Orbital periods of cataclysmic variables identified by the SDSS. IV. SDSS J220553.98+115553.7 has stopped pulsating

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9 May 2008

ABSTRACT
We present time-series VLT spectroscopy and NTT photometry of the cataclysmic variable SDSS J220553.98+115553.7, which contains a pulsating white dwarf. We determine a spectroscopic orbital period of \( P_{\text{orb}} = 82.825 \pm 0.089 \) min from velocity measurements of the Hα emission line. A period analysis of the light curves reveals a dominant periodicity at \( P_{\text{phot}} = 44.779 \pm 0.038 \) min which is not related to the spectroscopic period. However, the light curves do not exhibit a variation at any frequency which is attributable to GW Lib-type pulsations, to a detection limit of 5 mmag. This non-detection is in contrast to previous studies which have found three pulsation frequencies with amplitudes of 9–11 mmag at optical wavelengths. Destructive interference and changes to the thermal properties of the driving layer in direct response to accretion can be ruled out as causes of the non-detection. Alternatively, it is feasible that the object has cooled out of the instability strip since a previous (unobserved) dwarf nova superoutburst. This would be the first time this behaviour has been seen in a cataclysmic variable pulsator. Another possibility is that changes in the surface characteristics, possibly induced by accretion phenomena, have modified the surface visibility of the pulsation modes. Further observations, particularly improved constraints on the timescale for changes in the mode spectrum, are needed to distinguish among possible explanations.

Key words: stars: novae, cataclysmic variables – stars: binaries: close – stars: binaries: spectroscopic – stars: white dwarfs – stars: dwarf novae – stars: individual: SDSS J220553.98+115553.7

1 INTRODUCTION
The study of stellar pulsations is a powerful way of constraining the structure and evolution of many types of star (Pamyatnykh 1999). For white dwarfs (WDs), pulsations can occur at three stages during their evolution (Winget 1998). The ZZ Ceti instability strip is the coolest of these, with effective temperatures \( (T_{\text{eff}}) \) between about 10 800 K and 12 000 K depending on surface gravity (Mukadam et al. 2004a; Gianninas et al. 2005). The pulsation characteristics of ZZ Ceti stars depend on where they are within the instability strip (Mukadam et al. 2004b). The hotter ZZ Ceti stars generally pulsate with periods of 100–300 s and amplitudes of up to 3%, and the cooler ones pulsate with longer periods (up to 1200 s) and larger amplitudes (up to 30%).

Cataclysmic variables (CVs) are interacting binaries where a WD is accreting from a less evolved low-mass star (Warner 1995; Hellier 2001). A small number of CVs are known to harbour pulsating WDs, the prototype of this class being GW Lib (Warner & van Zyl 1998; van Zyl et al. 2000, 2004). The pulsation frequencies here hold information on a range of properties which can otherwise be very difficult to obtain for CVs, including the mass and internal structure of the WD, the accretion rate, and the WD rotational velocity and magnetic field strength (e.g. Townsley et al. 2004).

WDs in accreting binaries are observed to have pulsations for a much wider variety of effective temperatures \( (T_{\text{eff}}) \) than ZZ Ceti stars (single WDs), ranging from 10 500 K for HS 2331+3905 (Araujo-Betancor et al. 2003) to \(~15 000 K\) for several objects (Szczodry et al. 2007b). A theoretical explanation has been put forward by Arras et al. (2006), who found that WDs with a high helium abun-
dance may encounter an additional instability strip at $T_{\text{eff}} \approx 15\,000$ K due to the deeper convection zone resulting from helium ionization.

### 1.1 SDSS J220553.98+115553.7

We are currently engaged in a project ([Gänsicke 2003](#)) to measure the orbital periods and basic properties of the homogeneous sample of CVs which has been identified by the Sloan Digital Sky Survey ([SDSS; York et al. 2000](#), [Szkody et al. 2002a, 2003, 2004, 2005, 2006, 2007a](#)). Results have so far been presented by [Gänsicke et al. (2006), Szkody et al. 2002b, 2003, 2004, 2005, 2006, 2007a](#). As part of this project we have obtained time-resolved photometry and spectroscopy of the pulsating white dwarf system SDSS J220553.98+115553.7 (hereafter SDSS J2205) in order to measure its orbital and pulsation periods.

SDSS J2205 is a faint and blue object ($g = 20.05$, $q-r = 0.05$) which was identified as a CV by [Szkody et al. (2003)](#), from an SDSS spectrum which shows broad double-peaked Balmer emission lines. The presence of wide absorption features surrounding these emission lines indicates that the WD component contributes a significant proportion of the total light of the system. This is a prerequisite for observing brightness variations arising from WD pulsations. [Warner & Woudt (2004)](#) presented high-speed unfiltered optical photometry of SDSS J2205 which show periodicities of 575 s, 475 s and 330 s, with amplitudes of 9–11 mmag. [Szkody et al. (2007)](#) confirmed the presence of the lowest-frequency pulsation, finding a period of 576 ± 1.6 s and an amplitude of 46 ± 11 mmag from ultraviolet observations obtained with the Hubble Space Telescope. From a three-component fit to the spectral energy distribution of SDSS J2205, [Szkody et al. (2007)](#) found a WD $T_{\text{eff}}$ of 15,000 ± 1000 K and a distance of 810 pc. This $T_{\text{eff}}$ is consistent with temperatures found for other GW Lib stars ([Szkody et al. 2002a](#)) and with the theoretical predictions of [Arras et al. (2006)](#).

## 2 OBSERVATIONS AND DATA REDUCTION

Throughout our observations the apparent magnitude of SDSS J3305 was always found to be close to 20.1, which is in agreement with the SDSS imaging and spectroscopic data. This object has therefore never been observed to have large-scale brightness variations.

### 2.1 VLT spectroscopy

Spectroscopic observations were obtained in 2007 August using the FORS2 spectrograph ([Appenzeller et al. 1998](#)) at the Very Large Telescope (VLT), Chile (Table 1). The 1200R grism was used, giving a wavelength interval of 5870 Å to 7370 Å, with a reciprocal dispersion of 0.73 Å px$^{-1}$ and a resolution of 1.6 Å at Hα.

The data were reduced using optimal extraction ([Horne 1986](#)) as implemented in the [PAMELA](#) code ([Marsh 1989](#)), which also makes use of the [STARLINK](#) packages [FIGARO and KAPPA](#). Wavelength calibration was performed using one arc lamp exposure for each night, and shifts due to spectrograph flexure were measured and removed using the 6300.30Å night sky emission line (see [Southworth et al. 2006](#)).

The spectroscopic observing procedure of FORS2 included obtaining target acquisition images from which photometry can be obtained. We have extracted differential photometry from these images using the [STARLINK](#) package GAIA. The V-band apparent magnitude of the comparison star was calculated from its $g$ and $r$ magnitudes using the transformations provided by [Jester et al. (2005)](#).

### 2.2 NTT photometry

Light curves were obtained in 2007 August ([Table 1](#)) using the New Technology Telescope (NTT) at ESO La Silla, Chile, and the SUSI2 CCD mosaic imager ([D’Odorico et al. 1998](#)). CCD#45 was used, binned by factors of three in both directions to give a resolution of 0.24" px$^{-1}$. The observations were performed without a filter in order to maximise the throughput; this may reduce the pulsation amplitudes (which are larger at bluer wavelengths) but will not smear out the pulsations as they are coherent over all optical wavelengths ([Robinson et al. 1982](#)). Care was taken to place the target and comparison stars on parts of the CCD which were least affected by fringing. Exposure times of 20–30 s gave an observing cadence of 36–46 s.

Debiasing and flat-fielding of the raw images was performed with the [STARLINK](#) software packages [CONVERT and KAPPA](#). Optimal differential photometry ([Naylor 1998](#)) was obtained from the reduced images with the [MULTIPHOTOM](#) script ([Southworth et al. 2004](#)), which uses the [STARLINK](#) AUTOPHOTOM package ([Eaton et al. 1999](#)). We adjusted this

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[1] PAMELA and MOLLY were written by TRM and can be found at http://www.warwick.ac.uk/go/trmarsh
[2] Starlink software can be accessed from http://starlink.jach.hawaii.edu/

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3.1 Spectroscopic analysis

The SDSS spectrum of SDSS J2205 (Fig. 1) shows a faint blue continuum with double-peaked Balmer emission lines. Whilst the Balmer absorption of the WD is noticeable, there are no identifiable features arising from the low-mass secondary star. Our VLT spectra (Fig. 2) shows that He I 6678 Å emission is weak but detectable. The Hα emission equivalent width is 135 ± 15 Å in the SDSS spectrum and 140 ± 3 Å in the mean VLT spectrum.

We have measured radial velocities from this line by cross-correlation against single and double Gaussian functions (Schneider & Young 1980; Shafter 1983), as implemented in MOLLY. The radial velocities were searched for periods using periodograms computed by the Scargle (1982) method, as implemented within the T5 context in MIDAS. Spectroscopic orbits were fitted using the SBOF program, which we have found to give reliable error estimates (Southworth et al. 2003).

We first measured radial velocities from the 22 spectra obtained on the night of 2007 August 17, as these were obtained consecutively during a 196-min interval so yield a periodogram which is not affected by cycle count ambiguities. Consistent results were found for all measurement methods, giving a preliminary period of 83.04 ± 0.70 min.

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Figure 1. SDSS spectrum of SDSS J2205. For this plot the flux levels have been smoothed with a 10-pixel Savitsky-Golay filter. The units of the abscissa are 10^{-21} \, \text{W} \, \text{m}^{-2} \, \text{nm}^{-1}, which corresponds to 10^{-17} \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1}.

Figure 2. The averaged Hα emission line profile from our continuum-normalised VLT data. The He I 6678 Å emission line is detectable.

to an apparent magnitude scale using the mean of the g and r magnitudes of the comparison star. Photometry was also obtained for a check star and used to confirm that the comparison star is not variable.

The resulting light curves show a clear variation with airmass, arising from the use of unfiltered photometry and comparison stars which are significantly redder than SDSS J2205. A straight line was fitted to the trend of magnitude versus airmass, and was removed from the light curves.

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3 RESULTS

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http://www.eso.org/projects/esomidas/doc/user/98NOV/volb/node220.html

Spectroscopic Binary Orbit Program, written by P. B. Etzel, http://mintaka.sdsu.edu/faculty/etzel/
Table 2. Circular spectroscopic orbit found for SDSS J2205 using sbop. The reference time (defined to indicate zero phase) corresponds to inferior conjunction of the secondary star.

| Quantity                     | Value                          |
|------------------------------|-------------------------------|
| Orbital period (d)           | $0.0575175 \pm 0.000062$      |
| Reference time (HJD)         | $2454329.71251 \pm 0.00063$   |
| Velocity amplitude (km s$^{-1}$) | $44.0 \pm 2.3$               |
| Systemic velocity (km s$^{-1}$) | $-44.4 \pm 1.7$             |
| $\sigma_{\text{rms}}$ (km s$^{-1}$) | $9.8$                        |

Figure 4. Greyscale plots of the continuum-normalised and phase-binned trailed spectra around the Hα and He I 6678 Å emission lines. The binned spectra for He I have been smoothed with a Savitsky-Golay filter for display purposes. (using a double Gaussian with widths 300 km s$^{-1}$ and separation 1900 km s$^{-1}$).

When we add in the 15 spectra taken on the previous night (2007 August 16) we obtain periodograms with the usual pattern of peaks at the correct orbital period and its one-day aliases. The three highest peaks correspond to periods of 78.0, 82.7 and 88.1 min. The 82.7 min peak represents the orbital period, as the adjacent possibilities both differ by over 7σ from the preliminary period. We therefore find a final orbital period of $P_{\text{orb}} = 82.825 \pm 0.089$ min, which is close to the minimum period for CVs with relatively unevolved secondary stars (Knigge 2006).

The parameters of the spectroscopic orbit are given in Table 2. The periodogram and spectroscopic orbit from our full radial velocity dataset are plotted in Fig. 3. We have sorted the spectra into ten phase bins, and Fig. 4 shows the trailed spectra around the Hα and He I 6678 Å emission lines. The Hα profile is clearly double-peaked, with a fainter S-wave arising from the bright spot on the edge of the accretion disc (Smak 1985). The He I 6678 Å trailed spectrum has been smoothed to make the features of this faint line clearer, and shows very faint double peaks with a brighter S-wave superimposed.

3.2 Photometric analysis

We obtained ten hours of high-speed unfiltered photometry over two nights (Section 2.2). The light curves were searched for periods using Scargle (1982), AoV (Schwarzenberg-Czerny 1989) and ORT (Schwarzenberg-Czerny 1996) periodograms. Fig. 5 shows the light curves of SDSS J2205 and light curves of the comparison star relative to the check star.

We found no significant periodicities in the NTT light curve in the range expected for GW Lib-type pulsations. A number of small peaks were found in the AoV and ORT periodograms at higher frequencies (500–1000 cycle d$^{-1}$), but plots of the phased light curve showed that these were all related to the observing cadence rather than to real signals.

Figure 5. Top panels: NTT unfiltered light curve obtained over two nights. The higher light curve in each panel is SDSS J2205 minus comparison, and the lower curve is comparison minus check (offset). The light curves of SDSS J2205 have had their variation with airmass removed. The airmass term for the comparison star light curves is negligible, as it is a similar colour to the check star, and has not been removed. Panel 3: Scargle periodogram of the light curve with the most probable period indicated with an arrow. Panel 4: light curve phased at the most probable period (grey dots) and resampled into 25 phase bins (black filled circles).
The amplitude spectrum of the NTT light curve is shown in Fig. 6 over the range 0–500 cycle d$^{-1}$. The periodicities at 150, 182 and 262 cycle d$^{-1}$ found by Warner & Woudt (2004) and Szkody et al. (2007b) are indicated with arrows. Magnified plots around these frequencies show no significant power and confirm that the pulsations detected in previous works are not clearly present in our data.

We have determined our detection limit by adding sine waves (frequencies 100–300 cycle d$^{-1}$) to the NTT light curve and recalculating periodograms. We find that sine waves with amplitudes of 5 mmag or greater would be reliably detected. This detection limit applies specifically to a pulsation which is coherent and persists through the full dataset with a sinusoidal shape. If any of these conditions are not satisfied then the detection limit would increase. The pulsations found by Warner & Woudt (2004) had amplitudes of approximately 10 mmag, which would easily have been detected by our observations.

The NTT light curve does show a clear sinusoidal photometric variation with a period of about 45 min, which is much longer than expected for ZZ Ceti-like pulsations (Mukadam et al. 2004b). We have calculated periodograms for the individual nights and for the data from both nights. The individual nights give unambiguous periods of 44.8 min and 43.5 min; the second differs by 3.7% from the two individual nights, and the second differs by 3σ. We therefore identify the first periodicity as dominant variation in our light curves. A sine fit gives a final photometric period of $P_{\text{phot}} = 44.779 \pm 0.038$ min.

## 4 HOW COULD PULSATION AMPLITUDES VARY?

Non-radial pulsations have previously been observed in the WD in SDSS J2205 on two occasions (Warner & Woudt 2004, Szkody et al. 2007b), but were not detectable in our own observations. It is possible that amplitude variation could have taken the pulsations beyond our detection limit, which requires a physical explanation.

Given the current sparse observational coverage, it is plausible that the mode amplitude variations observed are induced by changes in driving. The timescales of amplitude variation in SDSS J2205 and other similar objects which have several epochs of observations (e.g. SDSS J0131, Szkody et al. 2007b, GW Lib, van Zyl et al. 2004) appear to be months to years. Driving and damping rates in the instability strip for hydrogen-envelope (DA) WDs have been calculated to be around $10^{-6}$ s$^{-1}$ to $10^{-7}$ s$^{-1}$ (Wu & Goldreich 1992). There are some differences due to the solar chemical composition in the envelopes of DA WDs in CVs, but these rates should have a similar order of magnitude. Thus it is possible that subtle changes in the driving and damping characteristics could explain order unity variations of the driven modes on the timescales relevant for SDSS J2205. Such variations in the properties of the driving zone have several possible physical origins, which we now discuss.

### 4.1 Changes in accretion?

The most obvious source of possible variations in driving the pulsations, changes in accretion, is also the most challenging from a physical viewpoint. By virtue of the nature of the driving mechanism, the thermal timescale of the driving region, on which its temperature structure can change, is similar to the mode period (Goldreich & Wu 1999) and therefore short compared to the driving timescale. As a result, in the absence of significant heat sources in this region, the thermal profile in the driving region is set by the heat flux rising from the underlying layers having longer thermal timescales. The surface luminosity of the WD in accretion quiescence derives from the compression of the accreted material throughout the accreted envelope (Townesley & Bildsten 2004). Only a very small outer portion of the envelope can respond on timescales of months to years, and this portion contributes only a small fraction of the energy flux streaming out through the mode-driving region (Townesley & Gänsicke 2008). Thus only large accretion events, such as superboutbursts, should be able to modify the thermal profile in the driving region. In such a case enough material is accreted that the driving region and layers with longer thermal timescales are replaced by material accreted at a high rate. This will then take some time to cool back to the state defined by the flux from the deepest layers (Piro et al. 2003). Such an event would have either been noticed directly or, failing that, would show up as a significant change in the
overall system brightness with respect to previous epochs, which we do not observe.

While variation in direct response to accretion is therefore unlikely, this leaves the possible explanation that SDSS J2205 had, at the time of our observations, cooled enough since its last superoutburst to leave the instability strip, but only future epochs of observations will tell. If true, this would be an exciting first for CV pulsators. The short-period CV WZ Sge had a superoutburst in 2001 July, and observations up to three years after this cataclysmic event have shown that the WD is still cooling (Long et al. 2003; Godon et al. 2006).

Another way to heat the WD surface is via infall heating arising directly from the impact of fresh material. The accretion rate necessary to raise the \( T_{\text{eff}} \) above that which is set by the underlying flux from envelope compression is only a few percent of the time-averaged accretion rate (Townsend & Bildsten 2003). Thus it is possible to temporarily raise the WD \( T_{\text{eff}} \) with an episode of fairly mild accretion, which, even if it were months long, might go unnoticed in a dim object like SDSS J2205. However, this type of heating does not affect the driving, because it is unable to penetrate to the driving region. The temperature in the driving region is \( \sim 10^5 \) K so mild increases in the photospheric temperature (which would naïvely appear to push the WD out of the instability strip) in fact have no significant effect on the thermal profile at the depths where energy is being pumped into the pulsation modes.

4.2 Changes in chemical composition?

The impure composition in the atmospheres of WDs in CV is an essential ingredient for the mode-driving features observed in these systems (Arras et al. 2006), particularly the enhanced helium abundance. This means that changes in the composition of the driving layers will be reflected in the balance between driving and damping of modes. If accretion were to cease completely, the timescale for helium to settle out of the convection zone and thus the driving layer for \( T_{\text{eff}} \sim 14000 \) K is of the order of months (Paquette et al. 1984). However the rate of accretion of material with a solar-like composition need only be \( \sim 10^{-14} \) M\(_\odot\) yr\(^{-1}\) to maintain a similar composition at the driving layer. Thus changes in the quiescent accretion have the potential to induce compositional variation in the driving layers on the timescales of interest. However, it is not clear that such variations would be enough to cause significant changes in mode driving. More detailed study would be necessary to characterize the time dependence of the chemical structure of the driving layers, and the concomitant impact on the driving. Additionally, without quantitative constraints on the properties of quiescent accretion, which are difficult due to the low accretion rates involved, conclusions will remain ambiguous even with detailed modelling.

4.3 Changes in detectability?

Variations in mode amplitude and therefore driving are not the only viable explanation for the observed amplitude variations. Another possibility is variations in the visibility of any given pulsation mode. Under the influence of rotation each mode will have a unique surface eigenfunction. Bildsten et al. 1996). Additionally, the flux perturbations of different modes are modified by the non-adiabatic surface layers in a way which depends on period and the presence of other modes (Brickhill 1992). In light of the changes in these surface layer which can be achieved by variations in quiescent accretion and the possibility of obscuration by that accretion or other system components, a number of system features could influence the visibility of any given mode. This type of effect has a much wider variety of timescales over which observed amplitude variations could occur. More continuous monitoring of pulsation properties would provide constraints on whether this type of mechanism is at work in these systems.

5 SUMMARY

In the context of our program to measure the basic properties of the CVs identified by the SDSS, we present VLT spectroscopy and NTT photometry of the faint short-period system SDSS J220553.98+115553.7. This object has twice previously been observed to exhibit low-amplitude brightness variations characteristic of nonradial pulsations (Szkody et al. 2007; Warner & Woudt 2004). Using radial velocities measured from the H\(\alpha\) emission line in the VLT spectra we find a high-precision orbital period of \( P_{\text{orb}} = 8.285 \pm 0.089 \) min, which is close to the observed minimum period for CVs with hydrogen-rich secondary stars.

Our light curves of SDSS J2205 cover ten hours over two consecutive nights with an observing cadence of 45 s. They have a clear sinusoidal variation on a period of \( P_{\text{puls}} = 44.779 \pm 0.038 \) min. This period is not clearly related to the orbital period or to pulsations, and has not been detected in previous observations of SDSS J2205. Unexplained periodicities have been observed in other CVs with pulsating WDs, for example GW Lib (Woudt & Warner 2002), HS 2331+3905 (Arraujo-Betancor et al. 2003) and SDSS J133041.12+484727.5 (Gänsicke et al. 2006). SDSS J2205 is unusual in this company, in that its photometric period is substantially shorter than its orbital period.

We have not found any periodicities in the light curves which are clearly attributable to GW Lib pulsations, to a detection limit of 5 mmag in amplitude. This is in conflict with the orbital light curve in which we do not observe. There are several potential explanations for the lack of observable pulsations in SDSS J2205. Firstly, it is possible for destructive interference to make pulsations unobservable for a few hours (Castanheira et al. 2006), but this would be extremely unlikely to occur for ten hours spread over two nights. A second possibility is cessation or changes in driving due to modification of the thermal state of the driving region. Such changes have several possible origins. If pulsations do not return in future observations, it is likely that,
in cooling since its last dwarf nova superoutburst, the object has just left the instability strip. This behaviour is expected for CV pulsators, but this would be the first time it has been observed. However, it is entirely possible that the current absence of pulsations is a temporary state. Modification of thermal properties of the driving region due to variation in the accretion rate can be excluded because a large increase in accretion would be required, whereas no change in the brightness of the system was observed. Accretion heating of the surface of the WD is also not viable, since it does not affect the driving layer. Changes in driving might also arise from changes in the chemical composition of the driving layer. The plausibility of such changes depends on an extremely low quiescent accretion rate, which is difficult to justify. After changes in driving, a third distinct possibility for variation is changes in the visibility of pulsation modes over the surface of the star. Distinguishing between the several possible origins for pulsation amplitude variation depends on new observations of systems exhibiting pulsations. Most essential for this purpose are constraints on the timescale over which the variations take place, which necessitates more frequent epochs of observation than have been taken to date.

ACKNOWLEDGEMENTS

The reduced spectra, light curves and radial velocity measurements presented in this work will be made available at the CDS [http://cdsweb.u-strasbg.fr/] and at

http://www.astro.keele.ac.uk/~jkt/

Based on observations made with ESO Telescopes at the La Silla and Paranal Observatories under programme ID 079.D-0024.

JS acknowledges financial support from PPARC in the form of a postdoctoral research assistant position. The following internet-based resources were used: the ESO Digitized Sky Survey; the NASA Astrophysics Data System; the SIMBAD database operated at CDS, Strasbourg, France; and the arxiv scientific paper preprint service operated by Cornell University.

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