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A Mini-Review of Accreting Pulsating White Dwarfs

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The discovery in 1998 of a pulsating white dwarf in the cataclysmic variable GW Lib opened up a new avenue of exploration in the asteroseismology of white dwarfs. Since dwarf novae undergo outbursts which heat the white dwarf and then subsequently cool, the temperature changes allow a study of the mode changes that occur as the white dwarf moves out of the instability zone and back. These changes occur on timescales of months-years, instead of the millennia for evolutionary cooling of single white dwarfs. At the current time, there are 18 known accreting white dwarf pulsators. This mini-review will summarize the results that have been achieved so far from coordinated space and ground observations, from sky surveys, and what is needed in the future to make further progress.

Keywords: asteroseismology, white dwarfs, star evolution, star atmospheres, binary stars

1 INTRODUCTION

Single DA white dwarfs are known to occupy an instability strip between 11,000 and 12,500 K for the common white dwarf mass of 0.6 solar mass (Gianninas et al., 2011). In 1998, the first paper on a pulsating white dwarf in the close binary system GW Lib was published (Warner and van Zyl, 1998), providing the beginning of a new class of accreting white dwarfs. Further objects accumulated since that time, with the current consensus of 18 that are listed in **Table 1**.

These white dwarfs exist in cataclysmic variables, which have active mass transfer from a late main sequence star to the white dwarf, usually *via* an accretion disk if the magnetic field of the white dwarf is under a few million Gauss. The accretion can be directly deposited to the magnetic poles of the white dwarf for higher field strengths. The systems with accretion disks undergo a disk instability that causes increased accretion, which results in what is termed a dwarf nova outburst [a review of properties of dwarf novae can be found in Warner (1995)]. The outburst provides a unique opportunity for the study of how the white dwarf atmosphere and convective interior responds to temperature changes, as the outburst heats the white dwarf, causing it to move out of its instability strip and cease pulsations. After the increased accretion ends, the white dwarf cools back to its quiescent temperature. During this interval, the expectation is that different modes will be driven, with shorter periods first visible after the outburst transitioning to the longer ones at quiescence, since the period of a driven mode should scale with the thermal timescale at the base of the convection zone, which is shorter when the outer layers of the white dwarf are heated by the outburst. Unlike evolutionary cooling, the timescale for these transitions is on an observable timescale of a few years. Unfortunately, the outbursts are unpredictable and most have intervals of 10–30 years between them so constant monitoring is required in order that subsequent followup can occur. The known outbursts of the accreting pulsators are listed in **Table 1**.

The pulsation periods in this Table are the main known periods that have been observed during quiescence. Amplitude modulation can lead to a range of periods (Mukadam et al., 2013) around a listed period and after an outburst, these periods can disappear/change until quiescence is reached.

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TABLE 1 | Dwarf novae with pulsating white dwarfs.

Object	P_{orb}(min)	P_{pulse}(sec)^a	T(°K)	Outbursts	Pulsation References
OV Boo	66.6	500, 660, 1140	14,200	1984, 2017	Patterson et al. (2008)
GW Lib	76.8	236,376,648	15,000	1983, 2007	van Zyl et al. (2004)
EQ Lyn	77.8	1,192–1,230	15,100	2006, 2012, 2019	Mukadam et al. (2007)
SDSS1457 + 51	77.9	582–642, 1200		2015	Uthas et al. (2012)
BW Scl	78.2	618,1242	14,800	2011	Uthas et al. (2012)
V386 Ser	80.5	221, 345, 609	14,500	2019	Warner and Woudt (2004)
PQ And	80.6	1358, 1967, 1988	12,000	1938, 1967, 1988, 2010, 2020	Patterson et al. (2005)
LV Cnc	81.3	214, 260	13,500		Mukadam et al. (2007)
GY Cet	81.5	335, 581, 595	14,500	1999, 2020	Warner and Woudt (2004)
V455 And	81.5	320–370	10,500	2007	Araujo-Betancor et al. (2005)
V355 UMa	82.5	641, 1065	12,500	2011	Gänsicke et al. (2006)
SDSS2205 + 11	82.8	330, 475, 575	15,000	2011	Warner and Woudt (2004)
SDSS0755 + 14	84.8	257–262	15,900		Mukadam et al. (2017)
EZ Lyn	85.0	256, 756	13,000	1979, 2006, 2010	Pavlenko (2009)
DY CMi	85.6	238, 684			Woudt and Warner (2011)
PP Boo	88.8	559	10,000		Nilsson et al. (2006)
RXJ0232-37	95.3	267	13,200	2007	Mukadam et al. (2017)
MT Com	119.5	668, 1236, 1344	12,000	1994	Patterson et al. (2005)

^{a}*Primary known periods visible at quiescence.*

2 SDSS DISCOVERIES

While a few of the objects in **Table 1** were observed to pulsate during the course of photometric time-series observations of a known dwarf nova, the majority were discovered as new cataclysmic variables (Szkody et al., 2011) in the Sloan Digital Sky Survey [SDSS; (York et al., 2000)]. This survey had the advantage of not only providing photometric colors, but also medium resolution spectra of faint systems with low mass transfer and corresponding low accretion disk brightness. It soon became apparent that the classic signature of a potential pulsator was the presence of broad Balmer absorption lines with strong central emission. The broad absorption originates from the white dwarf, signifiying a major contribution to the light from the white dwarf, which is a necessary condition in order to detect any pulsations. The emission line cores are from the accretion disk, which dilutes the pulsation amplitude, but reveals that it is an accreting white dwarf. Follow-up time-series photometry on the objects showing these types of spectra thus provided the highest yield of new accreting pulsators. While other sky surveys such as Hamburg, CRTS, MASTER and ASASSN have been very successful at finding new dwarf novae, they require followup quiescent spectra of most objects to select the best candidates for containing pulsating white dwarfs, This requires a large amount of telescope time, and then additional followup is needed with high-speed photometry to detect pulsations. As a result, there have been no new accreting pulsators found in the last several years.

3 THE HST ADVANTAGE

In order to locate the instability strip for the accreting pulsators, ultraviolet spectra with a sensitive large telescope are needed. The contamination of the optical spectrum by the accretion disk prohibits an accurate temperature determination from either the spectral energy distribution or the Balmer absoption lines, which are filled in by the disk emission. Thus, only the Hubble Space Telescope (HST) with a FUV detector such as STIS or COS is suitable, enabling both the continuum and the Si, N, absorption lines along with Lyα to be fit with white dwarf models (Toloza et al., 2016). The fit to the Lyα core is especially important as it provides an estimate of the contribution of the disk to the total UV light, which is normally about 10%. The temperatures derived from HST observations (Pala et al., 2017) are listed in **Table 1**. The FUV spectra obtained in time-tag mode are also valuable for detecting pulsations even with the short and interrupted sequence of HST orbits, since the ratio of the FUV to optical amplitudes are on the order of 6–10 (Szkody et al., 2007).

After the accumulation of observations and resulting temperature for several accreting pulsators, it was determined that the instability strip for accreting pulsators is hotter and wider (10,500–16,000 K; (Szkody et al., 2002, 2010); than that for single DA white dwarfs (11,000–12,000 K; (Gianninas et al., 2011). These features can be accounted for by the helium present in the white dwarf atmosphere due to the on-going mass transfer from the secondary (Arras et al., 2006), as well as the higher masses of the white dwarfs in CVs (Zorotovic et al., 2011). However, it is not clear why all the dwarf novae with temperatures within the strip do not all contain white dwarfs that show pulsations. Further data also showed that at least 6 known accreting pulsators could suddenly show no pulsations even though they had not undergone an outburst (Szkody and Mukadam, 2018). The most data exist for EQ Lyn, which shows several changes from pulsation to non-pulsation (Mukadam et al., 2013).

Currently, there are five objects that have been observed with both HST and optical observations preceding and following an outburst, so that the temperature and pulsation changes could be found. Two of these [EQ Lyn and V455 And cooled back to quiescence with their pre-ouburst periods within a few years (Mukadam et al., 2011; Szkody et al., 2013)]. EQ Lyn was not followed during its cooling while V455 And is complicated because its white dwarf has a high magnetic field. EZ Lyn only showed pulsations after its outburst. Only GW Lib and V386 Ser have been followed with both UV and optical data during several post-outburst time to determine the details of the pulsation mode changes.

3.1 GW Lib

GW Lib was followed with GALEX, HST and ground coverage since its 2007 dwarf nova outburst (Bullock et al., 2011; Szkody et al., 2016; Toloza et al., 2016; Chote et al., 2021) with surprising results. The initial UV results were from GALEX photometry in 2007–2009, which showed decreasing UV fluxes, and a new long period fluctuation at 4 h (Bullock et al., 2011). Without UV spectra, and because the accretion disk contributed most of the light during this time, a white dwarf temperature could not be determined. While ground coverage continued to show an intermittent 19 min period, temperature and time-resolved UV light curves had to await HST coverage. Instead of following a monotonic cooling from outburst to the 15,000 K quiescent temperature determined from HST STIS spectra 5 years prior to its outburst (Szkody et al., 2002), GW Lib followed an unusual sequence. Five sets of HST COS observations started 3 years after outburst and ended 7 years later. The first spectra in 2010 revealed an elevated temperature near 18,000 K, followed by the start of normal cooling in 2011 to 16,000 K (Szkody et al., 2012), but then the following 3 sets showed the same average higher temperature near 17,000 K (Toloza et al., 2016; Szkody et al., 2016; Gaensicke et al., 2019). Fitting with a 2-component model consisting of a 16,000 white dwarf resulted in the second component having a temperature of up to 25,000 K during some parts of the observations. The combined optical and UV coverage during these 7 years showed a complex array of periods from short periods different from quiescence (293, 275, 370) along with intermittent periods of 19 min and 4 h. It was not obvious if these were all pulsation modes or a combination of disk plus pulsations. Sorting out these periods required a long time-coverage and simultaneous UV and optical data (see **Section 4**).

3.2 V386 Ser

After discovery as a cataclysmic variable in SDSS (Szkody et al., 2002), pulsations were found by Warner and Woudt (2004). An HST SBC spectrum in 2005 showed a quiescent white dwarf temperature near 13,500 K (Szkody et al., 2007). The first known dwarf nova outburst was discovered in January 2019, and HST COS spectra were obtained in August 2019 and February 2020. The temperature determined from the first spectra was 19,000 K and 17,000 K for the second (Szkody et al., 2021). Thus, like GW Lib, the initial cooling sequence was normal. The combined UV and optical light curves showed a pulsation of 104 s 7 months after outburst, and at 175 and 187 s 13 months after outburst. These results follow theoretical expectations of heating and cooling modes. Further optical data over the next few years will determine if this trend continues or if any of the longer 19 min and 4 h modes seen in GW Lib appear.

4 LONG TIME SERIES ADVANTAGES

Single pulsating white dwarfs have had successful Whole Earth Telescope (WET) campaigns to obtain long time-series photometic data that could be used to refine pulsation modes e.g. (Provencal et al., 2012). While most of the objects in **Table 1** are too faint for WET, extended campaigns were tried for EQ Lyn, V386 Ser, and GW Lib. Unfortunately, during its observations with 5 observatories over 11 nights in Jan-Feb 2011, EQ Lyn stopped pulsating and reverted to a superhump type period of about 85 min (Mukadam et al., 2013), so no new information was provided. The 11 night campaign on V386 Ser conducted using seven observatories in 2007 May was more successful, as it enabled a precise measurement of its 609 s pulsation mode, an revealed it had a triplet structure (Mukadam et al., 2010). The even spacing of the triplet led to a rotation period of 4.8 days, unusually long for the typical rotation periods of the white dwarfs in dwarf novae, which are on the order of minutes (Sion et al., 1995). The rotation period of the accreting pulsator in GW Lib was measured to be 209 s from a fit to the HST absorption lines (Szkody et al., 2012). The result for V386 Ser suggests that the atmospheric rotation as measured for most dwarf novae, may be different from the rotation of the interior, as measured from the pulsation. The recent atmospheric rotation estimate of 250 ± 50 km s^{-1} from the HST ultraviolet lines appears to be the typical fast atmospheric rotation (Szkody et al., 2021) and supports differential rotation between the atmosphere and the interior.

GW Lib was later observed on 148 nights within 7.5 months in 2017 by the Next Generation Transit Survey [NGTS; Wheatley et al. (2018)]. While the 20 min period was present throughout this time, the longer periods of 83 min and 2–4 h changed on timescales of about a week (Chote et al., 2021).

Once the Kepler satellite showed the advantage of continuous high time resolution data obtained over months for pulsating white dwarfs, there was a push to have one of the K2 program fields shifted slightly to cover the bright accreting pulsating white dwarf in GW Lib during the times of HST observations in 2017. The end result was a much more detailed understanding of the mode changes from minute to hr timescales. Like the NGTS data, the 90 min period was present throughout, while the simultaneous K2 and HST observations showed that the 4 h period was apparent in both UV and optical, and the short period of 275 s was only visible in the UV during the peak of the 4 h variation, thus connecting these two with the white dwarf as the origin (Gaensicke et al., 2019). Unfortunately, further HST proposals were not accepted on these 2 targets so that the final UV temperature sequence cannot be determined. However, some pulsation information can still be obtained through ground-based campaigns.

5 CONCLUSION

Information on the small class of accreting, pulsating white dwarfs results from the advent of sky surveys like SDSS, the coordination of optical spectral and fast time-series observations from the ground and space, and UV spectra and light curves. The observations have shown that these objects can be identified from spectra that show Balmer lines with broad absorption flanking emission cores, their temperatures (necessarily determined by UV spectra), show a wider range than single pulsating white dwarfs, and long term monitoring by space and ground is necessary to sort out the mode changes occurring at the base of the convection zone as the white dwarf is heated and cooled following an outburst. Unfortunately, most sky surveys are now primarily photometric, and UV spectra of faint sources will not be readily available in the near future, so the window of taking advantage of these types of objects for an understanding of how accretion affects the interior of a white dwarf is disappearing. While the temperature sequence will not be possible without the UV wavelengths, further optical ground campaigns with fast-readout CCDs can still contribute to finding the mode changes following outbursts that will be discovered in future large sky surveys such as the Vera C. Rubin Observatory Legacy Survey of Space and Time.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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