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The Thermal Structure and Evolution of Accreting White Dwarfs

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Abstract. As mass is accreted on a White Dwarf (WD) in a mass-transferring binary, the inner layers are compressed and energy is released. The escape of this energy from the surface provides a floor to the WD surface temperature that can be observed directly during pauses in accretion. Released in the deep layers of the envelope, this energy also reheats the WD core, in effect resetting the cooling clock of the WD. We describe briefly how energy is released in the accreted envelope and core. The energy released by compression under accretion leads to an equilibrium core temperature, the key understanding the fate of all accreting WDs from progenitors of supernovae type Ia to the oldest low accretion rate systems. Both approach and departure from this equilibrium are important in relating the evolution of the WD to that of the binary. Consistent calculations of accreting WD thermal structure have led to new constraints on accretion rates in cataclysmic variables, have enabled classical novae observations to constrain the binary population, and have shed new light on the variety of classical novae. Evolutionary calculations have opened new avenues for discovery of the oldest CV systems, and have confirmed an evolutionary picture for AM CVn (double WD helium accreting) systems. Theoretical WD structures based on this work provide the essential basis for seismological studies of CV primaries which show non-radial oscillations.

1. Introduction

Cataclysmic variables (CVs; Warner 1995) are formed when, as a result of long term angular momentum losses from the orbit, the low-mass stellar companion of a WD finally (on timescales of $0.1 - 10$ Gyr) comes close enough to fill its Roche lobe. The previously fairly mundane system becomes quite active as mass is then steadily transferred onto the WD at an ever-diminishing rate. The WD will cool before mass transfer begins; a $0.6 M_\odot$ carbon/oxygen core WD would have $T_\mathrm{c} = 2.5 \times 10^6$ K in 4 Gyr (Salaris et al. 2000), leading to an effective surface temperature of $T_\mathrm{eff} \approx 5000$ K. However, once mass transfer starts, the WD accretes material at a time-averaged rate of $\langle \dot{M} \rangle \approx 10^{-11}$ to $10^{-8} M_\odot$ yr^{-1} (e.g. Howell et al. 2001) and can be reheated to higher T_eff's (Sion 1991).

Dwarf Novae (DN) are the subset of CVs with thermally unstable accretion disks. The transfer of matter onto the WD occurs in outbursts that last a few days to a week and which recur every month to year (or even longer in some systems). DN are naturally split into two classes by the "period gap";

almost no non-magnetic CV systems have been found with orbital period, $P_{\rm orb}$, between 2 and 3 hours (see Shafter 1992), and DN above the period gap have $\langle\dot{M}\rangle$'s approximately 10 times those of systems below the gap. During accretion disk quiescence, the $\dot{M}$ onto the WD is often low enough that the system's UV emission is dominated by light from the WD surface, allowing for a measurement of the WD $T_{\rm eff}$, 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 accretion (Sion 1995).

The effect of accretion on the thermal structure of the WD for these low accretion rate systems was discussed in detail by Townsley & Bildsten (2004). Here we summarize some conclusions of that work and present an example of the evolution of the core thermal state.

2. Compression of Material by Accretion

At the $\langle\dot{M}\rangle$ relevant for CV WDs, 10^{-11}–$10^{-8}M_\odot$ yr^{-1}, the accreted, solar composition material does not have time to separate, so that the entire accreted envelope has a fairly uniform composition inherited from the donor star. The accreted layer can be up to $10^{-3}M_\odot$, but this number depends strongly on $\langle\dot{M}\rangle$ and M, being more like $10^{-5}M_\odot$ for $\langle\dot{M}\rangle \sim 10^{-8}M_\odot$ yr^{-1}. The radiative layer is formed of accreted material, as is a small outer portion of the conductive core. This structure is shown in Figure 1, where a heavy line also indicates the extent of the small surface convection zone.

As material is buried by further accretion, it is compressed to higher pressures. This process occurs slowly in the sense that the local thermal time, $t_{\rm th} \equiv c_P T/(4acT^4/3\kappa y^2)$, is shorter than the time to accrete material to that point $\tau_{\rm acc} \equiv \Delta M/\langle\dot{M}\rangle$. Here ΔM is the mass of material above the point in question and $y = \Delta M/4\pi R^2$, and other parameters have their usual meaning. The condition $\tau_{\rm th} \ll \tau_{\rm acc}$ implies that material is free to transfer heat as it is compressed. Therefore the local thermal state of the envelope is determined by the temperature and flux from deeper layers. The line labeled as the adiabat in Figure 1 indicates the compression track of fluid if it were not allowed to exchange heat. The actual stellar structure is more shallow than this because the heat liberated in the compression is transferred both out the stellar surface (through overlying material) and into the core.

In fact the thermal state of the enveloped embodied in a structure curve like that shown in Figure 1 must be found in a self-consistent way such that the heat released due to the difference between the local thermal gradient and the adiabat matches the heat flux carried by that temperature gradient. We construct quasi-static solutions which assume that the size of the accreted layer $M_{\rm acc}$ changes slowly. The local heat equation is

$$-\frac{dL}{dM_r} + \epsilon_{\rm nuc} = T v_r \frac{ds}{dr} = -\frac{\langle\dot{M}\rangle}{4\pi r^2 \rho} T \frac{ds}{dr}, \qquad (1)$$

where L is the local luminosity, M_r is the mass interior to radius r, $\epsilon_{\rm nuc}$ is the nuclear energy deposition per mass and s is the mass-specific entropy. Equation 1

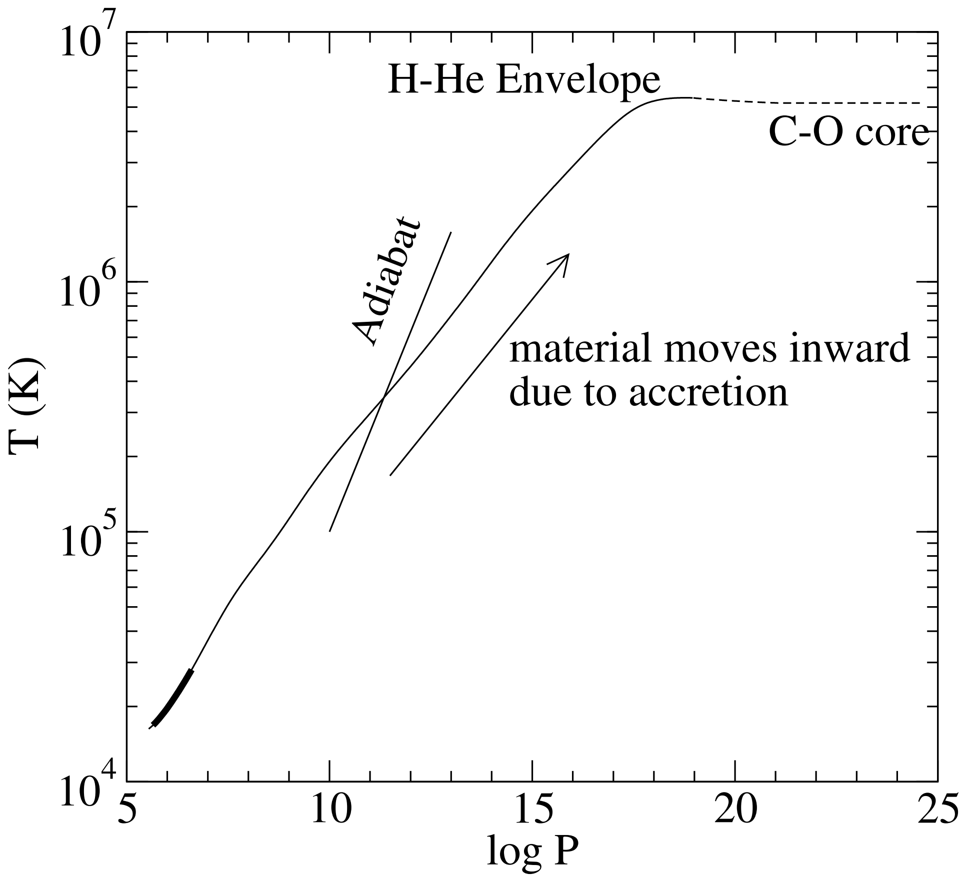

Figure 1. Structure of an accreting WD in temperature and pressure. The deep, nearly constant temperature, core is composed of C and O (*dashed line*) above which lies the accreted material of solar composition. There is a thin outer convection zone (*thick line*) overlying a radiative layer. Material is compressed to higher pressures by the addition of material at the surface. The profile is shallow with respect to the adiabatic path because heat is liberated and radiated away during this compression.

is solved in the envelope along with the structure equations

$$L = -\frac{4\pi r^2 ac}{\kappa\rho}\,\frac{dT^4}{dr} \qquad \text{and} \qquad \frac{dP}{dr} = -\frac{\rho G M_r}{r^2}\,.$$

The right hand side is dropped in the C/O layers. This is solved as a shooting problem to find $L(r)$ (and thus $T_{\rm eff}$) as a function of M, $T_{\rm c}$ and $M_{\rm acc}$. (See Townsley & Bildsten 2004 for more details.)

3. Evolution of the White Dwarf

By utilizing a sequence of such quasi-static structures it is possible to approximate the evolution of the accreted layer during the buildup of solar composition material between classical nova outbursts. Eventually the nuclear energy release at the base of the envelope runs away, leading to formation of a rapidly expanding convective envelope and vigorous ejection of effectively all of the accreted material (see e.g. Prialnik & Kovetz 1995 and references therein). The classical nova event itself is so short as to have little effect on the heat content of the underlying star. We define the net heat lost by the core *averaged* over the buildup to classical nova as $\langle L_{\rm core}\rangle$. As evidenced by Equation 1 this is not the same as the average surface L of the WD, due to the simple fact that much heat is released in the accreted layers that escapes through the surface. As a result of the fact that $\langle L_{\rm core}\rangle$ increases with $T_{\rm c}$, there exists a stable equilibrium $T_{\rm c}$ for every $\langle \dot{M}\rangle$ and M. Townsley & Bildsten (2004) found that this $T_{\rm c,eq}$ is not very sensitive to M, and that $T_{\rm c,eq}$ is much lower than has been typically used in classical nova simulations.

Using $\langle L_{\rm core}\rangle$ it is possible to go further and construct the evolution of $T_{\rm c}$ with time for a WD subject to some $\langle \dot{M}\rangle(t)$, which varies on long timescales. Such an accretion history must be constructed from known and hypothesized properties of cataclysmic binaries. Howell, Nelson, & Rappaport (2001, and earlier references therein) discuss the so-called disrupted magnetic braking scenario. In this scenario, when the companion star to the WD initially fills its Roche lobe, angular momentum loss from the binary is driven by the magnetically partially attached stellar wind from the companion. This leads to relatively quick evolution in which the binary goes from orbital period, $P_{\rm orb} \simeq 6$ hours to 3 hours in $\sim 10^7$ years with $\langle \dot{M}\rangle \sim 10^8 M_\odot$ yr^{-1}. After this the magnetic wind is disrupted (possibly by the companion becoming fully convective) and the angular momentum loss is afterward driven only by gravitational radiation. Such a sudden drop in the mass transfer rate in fact causes the companion, which was puffed up, to shrink and fall out of contact for a while. Evolution is now much slower, taking approximately a Gyr to come back into contact. After a few more Gyr the companion becomes so low mass ($\sim 0.08 M_\odot$) that it cannot cool in order to contract as the binary loses angular momentum, this causes the $P_{\rm orb}$ to begin to increase and the mass transfer rate to drop off. An example of this type of evolution is shown in Figure 2.

During the long interval during which evolution is driven by gravitational radiation, the WD accretes at nearly constant $\langle \dot{M}\rangle$, and therefore will have enough time to reach $T_{\rm c,eq}$. This equilibration can be seen in Figure 2 between 3 and 4 Gyrs. During this time the surface luminosity ($T_{\rm eff}$) is due to compression of material in the accreted layers, keeping the WD hot. Eventually as the accretion rate falls off after period bounce, the heat stored in the core becomes important and an increasing amount of the surface luminosity comes from the cooling WD core.

4. Enabled Studies

With a consistent thermal state of the WD in accreting binaries in hand, new light can be shed on several phenomena. By calculating $T_{\rm eff}$ and comparing with observations we placed constraints on the $\langle \dot{M}\rangle$ and M which are observed in DN systems (Townsley & Bildsten 2003). These provide support for the contrast in $\langle \dot{M}\rangle$ across the period gap and the consistency among the measured systems

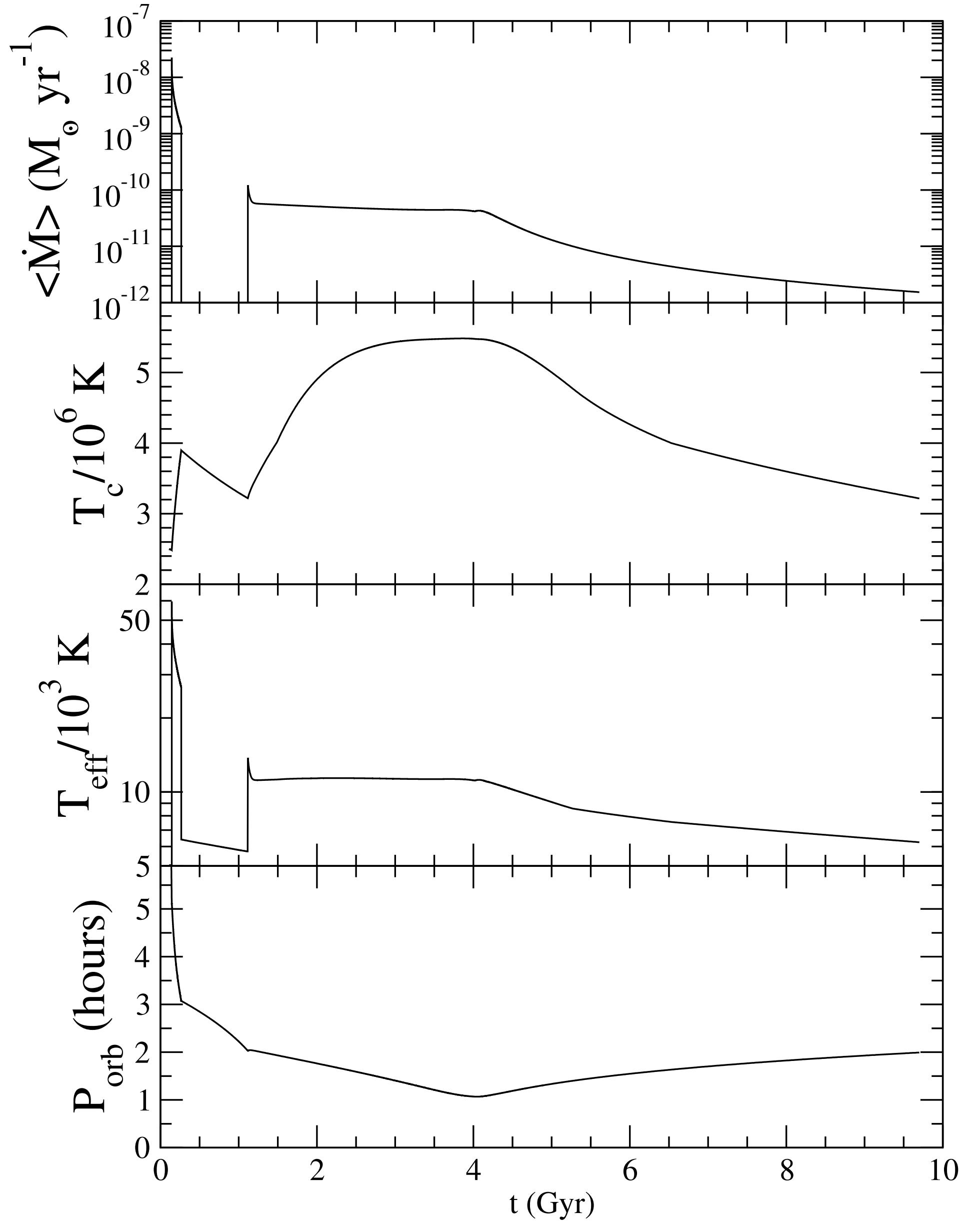

Figure 2. Evolution of the surface and inner thermal properties of a WD in a cataclysmic variable evolving according to the disrupted magnetic braking prescriptions (Howell et al. 2001). The top and bottom panels show the evolution of the binary in $\langle \dot{M} \rangle$ and $P_{\rm orb}$ as angular momentum is lost first to stellar wind and then gravitational radiation. The second panel shows the reheating of the core to the equilibrium temperature while $\langle \dot{M} \rangle$ maintains a consistent value under gravitational radiation. The minimum $T_{\rm eff}$ due to heat released by compression in the accreted layer is observed when the active accretion shuts off.

hints that the mass distribution of the WD primaries is much narrower than otherwise expected.

The knowledge of the inner thermal state allows a realistic determination of the ignition conditions of classical nova outbursts. Inclusion of theses thermal effects are essential for understanding the period distribution of classical novae, since the non-uniformity is entirely driven by the variation of $M_{\rm ign}$ with $\langle \dot{M} \rangle$ (Townsley & Bildsten 2005). Combining this with observed overall nova rates leads to an new constraint on the population and birthrate of CVs, giving a number interestingly similar to the supernovae type Ia rate. Also this indicates that possibly half of the material ejected from novae comes from only a few percent of the outbursts observed.

Seismology of accreting WDs is a promising new field of research, with several good objects available for study (van Zyl et al. 2000; Araujo-Betancor et al. 2005) and more being discovered. We have already performed the first seismological study of an accreting WD (Townsley et al. 2004), using the WD thermal structures constructed in the manner described here. This work will continue as more data is obtained, and we hope to derive spins, masses and accreted layer masses for a number of objects.

Cataclysmic variables are not the only binaries with accreting WDs. Ultra-compact WD–WD binaries are also observed with steadily accreting WDs (AM CVns, Nelemans et al. 2001). Similar evolutionary calculations can be performed for these systems, and have already lent support to a evolutionary picture for these objects evolving under the influence of gravitational radiation (Bildsten et al. 2006). In these object the cooling phase after reheating is very important in the late-time brightness of the system and therefore the expected discovery of systems.

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