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The instability strip for accreting pulsating white dwarfs as a probe for accretion heating/cooling

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Abstract. The presence of pulsating white dwarfs in close binaries that are accreting from a companion allow a unique probe of the effects of accretion on the white dwarf interior. The changing composition, increasing mass and rotation rate and elevated temperature due to the accretion differentiate the white dwarfs in these systems from ZZ Ceti stars. In addition, the infrequent outbursts of the systems with accreting white dwarfs provide the opportunity to follow the transition of these objects across the instability strip as they are heated by the outburst and subsequently cool on the order of years rather than the millenia required for evolutionary white dwarf cooling.

Key words. Novae, cataclysmic variables – Stars: white dwarfs

1. Introduction

Pulsating white dwarfs provide a unique opportunity to probe the stellar interior. Due to their uniform density, the non-radial pulsations penetrate the inner 99% of the star. Each independent pulsation frequency serves as a constraint on the stellar structure; detecting several frequencies is essential in obtaining a unique seismological fit. A unique model fit to the observed periods of the variable white dwarf can reveal information about the stellar mass, core composition, age, rotation rate, magnetic field strength, and distance. Thus, asteroseismology provides a very useful tool (Winget & Kepler 2008; Fontaine & Brassard 2008). Accreting, pulsating white dwarfs provide even further opporunities, as the effects of accretion on the interior can be explored. The white dwarfs in close binaries with mass transfer have generally higher temperatures than

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field white dwarfs (Sion 1999; Townsley & Gänsicke 2009), have increased rotation and are undergoing changes in their surface composition and stellar mass. Thus, we can identify three major questions for accreting white dwarf pulsators:

1. Where is the instability strip for accreting white dwarf pulsators versus that for non-accreting, hydrogen atmosphere white dwarfs (ZZ Ceti stars)?
2. What are the effects of outbursts (increased accretion rates and heating) on these objects?
3. How do mass, composition and spin affect the instability strip?

To answer these questions, we need ultraviolet spectra to accurately determine the temperature of the white dwarfs, outburst coverage to determine that an outburst has occured and to follow the white dwarf as it cools to quiescence, and high resolution spectra phased througout a binary orbit to determine masses from radial velocity curves and composition and rotation from model fitting. At the present time, there are 13 accreting, pulsating white dwarfs that have been identified from the presence of pulsations in their optical light curves. Many of these objects have been found by obtaining light curves of systems whose optical spectra show broad absorption lines from the white dwarf flanking the Balmer emission lines from the disk, indicating there is a significant contribution of the white dwarf compared to the accretion disk light. The Sloan Digital Sky Survey has been a good source of these spectra, as it was able to reach to the faint observed magnitudes that result when the accretion disk is not prominent (Szkody et al. 2007). However, due to the complicated optical line profiles and the larger contribution of the accretion disk in the optical, UV spectra and light curves are necessary. The Lyα region provides an optimum temperature fit in the wavelength region where the white dwarf dominates, and the pulsation amplitudes can be more than 10 times higher in the UV than the optical (Szkody et al. 2007).

2. Observations

UV spectra of 12 accreting pulsating WDs exist from HST observations from 2002-2011. The Space Telescope Imaging Spectrograph (STIS) was used in 2002 with grating G140L, providing spectra from 1150-1750Å with 1Å resolution in time-tag mode (Szkody et al. 2002; Araujo-Betancor et al. 2005). When this instrument failed, the Advanced Camera for Surveys (ACS) with the Solar Blind Channel was used in 2007-2008, providing lower resolution (6-40Å) spectra from 1200-1900Å with an integrating mode only (Szkody et al. 2007, 2010). Finally, after the repair mission, the Cosmic Origins Spectrograph (COS) was available for use in 2010-2011, providing increased sensitivity over STIS, and resolutions from 0.07-1Å with gratings G160M and G140L and time-tag mode (Uthas et al. (2011), Szkody et al. 2011, in preparation). These observations provide quiescent UV data on 12 systems.

3. The instability strip

The temperatures determined for the 12 systems are plotted in Figure 1, assuming a log g of 8.0 (0.6 solar mass). The uncertainties in temperature range from 500-1000K. The instability strip for ZZ Ceti stars determined by Gianninas et al. (2007) is shown by dashed lines. It is immediately apparent that the instability strip for the accreting white dwarfs is much wider than that for non-accreting, hydrogen white dwarfs. If the masses are higher, the temperature will increase slightly. For example, GW Lib fit with a temperature of 15,000K for log g=8 (0.6 $M_\odot$), becomes 16,000K for log g=8.7 (1 $M_\odot$), but it still remains far beyond the ZZ Ceti strip. Arras et al. (2006) find a H/HeI instability strip for accreting model white dwarfs with a blue edge near 12000 K for a 0.6 $M_\odot$ star, similar to the ZZ Ceti instability strip. They also find an additional hotter instability strip at $\sim$15000 K due to HeII ionization for accreting model white dwarfs with a high He abundance (> 0.38). While the instability strip for accretors suffers from small number statistics, our observations are consistent with this theoretical picture.

However, a complicating factor is that several other accreting white dwarfs for which UV spectra have been obtained show temperature in this same range (see summary of temperatures in Townsley & Gänsicke 2009) but these objects show no evidence of pulsations. Thus, the question is why only some of the white dwarfs are unstable. One reason for the lack of pulsation could be the dwarf novae outbursts, which heat the white dwarf (Godon et al. 2006). This could move them out of the instability strip and cause the pulsations to cease. However, this would mean that many of the temperature measurements were made when the white dwarfs were hotter than quiescence, even though their optical magnitudes were at quiescent values.

4. Effects of the outburst

The outburst situation provides an advantageous opportunity to study the changes to the interior of the white dwarf due to the increased accretional heating. Based on the cooling curves of dwarf novae (Godon et al. 2006), the white dwarfs should cool after outburst heating on timescales of 3-4 years. Thus, the expectation is that the pulsations should cease when the heated white dwarf moves out of its instability strip, and then resume when it re-enters. As the temperature crosses the blue edge, the pulsations should restart at shorter periods than observed at quiescence and progressively become longer as the thermal timescale at the base of the convection zone moves deeper into the star during the cooling. The prime advantage of accreting pulsating white dwarfs is that the cooling can be studied in only a few years, in contrast to ZZ Ceti stars, which take millions of years to cool by evolution.

Of the 13 known systems, eight have recorded outbursts. These are summarized in Table 1. Three systems had outbursts in 2006-2007 which were followed with HST and ground observations (GW Lib, V455 And and SDSSJ0745+45). Table 2 summarizes the basic properties of these 3 systems.

4.1. GW Lib

GW Lib is the first known accreting pulsator (Warner & van Zyl 1998) and was observed extensively prior to its 2007 outburst (Van Zyl et al. 2004). It is a low inclination (i=11° system with a relatively massive white dwarf ($\sim$1$M_\odot$, Steeghs et al. 2007) and a quiescent magnitude of V=17. During quiescence, it showed 3 prominent pulsation periods at 646, 376 and 237 seconds and these same periods were present with higher amplitudes during HST observations with STIS (Szkody et al. 2002). After outburst, GW Lib was followed with ground-based optical data, as well as with ultraviolet satellites using *GALEX* (Bullock et al. 2011) and COS. The HST data were obtained in March, 2010 and April, 2011, 3 and 4 years after outburst. AAVSO data shown in Copperwheat et al. (2009) reveal that after its outburst, which peaked near V=8 mag, it took about 23 days to reach mag 11, then it declined to 14th mag in 4 days, followed by a slow decline to V=16 in 50 days. Currently, at 4 years past outburst, GW Lib remains a few tenths above its quiescent magnitude.

An optical spectrum obtained one year after outburst (Bullock et al. 2011) showed a temperature near 23,000K, while the STIS spectrum at quiescence (Szkody et al. 2002) is best fit with a 16,000K (log g=8.7) white dwarf. In contrast, the COS data at 3 and 4 years past outburst fit white dwarf temperatures of 19,700K and 17,300K respectively.

The optical light curves showed a puzzling 19 min period from Mar-June 2008 (Copperwheat et al. 2009; Schwieterman et al. 2010; Bullock et al. 2011; Vican et al. 2011) that was attributed to the disk since it was more like a QPO than a non-radial pulsation. This period was not evident in the *GALEX* data (Bullock et al. 2011). These groups reported that at 3 years past outburst, there was still no significant evidence of non-radial pulsations. However, the COS time-tag data reveal a significant triplet with periods of 282, 288, and 292 s (amplitude of 20 mma) in March, 2010. In April 2011, we observed a period close to 293 s with an increased amplitude of 40 mma. These periods are quite different than

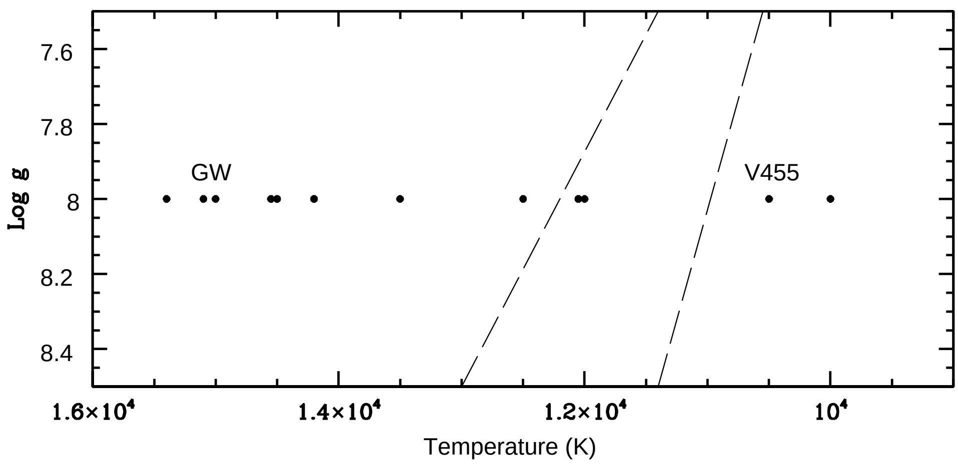

Fig. 1. Temperatures of accreting pulsating white dwarfs at quiescence determined from HST spectra and modeled with log g=8.0. GW Lib and V455 And are labeled. The dashed lines mark the instability strip for DA white dwarfs from Gianninas et al. (2007).

Table 1. Known Outbursts of Accreting White Dwarfs

Star	Outburst Year	Amp (mag)
PQ And	1938, 1967, 1988, 2010	10
GW Lib	1983, 2007	9
V455 And	2007	7.5
REJ1255+26	1994	...
SDSSJ0745+45	2006	> 5
SDSSJ0804+51	2006, 2010	5
SDSSJ1339+48	2011	7.2
SDSSJ2205+11	2011	5.6

the quiescent pulsation spectrum observed in the pre-outburst STIS data. The first indication of a possible pulsation in optical data appeared in April 2011 during our 4-day July observing run at Mt. John observatory, when periods in the range of 281-300s were visible with an amplitude of 10 mma. The Mt. John data obtained in March 2011 did not show this feature, and further data from Mt. John between July 27 and August 2 also did not show any significant period near this value so the amplitude may be highly variable.

4.2. V455 And

V455 And (HS2331+3905) was studied in the optical and ultraviolet (STIS) regimes during quiescence by Araujo-Betancor et al. (2005). It is a bright (V=16.4 mag) but complicated system, showing a spin period of the white dwarf at 67.6s, an eclipse which gives an orbital period of 81 min, a photometric period at 83 min likely due to superhumps, and a broad group of periods between 300-360 min which are attributed to non-radial pulsations. The COS data after outburst took place in

Table 2. System Properties

Object	P_{orb}(min)	i (deg)	P_{spin}(s)	M_{wd} ($M_{\odot}$)	T_{wd}(°K)
GW Lib	76	11	209	1.0	16,000
V455 And	81	75	67	0.6	10,600
SDSSJ0745+45	78	...	...	...	15,100

Table 3. Comparison of Objects at 3 yrs Past Outburst

Star	$(T_3 - T_0)/T_0$	$(P_3 - P_0/P_0)$
SDSSJ0745	< 0.06	< 0.002
V455 And	0.05	−0.19
GW Lib	0.23	−0.23

October 2010 and September 2011, 3 and 4 years after its outburst. The AAVSO data show it took about 19 days to reach the end of its plateau phase at 12th mag, then a steep drop to 14th mag by day 21 followed by a slow decline to V=15 by 40 days. Like GW Lib, V455 And currently remains a few tenths of a magnitude brighter than its pre-outburst magnitude.

After 3 years, the COS spectra are fit with a white dwarf temperature of 11,100K, only 500K hotter than the fit from the quiescent STIS spectrum (10,600K). At 4 years past outburst, the white dwarf was still a couple hundred degrees hotter than quiescence. Thus, while the temperature increase was not as large as in GW Lib, the time to return completely to quiescence in the ultraviolet and optical is also longer than 4 years. The optical light curves show a progressive return of the various periodicities of V455 And (Pyrzas et al. 2011, in preparation). First to appear was the first harmonic of the spin period, which emerged as early as October 8, about 1 month past outburst. By October 17, the 67.6s spin was also apparent, although the first harmonic remained stronger. By September 2008, the spin and harmonic were of comparable amplitudes. At 2 years past outburst, a strong peak (18 mma) was visible in the optical Discrete Fourier Transform at 250-263s and at 3 years, the range of periods increased to 269-284s, while the amplitude decreased to 8 mma. The HST ultraviolet data at 3 years past outburst shows a very high amplitude (140 mma) spin and first harmonic, as well as a strong (50 mma) peak at 274 s. As in the optical, at 4 years, the UV amplitudes for both spin and possible pulse are lower. If the non-coherent peaks at 250-284s are indeed the return of the non-radial pulsations (the most plausible explanation), the periods are noticeably shorter than pre-outburst (as expected for a cooling white dwarf).

4.3. SDSSJ0745+4538

The only outburst of this object was partially observed by the Catalina Sky Survey (Drake et al. 2009) as it returned to quiescence. Thus, we only know that the outburst was brighter by more than 5 magnitudes than its quiescent magnitude of 19.0. Optical data at quiescence identified non-radial pulsations of high amplitude (45-70mma) in the range of 1166-1290s (Mukadam et al. 2007). HST SBC spectra obtained one year after its outburst showed a temperature of 17,000K (Szkody et al. 2010) with no indications of pulsations in the UV nor optical at that time. Due to bad weather, followup observations were lost at a 2 year timescale but at 3 years past outburst, optical data showed the pulsations had returned at exactly the same period range (within the uncertainties of 1-2s) as pre-outburst (Mukdadam et al. 2010). The limits on the period change provide a constraint on the temperature change at the base of the convection zone of <0.6%. However, optical and HST COS data in March 2011 showed no significant pulsations with no evident outburst since the one in 2006. The temperature derived from the COS data is 15,100K, ~2000K cooler than the 2007 data. The intermittent nature of the pulsations here (and also in GW Lib) remains a puzzle as to whether small changes in accretion rate (without noticeably affecting the optical magnitude) can cause the disappearance of the pulsations, or whether some outbursts could be missed while the object is behind the sun. However, a missed outburst would create a brighter optical magnitude for several months past the outburst, which is not observed.

5. Conclusions

A comparison of the 3 systems at 3 years past outburst is given in Table 3, which lists the ratios of the temperature and pulsation period differences at 3 years past outburst (T_3,P_3) compared to quiescent values (T_0,$P_)$). Perusal of this table shows a possible trend of larger shortening of period with greater temperature. While SDSSJ0745 and V455 And are at or slightly above their quiescent temperatures at 3 years past outburst, they show the smallest differences in the periodicities that are present i.e. SDSSJ0745 shows the same periods as prior to outburst, while V455 And reveals shorter periods. In the same vein, GW Lib, with the largest difference in its post-outburst to pre-outburst periods, remained the most heated at 3 years after its outburst. At the present time, we have some answers regarding accreting pulsating white dwarfs, but many questions remain. We know the instability strip is much wider than for non-accreting hydrogen white dwarfs (ZZ Ceti) but we do not know why all objects with temperatures within the wider strip do not show pulsations. We know that pulsations can return at the same or shorter periods in the white dwarfs that are cooling after outburst and that the cooling times can vary. The intermittent nature of the appearance of the pulsations during supposed quiescence is not understood. The large range of parameters of mass, spin and temperature for the white dwarfs in these 3 objects (Table 2), as well as the differing inclinations that affect our view of the white dwarf could contribute to the wide range of post-outburst observed differences in their cooling curves and the return of the pulsations seen at quiescence. It will take many more observations over long timespans to sort out the cause of all these differences.

6. Discussion

DMITRY KONONOV: What, in your opinion, can cause such powerful outbursts in these systems implying very low mass transfer rates? Is it only accretion or, say, nuclear burning?
PAULA SZKODY: While nuclear burning was suggested many years ago, it was discounted as EUV observations did not support the high temperatures. John Cannizzo has been successful in modeling the very low mass transfer systems with extremely large outburst amplitudes (called TOADs), with an accetion disk instability (see 1995 ApJ, 439, 337).

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References

Araujo-Betancor, S. et al. 2005, A&A, 430, 629
Arras, P., Townsley, D. M. & Bildsten, L. 2006, ApJ, 643, L119
Bullock, E. et al. 2011, AJ, 141, 84
Copperwheat, C. M. et al. 2009, MNRAS, 393, 157
Drake, A. J. et al. 2009, ApJ, 696, 870
Fontaine, H. & Brassard, P. 2008, PASP, 120, 1043
Gianninas, A., Bergeron, P. & Fontaine, G. 2007, ASPCS, 372, 577

Godon, P. et al. 2006, ApJ, 642, 1018
Mukadam, A. S. et al. 2007, ApJ, 667, 433
Mukadam, A. S. et al. 2011, ApJ, 728, 33L
Schwieterman, E. W. et al. 2010, JSARA, 3, 6
Sion, E. M. 1999, PASP, 111, 532
Steeghs, D. et al. 2007, ApJ, 667, 442
Szkody, P., Gänsicke, B. T., Howell, S. B., & Sion, E. M. 2002, ApJ, 575, 79
Szkody, P., et al. 2007, ApJ, 658, 1188
Szkody, P. et al. 2010, ApJ, 710, 64
Townsley, D. M. & Gänsicke, B. T. 2009, ApJ, 693, 1007
Uthas, H. et al. 2011, MNRAS, 414, 85L
Van Zyl, L. et al. 2004, MNRAS, 350, 307
Vican, L. et al. 2011, PASP, 123, 1156
Warner, B. & van Zyl, L. 1998, IAU Symp. 185, 321
Winget, D. E. & Kepler, S. O. 2008, ARA&A, 46, 157