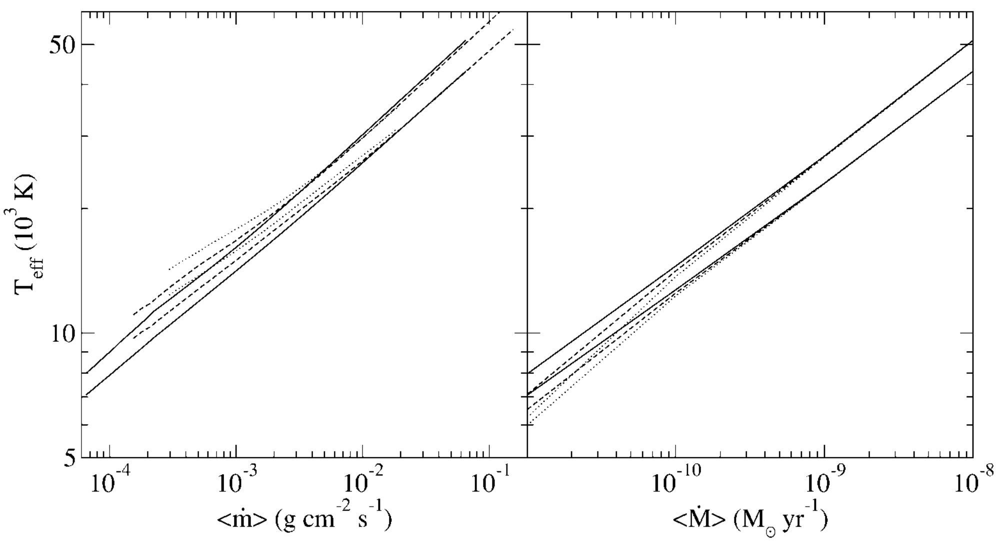

FIG. 1.—*Left*: Predicted range of $T_{\rm eff}$ (*between lines*) for $0.05M_{\rm ign} < M_{\rm acc} < 0.95M_{\rm ign}$ at $M = 0.6\ M_\odot$ (*solid lines*), 1.0 $M_\odot$ (*dashed lines*), and 1.2 $M_\odot$ (*dotted lines*). Without knowledge of M, $\langle \dot{m} \rangle$ is still fairly well constrained from $T_{\rm eff}$. *Right*: Dependence of $T_{\rm eff}$ range (as in left panel) on $\langle \dot{M} \rangle$ for $T_c = T_{c,\rm eq}$ (*solid lines*), $0.75T_{c,\rm eq}$ (*dashed lines*), and $0.5T_{c,\rm eq}$ (*dotted lines*), at $M = 0.6\ M_\odot$. This observable does not depend strongly on T_c except at the lowest $\langle \dot{M} \rangle$ values and therefore is relatively insensitive to the CV's evolution.

For this Letter we are primarily interested in the predictions for the surface luminosity, $L(M, \langle \dot{M} \rangle, T_c)$, for which we showed that the strongest dependence is $L \simeq \langle \dot{M} \rangle T_c/\mu m_p = 4\pi R^2 \sigma_{\rm SB} T_{\rm eff}^4$ and thus $T_{\rm eff}^4 \propto \langle \dot{M} \rangle / 4\pi R^2 = \langle \dot{m} \rangle$, even for different masses. The prime variance in this simple mapping is from the change in $T_{\rm eff}$ as the mass of the accumulated layer, $M_{\rm acc}$, increases between classical novae. In discussing our theoretical results we use the $T_{\rm eff}$ range for $0.05M_{\rm ign} \le M_{\rm acc} \le 0.95M_{\rm ign}$, which represents where an observed WD is most likely to be found. We set $X_{^3\rm He} = 0.001$ throughout as the difference between this and similar predictions, for $X_{^3\rm He} = 0.005$ is less than the uncertainty due to the unknown $M_{\rm acc}$. Figure 1 shows the range of $T_{\rm eff}$ traversed as a function of $\langle \dot{m} \rangle$ for $M = 0.6$–$1.2\ M_\odot$, showing that $T_{\rm eff}$ provides a reasonable constraint on $\langle \dot{m} \rangle$ even when M is not known. A $T_{\rm eff} = 15{,}000$ K implies that $0.4 \times 10^{-3} \le \langle \dot{m} \rangle \le 1.3 \times 10^{-3}$ g cm^{-2} s^{-1}, whereas a $T_{\rm eff} = 30{,}000$ K implies that $1.0 \times 10^{-2} \le \langle \dot{m} \rangle \le 1.7 \times 10^{-2}$ g cm^{-2} s^{-1}.

The insensitivity of L to M is the strongest qualitative difference between our calculation and Sion's (1995) estimate of $L \simeq 0.2\langle \dot{M} \rangle GM/R$, made from the steady state models of Iben (1982). While Iben's (1982) models are steady state in the sense of $L_{\rm core} = 0$, they were for high accretion rates, $\langle \dot{M} \rangle = 1.5 \times 10^{-8}\ M_\odot$ yr^{-1} for the best discussed models, with one at $\langle \dot{M} \rangle = 1.5 \times 10^{-9}\ M_\odot$ yr^{-1}, and use steadily burning shells. Such a steady state is inappropriate at the low $\langle \dot{M} \rangle$ values discussed here, where the burning is always unstable. Iben's (1982) models are also qualitatively very different from ours: in our models, compressional energy released in the accreted H/He shell provides the outgoing luminosity and helps to establish the equilibrium configuration of the core, whereas in Iben's (1982) models, the compressional heating term is entirely in the core, a contribution that is likely small (see Appendix A of TB). The results of TB are complementary to those of Godon & Sion (2002), which focuses on the response of the WD to the short-timescale $\dot{M}$ variations during DN outbursts.

The last parameter dependence to explore is T_c, the WD core temperature. As discussed in TB, DNs below the period gap have adequate time to reach an equilibrium core temperature, $T_{c,\rm eq}$, that depends on $\langle \dot{M} \rangle$ and M. However, DNs above the period gap have not been accreting long enough for T_c to reach $T_{c,\rm eq}$. Figure 1 shows how the traversed $T_{\rm eff}$ range depends on T_c for a $M = 0.6\ M_\odot$ WD. The curves show $T_{\rm eff}$ for $T_c = T_{c,\rm eq}$, $0.75T_{c,\rm eq}$, and $0.5T_{c,\rm eq}$. Because of a strong core/envelope decoupling for $\langle \dot{M} \rangle > 10^{-10}\ M_\odot$ yr^{-1} (TB), the $T_{\rm eff}$ range is nearly independent of T_c. For lower $\langle \dot{M} \rangle$ values, the WD core temperature should be close to the equilibrium value, allowing us to use $T_{c,\rm eq}$ as representative when finding $\langle \dot{m} \rangle$.

3. INFERRING ACCRETION RATES FROM $T_{\rm eff}$ MEASUREMENTS

Figure 2 shows the $\langle \dot{m} \rangle$ values inferred from the measured $T_{\rm eff}$ values tabulated in Winter & Sion (2003), with the following modifications: for WX Cet and VY Aqr we use the single-temperature fitted values, for CU Vel we correct the misquoted value, for AL Com we use a measurement longer after superoutburst (Szkody et al. 2002c), and we add GW Lib (Szkody et al. 2002a) and DW UMa (Szkody et al. 2002c). This observational $\langle \dot{m} \rangle$-$P_{\rm orb}$ relation shows clear evidence for a drop in $\langle \dot{m} \rangle$ below the period gap.

The relationship between $P_{\rm orb}$ and $\langle \dot{M} \rangle$ is still a very active area of theoretical inquiry and one that we hope our work can illuminate. The expectations from "standard" CV evolution (Howell et al. 2001) for $M = 0.7\ M_\odot$ (*solid line*) and 1.1 $M_\odot$ (*dashed line*) are shown in Figure 2. In this disrupted magnetic braking scenario, $\langle \dot{M} \rangle$ is set by magnetic braking above the period gap and by gravitational radiation below the period gap. Our deduced $\langle \dot{m} \rangle$ values are lower than the expected values above the period gap. It is important that we are inferring the long-term $\langle \dot{M} \rangle$, averaged over the thermal time of the radiative (nondegenerate) layer $\sim c_P T_c M_{\rm nd}/L \approx 10^4 (\langle \dot{M} \rangle / 10^{-10}\ M_\odot\ {\rm yr}^{-1})^{-0.75}$ yr for $M = 0.8\ M_\odot$ (TB), so this discrepancy cannot be due to a temporarily low $\dot{M}$. Although selection effects favor low $\langle \dot{M} \rangle$ values above the period gap, since such systems are more likely to have clean WD spectra, Patterson's (1984) estimates of $\langle \dot{M} \rangle$ for the systems above the gap in Figure 2 are not systematically below his estimates for other CVs.

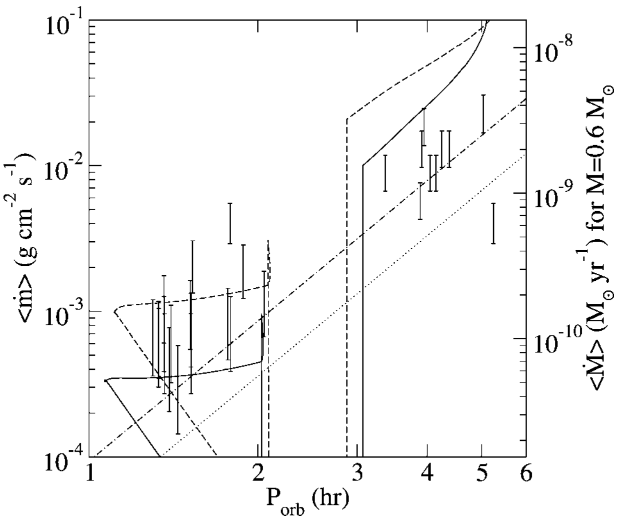

FIG. 2.—Values for the time-averaged accretion rate per WD surface area, $\langle \dot{m} \rangle \equiv \langle \dot{M} \rangle / 4\pi R^2$, derived from the T_{eff} measurements in the table appearing in Winter & Sion (2003). The ranges indicated for each measurement are those allowed for $0.05M_{ign} < M_{acc} < 0.95M_{ign}$ and $0.6\ M_\odot < M < 1.2\ M_\odot$. The curves show the $\langle \dot{m} \rangle$ predicted by Howell, Nelson, & Rappaport (2001) for $M = 0.7\ M_\odot$ (*solid line*) and $M = 1.1\ M_\odot$ (*dashed line*). Patterson's (1984) deduced relation from CV observations is shown by the dotted line for $M = 0.6\ M_\odot$ and by the dot-dashed line for 1.0 $M_\odot$. The right-hand scale gives $\langle \dot{M} \rangle_{0.6}$, the corresponding accretion rate if R is that for $M = 0.6\ M_\odot$. At the same $\langle \dot{m} \rangle$, $\langle \dot{M} \rangle_{1.0} = 0.4 \langle \dot{M} \rangle_{0.6}$.

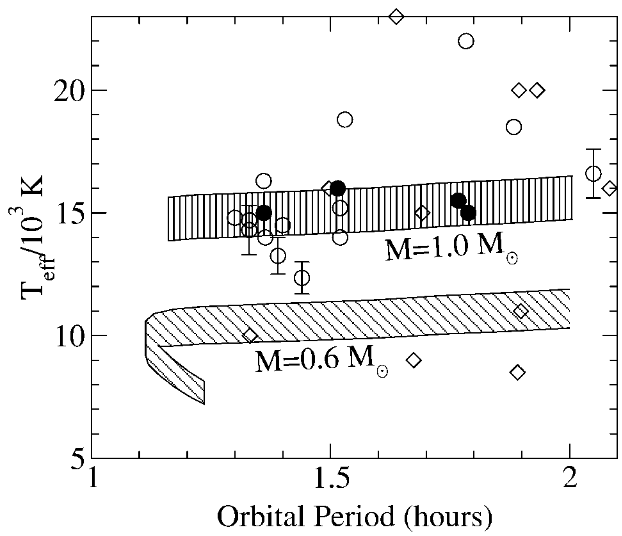

FIG. 3.—Comparison of our predicted ranges for T_{eff} with observed values for systems with $P_{orb} < 2$ hr. The filled areas indicate for each P_{orb} the range of T_{eff} that a quiescent CV primary is expected to traverse between thermonuclear outbursts, using the $\langle \dot{M} \rangle$ expected from angular momentum loss due to gravitational radiation (Kolb & Baraffe 1999). Measurements are from the table in Winter & Sion (2003) except as noted in the text. Error bars indicate systematic errors due to the unknown WD mass, and represent the range of T_{eff} obtained with $M = 0.3$–$0.9\ M_\odot$. All open points are subject to this same uncertainty. The filled points are systems that have well-measured WD masses (Patterson 2001); in order of increasing P_{orb} and in units of $M_\odot$ the masses are 0.9 ± 0.15, 0.82 ± 0.05, 0.61 ± 0.04, and 0.84 ± 0.09 for WZ Sge, OY Car, HT Cas, and Z Cha. The diamonds are magnetic CVs (Sion 1999; Gänsicke et al. 2001; Belle et al. 2003).

The most recently improved calibration of the magnetic braking law, using spin-down of open cluster stars (Andronov, Pinsonneault, & Sills 2003), yielded $\langle \dot{M} \rangle$ values above the period gap at least a factor of 10 lower than those of Howell et al. (2001), which falls below our inferences, so braking in CVs must be enhanced over that responsible for the spin-down of noninteracting low-mass stars.

In Figure 2, we also show Patterson's (1984) deduction from observations, $\langle \dot{M} \rangle \approx 5.1 \times 10^{-10} (P_{orb}/4\ \mathrm{hr})\ M_\odot\ \mathrm{yr}^{-1}$, for $M = 0.6\ M_\odot$ (*dotted line*) and 1.0 $M_\odot$ (*dot-dashed line*). Our points are consistent with those of Patterson (1984) above the period gap, within the uncertainty in his estimates. Below the gap, however, our measurements are roughly a factor of 3 above his. The Patterson (1984) estimates also suffer from the absence of reliable distances, but in a more direct way than ours, making systematic errors difficult to quantify.

The best-quality data are for CVs below the period gap, and Howell et al. (2002) and Szkody et al. (2002b) provide examples of these measurements with a discussion of how the uncertainty in the surface gravity, g, affects the T_{eff} results. We display our predictions for the T_{eff} ranges along with observed values for $P_{orb} < 2$ hr in Figure 3. The $\langle \dot{M} \rangle$-P_{orb} relation expected from gravitational radiation losses for $M = 0.6\ M_\odot$ is from Kolb & Baraffe (1999), and we use the same mass-radius relation for the donor to find $\langle \dot{M} \rangle$-P_{orb} for $M = 1.0\ M_\odot$. This gives $\langle \dot{M} \rangle = 3.6 \times 10^{-11}$ and $5.1 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ for $M =$ 0.6 and 1.0 $M_\odot$, respectively, at $P_{orb} = 1.5$ hr. Because of a difference in the donor mass-radius relation, these differ slightly from the values of Howell et al. (2001) shown in Figure 2, where $\langle \dot{M} \rangle = 4.6 \times 10^{-11}$ and $6 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ for $M = 0.7$ and 1.1 $M_\odot$ at $P_{orb} = 1.5$ hr.

The T_{eff} measurements shown by circles are again from the table in Winter & Sion (2003) (with the modifications discussed earlier). The error bars indicate systematic errors due to the unknown WD mass, as the spectral fits cannot independently constrain T_{eff} and g, and represent the range of T_{eff} obtained for $\log g = 8 \pm 0.5$ ($M = 0.3$–$0.9\ M_\odot$). All spectral measurements of these CV WD T_{eff} values are subject to this same uncertainty. The data with displayed error bars are the *best* measurements, and others have similar or larger uncertainties. The diamonds show T_{eff} for magnetic systems (Sion 1999; Gänsicke et al. 2001; Belle et al. 2003). The estimated masses for the two magnetic systems at 1.9 hr are 0.5 and 0.6 $M_\odot$ (Schwope et al. 1993; Schmidt, Stockman, & Grandi 1983) for the lower and higher points, respectively, placing their measured T_{eff} very close to that expected from our work.

When the WD mass, and thus radius, is known, $\langle \dot{M} \rangle$ can be directly constrained. The filled points are systems that have relatively secure WD masses from eclipse timing (Patterson 2001); in order of increasing P_{orb} and in units of $M_\odot$ the masses are 0.9 ± 0.15, 0.82 ± 0.05, 0.61 ± 0.04, and 0.84 ± 0.09 for WZ Sge, OY Car, HT Cas, and Z Cha. The best T_{eff} measurement is that for WZ Sge (Sion et al. 1995) giving $\langle \dot{M} \rangle = 6.4^{+1.7,+3.9}_{-1.7,-1.4} \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$, where the first errors represent the unconstrained value of M_{acc} and the second the uncertain mass. If the gravitational radiation prediction of $\langle \dot{M} \rangle$ (Kolb & Baraffe 1999) is taken as a lower limit, then comparison of these CVs to the predicted T_{eff} values of Figure 3 yields a maximum WD mass. For example, none of the CVs denoted with filled circles can have M in excess of $\approx M_\odot$, since a more massive WD would yield a higher T_{eff} than observed.

If the current $\langle \dot{M} \rangle$-P_{orb} relation predicted from gravitational radiation is correct, this comparison favors WD masses near 0.9–1.0 $M_\odot$. However, the systems with measured masses indicate another possible interpretation, that $M \approx 0.85\ M_\odot$ for many systems but $\langle \dot{M} \rangle$ is slightly greater than that predicted by Kolb & Baraffe (1999). The fact that the lower bound of measured values lies roughly parallel to what is expected for post-turnaround objects provides the exciting possibility that the turnaround is at roughly $P_{\rm orb} = 1.3$ hr and the objects with the lowest $T_{\rm eff}$ values, HV Vir and EG Cnc, are post-turnaround CVs. Under this interpretation, our work would indicate that the $\langle \dot{M} \rangle$ values for these post-turnaround objects are much higher than that expected from current modeling of evolution under the influence of gravitational radiation. Such an "extra" angular momentum loss has been mentioned by Patterson (2001) as a way to understand the location of the period minimum.

4. CONCLUSIONS

We have used our theoretical work on accreting WDs (Townsley & Bildsten 2003) to translate measurements of CV WD $T_{\rm eff}$ values into measurements of $\langle \dot{m} \rangle = \langle \dot{M} \rangle / 4\pi R^2$, the accretion rate per unit WD surface area averaged over the thermal time of the radiative envelope ($\gtrsim$1000 yr). Since the predictions of TB for $L(M, \langle \dot{M} \rangle, T_c)$ are insensitive to T_c (except where its value can be found self-consistently), we allowed for a range of WD masses, 0.6–1.2 $M_\odot$, and accumulated envelope masses, $0.05 M_{\rm ign} \le M_{\rm acc} \le 0.95 M_{\rm ign}$, to obtain a well-quantified uncertainty on $\langle \dot{m} \rangle$ from the observed $T_{\rm eff}$. We find evidence that above the period gap ($P_{\rm orb} > 3$ hr) DN accretion rates are slightly overestimated by CV evolution models (Howell et al. 2001), but that angular momentum loss is quite enhanced compared to spin-down of isolated low-mass stars (Andronov et al. 2003). Below the period gap, $P_{\rm orb} < 2$ hr, we find that $\langle \dot{M} \rangle$ is larger than that predicted by current models of gravitational radiation losses (Kolb & Baraffe 1999) when $M = 0.6\ M_\odot$, indicating either larger M or higher $\langle \dot{M} \rangle$.

It is well known that an isolated WD will pulsate when its $T_{\rm eff}$ is in the approximate range 11,000–12,000 K (Bergeron et al. 1995). While a difference in the outer atmospheric composition, H/He in an accreting WD versus pure hydrogen in the isolated case, will shift this range, it is likely that a similar pulsation mechanism will be active in accreting WDs. Our calculations indicate that accreting WDs with $M = 0.6$–1.0 $M_\odot$ should be near this range when $\langle \dot{M} \rangle$ is a few times 10^{-11} $M_\odot$ yr^{-1}. This $\langle \dot{M} \rangle$ is typical of that expected in CVs when accretion is driven by gravitational radiation losses, $P_{\rm orb} < 2$ hr (Kolb & Baraffe 1999). In fact, one system, GW Lib, has been found that does exhibit precisely this type of variability (van Zyl et al. 2000; Szkody et al. 2002a). Using the interior models developed in TB, we are now undertaking a seismological study of these systems. This offers the tantalizing possibility of measuring the WD mass, spin, and mass of the accumulated H/He layer.

Since the minimum light of $\langle \dot{M} \rangle < 10^{-10}$ $M_\odot$ yr^{-1} DNs in quiescence is determined by the hot WD, we can now calculate just how deep the large-scale optical surveys are probing into the predicted large population of CVs with very low mass companions (<0.1 $M_\odot$) (Howell, Rappaport, & Politano 1997). A typical survey complete to $V = 20$ would find all 0.9 $M_\odot$ (0.6 $M_\odot$) WDs with $T_{\rm eff} > 8500$ K (7000 K) that are within 200 pc (Bergeron, Wesemael, & Beauchamp 1995), and thus all DNs with $\langle \dot{M} \rangle > 0.8$ (1.0) $\times$ 10^{-11} $M_\odot$ yr^{-1}, including most DNs below the period gap that have not yet reached the period minimum. Selection of the faint CVs is still a challenge; color-selected surveys utilize their unusual combination of a hot WD plus a main-sequence M star (see Townsley & Bildsten 2002 for an earlier discussion and application to CVs in Galactic globular clusters). The second round of discoveries of faint CVs from the Sloan Digital Sky Survey, sensitive to ~20th magnitude, have just been announced (Szkody et al. 2003). On the basis of the initial set of 19 CVs and their orbital period distribution, Szkody et al. (2002d) claim that a large fraction of the 400 eventual CV discoveries will be of the low-$\langle \dot{M} \rangle$ variety below the period gap. Marsh et al. (2002) have also reported their discovery of three such systems in the Two-Degree Field Survey, sensitive to ~21st magnitude, and expect to have about 20 low-$\langle \dot{M} \rangle$ systems when the survey is complete.

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