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White Dwarfs in Cataclysmic Variables: An Update

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Abstract

In this review, we summarize what is currently known about the surface temperatures of accreting white dwarfs in non-magnetic and magnetic cataclysmic variables (CVs) based upon synthetic spectral analyses of far ultraviolet data. We focus only on white dwarf surface temperatures, since in the area of chemical abundances, rotation rates, WD masses and accretion rates, relatively little has changed since our last review, pending the results of a large HST GO program involving 48 CVs of different CV types. The surface temperature of the white dwarf in SS Cygni is re-examined in the light of its revised distance. We also discuss new HST spectra of the recurrent nova T Pyxidis as it transitioned into quiescence following its April 2011 nova outburst.

Keywords: cataclysmic variables - dwarf novae - intermediate polars - spectroscopy - UV - individuals: T Pyx, CC Syg.

1 Introductory Overview

The white dwarfs in cataclysmic variables (hereafter CVWD) are the central engines of the observed outbursts, either as potential wells for the release of gravitational energy during accretion (dwarf nova - DN), or as the sites of explosive thermonuclear runaway (TNR) shell burning (classical novae), steady shell burning (supersoft X-ray binaries) or instantaneous collapse and total thermonuclear detonation if the WD reaches the Chandrasekhar limit (Type Ia supernova? SN Ia). Therefore, the accreting WDs serve as probes of explosive evolution and accretion physics and diffusion, as they bear the thermal, chemical and rotational imprint of their long term accretion and thermonuclear history (Sion 1991 & 1995; Townsley & Bildsten 2003; Townsley & Gänsicke 2009).

Deeper physical insights however require a larger number of chemical abundances, rotation rates, surface temperatures, mass accretion rates, and masses for each spectroscopic subclass of CVs. Only then can any definitive conclusions be drawn. In order to adequately sample the parameter space (M_{wd}, i, $\dot{M}$, T_{eff}, P_{orb}) of the DNs, Nova-like variables, and magnetic CVs, a large GO program was approved in Cycle 20 (B.Gänsicke, Principal Investigator) to secure high quality COS spectra for CV classes underrepresented in the current overall CV sample. The data is in hand and undergoing analysis at the time of this writing. Ultimately, we hope to obtain data for > 30 CVs per class. Therefore, in this review our focus is restricted to white dwarf surface temperatures, since in the area of chemical abundances, rotation rates, WD masses and accretion rates, relatively little has changed since our last review in the 2011 Palermo meeting proceedings. In section 2, our FUV analysis techniques are briefly summarized, section 3 we address how the revised (shorter) distance to SS Cygni affects the results of our analysis of the FUSE + HST STIS spectra of SS Cygni by Sion et al. (2010), in section 4 we tabulate and display the current distribution of CVWD surface temperatures versus orbital period and in the final section, we include some remarks on new HST spectra of the recurrent nova T Pyxidis.

2 Synthetic Spectral Analysis of FUV Spectra of CVWDs

We have modeled the FUV spectra of WDs in CVs during DN quiescence and Nova-like low states from IUE, FUSE and HST (FOS, GHRS, STIS, COS) archival data, and through our ongoing collaboration with past HST surveys led by B.Gänsicke, and P. Szkody.

The IUE archival spectra and high quality FUSE and HST FUV data are fit with the latest versions of the TLUSTY/SYNSPEC model photosphere code and model accretion disk codes (Hubeny 1988; Hubeny & Lanz 1995). We are taking into account the BL explicitly in our modeling of the FUV spectra of disk accreting systems, by replacing the very inner rings of the standard accretion disk model with high temperature rings in agreement with the temperature and density in the boundary layer. This improves the model fitting at the shorter wavelengths. As an example of our CVWD photosphere fitting, in Fig.1, we display a WD solar composition fit to the HST STIS spectrum of V442 Cen with E(B-V) = 0.10. The WD model has T=47,000K ±2000K and $Log(g) = 8.3 \pm 0.2$, $V_{sin(i)}$ = 300km/s ±50 km/s (Sion et al. 2008).

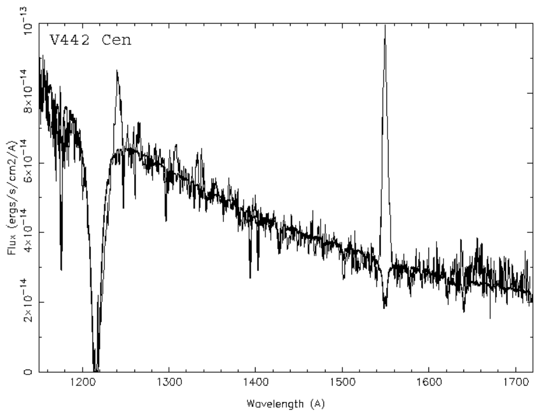

Figure 1: The best-fitting single temperature WD fit to the HST/STIS spectrum of V442 Cen. The model consists of a 47,000K WD with Log(g)=8.3 and scaled to a distance of 328pc.

3 The White Dwarf in SS Cygni:The VLBI and Corrected Hubble FGS Distance

Schreiber & Lasota (2007), and references therein, pointed out that the previously published Hubble FGS parallax of SS Cygni, with a distance of 166 +/- 12 pc, posed serious problems for the disc instability model (DIM) of dwarf nova outbursts because it would fail to explain the absolute magnitude during outburst. With the new VLBI-derived distance (Miller-Jones et al. 2013) to SS Cygni (114 pc), and the corrected HST distance (Nelan & Bond 2013) of 120 pc instead of 166 pc, the concern for the validity of DIM is alleviated. An obvious question is: How does the new, shorter distance affect the analysis of Sion et al. (2010) regarding their detection of the WD during quiescence and their derivation of the WD's surface temperature from the modeling of FUSE + HST STIS spectra?

To answer this question, we have carried out model fits using the new distance in the range of 114 pc to 120 pc. When we used single, steady state disk models, we obtained the same results as in Sion et al. (2010). The disk does not fit the flux in the shorter wavelengths unless the accretion rate is very large, which is inconsistent with dwarf nova quiescence, and the model-derived distance is far too large. When we combined a model disk with a model white dwarf photosphere (using the Bitner et al. WD mass as in Sion et al. (2010), the correct distance to SS Cygni was obtained for a low accretion rate and a lower temperature white dwarf. However, the fits with the WD + disk are inferior to the fits where the WD dominates the FUV flux. In order to match the best fit solution to the FUSE + HST STIS wavelength range in Sion et al. (2010), the white dwarf must have T_{eff} = 45000K - 50000K for a distance of 112 pc to 120 pc and a white dwarf mass $M_{wd} = 0.95 M_{\odot}$. This value of the WD mass is within the error range of the Bitner et al. mass. Our conclusion about the T_{eff} of the WD in SS Cygni during quiescence is essentially unchanged from Sion et al. (2010).

4 The Current Distribution of CV White Dwarf Surface Temperatures Versus Orbital Period

The effective temperatures T_{eff} of the WDs (obtained during dwarf nova quiescence and nova-like low states when the WD is exposed), are the critical key to revealing the thermal response of the WD to mass accretion and the long term accretion rate $< \dot{M} >$ which, through compressional heating by the accreted material, is linked to the WD surface temperature (Sion 1995; Townsley & Bildsten 2003; Townsley & Gänsicke 2009).

In Table 1, we have tabulated what we regard as the most reliably secured WD surface temperatures. The first column gives the name of the CV, the second column the CV subtype, the third column, the orbital period in minutes, the fifth column the WD T_{eff} and the sixth column, the reference for the temperature. These temperatures are derived from a variety FUV spectra and all are known with a precision of at least 3000K and in the majority of cases, better that +/- 2000K. With the paucity of FUV-derived temperatures per CV subclass, one should not ignore usable FUV data from IUE, FUSE and HUT because the "quality" of the data is deemed inferior to HST STIS and COS.

The current distribution of WD T_{eff} against the orbital period P_{orb} is displayed in Fig.2. (see also Fig.4 in Townsley & Gänsicke 2009). Note the continued relatively sparse coverage in temperature of the WDs in CVs above the period gap ($P_{orb} > 3hr$), compared with the coverage below the period gap.

It is possible that the apparent trend toward higher temperatures with increasing P_{orb} (i.e. higher long term average $< \dot{M} >$) could be due to observational selection since the WD T_{eff}'s were derived primarily in the FUV where the Planckian peak occurs for hotter accreting WDs. For example, Copperwheat et al. (2010) derive a $T_{eff} = 10 - 15,000$K in the optical for the WD in the eclipsing DN IP Peg which has P_{orb} = 3.8 h while the eclipsing system SDSS1006 with P_{orb} = 4.46 h, has $T_{eff} = 16,500 \pm 2000$K (Southworth et al. 2009) in the optical. Both of these objects should contain much hotter WDs (higher $< \dot{M} >$) for their orbital periods.

Table 1: The temperature of CV white dwarfs

SYSTEM	CV TYPE	P_{orb} (h)	T_{eff} (K)	REF
SDSS1507	DN/SU	1.11	11000	Szkody et al. (2010a)
GW Lib	DN/WZ	1.280	14700	Szkody et al. (2002a)
BW Scl	DN?	1.304	14800	Gänsicke et al. (2005)
LL And	DN/WZ	1.321	14300	Howell et al. (2002)
PQ And	DN/SU	1.34	12000	Szkody et al. (2010a)
EF Eri	AM	1.350	9500	Szkody et al. (2010b)
SDSS J1610-0102	DN?	1.34	14500	Szkody et al. (2007)
V455 And	DN/SU	1.35	10500	Szkody et al. (2013)
HS2331+3905	DN	1.351	10500	Araujob-Betancor et al. (2005a)
AL Com	DN/WZ	1.361	16300	Szkody et al. (2003)
WZ Sge	DN/WZ	1.361	14900	Sion et al. (1995)
SW UMa	DN/SU	1.364	13900	Gänsicke et al. (2005)
SDSS0919	DN	1.36	13500	Szkody (2014)
SDSS1035	DN?	1.37	10500	Southworth et al. (2006); Littlefair et al. (2006b)
HV Vir	DN/WZ	1.370	13300	Szkody et al. (2002b)
SDSS1339	DN	1.38	12500	Szkody et al. (2010a)
SDSS2205	DN	1.38	15000	Szkody et al. (2010a)
WX Cet	DN/WZ	1.399	13500	Sion et al. (2003)
T Leo	DN/SU	1.41	16000	Hamilton & Sion (2004)
EG Cnc	DN/WZ	1.44	12300	Southworth et al. (2006)
XZ Eri	DN/SU	1.468	15000	Szkody et al. (2010a)
SDSS1514	DN	1.48	10000	Szkody (2014)
DP Leo	AM	1.497	13500	Schwope et al. (2002)
V347 Pav	AM	1.501	11800	Araujob-Betancor et al. (2005b)
BC UMa	DN/SU	1.503	15200	Gänsicke et al. (2005)
EK TrA	DN/SU	1.509	18000	Godon et al. (2008)
VY Aqr	DN/WZ	1.514	14500	Sion et al. (2003)
OY Car	DN/SU	1.515	15000	Cheng et al. (2000)
SDSS0131	DN/SU	1.63	14500	Szkody et al. (2010a)
VV Pup	AM	1.674	11900	Araujob-Betancor et al. (2005b)
V834 Cen	AM	1.692	14300	Araujob-Betancor et al. (2005b)
HT Cas	DN/SU	1.768	14000	Wood et al. (1992)
VW Hyi	DN/SU	1.783	22000	Godon et al. (2008)
CU Vel	DN/SU	1.88	18500	Gänsicke & Koester (1999)
MR Ser	AM	1.891	14200	Araujob-Betancor et al. (2005b)
BL Hyi	AM	1.894	13300	Araujob-Betancor et al. (2005b)
ST LMi	AM	1.898	10800	Araujob-Betancor et al. (2005b)
AR UMa	AM	1.93	20000	Schmidt et al. (2005)
REJ1225	DN/SU	1.99	12000	Szkody et al. (2010a)
EF Peg	DN/WZ	2.01	16600	Howell et al. (2002)
DV UMa	DN/SU	2.138	20000	Feline et al. (2004)
HU Aqr	AM	2.084	14000	Gänsicke (1999)
QS Tel	AM	2.332	17500	Rosen et al. (2001)
SDSS J1702+3229	DN/SU	2.402	17000	Littlefair et al. (2006a)
TU Men	DN	2.813	28000	Sion et al. (2008)
AM Her	AM	3.094	19800	Gänsicke et al. (1995)
MV Lyr	NL/VY	3.176	45000	Godon et al. (2012)
DW UMa	NL/VY	3.279	50000	Araujob-Betancor et al. (2003)
TT Ari	NL/VY	3.301	39000	Gänsicke et al. (1999)
IP Peg	DN	3.80	15000	Southworth et al. (2009)
VY Scl	NL	3.99	45000	Hamilton & Sion (2008)
V1043 Cen	AM	4.190	15000	Araujob-Betancor et al. (2005a)
WW Cet	DN	4.220	26000	Godon et al. (2008)
UGem	DN/UG	4.246	30000	Sion et al. (2001)
SSAur	DN/UG	4.391	34000	Godon et al. (2012)
SDSS1006	DN	4.46	16500	Southworth et al. (2009)
V895 Cen	AM	4.765	14000	Araujob-Betancor et al. (2005b)
RX And	DN/ZC	5.037	34000	Sion et al. (2001)
SS Cyg	DN/UG	6.60	47000	Sion et al. (2010)
VY Scl	NL	3.99	45000	Hamilton & Sion (2008)
EM Cyg	DN/ZC	6.98	40000	Godon et al. (2012)
TT Crt	DN	7.30	29000	Sion et al. (2008)
RU Peg	DN	8.99	70000	Godon et al. (2012)
V442 Cen	DN	11.04	47000	Sion et al. (2008)

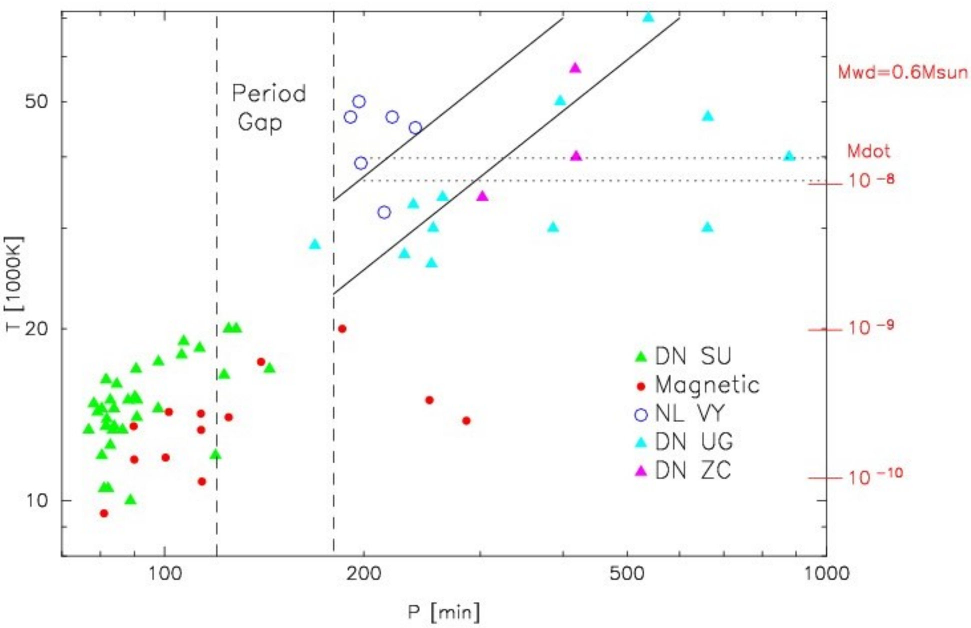

Figure 2: Effective White Dwarf Temperature as a function of the orbital period. The references for the indivdual temperatures can be found in Sion et al. 2008, Townsley & Gänsicke 2009, Araujo-Betancor 2005a & b and references therein). The traditional magnetic braking above the period gap is shown between the parallel diagonal solid lines. On the right hand side are the time-averaged accretion rates correpsonding to the temperature scale on the left hand side of the diagram. Shown for comparison between the dotted lines is the long term evolutionary path of a 0.8 solar mass white dwarf (with an initial core temperature of 30 million degrees K) which has undergone 1000 nova outburst cycles accreting at the long term rate of $10^{-8} M_{\odot}$/yr

5 The HST COS + STIS Spectra of the Recurrent Nova T Pyxidis:A Progress Report

The interstellar reddening E(B-V) of the recurrent nova T Pyxidis is a critical parameter in the determination of the best-fitting model parameters.

The UV spectra exhibit a minimum near 2175 A which is due to the interstellar extinction. Since the GALEX spectrum is the most reliable (i.e. highest S/N ratio) in that wavelength region, we used the GALEX spectrum to determine E(B-V). The value of E(B-V) for which the 2175 A feature disappears from the dereddened spectrum, E(B-V)=0.35, is taken as the E(B- V) value towards T Pyx (see Fig.3). We use this value to deredden the IUE, GALEX and HST spectra, and we also consider the effects of different reddening values on our results.

The HST STIS and COS spectra obtained in December 2012 and July 2013 are identical. Thus, we co-added them to improve the signal-to-noise (S/N). We have found that the pre-outburst IUE and GALEX spectra together with the HST post-outburst spectrum. We note that the UV flux has remained constant not only before the outburst, but it has now come back precisely to the same value. This is an indication that

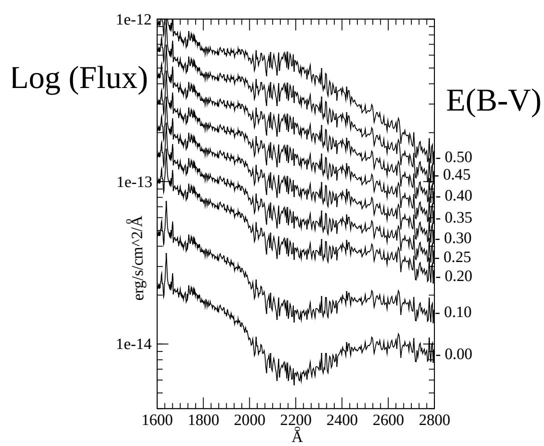

Figure 3: The merged Galex-IUE spectrum of T Pyx has been dereddened for different values of E(B-V) as indicated on the right. The 2175Å feature associated with the reddening is clearly seen in absoprtion for low balues of E(B-V), and it appears as extra flux for large values of E(B-V). We deduce that the reddening towards T Pyx must be E(B-V)=0.35, the value for which the 2175Å feature vanishes.

the mass accretion rate remained constant before and after the outburst (see Godon et al. 2014).

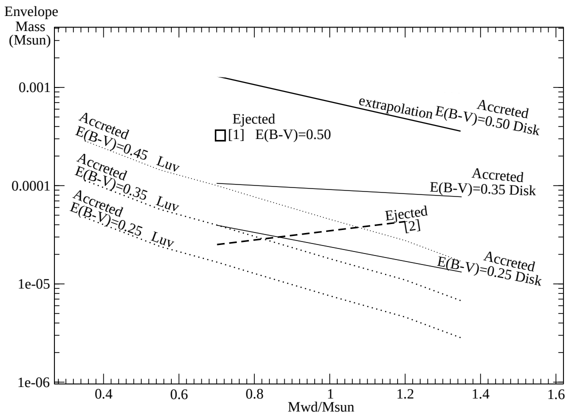

Figure 4: The mass of the accreted envelope and ejected envelope are shown as a function of the WD mass for different values of the reddening for T Pyx. Our disk model results are drawn with a solid line ("Disk"). The lower limit of the accreted envelope inferred from the UV flux is shown (dotted line, "Luv"). In comparison we show the ejected envelope [1] as estimated by Nelson et al. (2012) (square symbol), as well as [2] computed in Patterson et al. (2013) (dashed line). The accreted envelope is larger than the ejected envelope, except for a value of E(B-V)=0.25 *combined with* a WD mass $\sim 0.9 M_{\odot}$ and larger. However, the best results were obtained for a larger value of the reddening $E(B-V) > 0.30$.

Using the value of the reddening we derived, together with the new distance estimate of 4.8 kpc (Sokoloski et al. 2013), we fit the observed (back-to-quiescence) HST spectra with disk models for different WD masses. We then computed the accreted mass over a period of 44yrs, which we then compared to the estimates of the ejected envelope mass (during the 2011 outburst). We recapitulate our results in Fig.4, where we also consider different reddening values for the sake of completness. Our main finding is that the mass of the accreted material between the last two outbursts is larger than the mass of the ejected envelope in the last outbursts, unless the reddening is E(B-V)=0.25 (or smaller) *AND* the mass of the WD is $\sim 0.9 M_{\odot}$ or larger. However, such a small value of the reddening leads to a very bad fit and has therefore to be rejected.

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