Singing and Dancing White Dwarfs

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Abstract. Accreting white dwarfs have recently been shown to exhibit non-radial pulsations similar to their non-interacting counterparts. This allows us to probe the interior of the accreting white dwarf using seismology, and may be the only way to determine masses for non-eclipsing cataclysmic variables. Improving our understanding of accreting white dwarfs will have implications for models of supernovae Type Ia. Pulsating white dwarfs in cataclysmic variables are also useful in establishing the effects of accretion on pulsations.

A search for nonradial pulsations among suitable candidates has led to the discovery of twelve such systems known to date. With the goal of establishing an instability strip (or strips) for these pulsating accretors, we acquired HST ultra-violet time-series spectroscopy of six pulsating white dwarfs in cataclysmic variables in 2007 and 2008. This approach enables us to measure the effective temperature of the white dwarf using the co-added spectrum, and to simultaneously characterize the pulsations. We also intended to constrain the pulsation mode identification by comparing the ultra-violet amplitudes to those from near-simultaneous ground-based photometry. Our preliminary results indicate a broad instability strip in the temperature range of 10500–15400 K.

1. Introduction to accreting white dwarf pulsators

Cataclysmic variables are close binary systems in which a late-type star (secondary) fills its Roche lobe and transfers mass through the inner Lagrangian point to a white dwarf (primary). GW Librae was the first cataclysmic variable discovered in 1998 with an accreting white dwarf showing photometric variations consistent with nonradial g-mode pulsations (van Zyl et al. 2000, 2004), typically observed in non-interacting white dwarf stars. This discovery has opened a new venue of opportunity to learn about the stellar parameters of accreting variable white dwarfs using asteroseismic techniques (Townsley, Arras, & Bildsten 2004). 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 (see the review paper Winget 1998). There are now twelve accreting pulsating white dwarfs known to date.

The optical spectrum of an accreting pulsator includes prominent broad absorption lines from the white dwarf as well as the central narrow emission features from the accretion disk. When the orbital period of a cataclysmic variable is ~80-90 min, it is near the evolutionary orbital period minimum, where the rate of mass transfer is very low ~ 10^{-13} M_☉/yr (e.g. Gänscicke et al. 2006). The low rates of mass transfer allow a larger surface area of the white dwarf to be visible; 90% of the optical light is dominated by the white dwarf in these systems.
Accreting pulsators have probably undergone a few billion years of accretion and thousands of thermonuclear runaways. Studying these systems will allow us to address the following questions: to what extent does accretion affect the white dwarf mass, temperature, and composition and how efficiently is angular momentum transferred into the core of the white dwarf. White dwarf rotation rates constrain models of Type Ia supernovae (e.g. Piersanti et al. 2003), and also play a role in the formation of millisecond pulsars and gamma-ray bursts from collapsing white dwarfs (Yoon & Langer 2005). Accreting white dwarfs with sufficient angular momentum may be detectable sources of gravitational waves with frequencies of 0.1-1.0 Hz by the Laser Interferometer Space Antenna (Yoon & Langer 2004). Accreting pulsators in non-eclipsing cataclysmic variables may prove to be our only opportunity to obtain meaningful mass constraints for the primary white dwarfs. Constraining the population, mass distribution, and evolution of accreting white dwarfs is also important for studying supernovae Type Ia systematics.

2. Theoretical background: expected instability strip(s) for accreting pulsators
Arras et al. (2006) investigate the temperature range in which models of accreting white dwarfs with a wide range of masses and Helium enrichment from the donor star would be pulsationally unstable. They find a H/HeI instability strip for accreting model white dwarfs with a blue edge near $\leq 12000$ K for a 0.6 $M_\odot$ star. The blue edge shifts to hotter (cooler) temperatures by about 2000 K for a factor of 10 increase (decrease) in gravity; we can expect the blue edge at 14000 K corresponding to log $g = 9$ and at 10000 K for log $g = 7$. This theoretical instability strip is similar to the ZZ Ceti instability strip. Non-interacting hydrogen atmosphere (DA) white dwarfs are observed to pulsate in a narrow instability strip located within the temperature range 10800–12300 K for log $g \approx 8$ (e.g. Bergeron et al. 1995, 2004; Koester & Holberg 2001; Gianninas et al. 2005), and are also known as the ZZ Ceti stars.

For accreting model white dwarfs with a high He abundance ($> 0.38$), Arras et al. (2006) find an additional hotter instability strip at $\approx 15000$ K due to HeII ionization. The boundaries of this intermediate instability strip depend on the Helium abundance and the mass of the accreting white dwarf. For a He abundance higher than 0.48, models of the H/HeI and HeII instability strips essentially merge. Arras et al. (2006) expect that there are thus two distinct instability strips for accreting model white dwarfs with a He abundance between about 0.38 and 0.48.

3. Theoretical background: nature of white dwarf pulsations
Each nonradial pulsation mode in a white dwarf can be described with a unique set of indices, similar to the quantum numbers that describe the state of a bound electron in the spherical electrostatic potential of a nucleus. Mode identification is essential in asteroseismology as we cannot determine the inner structure of variable stars without mode-indices. The nonradial luminosity variations observed in white dwarfs are almost entirely due to temperature fluctuations (Robinson, Kepler & Nather 1982). The stellar surface is divided into zones of higher and lower effective temperature, depending on the degree of spherical harmonic $\ell$. Since we cannot resolve the stellar disk, geometric cancellation results in smaller observable amplitudes for these modes. At ultra-violet (UV) wavelengths, the increased limb darkening decreases the contribution of zones near the limb. Hence modes with $\ell = 3$ are canceled less effectively in the UV compared to the low $\ell \leq 2$ modes. However $\ell=4$ modes do not show a significant change in amplitude as a function of wavelength. Robinson et al. (1995) suggested a new mode identification technique based on this effect. We obtained optical photometry on the accreting pulsators, nearly simultaneous with the HST UV data, with the intention of constraining the mode identification of the observed pulsation periods.
4. Data acquisition & reduction

We acquired five orbits of HST UV time-series spectroscopy for each accreting pulsator using the Solar Blind Channel (SBC) on the Advanced Camera for Surveys (ACS). With exposure times of approximately 61 s and a dead time of 40 s, yields a time resolution of 101 s. Our wavelength coverage is approximately 1200 to 1960 Å. The dispersion varies from about 1.5 Å/pixel at the far blue end to about 25 Å/pixel at the red end. The first orbit of each target has typically 26 integrations (due to the initial overhead of setting up) and the remaining four orbits contain 29 integrations; each light curve has \( \sim 142 \) points.

We analyzed the time-series spectra using the software package aXe1.4. Summing the individual spectra yields a high S/N total spectrum, while summing over wavelength yields light curves that reveal the pulsation characteristics of the targeted accreting white dwarf. We used a fixed extraction width of \( \pm 17 \) pixels, corresponding to \( \pm 0.5 \) arcsecond from the dispersion axis, to obtain the co-added spectrum for each accreting pulsator. This gives us a uniform basis for flux calibration. To extract the light curves (differential photometry), we determined the optimal extraction width and wavelength range that gave us the least noise. We converted the mid-exposure times of the individual spectra to Barycentric Coordinated Time (TCB; Standish 1998). We computed the Discrete Fourier Transforms (DFTs) of the extracted light curves and conducted a least squares analysis of all those that showed signs of variability. The detected orbital and pulsation-related periods are shown in Table 1 for the observed systems with the corresponding wavelength range we used to determine the light curves.

| Accreting Pulsator | UT Date of Observation | Prism | Wavelength Range (Å) | Observed Periods |
|--------------------|------------------------|-------|----------------------|-----------------|
| PQ And             | 13 September 2007      | PR110L | 1200–1820            |                 |
| SDSS J0745+4538    | 1 November 2007        | PR110L | 1240–1910            |                 |
| SDSS J0919+0857    | 14–15 November 2007    | PR130L | 1226–1955            | 40.75 min       |
| REJ J255+266       | 14 May 2008            | PR110L | 1340–1885            |                 |
| SDSS J1339+4847    | 25 January 2008        | PR130L | 1245–1955            | 210.3 s, 229.6 s|
| SDSS J1514+4549    | 8 May 2008             | PR130L | 1324–1935            |                 |

5. Modeling the HST spectra

We model the HST UV spectra of these cataclysmic variables as a combination of the underlying white dwarf, the accretion disk, and a source of emission lines (e.g. Gänsicke et al. 2005). We use Hubeny white dwarf LTE models TLUSTY195 and SYNSPEC46 (Hubeny & Lanz 1995; Lanz & Hubeny 1995), consisting of a grid of temperatures, gravities, and abundances. Fixing the mass of the white dwarf to about 0.6 M\(_\odot\) corresponding to log \( g = 8 \), and the solar abundance at 0.01, we require that the best-fit white dwarf model must match the UV continuum shape, especially the broad Ly\(\alpha\) line, and its optical flux must fall below the observed optical fluxes. In the absence of reliable models of a non-steady state disk at low mass transfer rates, we model the disk as a simple black body, adding in emission lines as Gaussian functions. Our temperature determinations for the observed accreting white dwarfs are shown in Table 2; we also indicate whether they were pulsating at the time of acquisition of the spectrum or not. We also include the best-fit temperatures of GW Librae, V455 And, SDSS J0131-0901, SDSS J1610-0102, and SDSS J2205+1155 for completeness, calculated using a similar approach (Araujo-Betancor et al. 2005; Szkody et al. 2007). Defining the instability strip for accretors requires a statistically significant sample, but our preliminary results suggest a broad strip in the range of 10500–15400 K.
Table 2. Temperatures of the accreting white dwarfs from HST Spectroscopy

| Accreting White Dwarf | $T_{\text{eff}}$ (K) | Pulsating During Spectroscopy |
|-----------------------|----------------------|------------------------------|
| V455 And              | 10500 ± 1000         | Yes                          |
| PQ And                | 12000 ± 1000         | Ambiguous                    |
| REJ 1255+266          | 12000 ± 1000         | Ambiguous                    |
| SDSS J1339+4847       | 12500 ± 1000         | Yes                          |
| SDSS J0919+0857       | 13500 ± 1000         | No                           |
| SDSS J1610-0102       | 14500 ± 1000         | Yes                          |
| SDSS J0131-0901       | 14500 ± 1000         | Yes                          |
| SDSS J2205+1155       | 15000 ± 1000         | Yes                          |
| GW Librae             | 15400 ± 1000         | Yes                          |
| SDSS J0745+4538       | 16500 ± 1000         | No                           |

6. Data analysis for observed accreting pulsators

6.1. PQ And

The HST UV light curves we extracted for PQ And do not reveal any sign of pulsations (see Figure 1). However, simultaneous optical data acquired on September 13 reveal two periods at 1285±10 s and 2337±30 s with amplitudes close to 20 mma. The 2337 s period is beyond the typical range of ZZ Ceti pulsation periods of 70–1400 s, and may well be flickering noise as it does not show up in optical observations from September 15 and 19. The optical data from September 15 show a period at 1309±13 s, while that from September 19 show a period at 1301±13 s. Given the large uncertainties of these poor time resolution data (exposure time $\sim$180 s) acquired using 1 m class telescopes, the 1300 s period appears to be persistent for 6 days and is unlikely to be caused by flickering. We expect that for $\ell=1$ or $\ell=2$ modes, typically observed in pulsating white dwarfs, the UV amplitudes should be significantly higher than the optical amplitudes. The absence of the 1300 s from the HST UV data suggests that it is either a high $\ell$ mode or not related to nonradial pulsation.

![Figure 1](https://example.com/figure1.png)

Figure 1. Comparing the HST UV DFT to simultaneous optical data on PQ And.
6.2. **SDSS J0745+4538**

The HST UV data acquired on 1 November 2007 and the optical data acquired on four consecutive nights from 30th October to 2nd November 2007 reveal no sign of the large amplitude pulsations (see Figure 2 below), previously reported by Mukadam et al. (2007). The optical light curves prominently display the orbital period of about 85.8 min with harmonics. We found that this star had undergone an outburst around October 2006 when its brightness increased by five orders of magnitude; this event was recorded by the Catalina Sky Survey (Figure 3). The white dwarf is heated to high temperatures well beyond the instability strip during such an outburst, and we expect the pulsations to cease. Godon et al. (2006) obtained a far UV spectrum of the dwarf nova WZ Sge three years after its superoutburst of 2001, and found the white dwarf was still \( \sim 1500 \) K above its quiescent temperature. Light curves of SDSS J0745+4538 may reveal pulsations again by 2010.

![Figure 2. Optical data obtained on SDSS J0745+4538 reveal the cessation of previously observed pulsations in the accreting white dwarf.](image)

![Figure 3. The Catalina Sky Survey captured the Fall 2006 outburst of SDSS J0745+4538.](image)
6.3. **SDSS J0919+0857**

The HST UV observations acquired on SDSS J0919+0857 during 14–15 November 2007 reveal only a harmonic of the orbital period at 40.75 min (Figure 4). The DFT shows no signs of the previously observed nonradial pulsation period near 260 s (Mukadam et al. 2007). The optical data we acquired on 12 November 2007 also do not reveal any periods in the vicinity of 260 s above 4 mma. We are at a loss to comprehend why pulsations may have disappeared from this star. It is possible that due to accretion heating, the temperature of the white dwarf changed slightly, causing the white dwarf to move just beyond the blue edge of the instability strip.

![Figure 4](image)

**Figure 4.** The HST UV SDSS J0919+0857 data reveal the orbital modulation at 40.75 min. The window function shown is the DFT of a single noiseless sinusoid with the same time sampling as the data.

6.4. **REJ 1255+266**

Our HST UV data on REJ 1255+266 reveal only a long period at 1.9 hr, while the optical data reveal two shorter periods at 582.1 s and 654.5 s, both with similar amplitudes of 12–13 mma (Figure 5). This is the second case where short periods detected in the optical are not present in the UV data, suggesting that either we are dealing with high $\ell$ modes or not dealing with nonradial pulsations at all.

![Figure 5](image)

**Figure 5.** The HST UV data on REJ 1255+266 reveal no periods, although the optical data reveal two periods at 582.1 s and 654.5 s.
6.5. SDSS J1339+4847
The HST UV observations of SDSS J1339+4847 from 25 January 2008 reveal both high and low frequency variations (Figure 6). We observe a long period of 7.4 hr along with short periods at 229.6 s and 210.3 s, both close to the Nyquist frequency. We acquired optical data on SDSS J1339+4847 on 23 January 2008 for 1.5 hr. These data reveal the orbital period at 83.2 min, besides another long period at 1539 s above the 3σ limit. We suspect that the 1539 s period may have been caused by flickering as it lies beyond the typical ZZ Ceti pulsation period range of 70–1400 s. It is possible that the amplitudes of the 229.6 s and 210.3 s observed in the UV are below the detection limit in the optical. We expect typical pulsations modes with ℓ ≤ 2 to have significantly lower optical amplitudes compared to those in the UV. Both these modes cannot be the same ℓ if they are both real.

![Figure 6](image_url)

Figure 6. We show the HST UV light curve (top panel) and DFT (bottom panel) of SDSS J1339+4847 that reveal a long period at 7.4 hr besides two short periods close to the Nyquist frequency at 229.6 s and 210.3 s.

6.6. SDSS J1514+4549
We acquired HST observations of SDSS J1514+4549 on 8 May 2008 and optical observations on 7 May 2008; neither the UV nor the optical data reveal any periodicities. Since there is only a scarce amount of data published on SDSS J1514+4549 (see Nilsson et al. 2006), we strongly suggest that long-term observations of this object are necessary to test whether it is a genuine pulsator.

7. Discussion of results
Szkody et al. (2007) used HST UV observations to determine the temperatures of three accreting pulsators, all of which showed distinct pulsation periods. Contrary to those well behaved systems, our preliminary results for six accreting pulsators observed similarly show peculiar results. We can dismiss SDSS J1514+4549 from further analysis as it may not actually be a pulsator. We expect that after its outburst in October 2006, SDSS J0745+4538 is still heated and will probably not reveal any pulsations until 2010. Two of the accreting pulsators PQ And and REJ 1255+266 revealed periods within the ZZ Ceti range in the optical, but none in the HST UV data. It is possible that these pulsators have a selection effect biased towards high ℓ
modes, or we are mistaking other variability in the system for nonradial pulsations. The pulsator SDSS J1339+4847 reveals two short periods in the UV data, but these are not visible above the noise in the optical DFT. We cannot easily explain the non-variability of SDSS J0919+0857, and expect that perhaps accretion heating may have driven the star just outside the instability strip. Note that the complete disappearance of pulsations has not been observed for any well-established ZZ Ceti star. The cessation of pulsations must not be confused with the phenomenon of amplitude modulation that causes the pulsation spectrum to change from time to time.

Our conclusion is that we need to monitor each accreting white dwarf for several years to improve our understanding of the variability of these systems, and to truly establish the subset that are accreting pulsators from amongst those that have been suggested to be nonradial pulsators.

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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
Bergeron P Fontaine G Billères M Boudreault S & Green E M 2004 ApJ 600 404
Gänsicke B T Szkody P Howell S B & Sion E M 2005 ApJ 629 451
Gänsicke B T et al. 2006 MNRAS 365 969
Gianninas A Bergeron P & Fontaine G 2005 ApJ 631 1100
Godon P Sion E M Cheng F Long K S Gänsicke B T & Szkody P 2006 ApJ 642 1018
Hubeny I & Lanz T 1995 ApJ 439 875
Koester D & Holberg J B 2001 ASP Conf Ser 226: 12th European Workshop on White Dwarfs 226 ed J L Provencal H L Shipman et al. (San Francisco: Astronomical Society of the Pacific) p299
Lanz T & Hubeny I 1995 ApJ 439 905
Mukadam A S Gänsicke B T Szkody P Aungwerojwit A Howell S B Fraser O J & Silvestri N M 2007 ApJ 667 433
Nilsson R Uthas H Ytre-Eide M Solheim J -E & Warner B 2006 MNRAS 370 L56
Piersanti L Gagliardi S Iben I J & Tornambé A 2003 ApJ 583 885
Robinson E L Kepler S O & Nather R E 1982 ApJ 259 219
Robinson E L et al. 1995 ApJ 438 908
Standish E M 1998 A&A 336 381
Szkody P et al. 2007 ApJ 658 1188
Townsley D M Arras P & Bildsten L 2004 ApJ 608 L105
van Zyl L Warner B O’Donoghue D Sullivan D Pritchard J & Kemp J 2000 Baltic Astronomy 9 231
van Zyl L et al. 2004 MNRAS 350 367
Winget D E 1998 Journal of Physics: Condensed Matter 10 11247
Yoon S -C & Langer N 2004 A&A 419 623
Yoon S -C & Langer N 2005 A&A 435 967