The Evolution of White Dwarfs in Cataclysmic Variables

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Abstract

Accretion of matter and angular momentum affects the general properties of the white dwarfs in cataclysmic variables. Some consequences are secular core mass erosion, spin-up, short-term heating and cooling of the white dwarf envelope in response to changes in the accretion rate, retarded core cooling compared to non-accreting white dwarfs, and enrichment of the white dwarf photosphere with heavy elements. I present an overview of our present knowledge of the fundamental properties of these accreting white dwarfs, and I sketch the conclusions that can be drawn from the present observational database.

1 Introduction

Cataclysmic variables (CVs) are semi-detached close binaries containing a white dwarf (primary) which accretes from a late-type main-sequence star (secondary) slightly overfilling its Roche volume. With mass transfer rates in the range $10^{-11} - 10^{-9}\,M_\odot\,\mathrm{yr}^{-1}$, accretion will affect most of the fundamental properties of CV white dwarfs, such as their masses, temperatures, rotation rates, and chemical surface abundances. Some of the white dwarf characteristics will in turn deeply affect the accretion process – e. g. the mass of the white dwarf defines the depth of the potential well, and, thereby, the amount of energy released per accreted gram of matter, and the magnetic field determines the accretion geometry.

While most of the above stellar parameters can directly be measured with relative ease for single white dwarfs from spectroscopic observations, determining these properties for the accreting white dwarfs in CVs is a relatively new research field. Even though the first CV white dwarf was spectroscopically

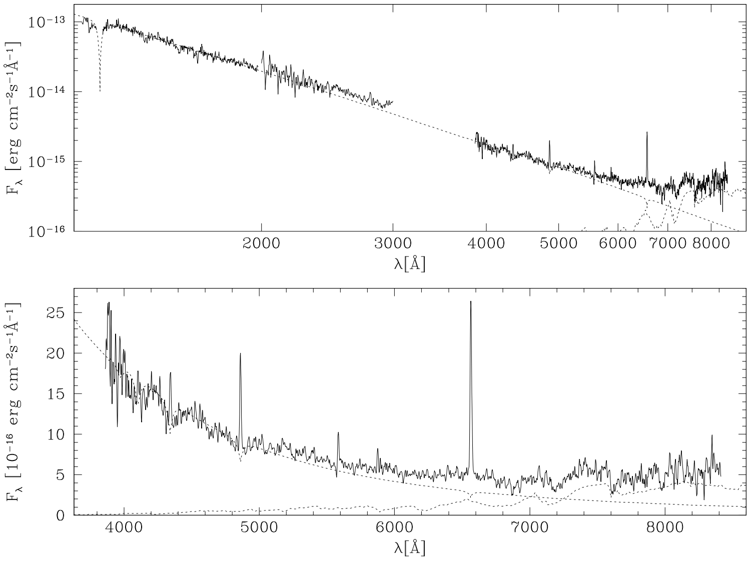

Figure 1: During phases of very low mass transfer, the white dwarf in the novalike variable TT Ari may be detected from the ultraviolet through the optical wavelength range. At the red end of the optical spectrum, the secondary star dominates the emission of the system (Gänsicke et al. 1999b).

identified as early as 1957[1] the number of CV white dwarfs with satisfying spectroscopic data available reaches only ~ 35 at the time of writing (Gänsicke 1997, Sion 1999), out of a total of ~ 1000 CVs known (Downes et al. 1997).

The scarcity of the observational database is mainly due to the fact that the flow of matter between the two stars dominates the emission of most CVs in the easily accessible optical wavelength band. Even though the photospheric white dwarf emission may be picked up in the optical regime in a small number of systems during episodes of very low accretion activity (Fig. 1), it is only in the ultraviolet that the white dwarf significantly contributes to – or even dominates – the emission in a large number of systems. Unmistakable spectroscopical identifications of accreting CV white dwarfs generally comes from the detection of a broad Lyα absorption profile (Fig. 2). However, because of their faintness, most CVs were beyond the reach of *IUE*, limiting the number of observable systems to $\lesssim 20$. So far, the impressive ultraviolet capabilities of *HST* have been focussed mainly on in-depth studies of a few well-known systems (e. g. de Martino et al. 1998, Gänsicke et al. 1998, Long

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[1] Based on the observed broad Balmer absorption lines and blue colour, Greenstein (1957) suggested that WZ Sge is/contains a white dwarf. The identification of the white dwarf as the source of the observed broad Balmer absorption lines was later doubted by Robinson et al. (1978), who argued that these lines originate in an optically thick accretion disc rotating at Keplerian velocities. *IUE* spectra later showed that the white dwarf is indeed a major source of light in this system (Sion et al. 1992).

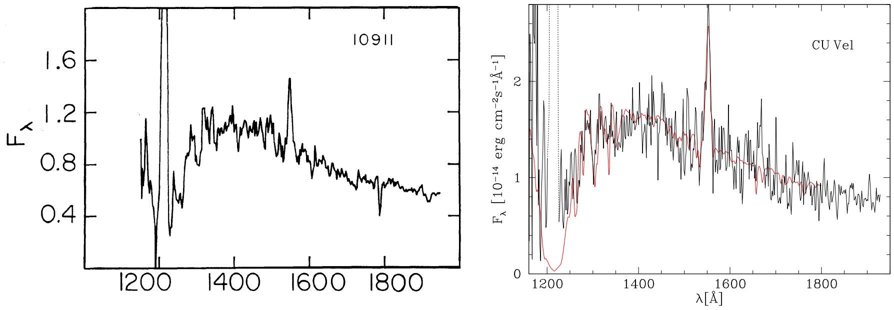

Figure 2: *IUE* ultraviolet observations of the white dwarfs in the dwarf novae VW Hyi (left, from Mateo & Szkody 1984) and CU Vel (right, from Gänsicke & Koester 1999). The right panel includes a fit of a white dwarf model spectrum computed for $T_{\rm eff} = 18\,500\,{\rm K}$, $\log g = 8$ and solar abundances, indicating that the photospheres of the CV white dwarfs may contain a significant fraction of heavy elements.

et al. 1999, Sion et al. 1997, Stockman et al. 1994). A significant broadening of the available sample is still awaited.

In the following, I will review the fundamental properties of CV white dwarfs and I will elucidate the correlations that can be drawn from the present observational database. I will also highlight results on some individual systems which show the level of detail that analyses can reach if dedicated observations are obtained.

2 Setting the scene

Before immersing in the details of CV white dwarf properties, a few concepts on the *accretion geometry* and on the *evolution* of CVs are recalled for the reader's convenience. A full review of CVs can be found in Warner (1995).

Depending on the strength of the magnetic field on the white dwarf, very different accretion geometries may be realized. In the case of a non (or very weakly) magnetic white dwarf, the infalling material spirals through an accretion disc towards the white dwarf and is eventually accreted through the boundary layer, a geometrically thin interface between the accretion disc and the white dwarf. CVs falling into this category are dwarf novae and disc-accreting novalike variables. If, in contrast, the magnetic field of the white dwarf is strong ($B \gtrsim 10\,{\rm MG}$), it prevents the formation of an accretion disc. The matter lost from the secondary star through the L_1 point follows a ballistic trajectory until the magnetic pressure exceeds the ram pressure in the accretion stream. From then on, the matter follows the magnetic field lines and is accreted in small spots near one or both magnetic poles of the white dwarf. CVs with a strongly magnetic white dwarf are called *polars* or *AM Herculis stars*. For CVs with weakly magnetic white dwarfs, the accretion geometry is somewhere in between these two extremes. A partial accretion disc may form, disrupted at some critical inner radius, with the white dwarf accreting through magnetic funnels from the inner edge of the disc. These type of CVs are therefore called *intermediate polars*.

Cataclysmic variables evolve under loss of angular momentum from long orbital periods ($P_{\rm orb}$) to short orbital periods, with typical CV orbital periods ranging from around a day down to a minimum of $\lesssim 80\,$min. According to the standard theory of CV evolution (see e. g. King 1988 and Kolb 1996) two different angular momentum loss mechanisms operate in different $P_{\rm orb}$ regimes, stellar magnetic wind braking for $P_{\rm orb} > 3\,$h and gravitational radiation for $P_{\rm orb} < 3\,$h. Typical evolutionary timescales are $\sim 10^8\,$yrs for $P_{\rm orb} > 3\,$h and $\sim 10^9\,$yrs for $P_{\rm orb} < 3\,$h. It is, thus, possible to give a rough estimate of the *average CV age* at a given orbital period (Kolb & Stehle 1996)[2]. In the so-called *period gap* in the range $2-3\,$h, the secondary temporarily detaches from its Roche surface, and the binary orbit shrinks without mass transfer. The observational consequence is an extreme paucity of CVs in the $P_{\rm orb} = 2-3\,$h range. Because of the different efficiencies in removing angular momentum from the binary, the mass transfer rate in systems evolving under magnetic braking is higher ($\dot{M} \sim$ a few 10^{-10} to $10^{-9}\,M_\odot\,{\rm yr}^{-1}$) than in systems evolving under gravitational radiation ($\dot{M} \sim$ a few $10^{-11}\,M_\odot\,{\rm yr}^{-1}$).

Summarizing, short-period CVs are, on average, older and have lower mass transfer rates than long-period CVs.

3 The white dwarf mass

Mass overflow from the secondary star onto the white dwarf will obviously increase the mass of the latter one. Just considering typical accretion rates and timescales mentioned above, it seems that the white dwarf mass might grow by as much as a few tenths of a solar mass, leading to the question whether CV white dwarfs could overcome the Chandrasekhar limit and turn into a type Ia Supernova (SN Ia).

Observations and theory of classical novae teaches, however, that the white dwarf mass does not grow monotonously over the life time of a typical CV. After accreting a layer of $\sim 10^{-6} - 10^{-4}\,M_\odot$ of hydrogen, depending on the mass and temperature of the white dwarf and on the accretion rate, an explosive thermonuclear reaction unavoidably ignites at the boundary of the degenerate core. These nova eruptions blow off not only the accreted layer but also some dredged-up core material. An observational consequence are enhanced CNO or Ne abundances in the nova shells expelled during nova eruptions (for a recent review on nova eruptions, see Starrfield et al. 1998). The most detailed nova simulations, following the white dwarf structure through many subsequent cycles, were carried out by Prialnik & Kovetz (1995). They found that for accretion rates $\dot{M} \leq 10^{-9}\,M_\odot\,{\rm yr}^{-1}$ the white dwarf mass will *decrease* un-

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[2] It is, however, impossible to judge the age of an individual CV from its orbital period alone, as CVs can be "born", i. e. develop from a detached state into semi-detached configuration, at any orbital period depending on the mass of the secondary star.

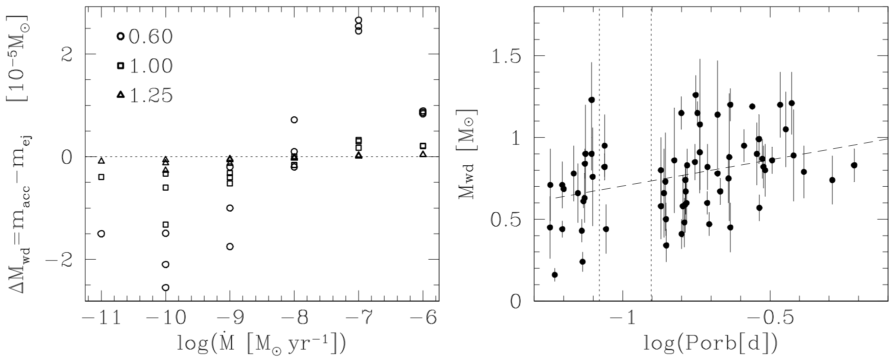

Figure 3: Left: Change of the white dwarf mass during a single nova eruption as function of the mass transfer rate $\dot{M}$ (adapted from Table 1 of Prialnik & Kovetz 1995). For each $\dot{M}$ and $M_{\rm wd}$, computations with three different white dwarf temperatures were carried out. Right: Estimates of CV white dwarf masses, compiled from Ritter & Kolb (1998), excluding the masses quoted as "uncertain". The two dashed lines mark the 2 h and 3 h boundaries of the period-gap.

der all circumstances; only for $\dot{M} \geq 10^{-8}\, M_\odot\, {\rm yr}^{-1}$ may the white dwarf mass increase. Figure 3 summarizes the evolution of the white dwarf mass during a *single* nova eruption as a function of the accretion rate. For CVs, with typical accretion rates of $\dot{M} < 10^{-8}\, M_\odot\, {\rm yr}^{-1}$, the white dwarf mass should therefore be eroded with time. It is not straightforward to estimate how many nova eruptions a CV suffers during its lifetime, but it may be a few $10^3 - 10^4$. Thus, the white dwarf mass may eventually decrease by a few tenths of a solar mass. It seems clear that typical CVs are poor SN Ia progenitors. Figure 3 shows, however, that for mass transfer rates *higher* than $\sim 10^{-8}$, the mass of the accreting white dwarf *can* increase with time, and I will discuss the nature of such systems below.

Figure 3 also shows the masses of white dwarfs in CVs estimated from observations as a function of the orbital period $P_{\rm orb}$. Even though the masses in Fig. 3 show considerable scatter and the individual errors are large, the general trend agrees with the prediction of nova theory: old (short-period) CVs contain less massive white dwarfs – due to erosion of the core mass by repeated nova eruptions – than young (long-period) CVs. However, the Ritter & Kolb sample is not statistically complete; it is simply a list of CVs with known orbital periods. A detailed discussion of possible selection effects has been given by Ritter & Burkert (1986).

Clearly, preciser mass measurements for a significant number of CV white dwarfs are highly desirable. Most mass determinations are based on binary orbit dynamics. In non-magnetic CVs, the motion of the white dwarf is thought to be best represented by the radial velocity in the wings of the broad emission lines originating in the inner part of the accretion disc, where it is assumed that the disc follows neatly the motion of the white dwarf. Pitfalls of this method are given e. g. by Shafter (1983). In magnetic CVs, the thermal bremsstrahlung emitted from the hot accretion region just above the white dwarf is very sensitive to the mass of the white dwarf, and fitting the hard X-ray emission of polars has been used various times to estimate the masses of their accreting white dwarfs (e. g. Cropper et al. 1998, see Ramsay et al. 1998 for a critical discussion of the method). Another method applicable to both magnetic and non-magnetic CVs with high orbital inclinations is to measure the white dwarf radius from eclipse durations and then to compute the white dwarf mass under the assumption of a mass-radius relation (e. g. Wood et al. 1986). The precisest methods involve (a) measuring the white dwarf radial velocity from narrow metal absorption lines originating in its photosphere (e. g. U Gem: Long & Gilliland 1999) and (b) to measure the gravitational redshift, again using narrow photospheric metal lines (e. g. U Gem: Sion et al. 1998). In the case of U Gem, both approaches yield consistent results. Obviously, these methods are limited to CVs where the white dwarf can clearly be discerned at ultraviolet wavelengths.

White dwarfs in high $\dot{M}$ CVs: Supersoft X-ray binaries. Figure 3 shows that for high accretion rates ($\dot{M} \gtrsim 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$) accretion may cause the white dwarf mass to grow. Already in the late seventies, Shara et al. (1977) predicted that white dwarfs accreting at very high mass flow rates will be subject to non-explosive hydrogen burning on their surface, and called them *non-ejecting novae*. Iben (1982) discussed in great detail the theoretical properties of such sources as well as some observational predictions. The first observational counterparts of these non-ejecting novae were already discovered in 1981 (Long et al. 1981), but not yet recognized as such systems. Van den Heuvel et al. (1992) resurrected the by-then forgotten idea of an accreting white dwarf with a steady-state hydrogen burning surface, and proposed that the secondary stars in these systems may be main-sequence stars that are more massive than the white dwarf primaries ($M_\mathrm{sec} \sim 1 - 2\,M_\odot$). The lack of observational evidence for massive secondaries lead van Teeseling & King (1998) to propose late-type main-sequence stars as secondaries.

Even though the nature of the secondary stars in the now-called *supersoft X-ray binaries* (SSXBs) is still debated, at least two observational findings support the white dwarf nature of the accreting primary. (a) The X-ray spectra of the SSXBs can be fitted with blackbody or white dwarf model spectra of several 10^5 K. If the distance is known, as it is the case for SSXBs in the Large Magellanic Cloud (LMC), the corresponding radii of the X-ray sources equal roughly that of a white dwarf ($\sim 10^9$ cm). However, the fitted temperature is highly correlated with the (usually badly determined) neutral hydrogen absorption column density N_H, which leaves also the source dimension relatively uncertain. For two of the LMC SSXBs, Cal 83 and RX J0513.9−6951, Gänsicke et al. (1998b) could determine N_H independently from the X-ray data by fitting the interstellar Lyα profile observed in *HST* spectra. Re-assessing the X-ray data with N_H fixed yields source radii with relatively small errors, which are consistent with those of massive white dwarfs. (b) In three SSXBs,

System	$P_{\rm orb}$ [min]	$v \sin i$ [km s^{-1}]	Reference
RX And	302	150	Sion et al. in prep
U Gem	255	75	Sion et al. 1994
VW Hyi	107	600	Sion et al. 1995
WZ Sge	82	1200	Cheng et al. 1997

Table 1: Rotation rates of white dwarf in non-magnetic CVs.

RX J0513.9−6951, QR And, and MR Vel, twin-outflow jets with escape velocities of $\sim 4000\,{\rm km\,s^{-1}}$ have been detected in optical/IR spectra (Southwell et al. 1996, Tomov et al. 1998, Motch 1998). If, as in all other known cases of jet manifestations, the terminal velocity equals the escape velocity of the central object, these observations strongly support white dwarfs as the accreting object in the SSXBs.

In summary, SSXBs are viable supernova type Ia progenitors (King & van Teeseling 1998).

4 The white dwarf spin

Along with matter, the white dwarf accretes angular momentum, which tends to spin it up. While a strong magnetic field locks the white dwarf into synchronous rotation with the binary orbital period (polars), the white dwarf spin period is always shorter than the binary period in the weakly magnetic intermediate polars (e. g. King & Lasota 1991, Hellier 1999).

Precise measurements of the white dwarf spin (better: $v \sin i$ with i the binary inclination) in non-magnetic CVs can be derived from rotationally broadened metal lines forming in the white dwarf photosphere (Fig. 5). The necessity of high-resolution *HST* spectroscopy limits this approach so far to four systems (Table 1). Again, using the orbital period as a measure for the age of the system, the trend is as expected: older CVs contain faster spinning white dwarfs. Nevertheless, all four white dwarfs rotate at velocities far below breakup, which would already be reached after the accretion of $\sim 0.1\,M_\odot$ (King et al. 1991). One effect competing with spin-up is that the shell expelled during a nova eruption carries off angular momentum (King et al. 1991). Livio & Pringle (1998) recently discussed the angular momentum coupling between the extended nova envelope and the core of CV white dwarfs.

5 The magnetic field of the white dwarf

Polars or *AM Herculis* stars, which harbour an accreting white dwarf with a magnetic field in excess of ~ 10 MG, represent 6 to 16 % of the known CVs (Downes et al. 1997, Ritter & Kolb 1998). This number is somewhat higher

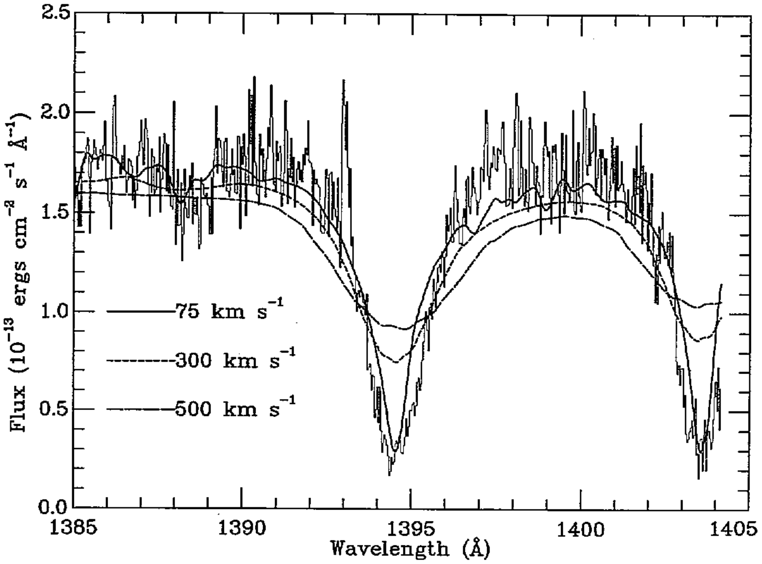

Figure 4: The *HST/GHRS* spectrum covering the Si IV1394/1403 region of the photospheric emission of the slowly rotating white dwarf in the dwarf nova U Gem. Model spectra convolved with Doppler-broadening for several rotational velocities are overplotted (from Sion et al. 1994).

than the percentage of magnetic white dwarfs among the single white dwarfs, but this fact is likely to be due to a higher discovery probability of polars with respect to non-magnetic CVs[3]. As outlined above, such a strong field has a major impact on the actual accretion geometry and on the physical processes that mass accretion involves in these systems. Accretion and magnetism have been covered already twice in this series (Schwope 1990, 1995), and I will highlight here only the major progress achieved since then.

A much-discussed issue over the first ~ 20 years of research on polars has been the apparent lack of high-field systems. Single white dwarfs with fields up to 1000 MG are known (Jordan 1997), however, all known polars had fields much below 100 MG. Schwope (1995) lists still QS Tel ($B \approx 70-80$ MG) as the polar with the strongest field. It has been claimed on theoretical grounds that a very high field might considerably enhance the mass transfer from the secondary, thus accelerating the binary evolution and decreasing the

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[3] Polars are extremely bright and soft X-ray sources, and the ROSAT All Sky Survey more than doubled the number of known polars to $\gtrsim 60$ (Beuermann 1998). In contrast to this, non-magnetic (disc-accreting) CVs are only relatively weak X-ray sources, and especially many high $\dot{M}$ systems (novalike variables) and very low $\dot{M}$ systems (short-period dwarf nova) might have slipped discovery so far because of their low variability and their lengthy outburst cycles, respectively.

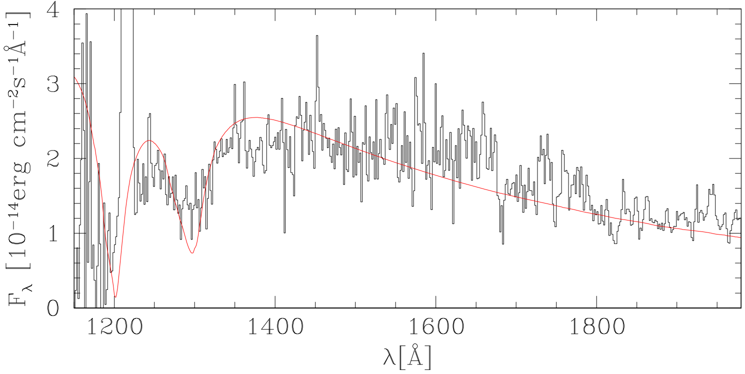

Figure 5: Low-state *IUE* spectrum of AR UMa with the best-fit magnetic white dwarf model for $B = 190\,$MG and $T_{\rm wd}$=25 000 K. (model spectrum provided by S. Jordan). The absorption feature at 1300 Å is interpreted as σ^+ component of Lyα in a strong magnetic field (Schmidt et al. 1996, Gänsicke et al. 1997a).

discovery probability of such systems (Hameury et al. 1988, King 1985). It has to be mentioned, though, that contradicting theories predict a reduced mass transfer in high-field polars, implying a reduced accretion luminosity (Li et al. 1994).

Somewhat surprisingly, in the few years since Schwope's (1995) review, three polars with fields near or in excess of 100 MG have been discovered. AR UMa, the recordholder with $B \sim 190-230\,$MG, is actually the first polar in which the Zeeman-splitting of Lyα could be detected[4] (Fig. 5, Schmidt et al. 1996, Gänsicke et al. 1997a). In RX J1007−20, a field of $B \sim 100\,$MG is derived from the observed cyclotron emission (Reinsch et al. 1999). Finally, spectropolarimetry indicates a field of $B \sim 100\,$MG in V884 Her (Schmidt 1999). Figure 6 shows the updated distribution of magnetic field strengths for the AM Herculis stars, and, for comparison, the field strength distribution of single magnetic white dwarfs from Jordan (1997).

Clearly, the field strength distributions of accreting and field white dwarfs still differs significantly. While there is roughly an equal number of single magnetic white dwarfs per decade in field strength, the number of accreting white dwarfs peaks at a field strengths of $\sim 20-30\,$MG, and declines rapidly towards lower and higher fields. The lack at the low-field end is easily explained, as the intermediate polars populate this regime. Measurements of the white dwarf field are extremely difficult in intermediate polars, as the accretion disc/funnel are very intense sources of optical/IR emission, and, in consequence, very few intermediate polars exhibit cyclotron radiation and in non of them Zeeman-splitting of photospheric Balmer lines could be observed. On the high-field end of the distribution, the situation is not that easy. Even though the maximum field measured in a polar is now higher than what the early theories predicted it to be, no CV with an ultrahigh magnetic

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[4] Lyα is the hydrogen line with the weakest Zeeman-splitting.

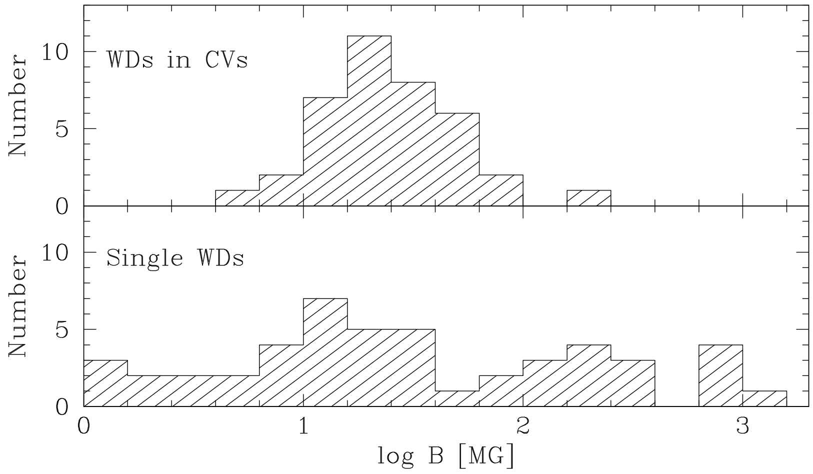

Figure 6: Magnetic field strength distributions of white dwarfs in polars (top) and of single white dwarfs (bottom).

white dwarf has been found so far, and the number of high-field polars is still small. The observed long-term variability of AR UMa might give a clue on the paucity of high-field polars. In contrast to almost all other known polars, AR UMa lurks for most of the time in a state of low accretion activity, and it is only during 10 % of its observed history that it leaps into a bright state. During these short accretion episodes, AR UMa is a very intense soft X-ray source, but it has been, as possibly many similar systems, overlooked during the ROSAT All Sky Survey. In the optical, the variability is $\Delta V \approx 3\,\mathrm{mag}$, not impressive compared to most dwarf novae, and again the rare bright states of other high-field polars are easily missed by amateur observers and sky patrols. A tentative hypothesis for this long-term variablity is that the strong magnetic field may act as an additional potential barrier in/near the L_1 point, preventing mass transfer until a necessary pressure has been built up Schmidt (1999).

6 The temperatures of white dwarfs in CVs

Accretion affects the temperatures of the white dwarfs in CVs mainly on two different timescales. Allmost all CVs show brightness variations on timescales of days to years, due to fluctuations in the accretion rate onto the white dwarf. These variations in the accretion rate cause a thermal response of the white dwarf envelope on similar timescales, observed as short-term changes in the white dwarf temperature or in the temperature distribution over the white dwarf surface. In addition, part of the accretion luminosity goes into deep heating of the entire white dwarf and partially counteracts the secular core cooling (e. g. Iben 1982).

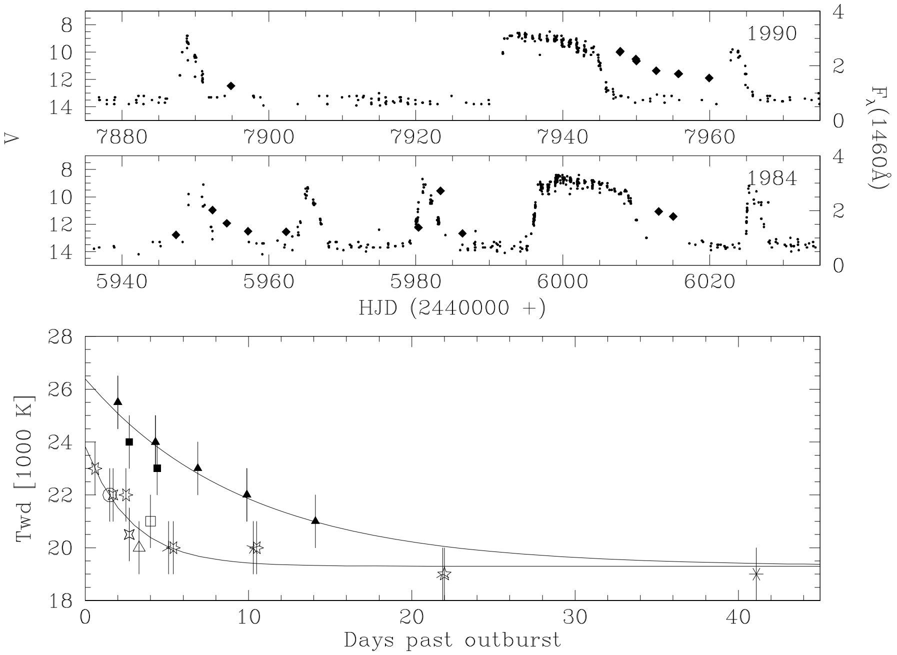

Figure 7: Top: optical light curve of VW Hyi from the Variable Star Section of the Royal Astronomical Society of New Zealand (F. Bateson, private communication). The diamonds give *IUE* $1420 - 1500\,\text{Å}$ continuum fluxes in $10^{-13}\,\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1}$. Bottom: The temperature of the white dwarf in VW Hyi determined from all available quiescent *IUE* spectra as a function of the time since the last outburst. The filled and open symbols represent data taken after superoutbursts and normal outbursts, respectively (adapted from Gänsicke & Beuermann 1996).

6.1 Short-term heating and cooling

White dwarf heating during dwarf nova outbursts: Dwarf novae are a CV subclass with non-magnetic white dwarfs and relatively low accretion rates. Their main observational characteristic are quasiperiodic brightenings by $2-6$ magnitudes, lasting for several days to weeks. The physical principle underlying these dwarf nova outbursts is a limit cycle of the mass transfer rate through the accretion disc, resulting in phases of enhanced viscous dissipation and correspondingly higher temperatures (see Osaki 1996 for a review on disc instabilities).

A consequence of the disc instability limit cycle is that the white dwarf accretes matter in a quasi-periodic manner, with high inflow rates during the outbursts and very low inflow rates during quiescence. Figure 7 shows part of the optical long term light curve of the dwarf nova VW Hyi, which has frequent short *normal outbursts*, and less frequent brighter and longer lasting *superoutbursts*. Plotted along with the optical magnitude are ultraviolet fluxes measured by *IUE*. Apparently, the ultraviolet flux continues to decline for some time after the system reaches optical quiescence. This is most pronounced after superoutbursts. Gänsicke & Beuermann (1996) have fitted 28 quiescent *IUE/SWP* observations of VW Hyi using solar abundance model spectra in order to derive the white dwarf temperature as a function of the time past the last outburst. The results are summarized in Fig. 7: the outer layers of the white dwarf are heated deeper and to higher temperatures during the longer lasting superoutbursts than during normal outbursts. The cooling of the white dwarf can be approximated by an exponential decline

$$T_{\rm exc}(t) = T_{\rm wd}(t) - T_\infty = T_{\rm exc}(0)\exp(-t/\tau)$$

with $T_{\rm exc}$ the temporary temperature excess over the equilibrium white dwarf temperature T_∞ and τ the cooling timescale. For VW Hyi, $T_{\rm exc}(0) = 7\,100\,{\rm K}$, $\tau = 9.8\,{\rm d}$ after a superoutburst and $T_{\rm exc}(0) = 4\,500\,{\rm K}$, $\tau = 2.8\,{\rm d}$ after a normal outburst, with $T_\infty = 19\,300\,{\rm K}$. However, it may be that in VW Hyi the white dwarf never reaches a true equilibrium temperature due to the frequent outbursts (every $\sim 14\,{\rm d}$). A corresponding study in a dwarf nova with similar characteristics, but with a longer outburst period would be promising (e.g. EK TrA with normal outbursts every $\sim 230\,{\rm d}$, Gänsicke et al. 1997b). An ultraviolet afterglow after the return into optical quiescence has been observed and interpreted as cooling of the white dwarf in four other systems: U Gem (Long et al. 1994), WZ Sge (Sparks et al. 1993), OY Car (Cheng et al. 1994), and AL Com (Szkody et al. 1998).

Apart from studying the thermal response of the white dwarf envelope to intermittent accretion, measuring the amount of energy stored during an outburst in the white dwarf envelope offers a new diagnostic tool to probe the physics in the boundary layer – the geometrically small interface between the accretion disc and the star. The energy liberated in the boundary layer amounts for up to half of the total accretion luminosity, depending on the rotational velocity $\Omega_{\rm wd}$ of the white dwarf:

$$L_{\rm BL} \approx \frac{1}{2}\frac{GM_{\rm wd}\dot{M}}{R_{\rm wd}}\left(1 - \frac{\Omega_{\rm wd}}{\Omega_{\rm K}(R_{\rm wd})}\right)^2$$

where $\Omega_{\rm K}$ is the break-up velocity of the white dwarf. A persisting problem in accretion disc theory and observation is that the observed boundary layer luminosities are below the expected values in many systems.

The ratio of the energy stored in the white dwarf envelope to the total energy emitted during an outburst is $\sim 7\,\%$ for U Gem and $\sim 1\,\%$ for VW Hyi (Gänsicke 1997). A tempting explanation for this difference are the white dwarf rotation rates given in Sect. 4: the white dwarf in VW Hyi rotates faster than that in U Gem, so a lower boundary layer luminosity and a lower white dwarf heating are expected for VW Hyi. This idea is supported by EUVE observations of both systems, showing that the boundary layer luminosity of VW Hyi is indeed a factor ~ 10 lower than in U Gem (Mauche 1996, Long et al. 1996). At present, it is not clear how WZ Sge – with its high rotational velocity – fits in that picture. It is clear, however, that the white dwarf rotational velocity is a fundamental parameter in understanding disc accretion and needs to be measured in a larger number of systems.

The exact mechanism(s) that heat(s) the white dwarf during dwarf nova outbursts are still poorly understood. Basically, three models have been proposed. The first attempt to model the observed post-outburst cooling involved the heating of the white dwarf by irradiation from the hot boundary layer (Pringle 1988). This approach may explain the very short cooling time observed in VW Hyi, even though the boundary layer temperatures inferred from the model are at the upper limit of what is consistent with EUV/X-ray observations. However, the irradiation model is unable to explain the long cooling timescale observed e. g. in WZ Sge. A second possibility is compressional heating caused by the quasi-periodic accretion of matter (Sion 1995). The secular effect of cyclic accretion events is to heat the white dwarf to an equilibrium temperature several 1000 K above the initial temperature at the onset of accretion. In addition, the white dwarf is heated during each individual accretion episode by several 1000 K above that equilibrium temperature, with post-outburst cooling timescales comparable to those observed. The third approach, though not originally aiming at the problem of white dwarf heating in dwarf novae, suggests that the accreted matter is not immediately slowed down to the white dwarf rotational velocity, but is stored in a rapidly rotating equatorial belt (Kippenhahn & Thomas 1978). This belt represents a reservoir of kinetic energy, which can slowly be converted into heat by viscous dissipation during quiescence. Kippenhahn & Thomas found that molecular viscosity alone is not sufficient to decelerate the accretion belt on reasonably short timescales. However, Kutter & Sparks (1987), assuming turbulent mixing, show that an efficient conversion of kinetic energy into heat is possible. One very exciting observational result of the last few years has been the discovery of a Kippenhahn-Thomas belt in VW Hyi (Gänsicke & Beuermann 1996, Huang et al. 1996).

6.2 Heated polar caps in AM Herculis stars

In the strongly magnetic CVs (polars), no accretion disc forms. Instead, the matter is channelled along the field lines to the magnetic pole(s), where it is decelerated and heated to a few 10^7K in a shock shortly above the white dwarf surface. The post-shock plasma cools by emission of thermal bremsstrahlung and cyclotron radiation. The standard model (Lamb & Masters 1979) predicts that half of this emission is intercepted by the white dwarf, and re-emitted as a quasi-blackbody soft X-ray spectrum. Observations show, however, that in most polars the soft X-ray flux is much higher and must be produced by another process (see the review by Beuermann 1998).

Phase-resolved *IUE* observations of the brightest polar, AM Herculis, revealed an orbital modulation of the ultraviolet continuum flux, peaking at the phase of maximum hard X-ray flux, both during the low and high states (Heise & Verbunt 1988, Gänsicke et al. 1995). In the low state, this flux modulation is accompanied by an orbital variation of the broad Lyα absorption profile. The modulation of both continuum flux and Lyα absorption width can be explained with a large, moderately hot spot near the main accretion pole on the white dwarf. The spot temperatures estimated from the *IUE* data were $\simeq 24\,000$ K and $\gtrsim 37\,000$ K in the low and high states, respectively, with the spot covering $f \sim 0.1$ of the white dwarf surface (Gänsicke et al. 1995). The unheated regions of the white dwarf have $T \simeq 20\,000$ K (Heise & Verbunt 1988, Gänsicke et al. 1995). Considering that the sum of the observed hard X-ray flux and cyclotron emission roughly equals the ultraviolet excess flux of the spot, Gänsicke et al. (1995) concluded that irradiation by thermal bremsstrahlung and/or cyclotron emission from the hot post-shock plasma is the most probable cause for the heating of the spot. Thus, at least in AM Her, the reprocessing model is valid, but the reprocessed component peaks in the ultraviolet, and not at soft X-rays[5]. A more detailed anlysis of the properties of the heated polecap in AM Her was prevented by the low temporal resolution ($25 - 60$ min per spectrum) of the *IUE* data.

In January 1997, a complete binary orbit of time-resolved *HST/GHRS* spectroscopy was obtained, resulting in a total of 341 spectra with a time resolution of 30 sec (Gänsicke et al. 1998a). Continuum light curves, extracted from the phase-folded *GHRS* spectra in emission line free wavelength bands, display a quasi-sinusoidal modulation with the modulation increasing towards blue wavelengths. The 1254–1286 Å light curve is displayed in Fig. 8. As for the *IUE* observations, the phase of the ultraviolet flux maximum agrees with that of the maximum hard X-ray flux (e. g. Paerels et al. 1994, Gänsicke et al. 1995) and EUV flux (Paerels et al. 1996), underlining that the ultraviolet excess radiation originates close to the main accreting pole.

In order to constrain the temperature distribution over the white dwarf surface, synthetic phase-resolved spectra and light curves were computed using a 3D model of the white dwarf. The heated pole cap is represented by a circular spot with an opening angle $\theta_{\rm spot}$. The temperature in the spot decreases linearly in angle from the central value $T_{\rm cent}$ at the spot centre until meeting the temperature of the underlying white dwarf $T_{\rm wd}$ at $\theta_{\rm spot}$. The centre of the spot is offset from the rotational axis by an angle $\beta_{\rm spot}$, the colatitude, and from the line connecting the two stars by an angle Ψ, the azimuth. Fitting the *GHRS* light curves with the inclination and the distance fixed ($d = 90$ pc, Gänsicke et al. 1995, C. Dahn, priv. communication; $i = 50°$, Davey & Smith 1996) results in $T_{\rm wd} = 21\,000$ K, $R_{\rm wd} = 1.12 \times 10^9$ cm, $T_{\rm cent} = 47\,000$ K, $\theta_{\rm spot} = 69.2°$, $\beta_{\rm spot} = 54.4°$ and $\Psi = 0.0°$. The opening angle converts into a fractional spot area $f \sim 0.09$. The fit proved to be robust in $T_{\rm wd}$, $R_{\rm wd}$, Ψ and $\beta_{\rm spot}$. However, the opening angle can be traded for the central temperature of the spot within certain limits because the continuum slope of the white dwarf model spectra approaches a Rayleigh-Jeans distribution for temperatures $\gtrsim 50\,000$ K and becomes independent of the temperature. Figure 8

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[5] This implies that the soft X-ray/EUV emission, which is the dominant flux component in AM Her during high states, must have a different physical origin, e.g. deep heating of the white dwarf photosphere by submerged shocks (Kuijpers & Pringle 1982).

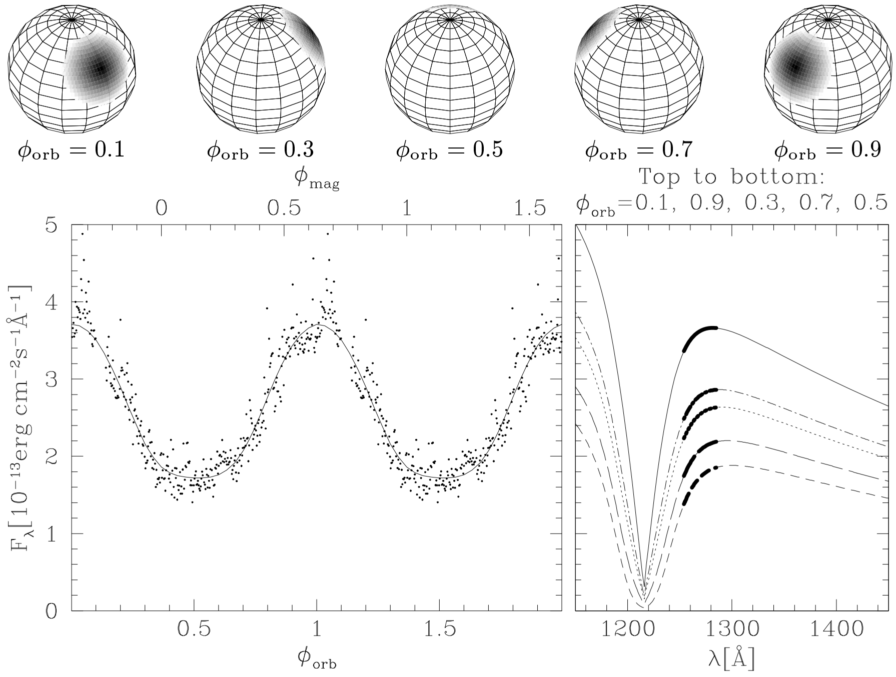

Figure 8: Left: 1254−1286 Å light curve of AM Her obtained from fast *HST/GHRS* spectroscopy. The solid curve is the best-fit synthetic light curve from a white dwarf + hot spot model as illustrated on top. Right: Simulated phase-resolved spectra corresponding to the five orbital phases displayed on top. The wavelength range from which the synthetic light curve was extracted is plotted bold.

shows the best fit to the 1254−1286 Å light curve. The white dwarf temperature derived from the *HST* light curves is in good agreement with the value of 20 000 K based on *IUE* low state spectra (Heise & Verbunt 1988, Gänsicke et al. 1995).

Applying a mass-radius relation (e. g. Hamada & Salpeter 1961, carbon core), it is possible to estimate also the mass of the white dwarf in AM Herculis from the derived radius, $M_{\rm wd} = 0.35\,M_\odot$. This can be considered a lower limit of $M_{\rm wd}$ as we assumed that all the continuum light comes from the (heated) white dwarf; any contribution from the accretion stream will decrease the white dwarf radius and increase its mass. Our estimate is significantly lower than the value derived from the interpretation of the hard X-ray emission of AM Her, which yielded $M_{\rm wd} = 1.22\,M_\odot$ (Cropper et al. 1998). However, such a high mass, corresponding to $R_{\rm wd} = 3.9 \times 10^8$ cm, would reduce the distance of AM Her to $d \approx 45$ pc in order to reproduce the observed ultraviolet flux. A distance that low can be excluded both from the spectrum of the secondary star and from the parallax.

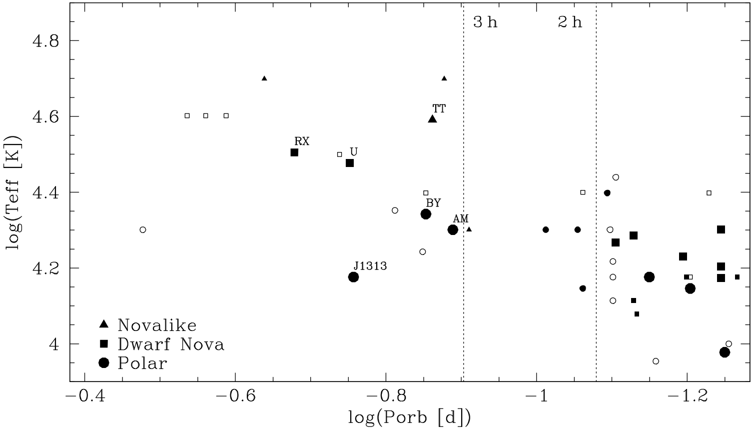

Figure 9: CV white dwarf effective temperatures vs. orbital period. The accuracy of the temperatures is coded as follows: large filled symbols = reliable (error in $T_{\rm eff} \leq 10\,\%$) , small filled symbols = good estimate (error in $T_{\rm eff} \leq 20\,\%$), small open symbols = crude estimate only. The two dashed lines mark the 2 h and 3 h boundaries of the period-gap.

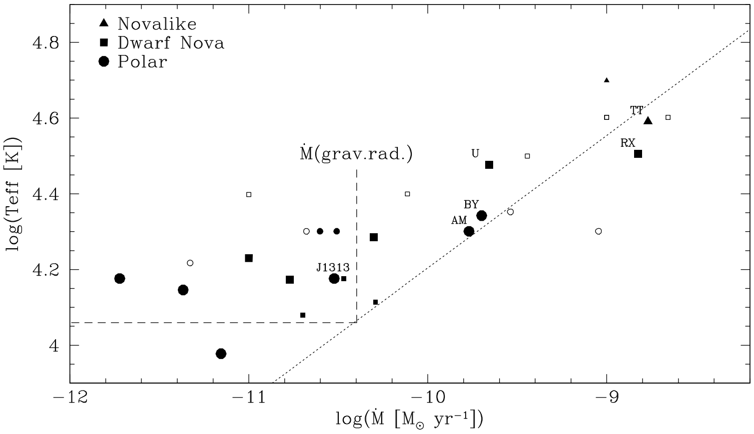

Figure 10: CV white dwarf effective temperatures vs. mass accretion rate, with the same encoding as in Fig. 9. Typical errors in the accretion rate are half a magnitude. The dotted line shows the effective temperature expected for compressional heating of the white dwarf envelope. The dashed vertical line indicates the accretion rate expected from angular momentum loss driven by gravitational radiation, the dashed horizontal line is the corresponding white dwarf temperarture due to compressional heating.

IUE and *HST/FOS* observations of several other polars indicate that a large, moderately heated spot on the white dwarf is a rather common feature. However, the quality of the available data prevents detailed analyses (de Martino et al. 1998, Gänsicke 1997, Gänsicke et al. 1999a, Stockman et al. 1994).

Dedicated ultraviolet observations will help to understand the actual mechanism(s) that heat(s) the pole caps, to establish the overall energy balance of the accretion process, and to derive accretion geometries as well temperatures and, in some cases, mass estimates for the accreting magnetic white dwarfs.

6.3 Secular heating

In addition to the short-term heating and cooling discussed above, accretion partially compensates the secular core cooling of the white dwarf. Indeed, CV white dwarfs have – on average – higher temperatures than isolated white dwarfs of comparable age. Fig. 9 shows the temperatures of CV white dwarfs plotted over the orbital period. A main result read from this plot is that the CVs below the period gap contain colder white dwarfs than those above the gap. This agrees with intuitive expectations based on Sect. 2, i. e. that the short-period CVs are on average older and have lower accretion rates than the long-period ones. However, the large scatter in temperature prevents a more detailed interpretation, and indicates fundamental differences between CVs of (nearly) identical orbital periods.

Figure 10 shows the CV white dwarf temperature plotted over the mass transfer rate, the latter one being another fundamental property of a CV. Even though this representation of the data introduces an additional large uncertainty – the mass transfer rates have typical errors of half a magnitude while the orbital periods are known with extreme precision – the scatter appears to be somewhat reduced. The long-period systems with reliable temperatures now cluster neatly around the temperature predicted for compressional heating of the envelope (Gänsicke et al. 1999a, Sion 1995).

The fact that no CV white dwarf with a reliable temperature lies much below the dotted line indicates that compressional heating is a significant or even dominating source of energy. In white dwarfs above the dotted line, the thermal energy of the core may still contribute to the overall luminosity of the accreting primary. Finally, it is interesting and satisfying to observe that no CV white dwarf is significantly colder than $\sim 11\,000$ K, the temperature corresponding to an accretion rate driven by angular momentum loss through gravitational radiation.

7 Photospheric abundances

Accretion of *bona fide* solar abundance material from the secondary star enriches the photosphere of the CV white dwarfs with metals. So far, observations do not support any strong metallicity anomalies in the secondary stars (Beuermann et al. 1998). A large number of metal lines are observed in ultraviolet spectra of the exposed white dwarfs in non-magnetic CVs (e. g. Gänsicke & Beuermann 1996, Gänsicke & Koester 1999, Long et al. 1994, Sion et al. 1990, 1998), proving that the accreted material spreads over all, or at least a considerable part of the white dwarf surface. Fitting the observed absorption-line spectra with state-of-the art model spectra allows extraction of information on the abundances in the photospheres of the accreting white dwarfs. Intuitively, these abundances should reflect an equilibrium between accretion and gravitational settling. All abundances derived so far deviate from solar values, however, without a homogenous trend. The largest deviation was found in VW Hyi, where a 900×solar abundance of Phosphorus was measured from an *HST* high resolution spectrum (Sion et al. 1997). Sion et al. suggested that this large amount of Phosphorus in the atmosphere of the white dwarf in VW Hyi is a fossil imprint of a nova eruption, formed by proton capture from Silicon. If this hypothesis can be confirmed, it would be the first direct evidence in a known CV for a past unrecorded nova explosion.

In contrast to non-magnetic CVs, the white dwarfs in polars show at best traces of heavy elements in their atmospheres. Co-adding *IUE* spectra, Gänsicke et al. (1995) found some weak evidence for absorption of Si II $\lambda\lambda\,1260{,}65$. However, other lines expected in a 20 000 K atmosphere were not detected. Extreme ultraviolet observations, covering the emission from the hot (200 000 – 300 000 K) footprint of the accretion column show a rather smooth, blackbody-like spectrum without the strong O VI absorption edges expected from a hot, high-gravity atmosphere (Paerels et al. 1996). The most promising experiment to probe the chemical surface composition of the magnetic accreting white dwarfs in polars, that is *HST* high-resolution observations of such systems during phases of low accretion, have not yet been obtained.

8 Conclusions and future work

Even though considerable progress has been achieved in the field of CV white dwarfs, the fraction of CVs with a spectroscopic identification of the accreting WD is small, and an even smaller number of systems has been studied at a sufficient level of detail. Hence, a *global* understanding of the complex interaction between the properties of CV white dwarfs and the accretion process still escapes us. Establishing correlations between the various properties of the accreting white dwarfs in CVs (T_{eff}, M_{wd}, B, $v \sin i$, chemical abundances) and the global characteristics of the CVs (P_{orb}, $\dot{M}$) on statistically firm grounds has many applications beyond the field of CVs. The possibility of measuring the characteristics of the accreting compact objects provides essential input parameters for accretion disc theory, which in turn has a vast number of applications, e. g. in young stellar objects, in X-ray binaries, and even in active galactic nuclei. Polars and intermediate polars allow detailed studies of the physics involved in magnetically funnelled accretion. Even though the processes involved may differ in some aspects, general similarities are found with magnetic T Tauri stars, accreting neutron stars, and wind-accreting symbiotic stars. Finally, classical nova eruptions and supernovae Ia both enrich the interstellar medium with heavy elements and are usefull standard candles for extragalactic distance estimates.

The main workload in providing a statistically significant database lies on the *HST*. The sensitivity and time resolution of *STIS* have only begun to be exploited, and the next-generation spectrograph *COS* will allow observation of a fainter and larger sample of CV white dwarfs at an excellent level of detail. The extended wavelength range of *FUSE* (down to the Lyman edge) will provide important additional information for the brightest CVs. Finally, the ultraviolet survey mission *GALEX* may play an important rôle in expanding the overall CV sample.

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