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Stars, Companions, and their Interactions: A Memorial to Robert H. Koch

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White Dwarfs in Cataclysmic Variable Stars: Surface Temperatures and Evolution

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A summary is presented of what is currently known about the surface temperatures of accreting white dwarfs (WDs) detected in non-magnetic and magnetic cataclysmic variables (CVs) based upon synthetic spectral analyses of far ultraviolet data. A special focus is placed on WD temperatures above and below the CV period gap as a function of the orbital period, P_{orb}. The principal uncertainty of the temperatures for the CV WDs in the T_{eff} - P_{orb} distribution, besides the distance to the CV, is the mass of the WD. Only in eclipsing CV systems, an area of eclipsing binary studies, which was so central to Robert H. Koch's career, is it possible to know CV WD masses with high precision.

Keywords: cataclysmic variables, white dwarfs

1. INTRODUCTION

Hubble space telescope (HST) and FUSE far ultraviolet spectroscopy, along with X-ray and extreme ultraviolet spectroscopy using Hopkins ultraviolet telescope (HUT), Orfeus, Chandra, XMM-Newton, EUVE, EXOSAT, ROSAT and ASCA have led to a windfall in our knowledge of the underlying white dwarfs (WDs) in cataclysmic variables (CVs) and how they are affected by the accretion process. These space observatories have made it possible to detect numerous WD accretors, the boundary layer between the accretion disk and the WD surface, the accretion disk itself and wind outflow in the wavelength domains where they emit most of their energy between ~3 Å and 2,000 Å. For the WDs in CVs, space observations are obtained when the luminous accretion disks or bright accretion columns are absent during quiescence / low states of non-magnetic systems and low states of magnetic CVs. Thus, it has become possible to determine many poorly known basic physical properties of these systems both above and below the CV period gap, an orbital period range between two and three hours in which very few systems are found. Among the newly determined physical properties are surface temperatures T_{eff}, mass accretion rates, rotational velocities $V \sin i$, chemical abundances, the accretion energy budget and how accretion and thermonuclear runaways can drastically alter the structure, evolution and atmospheric chemistry of the accreting WD over time. This paper will focus on the surface temperatures of the WDs in CVs, the heating and the subsequent observed cooling of WDs and their distribution versus orbital period, Porb, with implications for their long term evolution through comparison with evolutionary models.

2. TEMPERATURES OF CV WDs

The photospheric temperatures of non-accreting WDs in the field directly measure their cooling ages since their formation but for CV WDs, their photospheric temperatures are relics of their history of long term average accretion and the effects of novae explosions. This makes their temperatures immensely important to understand their evolution. These temperatures have been derived from fitting their observed spectra during dwarf novae quiescence, nova-like low states and low states of Polars

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with WD model atmospheres computed primarily with continually updated versions of the codes TLUSTY (Hubeny 1988) and SYNSPEC (Hubeny & Lanz 1995). In the simplest case of a dwarf nova below the period gap whose accretion rate during quiescence is extremely small and whose disk is in a cold state, single temperature WD models have been successfully fit to the FUV and optical spectra (Sion 1999). The best fits are determined with standard chi2 minimization techniques, visual appearance of the fit to the continuum shape and profiles of absorption lines in the accreted atmosphere. In general, the best-fit is constrained by the minimum chi2, the CV distance estimates, measurement or clues, physical plausibility, fitting-derived parameters and the constraint that the combined optical model flux of the WD + disk yields an optical magnitude no brighter that the observed V-magnitude of the CV, since the disk and other cooler emitting components contribute flux in the optical.

Unlike the temperature determinations for non-accreting single degenerates, which have typical precisions of ±100 K or better, this precision cannot normally be achieved for CV WDs because of the typically poorly known WD mass, and distance errors. These are the two largest, most important uncertainties. In FUV spectra of an exposed WD in a CV, the derivation of the surface gravity is uncertain because Ly α with its ground state electron, is less sensitive to pressure broadening, hence gravity/mass, than the Balmer lines, which are usually hidden due to disk/BL emission in the optical even during quiescence. It is only with eclipsing binaries, an area of research so central to Robert H. Koch's scientific career, that its possible to know the mass of a CV WD with high precision. Thus, it is critical to identify and analyze ever more eclipsing CVs.

There are also considerable uncertainties in the reddening, unidentified FUV flux contributors other than the WD, temporal changes due to time variable accretion heating and cooling, variations imposed by the aspect of orbital phase, intrinsic differences in the codes employed by workers in the field and even the specific ways in which different workers eliminate emission line regions and artifacts in the fitting. Added to these difficulties are missing atomic physics, for example, unknown oscillator strengths, unknown opacity sources and instrumental flux calibration problems. There is also the problem of consistency between temperatures derived from spectral fitting in different wavelength domains, both in the far UV down to the Lyman limit (FUSE, HUT) and the optical, and in the far UV (HST, international ultraviolet explorer [IUE]) and the optical. In some cases where quiescent dwarf nova spectra are obtained by two observatories, the flux levels in overlapping wavelength regions match and spectral fitting has been carried out for the combined spectra yielding a broader wavelength coverage. Experience has taught that temperature determinations of CV WDs approach, in successive approximations, an absolute value, but unlike the precision temperatures of single WDs, it is generally unrealistic to claim a unique value of surface temperature. Despite all of the above caveats, we plot what we consider

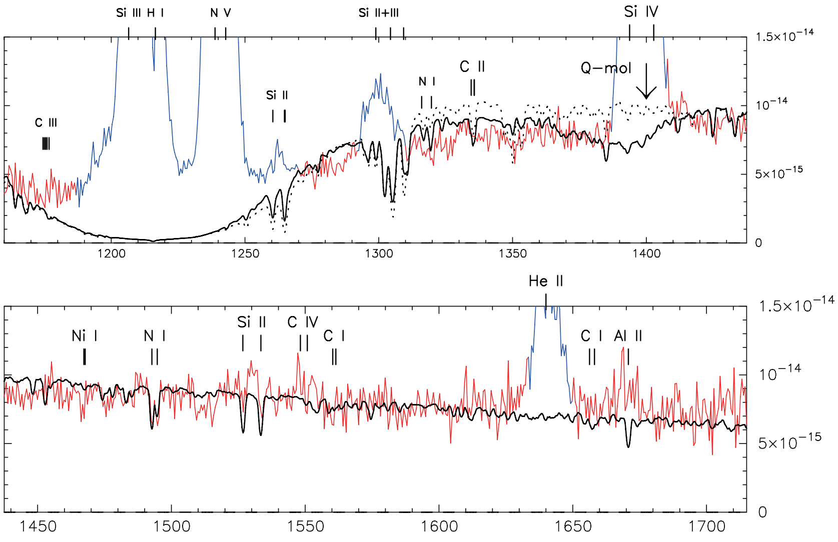

Fig. 1. The best-fitting single temperature white dwarf (WD) fit to the Hubble space telescope imaging spectrograph spectrum of the dwarf nova BZ UMa. The WD model has temperature of 15,000 K, log (g) = 7.5 for a distance of 156 pc. Note the extremely strong N V (1,240) emission feature, the near absence of C IV (1,550) and how the hydrogen quasi-molecular satellite lines opacity affects the spectrum around 1,300-1,400 Å.

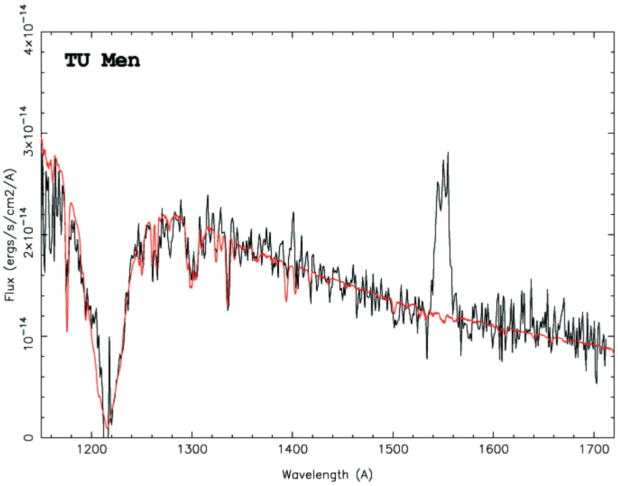

Fig. 2. The best-fitting single temperature WD fit to the Hubble space telescope imaging spectrograph spectrum of TU Men, the longest period SU UMa-type dwarf nova. The WD model has temperature of 28,000 K for a distance of 288 pc. The model metal line profiles are a bit broader than the observed profiles implying *v* sin *i* = 400 km/s.

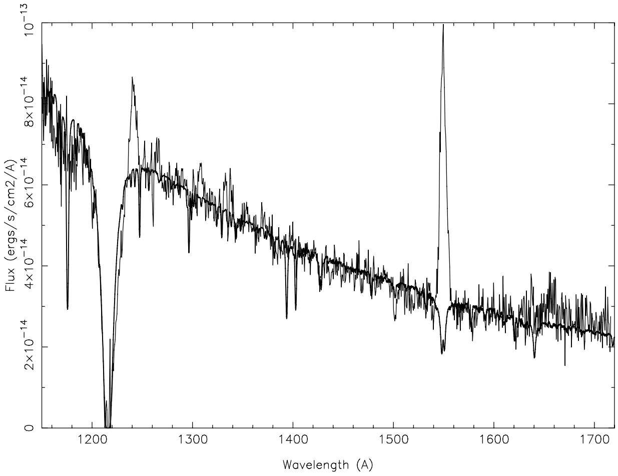

Fig. 3. A WD fit to the Hubble space telescope space telescope imaging spectrograph spectrum of V442 Cen with E (B-V) = 0.10. The best-fitting model by far consisted of a 47,000 K WD with Log g = 8.3 but for a distance of only 328 pc, well below our best estimate of 800 pc.

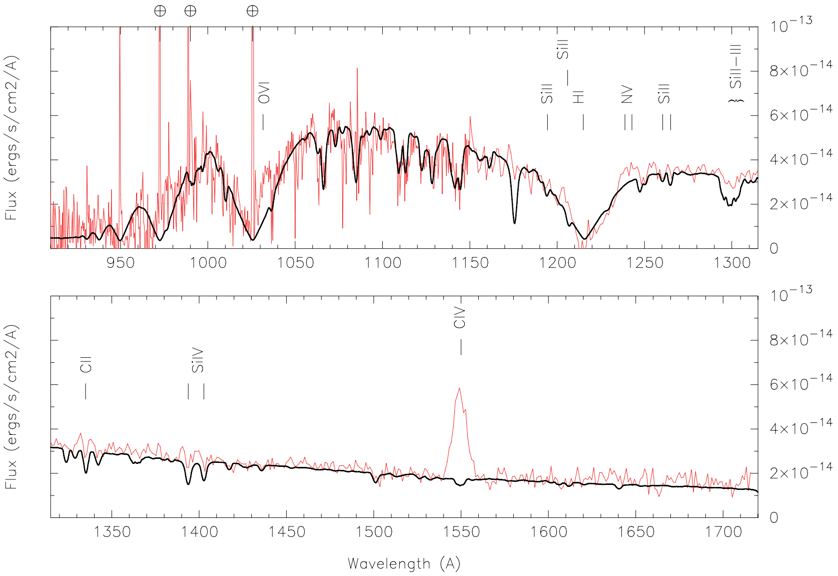

Fig. 4. Combined far ultraviolet spectroscopic explorer (FUSE) and space telescope imaging spectrograph spectrum of SS Aur together with the best-fit WD model (black). The regions that have been masked for the fitting are shown in dark gray. The synthetic stellar spectrum has a temperature of 34,000 K assuming log (g) = 8.93 and the parallax distance of 200 pc, a projected rotational velocity of 400 km/s and solar abundances. The spectrum has been dereddened assuming E (B-V) = 0.08.

the best, most reliable temperatures, Teff to date, below where we discuss the Teff versus Porb distribution. In Figs. 1-3, we display reasonable model atmosphere fits to the CV WDs in the dwarf novae BZ UMa (Godon et al. 2011), TU Men, Sion et al. (2008), and V442 Cen (Sion et al. 2008), respectively. BZ UMa exhibits the nitrogen to carbon abundance anomaly indicative of CNO-processing, TU Men is the only SU UMa-type dwarf nova above the lower boundary of the CV period gap. And V442 Cen is a U Gem-type dwarf nova.

In some cases where quiescent dwarf nova spectra are obtained by two observatories, the flux levels in overlapping wavelength regions match and spectral fitting has been carried out for the combined spectra yielding a broader wavelength coverage. An example of model fitting to merged FUSE and HST space telescope imaging spectrograph

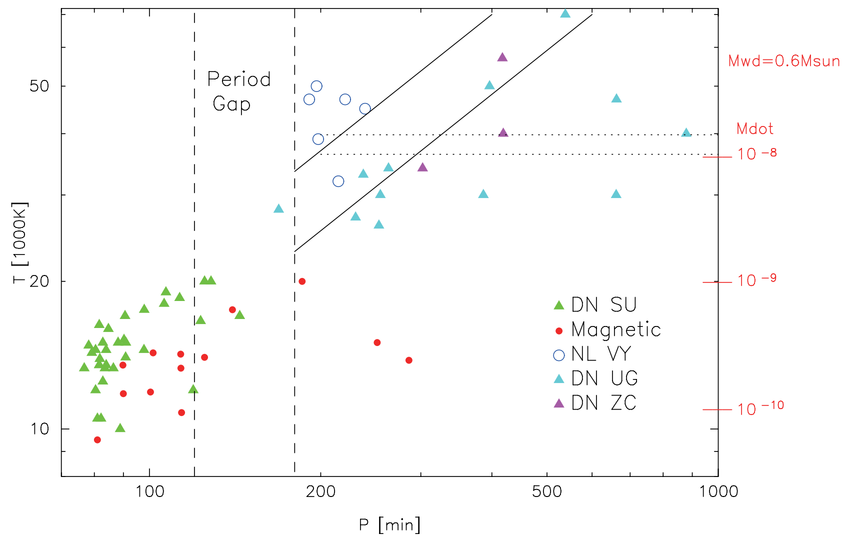

Fig. 5. WD effective temperature as a function of the orbital period. The references for the individual temperatures can be found in Sion et al. (2008), Townsley & Gaensicke (2009), and Araujo-Betancor et al. (2005) and references therein. The traditional magnetic braking above the period gap (Howell et al. 2001) is shown between the parallel diagonal solid lines. On the right hand side are the time-averaged accretion rates corresponding to the temperature scale on the left hand side of the diagram based upon the $<T_{eff}>$ versus $<\dot{M}>$ relation of Townsley and Bildsten 2003) for a 0.6 $M_\odot$ WD. Shown for comparison is the long term evolution (at a constant accretion rate) of a WD which has undergone 1,000 nova outburst cycles accreting at the long term rate of 10^{-8} $M_\odot$/yr, between the dotted lines.

(STIS) spectra of the long period dwarf nova SS Aur during quiescence is displayed in Fig. 4. A single temperature WD best fit corresponding to the parallax distance of 201 pc yields T_{eff} = 34,000 K, log (g) = 9, $V \sin i$ = 200 km/s.

3. SURFACE TEMPERATURE VERSUS ORBITAL PERIOD

In this section, we present a preliminary discussion of the distribution function of CV WD surface temperatures versus the orbital period, P_{orb}. In Fig. 5, we display the distribution of CV WD effective temperatures as a function of the orbital period. The references for the individual temperatures can be found in Sion et al. (2008), Townsley & Gänsicke (2009) and, Araujo-Betancor et al. (2005) and references therein. We have also included temperatures determined from HST STIS spectra of CV WD pulsators. The number of temperatures we have plotted, with separate symbols for each CV subclass, are 13 polars with known WD temperatures, 35 dwarf novae below the period gap with known WD temperatures, 6 nova-like variables of the VY Scl subclass with known WD temperatures, 12 U Gem-Type dwarf novae above the period gap with know WD temperatures and 3 Z Cam-Type dwarf novae with known WD temperatures.

In Fig. 5, there is a well defined separation between Polars and DN below the gap, and apparently also above the gap (Sion 1991, Araujo-Betancor et al. 2005) There remains a paucity of data points above the gap for Z Cam's, Polars and VY Scl's. There seems to be a separation in the P_{orb} - T_{eff} parameter space between Polars, SU UMa's, U Gem's and possibly VY Scl's.

The traditional magnetic braking above the period gap (Howell et al. 2001) is shown between the parallel diagonal solid lines. On the right hand side are the time-averaged accretion rates corresponding to the temperature scale on the left hand side of the diagram, based upon the $<T_{eff}>$ versus $<\dot{M}>$, the time-averaged accretion rate relation of Townsley & Bildsten (2003) for a 0.6 $M_\odot$ WD. Shown for comparison is the long term evolution (at a constant accretion rate) of a WD (Prialnik 2008) which has undergone 1,000 nova outburst cycles accreting at the long term rate of 1E-8 $M_\odot$/yr. The model WD has a core temperature of 3E + 7 K.

The clustering of dwarf novae WDs around 15,000 K was first evident from the results of the medium HST program of Szkody et al. (2002), see also Gänsicke et al. (2005). The temperatures of the WDs in the magnetic and non-magnetic systems below the period gap are roughly consistent with $<\dot{M}>$ values identified with angular momentum loss due to gravitational radiation as the sole driver of mass transfer. For the WDs in CVs below the gap, hotter than 15,000 K, up to ~ 20,000 K, the implied $<\dot{M}>$ values are higher than that expected from gravitational wave emission. The WDs in magnetic CVs are cooler than the WDs in non-magnetic CVs at a given P_{orb}, a result first reported by Sion (1991) and later with a much larger number of magnetic WDs in CVs by Araujo-Betancor et al. 2005). Thus, their average $< \dot{M} >$ is lower than non-magnetic systems which my be related to a suppression of magnetic wind outflow from the donor star. Above the period gap, the much greater dispersion of surface temperatures is clearly seen and speaks to a higher $< \dot{M} >$ than the characteristically lower $< \dot{M} >$ below the period gap. A more complete discussion of Fig. 5, which includes more theoretical models will appear elsewhere.

4. FUTURE WORK

It is clear that large FUV surveys of CVs with IUE, HST, HUT and FUSE have yielded many insights into accreting WD properties, accretion physics and accreting WD evolution. At the same time the enlarged samples of magnetic and non-magnetic CV WDs have raised exciting questions and possibilities. Much of the progress to date has resulted from ground-based surveys like Hamburg-Schmidt, SPY and the Sloan Digital Sky Survey as well as space ultraviolet surveys of CVs carried out with HST and FUSE. These and other surveys have led to discoveries of new phenomena, enlargement of existing CV samples, and the existence of new types of CVs and pre-CVs. With the prospect of having renewed FUV spectroscopy of CV WDs with HST COS as well as STIS, even greater progress and deeper insights into CV WDs and CV evolution should result. This will require the analysis of a much larger sample size, precision masses from more eclipsing CV systems, vitally important parallax data eventually from GAIA and greater light throughput to reach extremely faint objects, high resolution and broader UV wavelength coverage.

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