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ULTRACAM observations of two accreting white dwarf pulsators

C. M. Copperwheat,[1] T. R. Marsh,[1] V. S. Dhillon,[2] S. P. Littlefair,[2] P. A. Woudt,[3] B. Warner,[3] D. Steeghs,[1] B. T. Gänsicke[1] and J. Southworth[1]

[1]*Department of Physics, University of Warwick, Coventry, CV4 7AL*
[2]*Department of Physics and Astronomy, University of Sheffield, S3 7RH*
[3]*Department of Astronomy, University of Cape Town, Rondebosch 7701, South Africa*

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ABSTRACT

In this paper, we present high time-resolution observations of GW Librae (GW Lib) and SDSS J161033.64−010223.3 (SDSS 1610) – two cataclysmic variables which have shown periodic variations attributed to non-radial pulsations of the white dwarf (WD). We observed both these systems in their quiescent states with ULTRACAM on the Very Large Telescope (VLT) and the University of Cape Town Photometer on the SAAO 1.9 m telescope, and detect the strong pulsations modes reported by previous authors. The identification of further periodicities in GW Lib is limited by the accretion-driven flickering of the source, but in the case of SDSS 1610 we identify several additional low-amplitude periodicities. In both the sources, we find the pulsation modes to be stronger in amplitude at bluer wavelengths. In the case of SDSS 1610, there is evidence to suggest that the two primary signals have a different colour dependence, suggesting that they may be different spherical harmonic modes. We additionally observed GW Lib during several epochs following its 2007 dwarf nova outburst, using ULTRACAM on the VLT and the Auxiliary Port Imager on the William Herschel Telescope. This is the first time a dwarf nova containing a pulsating WD has been observed in such a state. We do not observe any periodicities, suggesting that the heating of the WD had either switched-off the pulsations entirely, or reduced their relative amplitude in flux to the point where they are undetectable. Further observations 11 months after the outburst taken with RATCam on the Liverpool Telescope still do not show the pulsation modes previously observed, but do show the emergence of two new periodic signals, one with a frequency of 74.86 ± 0.68 cycles d^{-1} ($P = 1154$ s) and a g'-band amplitude of 2.20 per cent ± 0.18 and the other with a frequency of 292.05 ± 1.11 cycles d^{-1} ($P = 296$ s) and a g' amplitude of 1.25 per cent ± 0.18. In addition to the WD pulsations, our observations of GW Lib in quiescence show a larger amplitude modulation in luminosity with a period of approximately 2.1 h. This has previously been observed, and its origin is unclear: it is unrelated to the orbital period. We find this modulation to vary over the course of our observations in phase and/or period. Our data support the conclusion that this is an accretion-related phenomenon, which originates in the accretion disc.

Key words: stars: dwarf novae – stars: individual: GW Librae – stars: individual: SDSS J16103.64−010223.3 – stars: oscillations – white dwarfs.

1 INTRODUCTION

Cataclysmic variable stars (CVs: Warner 1995) provide examples of white dwarfs (WDs) accreting from low-mass companions and are the progenitor class of classical novae. Dwarf novae (DNe) are a subset of CVs which feature periodic outbursts, thought to be the result of thermal instability in the accretion disc leading to accretion at rates far in excess of the rate in quiescence. The emission from CVs is generally dominated by these accretion processes, making it difficult to probe the WD itself. Some isolated WDs show periodic variations which have been attributed to non-radial pulsations of the WD at surface temperatures between 11 000 and 13 000 K (Gianninas, Bergeron & Fontaine 2006). These are termed DAV WDs or ZZ Ceti stars (see Bradley 1998 for a review). These WDs are relatively cool and lie within a region in the

⋆E-mail: c.copperwheat@warwick.ac.uk

$T_{\rm eff}$–log g plane termed the ZZ Ceti instability strip (Gianninas et al. 2006).

In recent years, photometric observations of some DNe during quiescence have revealed the accreting analogues of the ZZ Ceti WDs. The first CV of this type was the ∼17 mag DN GW Librae (GW Lib) (Warner & van Zyl 1998; van Zyl et al. 2000). A spectroscopic period of 76.78 min has been reported by Thorstensen et al. (2002) for this source, which makes it one of the shortest orbital period CVs known. van Zyl et al. (2000, 2004) presented amplitude spectra of GW Lib from observing campaigns conducted during 1997, 1998 and 2001. They found the dominant pulsation modes to be clustered at periods near 650, 370 and 230 s. Observations at ultraviolet (UV) wavelengths showed these same pulsation modes (Szkody et al. 2002). Further examples of accreting pulsators have been discovered largely as a result of the Sloan Digital Sky Survey (SDSS; Szkody et al. 2007a). Of the CVs discovered by the SDSS, the first found to contain a pulsating WD was SDSS J161033.64−010223.3 (SDSS 1610; Szkody et al. 2002). Woudt & Warner (2004) reported high-speed photometry of this source, taken with the University of Cape Town CCD Photometer mounted on the 74-inch Radcliffe reflector. They measured an orbital period of 80.52 min, and non-radial pulsations with principal modes near 606 and 345 s. Signals at 304 and 221 s were also discovered. These frequencies of these modes suggest that they are, respectively, a harmonic of the first mode and a linear combination of the principal modes.

Stellar pulsations in CVs have huge potential as probes of the WDs. The outer layers of the WD are modified by accreting solar abundance material at $\sim 10^{-10}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ and by the ejection of this accreted material via nova eruptions. The surface structure of WDs in CVs is determined by the interplay between accretion and nova explosions which occur through thermonuclear runaways in the accreted material. Measurement of the mass of the accreted layers is of interest for classical nova models, and for assessing the contribution made by novae to the interstellar medium (Gehrz et al. 1998). The amount of hydrogen in the accreted envelope versus the accretion rate would show how long it has been since the last nova eruption, something that is otherwise very difficult to measure. Asteroseismological studies have the potential to lead to very precise parameter estimates. The analysis of pulsations in GW Lib by Townsley, Arras & Bildsten (2004) suggested that the mass of the WD can be constrained to within 3 per cent, a level of precision very difficult to observe in the field of CVs, while the mass of the accreted layer can be tied down to ∼20 per cent. Masses as precise as this allow the issue of the long-term evolution of WD masses in CVs to be addressed, which is central to Type Ia supernova models. It is unknown as to whether the WDs gain mass as they accrete or whether they are eroded by nova explosions (Gänsicke 2000; Littlefair et al. 2008). The analysis of GW Lib by Townsley et al. (2004) was limited due to only three independent modes being known, making it difficult to identify which normal mode corresponds to which frequency. Townsley et al. (2004) assumed that the modes in GW Lib are $l = 1$ spherical harmonics. Asteroseismological mode identification is normally constrained by particular frequency differences and ratios, multiplet structures and direct period matching. The identification problem is better constrained if a large number of frequencies can be identified. Townsley et al. (2004) predicted additional mode periods that would require more sensitive observations in order to be observed.

Another important feature of the CV pulsators is that they are subject to irregular heating events from accretion-driven outbursts. GW Lib was caught on the rise to outburst on 2007 April 12: the first outburst observed in this source since the one which led to its discovery in 1983, and the first outburst to be observed in any CV known to contain a pulsating WD. Events such as this one allow us to study the interplay between the WD temperature and the pulsations. CV pulsators all exist within a well-constrained region of parameter space: in order for the pulsations to be detectable, they must be low-luminosity systems in which the WD dominates the flux. However, some spectral fits to CV pulsators suggest a WD surface temperature that is too high to fall in the instability strip for non-accreting ZZ Ceti stars (Szkody et al. 2002, 2007b). This discrepancy may be a result of abundance and atmospheric temperature differences in the accreting systems (Arras, Townsley & Bildsten 2006), due to accretion of He-rich material (Gänsicke et al. 2003). Unlike the instability strip for isolated ZZ Ceti WDs, the empirical boundaries of the CV instability region are yet to be determined with precision (Gianninas, Bergeron & Fontaine 2007).

In this paper, we report high time-resolution observations of GW Lib and SDSS 1610 taken in 2005 May. Our observations were simultaneous in multiple bands and of a higher sensitivity than previous studies. We therefore sought to determine additional pulsation modes to those already known and to investigate the colour-dependence of these pulsations, in order to provide more reliable determinations of the system parameters. We also report high time-resolution observations of GW Lib taken in 2007 in order to examine the effect of heating due to the outburst on the WD pulsations. We aimed to determine if the heating of the WD had affected the known modes (perhaps even suppressing them entirely due to the WD being pushed above the CV instability region) and we sought also to determine if new periodicities were visible in this source, due the WD having been moved into higher $T_{\rm eff}$ instabilities caused by ionization of helium. We continued to monitor GW Lib through 2008 so as to examine the evolution of the pulsations as the WD cools.

In Section 2 of this paper, we detail our observations and data reduction. In Sections 3 and 4, we present our results for GW Lib (before and after outburst, respectively). In Section 5, we present our results for SDSS 1610. In these three sections, we give light curves and variability amplitude versus frequency spectrograms (which we will refer to as 'amplitude spectra' in this paper). In Section 6, we examine these results further and discuss their implications for the physical nature of the WDs in these two systems.

2 OBSERVATIONS

A complete log of the observations is given in Table 1.

The high-speed CCD camera ULTRACAM (Dhillon et al. 2007) was mounted on the European Southern Observatory (ESO) Very Large Telescope (VLT) UT3 (*Melipal*) in 2005 May as a visiting instrument. Two nights of this run were dedicated to observations of GW Lib and SDSS 1610. ULTRACAM is a triple beam camera and the observations of both targets were made using the SDSS u', g' and r' filters. The dead time between frames for all the VLT + ULTRACAM data was 25 ms. GW Lib was observed on May 7 and 8. There is a ∼20 min gap in the May 7 data due to the target passing through the zenith blind spot of the telescope. We took an additional, shorter observation of this target ∼1 week later on May 15. The data were unbinned and the CCD was windowed in order to achieve the required exposure time. SDSS 1610 was observed on May 9 and 10. This source is much fainter than GW Lib (V magnitude ∼19, Woudt & Warner 2004), and so a longer exposure time was used and a CCD window was not required. A binning factor of 2 × 2 was used for the VLT + ULTRACAM observations in order to improve the count rate in the u' band.

Table 1. Log of the observations.

Source	Start date	UT Start	UT End	Filter (s)	Average exposure Time (s)	Binning	Conditions
				VLT + ULTRACAM, 2005 May			
GW Lib	May 07	03:09	09:54	u' g' r'	4	1 × 1	Clear, seeing 0.9– 1.5 arcsec
	May 08	05:08	09:46	u' g' r'	4	1 × 1	Clear, seeing 1.0– 1.5 arcsec
	May 15	04:50	06:00	u' g' r'	2	1 × 1	Light cloud, seeing ∼0.6 arcsec
SDSS J1610	May 09	05:32	09:54	u' g' r'	10	2 × 2	Light cloud, seeing 0.8–1.5 arcsec
	May 10	04:56	10:09	u' g' r'	10	2 × 2	Clear, seeing 0.5–0.6 arcsec
				SAAO 1.9 m + UCT CCD photometer, 2005 May			
GW Lib	May 07	19:20	02:01	None	15	6 × 6 to 3 × 3	Light cloud, seeing decreasing from 5 to 2 arcsec
	May 08	18:38	01:59	None	15	5 × 5	Clear, seeing ∼4 arcsec
	May 12	20:54	00:01	None	15	6 × 6	Clear, seeing ∼4 arcsec
SDSS J1610	May 09	19:38	02:34	None	60	5 × 5	Clear, seeing 4 arcsec
	May 10	22:19	01:25	None	60	5 × 5	Heavy cloud towards the end of run.
				VLT + ULTRACAM, 2007 June			
GW Lib	June 13	22:41	00:27	u' g' i'	3	1 × 1	Heavy cloud, seeing ∼1.5 arcsec
	June 14	22:54	01:10	u' g' i'	0.65	1 × 1	Heavy cloud, seeing ∼1 arcsec
	June 16	01:35	04:37	u' g' r'	0.65	1 × 1	Some light cloud, seeing 0.6– 0.7 arcsec
	June 18	22:58	01:27	u' g' r'	0.65	1 × 1	Clear, seeing 0.7– 1.5 arcsec
				WHT + API, 2007 July			
GW Lib	July 22	20:50	23:09	*B*	30	1 × 1	Clear, seeing ∼1.6 arcsec
	July 23	20:56	22:58	*B*	30	1 × 1	Clear, seeing 1.2– 1.5 arcsec
				LT + RATCam, 2008 March–June			
GW Lib	March 08	03:00	05:06	g'	30	2 × 2	Heavy cloud, seeing 2–3 arcsec
	March 11	02:51	04:56	g'	30	2 × 2	Light cloud, seeing decreasing from 5 to 2 arcsec
	March 16	02:50	04:56	g'	30	2 × 2	Generally quite clear, seeing <2 arcsec
	March 19	02:19	04:24	g'	30	2 × 2	Clear, 2 arcsec seeing
	March 20	02:31	04:36	g'	30	2 × 2	Clear, 2–3 arcsec seeing
	March 30	01:31	03:36	g'	30	2 × 2	Light cloud, seeing 2–3 arcsec
	March 31	01:39	03:44	g'	30	2 × 2	Light cloud, seeing 3–5 arcsec
	April 12	00:38	02:43	g'	30	2 × 2	Moderate cloud, seeing 1–2 arcsec
	April 29	23:57	02:02	g'	30	2 × 2	Moderate cloud, seeing 2–5 arcsec
	May 11	22:59	01:04	g'	30	2 × 2	Light cloud, seeing 1–2 arcsec
	June 01	21:39	23:44	g'	30	2 × 2	Light cloud, seeing 1–2 arcsec
	June 02	21:40	23:45	g'	30	2 × 2	Light cloud, seeing 1–3 arcsec
	June 21	21:26	23:30	g'	30	2 × 2	Clear, seeing ∼1 arcsec

Additional, complementary observations were made in 2005 with the University of Cape Town (UCT) CCD photometer (O'Donoghue 1995), mounted on the 1.9 m telescope at the South African Astronomical Observatory (SAAO). This instrument was used in frame-transfer mode and the observations were made in white light in order to maximize the count rate. GW Lib was observed on May 7, 8 and 12, and SDSS 1610 was observed on May 9 and 10.

GW Lib went into outburst in 2007 April. In Fig. 1, we plot five months of amateur observations of this source, following the initial outburst. We see in this figure that the *V*-band magnitude of the source rapidly rose to ∼8 as the disc moved into a high state. The luminosity of the source then declines over ∼20 d as the amount of matter in the disc decreases. This is followed by a very rapid decline as the disc returns to a low state. From ∼30 d after the initial rise to outburst, we see a much more gradual decline in luminosity, leading us to believe that emission from the heated WD began to dominate. On May 23, the spectrum of GW Lib showed broad absorption lines (Steeghs, private communication), confirming this belief. In 2007 June, we were awarded discretionary time with VLT + ULTRACAM with which to study the effects of the 2007 April outburst of GW Lib. The *V*-band luminosity of the source at this point was estimated to be ∼16 – still more than a magnitude brighter than before the outburst. We were therefore

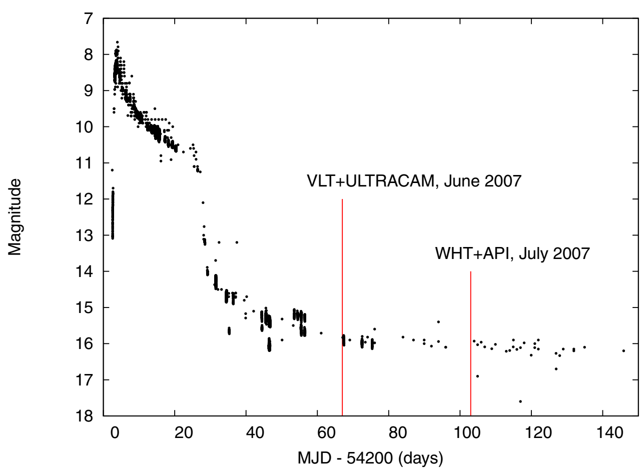

Figure 1. *V*-band light curve for GW Lib, taken between 2007 April and August. These data are taken from the website of the American Association of Variable Star Observers (http://www.aavso.org/), and show the outburst and subsequent decline. We mark the times of our observations with VLT + ULTRACAM and WHT + API.

able to use a much shorter exposure time compared to our 2005 May observations. The data were unbinned and we used the same CCD window as for the 2005 May observation. For the first two nights, we used the SDSS i' filter in place of r', for scheduling reasons.

We observed GW Lib again on 2007 July 22 and 23 with the Auxilary Port Imager (API) on the 4.2 m William Herschel Telescope (WHT). We used the Harris B-band filter, and an exposure time of 30 s. In 2008, we began a monitoring program for GW Lib, using RATCam on the Liverpool Telescope (LT; Steele et al. 2004). In this paper, we present 12 two-hour blocks of data taken between March and June. We used the SDSS g' filter and a 2×2 binning. The exposures were 30 s in length, with a ∼10 s dead time.

All of these data were reduced with aperture photometry using the ULTRACAM pipeline software, with debiassing, flat-fielding and sky background subtraction performed in the standard way. The source flux was determined using a variable aperture (whereby the radius of the aperture is scaled according to the full width at half-maximum). Variation in observing conditions was accounted for by dividing the source light curve by the light curve of a comparison star. The stability of this comparison star was checked against the other stars in the field. For the ULTRACAM data, we determined atmospheric absorption coefficients in the u', g' and r' bands and subsequently determined the absolute flux of our targets using observations of standard stars taken in evening twilight. We use this calibration for our determinations of the apparent magnitudes of the two sources, although we present all light curves in flux units normalized to unity. Using our absorption coefficients, we extrapolate all apparent magnitudes to an airmass of 0. The systematic error introduced by our flux calibration was <0.1 mag in all bands.

3 GW LIB: PULSATIONS IN QUIESCENCE

In this section, we examine the GW Lib observations taken in 2005 May, during which the CV was in its quiescent state. In Fig. 2, we show light curves of the reduced data. The long period first seen 4 yr prior to these observations by Woudt & Warner (2002) is apparent, and overlaid on this is significant variation on shorter time-scales. Note that this flickering is not instrumental noise: it is intrinsic variation in the source itself. The MJD times given here and in all subsequent plots are on the barycentric dynamical time-scale. We find the mean apparent magnitude of GW Lib at this time to be 16.95 in r', 16.78 in g' and 17.01 in u', with amplitudes of ∼0.12, 0.08 and 0.09 in u', g' and r', respectively, as a result of the long period.

3.1 Determination of the long period

Before determining the pulsation modes, we first examine the long period. In order to determine the parameters of this modulation, we defined a four-parameter sine function of the form $a \sin[2\pi\,(t - T_0)/P] + d$. We attempted to fit this model to each night of data separately, as well as the combined data set. This model provides a good fit, but it can be seen in Fig. 2 that the variation is something of a departure from a sinusoid, particularly in u', in which the data appear to have a somewhat saw-toothed shape. However, a fit to a sinusoid is sufficient for determination of the phase and period of this modulation.

We find a consistently good fit between the model and the data when we fit each night of data separately. However, we find that our best-fitting parameters are not consistent from night to night. The fitted phase varies by up to 0.072 and the period takes values of between 2.08 and 2.13 h. This suggests that the variation is not constant in phase and/or period, although the amplitude of the modulation remains approximately constant. We confirm this when we attempt to fit the entire data set – a good fit cannot be found for any constant phase/period model.

We illustrate the changing phase/period of the modulation by plotting a constant phase/period model over the g'-band data in Fig. 2. We find that the combined May 7 and 8 data are well fitted by a model with a frequency of 11.335 ± 0.001 cycles d^{-1} ($P = 2.117$ h) and a zero phase of $T_0 = 53\,497.268\,52(8)$ d. The amplitudes in u', g' and r' are 0.12, 0.08 and 0.09 mag, respectively. However, it can be seen in the figure that this model with these parameters is out of the phase with the data taken on May 12 and 15. The data for these nights are best fitted when a shorter period $P = 2.108$ h and a zero phase $T_0 = 53\,497.338$ are used, but a model with these parameters fits poorly with May 7 and 8 data.

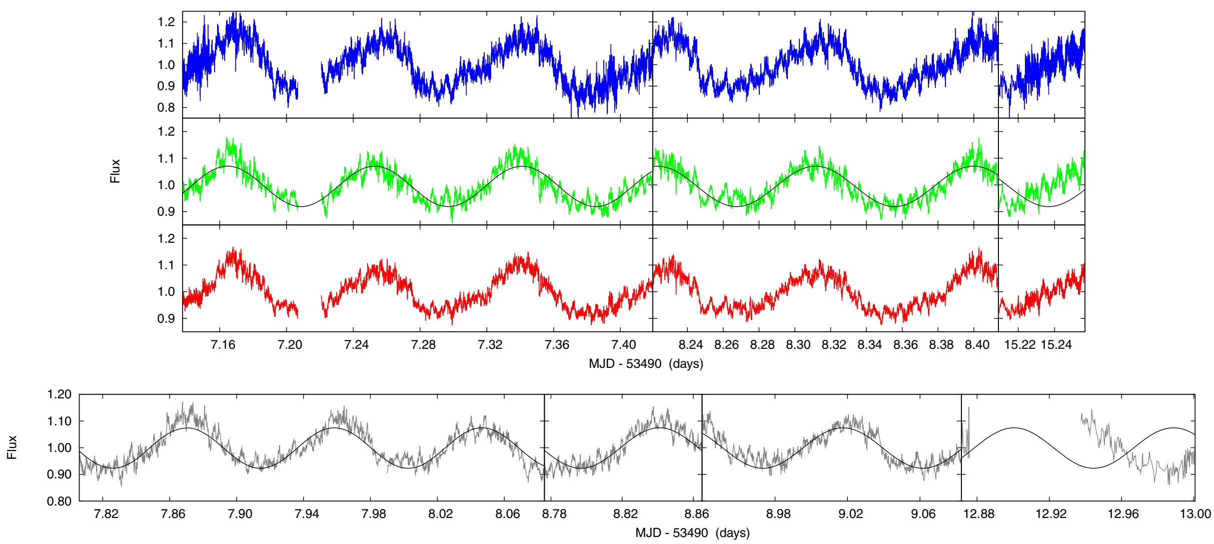

Figure 2. Light curves for GW Lib, taken during quiescence in 2005 May. The top plot shows the data taken with VLT + ULTRACAM in the u' (blue, top), g' (green, middle) and r' (red, bottom) filters, taken on 2005 May 7, 8 and 15. The bottom plot shows data taken with the SAAO 1.9 m + UCT photometer, on May 7, 8 and 12. We use a flux scale with the mean level normalized to one for both plots. In the g' and SAAO plots, we overplot a fit to the ∼2.1 h modulation, using the model parameters given in Section 3.1.

To summarize, we observe that the ∼2.1 h variation first reported by Woudt & Warner (2002) is persistent on time-scales of years. This phenomenon is quasi-periodic, with a period which varies by minutes over time-scales of a few days. We discuss the possible causes of this variation in Section 6.2.

3.2 Amplitude spectra

We determine the frequencies and amplitudes of the WD pulsations by fitting a model consisting of a series of sine functions to our data. In order to determine the uncertainties on these fits, we generated a large number of data sets, resampled from the original data using the bootstrap method (Efron 1979; Efron & Tibshirani 1993). The model is fitted to each one of these data sets, generating an array of frequencies and amplitudes for each of the three modes, from which the mean and the rms error are determined. These uncertainties are an improvement on the formal errors, since, as well as the photon and readout noise, they include effects such as scintillation. However, in accreting systems the amplitude spectra show a large amount of high-amplitude, low-frequency signals, predominantly due to accretion-driven flickering (and in the case of GW Lib, the long-period modulation). When the bootstrap method is used on these data, this low-frequency power can be spread to high frequencies as a result of the poor window function of the resampled data. In order to compensate for this, we whiten our data to remove most of the low-frequency signals. We first fit sinusoids to each individual night as described in Section 3.1, and used the resulting fits to remove most of the long-period component and any harmonics. We then fit and subtract a polynomial to the data to remove the low-frequency flickering power. We find that the uncertainties from the bootstrap do not reduce any further beyond a ∼10th order polynomial. We compute amplitude spectra from these whitened data, which we plot in the left-hand panels of Fig. 3. Using the VLT + ULTRACAM data, we plot separate spectra for the u'-, g'- and r'-band data. We also plot the results combining the SAAO 1.9 m + UCT photometer observations with the ULTRACAM g'-band data (these data sets are not simultaneous). As well as the results shown here, we also calculated separate spectra for each night of observations, in order to check that any signals we detect are persistent over multiple nights.

When we examine Fig. 3, we see first of all that there are some periodicities clearly evident in these data, in all bands, with amplitudes of 1–2 per cent. There are three strong signals with frequencies of between 100 and 400 cycles d^{-1}, and a number of low-frequency (<50 cycles d^{-1}) signals. We also see many peaks at the 0.1–0.4 per cent amplitude level across the entire frequency range. Much of this is accretion-driven 'flickering' in the source luminosity. The amplitude of this flickering tends to be highest in the u'-band data, and increases at lower frequencies. For example, if we examine the g' data after removing the three dominant signals, we find the mean amplitude to be 0.10 per cent ±0.06 between 100 and 300 cycles d^{-1}, and 0.08 per cent ±0.04 between 300 and 600 cycles d^{-1}.

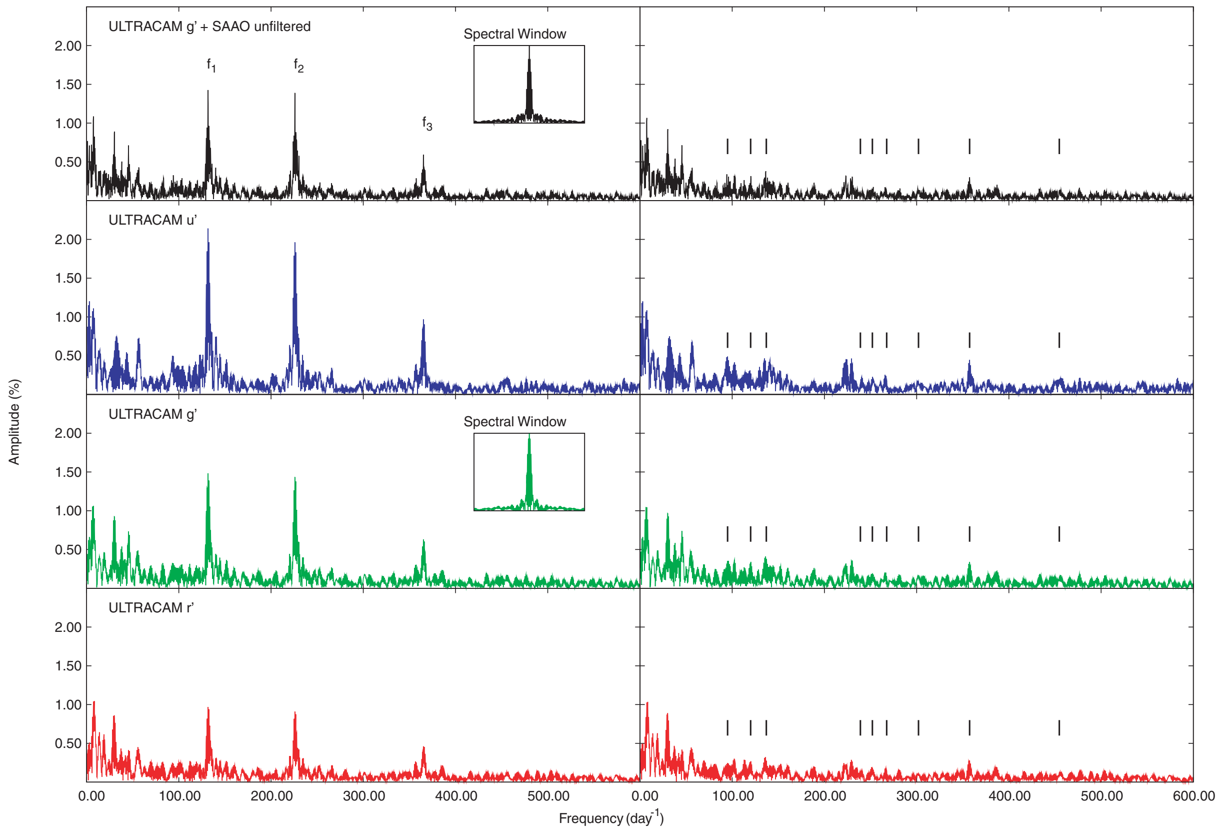

Figure 3. Amplitude spectra for the 2005 May observations of GW Lib. On the left, we plot the unwhitened spectra, on the right we plot the same data with the f_1, f_2 and f_3 modes subtracted. Both the left- and the right-hand plots have been pre-whitened to remove the long-period modulation and the majority of the low-frequency flickering. The top plots use the VLT + ULTRACAM g'-band data combined with the SAAO 1.9 m + UCT photometer white-light data. The blue, green and red plots use just the VLT + ULTRACAM u', g' and r' data, respectively. Note that the spectral window for the VLT + ULTRACAM g' data is also applicable to the u' and r' plots. In the right-hand plot, we mark the marginal signals listed in Table 2.

Table 2. Main periods in GW Lib during quiescence. The three main periodicities were first identified in van Zyl et al. (2000).

Frequency (cycles d^{-1})	Amplitudes (%) u'	g'	r'	ID
Main periodicities				
131.639 ± 0.005	2.191 ± 0.036	1.582 ± 0.028	1.042 ± 0.023	f_1
225.862 ± 0.006	1.916 ± 0.038	1.396 ± 0.030	0.893 ± 0.025	f_2
365.237 ± 0.013	0.991 ± 0.036	0.698 ± 0.029	0.528 ± 0.025	f_3
Marginal detections				
95.041 ± 0.094	0.474 ± 0.163	0.407 ± 0.077	0.314 ± 0.068	
120.183 ± 0.032	0.349 ± 0.038	0.339 ± 0.028	0.287 ± 0.025	
137.248 ± 0.023	0.414 ± 0.037	0.432 ± 0.029	0.316 ± 0.025	
239.191 ± 0.050	0.196 ± 0.042	0.167 ± 0.028	0.184 ± 0.024	
252.069 ± 0.047	0.231 ± 0.039	0.192 ± 0.028	0.196 ± 0.024	
267.522 ± 0.052	0.143 ± 0.039	0.167 ± 0.028	0.162 ± 0.025	
302.036 ± 0.172	0.188 ± 0.052	0.165 ± 0.024	0.117 ± 0.023	
357.423 ± 0.025	0.390 ± 0.037	0.376 ± 0.028	0.321 ± 0.025	$f_1 + f_2$?
454.632 ± 0.167	0.222 ± 0.038	0.165 ± 0.026	0.130 ± 0.022	

This flickering is the dominant source of 'noise' in our data (the Poisson noise level can be determined by looking at the amplitude spectra at very high frequencies, and we find it to be at the ~0.01 per cent level) and the challenge in interpreting these data involves distinguishing genuine periodic signals from this flickering.

The source flickering increases significantly at low frequencies, and is most likely the cause of the signals we see at <50 cycles d^{-1}. We therefore choose to disregard these signals, which leaves three dominant signals with frequencies of between 100 and 400 cycles d^{-1}. We began by determining the frequencies and amplitudes of these dominant signals, and we list the results in Table 2, as well as the uncertainties we determined with the bootstrap method. We find these modes to have frequencies consistent with the f_1,f_2 and f_3 modes originally reported by van Zyl et al. (2000).

We whitened our data set by removing the f_1,f_2 and f_3 modes in order to find weaker signals in our data. We plot the results in the right-hand panels of Fig. 3. We find that the whitening leaves some residual peaks very close to the primary peaks. In the case of the f_1 mode, there is no signal which stands out compared to the surrounding peaks, but there is some evidence of residual signals around the positions of the f_2 and f_3 modes. In Fig. 4, we show amplitude spectra around the positions of these two modes before and after whitening. In the f_2 case, there are two signals either side of the main peak. These are very close in frequency (~2–3 cycles d^{-1}) to the main peak and so we take these to be associated with the f_2 mode and do not consider them further. These signals could be spectral leakage due to modulation of the amplitude of the f_2 mode by the accretion disc. If we now examine the amplitude spectra around the f_3 mode, we see after whitening there is a signal left in the data with a frequency ~8 cycles d^{-1} lower than the f_3 mode. In this case, the separation between the mode and the 'residual' peak is sufficiently large for us to consider these two peaks to be distinct.

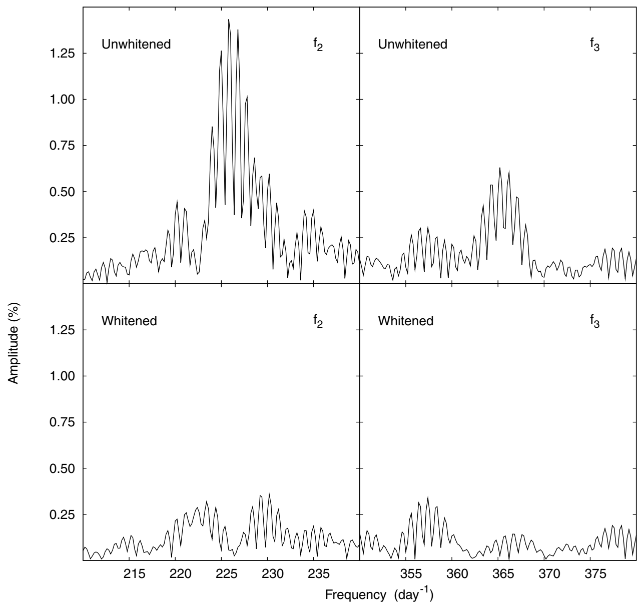

Figure 4. We plot here the g'-band amplitude spectra for the 2005 May observations of GW Lib around the positions of the f_2 and f_3 modes (taken from the complete spectra given in Fig. 3). In the top panels, we plot the unwhitened spectra, and in the bottom panels we plot the same data with the f_2 and f_3 modes subtracted. In the case of the f_2 mode (left), the subtraction leaves two residual signals which are very close in frequency to the mode, and are very likely associated with it. In the case of the f_3 mode, there is a second signal close to the mode, but the separation is larger and these two signals are more likely to be unrelated.

Other than these signals near the f_2 and f_3 modes, we see in Fig. 3 that there are no signals other than the main three modes that stand out as being particularly strong in amplitude over the flickering level. There may be periodic signals present at the 0.1–0.4 per cent level, but it is impossible to distinguish them from the source flickering. The criteria by which we try to determine real periodicities in our data are somewhat subjective. We looked for signals which have an amplitude that is greater than the mean level in their vicinity, and which appear to be present on every night. We then determined the frequencies and amplitudes of all of these signals by simultaneously fitting a series of sine functions to the data set. The uncertainty on each signal was determined using the bootstrap method described above. We eliminated from further consideration any signals for which the determined error on the amplitude was comparable to or greater than the value itself. We are left with a list of nine candidates for periodic signals in our data. We list these detections in Table 2, but they should be treated as marginal at best. Some are better candidates than others: the aforementioned signal near the f_3 mode seems significant. We also note that this signal has a frequency of 357.424 cycles d^{-1} ($P = 242$ s), and is within

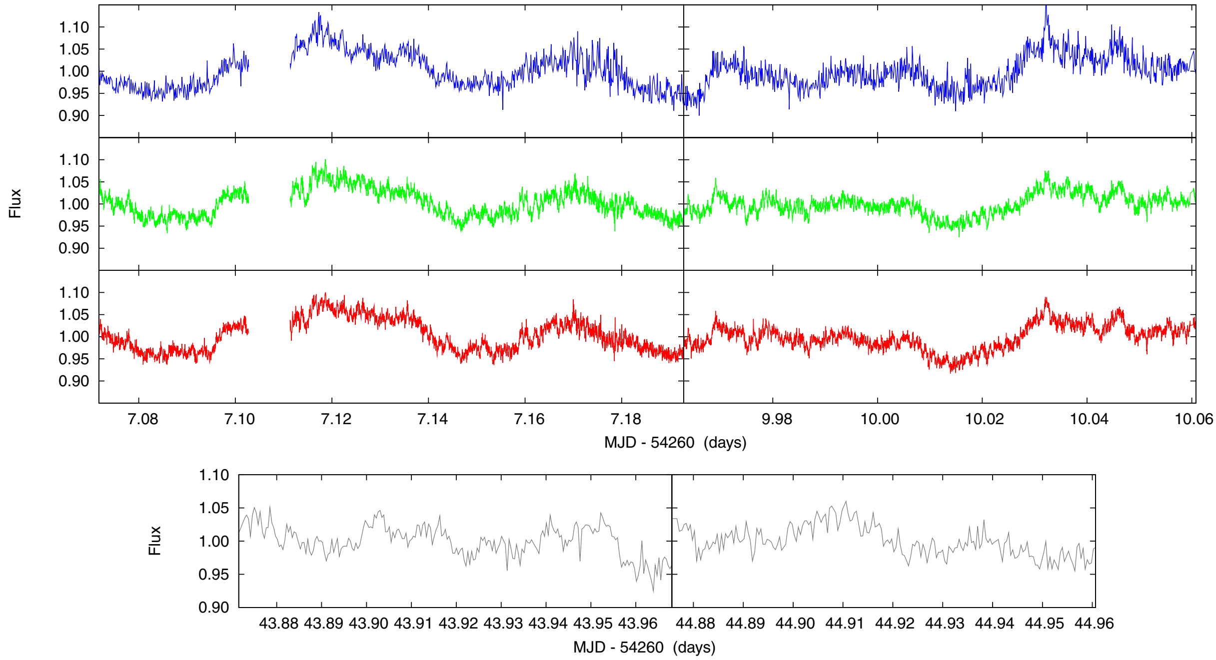

Figure 5. Light curves for GW Lib, taken a few months after outburst. The top plot shows the data taken with VLT + ULTRACAM in the u' (blue), g' (green) and r' (red) filters in 2007 June. The u'-band data are binned in order to compensate for poor conditions. The bottom plot shows the data taken with WHT + API in 2007 July, with a g' magnitude scale.

3σ of the position of the $f_1 + f_2$ linear combination. We also note that we see a number of low-frequency (<100 cycles d^{-1}) signals, none of them consistent with the spectroscopic period reported by Thorstensen et al. (2002) ($\nu_{orb} = 18.75$ cycles d^{-1}).

4 GW LIB: PULSATIONS AFTER OUTBURST

In this section, we examine the GW Lib data, taken in the aftermath of the 2007 April outburst. We plot the light curves of these data in Figs 5 and 7.

4.1 2007 June/July: two to three months after outburst

We begin by discussing the data collected a few months after the outburst (Fig. 5). For 2007 June VLT + ULTRACAM data, we plot only the data taken on June 16 and 18, since the other data were seriously affected by poor weather conditions. We plot the complete data set obtained in 2007 July with WHT + API. The mean apparent magnitudes of GW Lib are 15.6, 15.5 and 15.2 in u', g' and r' at this time: an increase in brightness of ∼1.35, 1.25 and 1.81 mag, respectively, over the mean values we determined in quiescence. The source is both significantly more luminous and bluer in colour in these months after the outburst.

There is some large amplitude, long-period modulation apparent in these data. This variation is clearly not sinusoidal but does appear to be somewhat periodic. While we cannot fit this modulation with any degree of certainty, we find it to have a period close to the spectroscopic period reported by Thorstensen et al. (2002), and so this may be an orbital modulation. Secondly, we note that these light curves do not show the coherent, short-period variation indicative of the pulsation of the WD, which was so obvious in the quiescent data (Fig. 2).

We plot the amplitude spectra for the four epochs of GW Lib data in Fig. 6. We see in this figure that in 2007 June and July, two to three months after the outburst, we do not detect any of the pulsation modes that were observed in the quiescent data. The luminosity of the source, combined with the very gradual decline we see in Fig. 1, leads us to believe that the WD makes a larger contribution to the flux in these post-outburst data compared to quiescence, and thus one would expect to detect the modes more easily if they persist. The spectra are dominated by low-amplitude flickering at all frequencies. In the VLT + ULTRACAM data, this flickering level is ∼0.2 per cent, which is the same as in the equivalent quiescent data. However, we do observe the source flickering to be of a slightly higher amplitude at low frequencies, with an amplitude of ∼0.3–0.5 per cent over the frequency range where we previously observed the f_1 and f_2 modes. There is no single signal that stands out as being a coherent pulsation mode. In the WHT + API data, we see a couple of peaks with amplitudes ∼0.5 per cent at a frequency of between 50 and 100 cycles d^{-1}. These may just be flickering, or the largest peak may be related to the strong signal we see in 2008 March data (see Section 4.2). If this is an early detection of this signal, it is marginal at best.

4.2 2008 March–June: ∼1 year after outburst

When we flux calibrate the LT + RATCam data, we find that 11 months after the outburst, the source is still more than half a magnitude more luminous than during quiescence, with a mean g' band apparent magnitude of ∼16.2. We plot the data on a relative flux scale in Fig. 7. We see that there is a degree of luminosity variation throughout, and in particular in the June observations we see a variation with an apparent period of the order of 2 h. This may be the re-emergence of the long-period variation observed in quiescence.

We do not see the quiescent periodicities in any of these data. However, over the course of these runs we do see a new periodic signal emerge at a frequency of ∼75 cycles d^{-1}. There is evidence

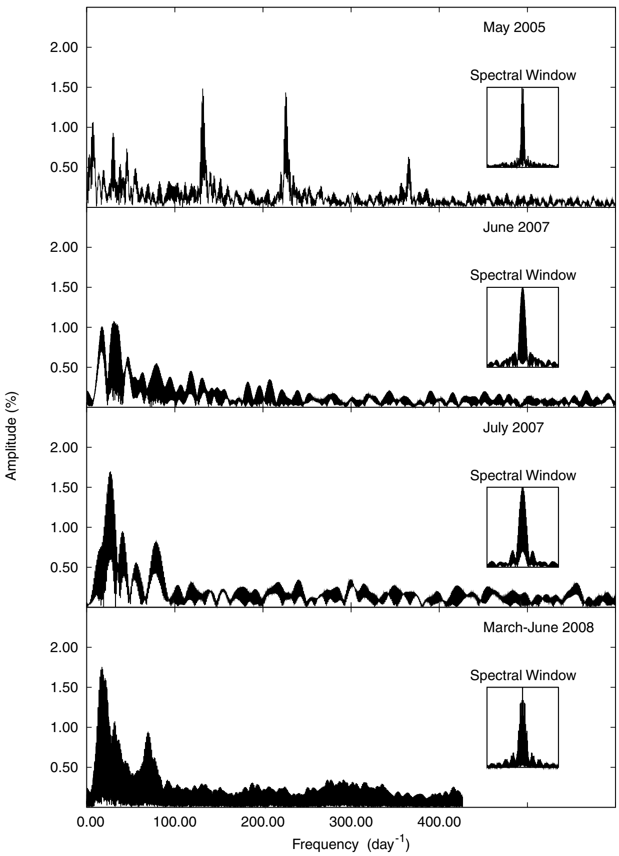

Figure 6. Amplitude spectra for GW Lib. In the top panel, we plot the quiescent g' data taken in 2005 May. In the other three panels, we plot the three epochs of post-outburst data. In the second panel, we plot the g'-band amplitude spectrum obtained in 2007 June with VLT + ULTRACAM. In the third panel, we plot the spectrum obtained in 2007 July with WHT + API. In the bottom panel, we plot the g'-band spectrum of the combined data set obtained with LT + RATCam.

for this signal from March 11 onwards, but in the early March data it appears to drift in frequency. This may be real, or it may be the result of confusion with low-amplitude flickering. This signal is consistent in frequency in the March 30–April 29 data. Throughout April, it declines in amplitude, and it is not apparent in the May/June data. We fit a sine function to the March 31 data where this signal is most prominent, and find it to have a frequency of 74.86 ± 0.68 cycles d^{-1} ($P = 1154$ s) and a g' amplitude of 2.20 per cent $\pm$ 0.18. This amplitude is greater than that of the periodicities observed in the quiescent data sets.

In the last data set, taken on June 21, there is evidence for another new periodicity in this source. When we fit this signal we find it to have a frequency of 292.05 ± 1.11 cycles d^{-1} ($P = 296$ s) and a g' amplitude of 1.25 per cent $\pm$ 0.18.

5 SDSS 1610: PULSATIONS IN QUIESCENCE

In this section, we examine the SDSS 1610 observations taken in 2005 May. We plot the light curves in Fig. 8. The pulsations of the WD can be clearly seen in these data. There is no clear evidence for a long-period modulation in this source similar to that observed in GW Lib. The gradual variation in the mean count rate that can be observed in the SAAO observations is due to the changing airmass over the course of these white-light observations.

We compute amplitude spectra from these data as we did with GW Lib. We plot the results in Fig. 9. Using the VLT + ULTRACAM data, we plot separate spectra for the u'-, g'- and r'-band data. We also plot a spectrum that is computed from combining the SAAO 1.9 m + UCT photometer observations with the ULTRACAM g'-band data. We find the mean apparent magnitudes of this source to be 19.10, 19.04 and 19.33 in u', g' and r', respectively, with a variation of ∼0.1 mag in all bands which is due to the pulsations.

We list the main periods evident in these data in Table 3. We use the same method to determine these frequencies, amplitudes and uncertainties as we did for GW Lib. The strongest signals are the peaks which match the periodicities identified by Woudt & Warner (2004). We see the two principal modes f_1 and f_2 at frequencies of 143.40 and 250.23 cycles d^{-1}, respectively ($P = 603$ and 345 s), and at frequencies 284.87 and 393.60 cycles d^{-1} ($P = 303$ and 220 s), we see peaks which were presumed by Woudt & Warner (2004) to be the $2f_1$ harmonic and the $f_1 + f_2$ combination. Using our calculated uncertainties, we find the peak at 393.60 cycles d^{-1} to be consistent with the position of the $f_1 + f_2$ combination to within 1σ. However, the 284.87 cycles d^{-1} signal is more than 5σ from the expected position and so may be an independent mode. We also identify a number of additional signals with amplitudes of ∼0.2– 0.4 per cent. We followed the same procedure for identifying potential low-amplitude signals as was used for GW Lib, but for this source the process was much less subjective since the amplitude of the source flickering is much lower. The signals we identify are of a significantly larger amplitude than neighbouring peaks, but in order to confirm the significance of these signals we compared our amplitude spectra to fake data sets consisting only of Gaussian white noise. We were hence able to determine the signal/noise amplitude ratio across the entire frequency range. We use the Breger criterion (Breger et al. 1993) to distinguish between peaks due to pulsation and noise, and we find all of the signals listed in Table 3 to satisfy this criterion. We therefore have confidence in these signals being real periodicities in the source.

Woudt & Warner (2004) saw some evidence in their data for the $2f_2$ harmonic and $2f_1 + f_2$ combination. We see signals at 502.476 and 534.951 cycles d^{-1}($P = 172$ and 162s) which are close to the expected position of these signals, but fall outside of our calculated uncertainties. We see also a number of high-amplitude, low-frequency (<100 cycles d^{-1}) signals. None of these is consistent with the orbital period (80.52 min: Woudt & Warner 2004) and they are most likely due to flickering. As with GW Lib, we note the amplitudes of the pulsation modes are highest in the u' band.

6 DISCUSSION

In this section, we examine the results presented in Sections 3–5. We divide this discussion into three parts. We begin by examining in more detail the periodicities we find in the two sources when we observed them in quiescence. We then discuss the ∼2.1 h modulation in GW Lib. Finally, we discuss the post-outburst observations of GW Lib.

6.1 Pulsations in GW Lib and SDSS 1610 during quiescence

6.1.1 Pulsations in GW Lib

In Table 2, we list the main periodicities which we observe in the amplitude spectra of GW Lib. Note that the amplitudes we detect are not the true pulsation amplitudes of the WD: there is considerable

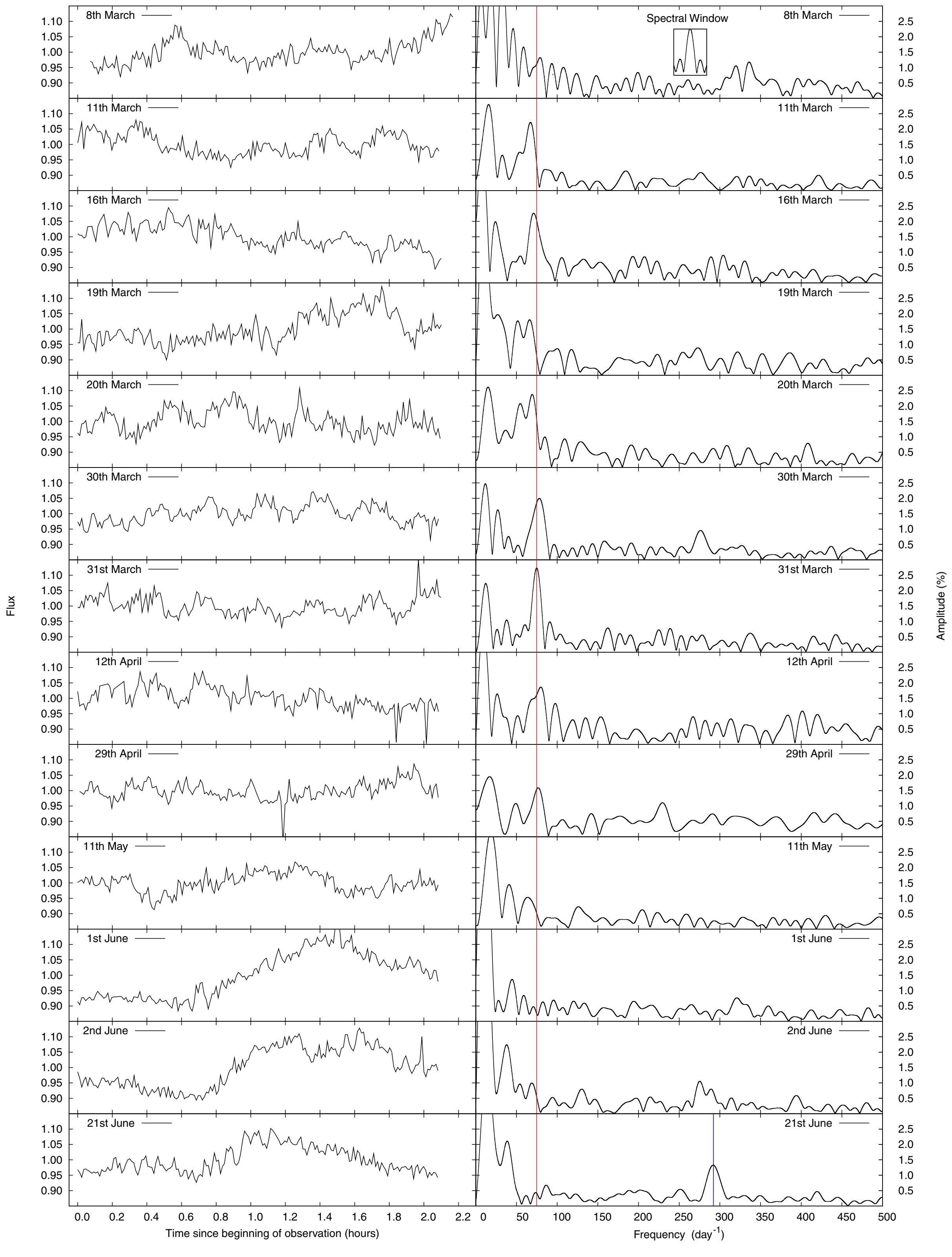

Figure 7. The data sets obtained for GW Lib with the Liverpool Telescope + RATCam, taken between 11 and 14 months after outburst. We plot light curves (left-hand panel) and amplitude spectra (right-hand panel), using a g' filter. On the amplitude spectra, we mark with a red line the position of the ∼75 cycles d^{-1} periodicity observed in late March and early April. In the June 21 panel, we mark with a blue line the position of the ∼292 cycles d^{-1} periodicity.

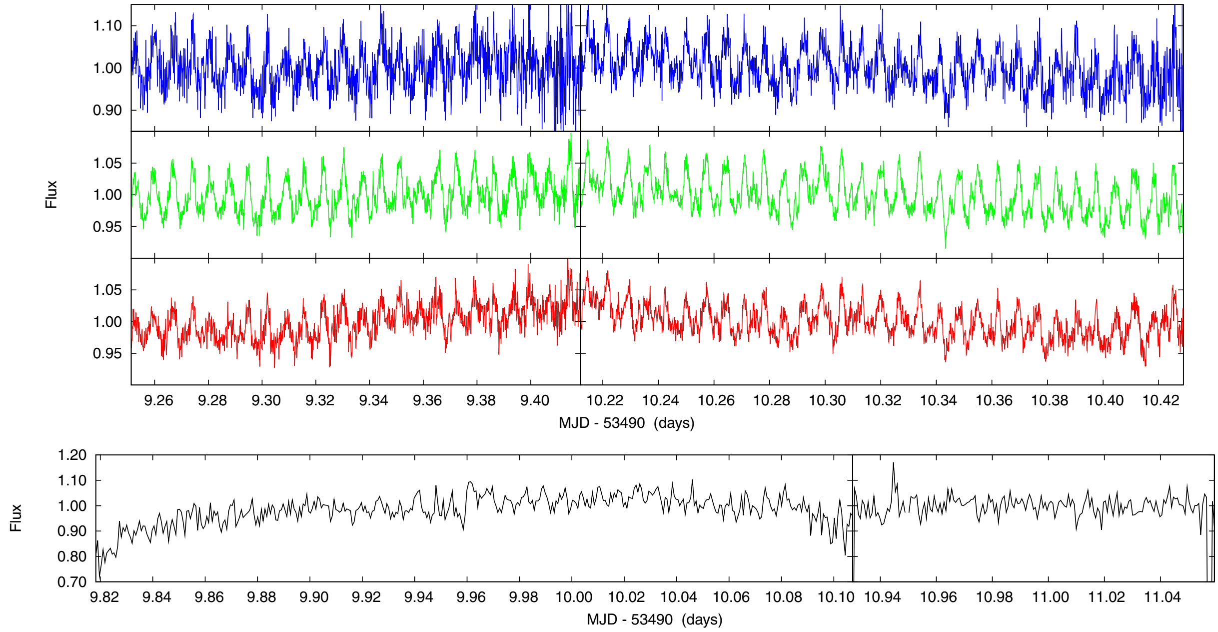

Figure 8. Light curves for SDSS 1610, taken during quiescence in 2005 May. The top plot shows the data taken with VLT + ULTRACAM in the u' (blue), g' (green) and r' (red) filters. The bottom plot shows the data taken with the SAAO 1.9 m + UCT photometer. We use a magnitude scale for the VLT + ULTRACAM data, and a flux scale with the mean level normalized to one for the white-light SAAO data.

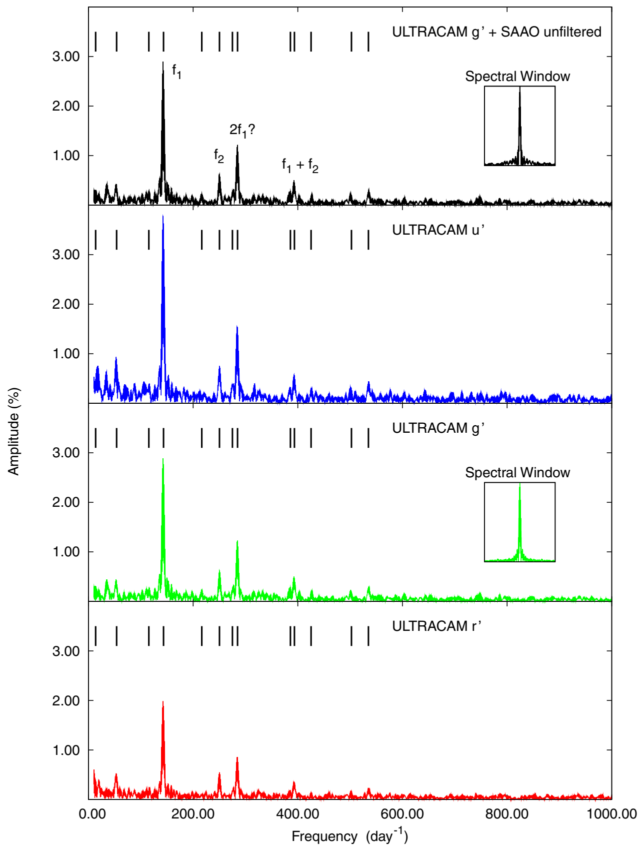

Figure 9. Amplitude spectra for the 2005 May observations of SDSS 1610. The top plot uses the VLT + ULTRACAM g'-band data combined with the SAAO 1.9 m + UCT photometer white-light data. The blue, green and red plots use just the VLT + ULTRACAM u', g' and r' data, respectively. We mark the signals listed in Table 3, with the longer marks showing the main modes and the possible linear combinations.

accretion luminosity present, which dilutes the pulsation amplitudes. We find that the spectrum is dominated by three main peaks. These are the pulsation modes discovered and designated f_1, f_2 and f_3 by van Zyl et al. (2004). We find a number of additional signals with amplitudes in the 0.2–0.4 per cent range. One is close to the position of the $f_1 + f_2$ linear combination, and was also reported by van Zyl et al. (2004). However as we noted in Section 3.2, the amplitudes of the other signals are comparable to the flickering in the source and so it is impossible to be certain that these are true periodicities. These detections should be treated as being marginal at best. The remaining signals listed cannot be associated with any of the main modes.

We also note that van Zyl et al. (2004) reported a number of signals in their data which they identified as linear combinations. These signals were clustered at frequencies of ~240, 340, 580 and 905 cycles d^{-1}. We see no evidence for these signals in our data. Additionally, we note that the theoretical model of Townsley et al. (2004) predicted a number of additional periodicities which should be apparent in GW Lib. One of these periods is 191 s (452 cycles d^{-1}), which is close to the signal we identify at 454.632 cycles d^{-1}. The remaining predicted periods do not match any of our findings.

6.1.2 *Pulsations in SDSS 1610*

In Table 3, we list the main signals we observe in the amplitude spectra of SDSS 1610. As for GW Lib, we should note that the amplitudes we detect are diluted by the accretion luminosity. Woudt & Warner (2004) reported two main modes and four linear combinations or harmonics in this source. However, our detections of the signals reported as $2f_1$, $2f_2$ and $2f_1 + f_2$ in Woudt & Warner (2004) have frequencies which are not formally consistent with those identifications. We also note that Woudt & Warner (2004) reported a number of signals in their data at frequencies 334, 596, 711, 754 and 839 cycles d^{-1}. These were marginal detections, each of which

Table 3. Main periods in SDSS 1610. The two primary modes and four combinations were first identified in Woudt & Warner (2004).

Frequency (cycles d^{-1})	Amplitudes (%) u'	g'	r'	ID
		Main periodicities		
143.401 ± 0.004	3.696 ± 0.070	2.817 ± 0.035	1.913 ± 0.035	f_1
250.232 ± 0.020	0.746 ± 0.075	0.622 ± 0.038	0.540 ± 0.038	f_2
284.866 ± 0.010	1.573 ± 0.072	1.251 ± 0.035	0.858 ± 0.036	$2f_1$?
393.598 ± 0.030	0.546 ± 0.074	0.484 ± 0.035	0.350 ± 0.035	$f_1 + f_2$
		Other signals		
13.638 ± 0.023	0.851 ± 0.116	0.537 ± 0.057	0.605 ± 0.048	
53.715 ± 0.031	0.873 ± 0.085	0.413 ± 0.049	0.518 ± 0.043	
115.382 ± 0.051	0.404 ± 0.146	0.330 ± 0.071	0.281 ± 0.061	
216.510 ± 0.065	0.107 ± 0.094	0.243 ± 0.040	0.113 ± 0.039	
275.132 ± 0.040	0.366 ± 0.071	0.297 ± 0.035	0.213 ± 0.038	
385.973 ± 0.057	0.285 ± 0.076	0.245 ± 0.036	0.162 ± 0.035	
425.328 ± 0.055	0.325 ± 0.078	0.214 ± 0.036	0.153 ± 0.039	
502.476 ± 0.066	0.265 ± 0.091	0.202 ± 0.037	0.155 ± 0.040	
534.951 ± 0.069	0.474 ± 0.073	0.319 ± 0.038	0.244 ± 0.037	

only appeared in one run. We found no evidence for these signals in our data.

6.1.3 *Colour dependence of pulsations*

We now investigate the colour dependence of the modes in GW Lib and SDSS 1610. In Fig. 10, we plot g'/r' versus u'/g' for the dominant periodicities in the two sources. We also plot the 1σ error contour for each signal. These contours are elliptical because we use the g'-band flux as a component in both the ordinates. We chose the g'-band flux since these data have the lowest uncertainty.

For GW Lib, we plot the f_1, f_2 and f_3 modes. For SDSS 1610, we plot f_1 and f_2, as well as the two high amplitude combinations of these two modes. We see first of all in this plot that both g'/r' and u'/g' are >1 for all signals, indicating that the amplitude of these signals increases at bluer wavelengths in both the sources. For GW Lib, we see that the three modes seem to be similar in colour, with all three modes occupying an overlapping region in the parameter space. In the case of SDSS 1610, however, there is a possible discrepancy between the two primary modes. This may be significant. It has been shown that for a given stellar temperature, pressure and geometry, the change in flux as a result of a non-radial pulsation is sensitive to the l number of the pulsation (Watson 1988). The fact that the two principal modes in SDSS 1610 have a different colour dependence might suggest that they have different l values.

6.2 The 2.1-h period in GW Lib

The 2.1-h modulation in GW Lib was first observed in 2001 by Woudt & Warner (2002). It was not seen in any previous photometric observations of this source. We observed this modulation in all three bands in 2005, confirming it to be a persistent feature in the light curve of GW Lib over several years. Our 2005 observations of this source were separated by a number of days, and we found that we could not fit this entire data set with any constant phase/period model. The period of this modulation appears to vary by minutes on time-scales of days. There is, however, no persistent trend since all of the data combined showed a period that was consistent with the findings of Woudt & Warner (2002) to within a few minutes. It is possible that this apparent variation in phase/period is due to

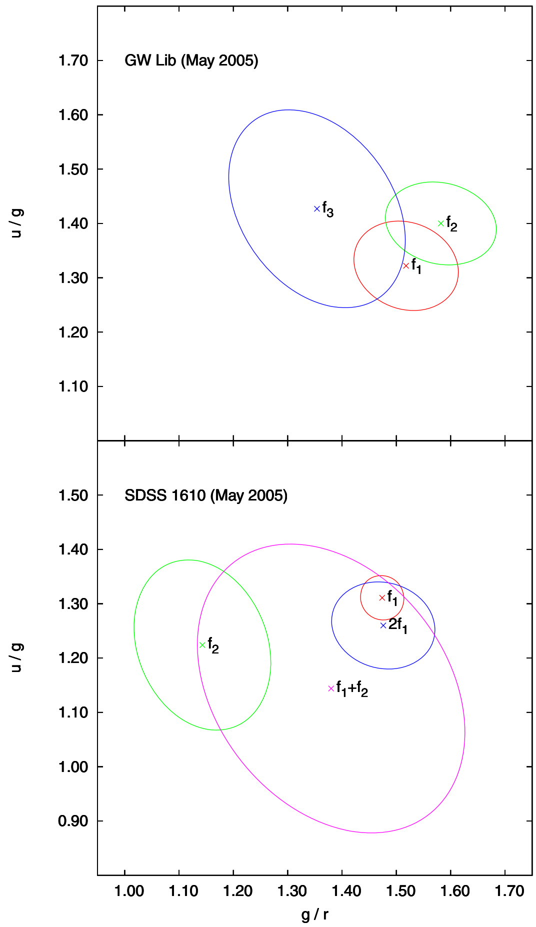

Figure 10. The colour dependence of the pulsations in the quiescent GW Lib and SDSS 1610. We calculate the g'/r' and u'/g' colour ratios for the main signals in each source and plot the resulting 1σ error contours.

multiperiodicity, but we have insufficient data to properly explore this possibility.

This variation is difficult to explain. Spectroscopic determination of the orbital period has shown it to be much shorter (76.78 min, Thorstensen et al. 2002). The 2.1-h period therefore cannot be ascribed to an orbital modulation, such as obscuration of the bright spot or an elliptical accretion disc. There are other systems which display a photometric period that is much greater than the spectroscopic period. One example is V2051 Oph, in which a photometric period of 274 min is found (Warner & O'Donoghue 1987). This is an eclipsing system, and the orbital period has been determined to be 89.9 min. Another example is FS Aur, in which a long period of ∼3 h was found by Neustroev (2002). This variation was confirmed and found to be persistent by subsequent ULTRACAM observations (Neustroev et al. 2005). A further example is V445 And (HS 2331+3905), with spectroscopic and photometric periods at 81.1 min and ∼3.5 h (Araujo-Betancor et al. 2005). One proposed explanation for these sources is an intermediate polar model with a rapidly rotating and precessing WD (Tovmassian et al. 2003; Tovmassian, Zharikov & Neustroev 2007). However, in the case of GW Lib, there is no evidence in the spectra for a strong magnetic field. This model is also inconsistent with our finding of a quasi-periodic nature for the GW Lib modulation.

The fact that this modulation is apparently quasi-periodic in nature suggests that it is not directly related to the spin, precession or orbit of the WD. We suggest that it is an accretion-driven phenomenon that most likely originates in the accretion disc. We also note that the 2007 July post-outburst data show some evidence for a long-period modulation. The pre- and post-outburst modulations may caused by the same phenomena. On one hand, they have consistent amplitudes in absolute flux terms. On the other hand, the period of the post-outburst modulation appears to be close to the spectroscopic period, so this variation may be an orbital modulation due to irradiation/ellipsoidal variations as a result of the changing aspect of the secondary star, or the result of the disc becoming elliptical during outburst, causing superhumps in the light curve as seen in the SU UMa stars. We also note that in the 2008 June LT data, the variation in GW Lib again seems to be dominated by a modulation with a period of ∼2 h. An accurate determination of this period is not possible from these data, since each observation is only 2 h in length.

6.3 The effects of the outburst in GW Lib

In the post-outburst data, we observe GW Lib to be more luminous and bluer in colour than in 2005 May. We noted in Section 2 that the observational data support the conclusion that this increased luminosity is due to the heating of the WD by the 2007 April outburst. The GW Lib outburst is reminiscent of the outbursts in the well-studied system WZ Sge. Studies of the most recent outburst in this system (Kuulkers et al. 2002; Patterson et al. 2002; Long et al. 2003) showed significant heating followed by a long-term cooling over a number of years (Sion et al. 2003; Godon et al. 2004, 2006).

The 2007 June/July light curves taken two to three months after the outburst (Fig. 5) show much short-time-scale variation, but we do not see the coherent pulsations which are apparent in the quiescent data (Fig. 2). If we examine the amplitude spectra for the 2007 June/July data (Fig. 6), we do not see any well-defined periodicities corresponding to the pulsation modes seen in the quiescent data, or any new periodicities. There are two possible explanations for this. The first is that the heating of the WD has moved it outside of the CV instability region in the $T_{\rm eff}$–log g plane and the pulsations have been 'switched-off'. Alternatively, the source may still feature the same coherent pulsations, but they now have an amplitude below the level of the accretion-driven flickering and are therefore undetectable.

We can estimate a minimum possible percentage amplitude for the pulsations by supposing that the amplitude in absolute flux is unchanged by the heating of the WD. Given our measurements of the source luminosity in 2005 May and 2007 June, we find that the minimum amplitude for the f_1 and f_2 modes in the post-outburst 2007 June data is ∼0.4 per cent and the minimum amplitude for the f_3 mode is ∼0.2 per cent. These amplitudes are approximately the same in all three bands (the change in colour of the source post-outburst compensates for the fact that the amplitudes of the modes are greater at bluer wavelengths during quiescence). Given that the flickering level in our data is generally ∼0.2 per cent (approximately the same as in quiescence), we would expect to detect at least the f_2 mode, if it were present. We do see the flickering increase in amplitude at low frequencies, and at the position of the f_1 mode it is ∼0.5 per cent, which may be enough to obscure the mode. The presence of this periodicity is unlikely, however, given that we would expect to detect the f_2 mode at a comparable level. The 0.5 per cent amplitude signals at 125 cycles d^{-1} could be a manifestation of the f_1 periodicity itself, but since we do not observe a single, coherent peak, we suspect not.

The fact that the heating of the WD has apparently suppressed or switched-off the pulsations is significant. If the pulsations originated deep within the star, then even if the driving mechanism were to be switched-off, one might suspect that the pulsations continue simply due to inertia. The fact that the pulsations have been switched-off indicates that in the absence of excitation they are damped on time-scales of weeks. This is in line with some current theoretical models: for example, Wu & Goldreich (1999) predict that $l = 1$ modes in ZZ Ceti stars with periods comparable to those in GW Lib will be damped on this time-scale.

In the 2008 data (Fig. 5), we see that the three known modes are still not present. The luminosity of the source suggests that the WD is still significantly hotter at this stage than during quiescence, so this is perhaps not surprising. We do see very clearly in the 2008 March/April data a new signal with a frequency of ∼75 cycles d^{-1}. This is apparently unrelated to any of the known modes. This signal may be a quasi-periodic oscillation originating in the disc, or it may be a WD pulsation. If this signal is associated with the WD, then its low frequency is puzzling. It has been shown that the effective temperature of the WD is well correlated with the amplitude and period of the pulsations in isolated ZZ Ceti WDs (Clemens 1993; Mukadam et al. 2006). The lowest frequency pulsations are seen in the coolest WDs (e.g. G29–38, Kleinman et al. 1998). In the case of GW Lib therefore, we would expect that as the WD cools and enters the CV instability region we would see higher frequency pulsations develop, consistent with the high WD temperature. From the correlation shown in fig. 1 of Mukadam et al. (2006), the ∼75 cycles d^{-1} implies a WD temperature of <11 000 K. This is clearly not the case, since spectral fits of GW Lib have shown the WD to be hotter than this during quiescence (14 700 K, Szkody et al. 2002). If the ∼75 cycles d^{-1} pulsation is associated with the WD, then this suggests that the correlation between effective temperature and period does not apply to GW Lib (and potentially other CV pulsators), probably due to the chemical composition of the accreted outer layers. It is possible that this signal is a DBV pulsation driven by the ionization of helium (Arras et al. 2006). We see a second new signal develop in the 2008 June, with a frequency of ∼292 cycles d^{-1}. This frequency does not correspond to any known modes, or any of the predictions of Townsley et al. (2004).

It is unclear as to when the ∼75 cycles d^{-1} periodicity first became apparent. We see in Fig. 6 that there is some evidence for a signal at a similar frequency in the 2007 July data, although given the amplitude of this peak we suspect it is just flickering in the source. The signal is very clear at the end of 2008 March but there is evidence for its presence from when our 2008 observations began. However, the signal is significantly weaker at this point so we suggest that our March observations are very close in time to the first manifestation of this periodicity in the source emission. In the case of the ∼292 cycles d^{-1} pulsation, further monitoring will be necessary in order to determine its persistence.

7 CONCLUSIONS

In this paper, we report observations of two CV pulsators: GW Lib and SDSS 1610. We took multiband, high time-resolution observations of both the sources in quiescence in 2005 May, using the high-speed CCD photometer ULTRACAM mounted on the VLT. We supplemented this with additional data from the University of Cape Town photometer mounted on the 1.9 m telescope at SAAO. In both the sources, we resolve the dominant periods which have been observed by previous authors. In SDSS 1610, we do detect some additional lower amplitude signals: the large collecting area of the VLT provides a distinct advantage over previous studies for SDSS 1610, which is much less luminous than GW Lib and is a more challenging target for high time-resolution photometry. The VLT does not provide the same advantage over previous studies in the case of GW Lib, since in this source the accretion-driven flickering of the source is the limiting factor in further mode identifications. We find in both sources that the signals tend to be stronger towards the blue end of the visible spectrum. Of particular significance is the finding that the two principal modes in SDSS 1610 have a different colour dependence. This may be evidence that these modes are spherical harmonics with different l numbers. Further multiband observations of this source could confirm this. We also note that our frequency determination of the signal identified as the $2f_1$ combination by previous authors suggests that this identification may be incorrect and this period is an independent mode.

We took additional observations of GW Lib in 2007 June with VLT + ULTRACAM, which we supplemented with data from the WHT taken a month later. These observations were made in the aftermath of an outburst in this source: the first outburst observed since its discovery and the first outburst observed in a CV known to contain a pulsating WD. We believe that at the time of our observations, the emission from the source is dominated by the WD, and we find it to be more than a magnitude brighter than in our previous observations due to heating by the outburst. We observe much short-time-scale variation in this source but we do not observe the coherent pulsations we detected in quiescence, leading us to believe that these have been suppressed by the heating of the WD. Our results suggest the heating of the WD has pushed it outside of the instability region in the $T_{\rm eff}$–$\log g$ plane. We observed this source again 11 months after outburst with LT + RATCam. The WD is still significantly hotter than during quiescence. We still do not observe the known modes, but we report the emergence of two new periodicities. The first was apparent in 2008 March/April with a frequency of 74.86 ± 0.68 cycles d^{-1} ($P = 1154$ s) and a g'-band amplitude of 2.20 per cent ± 0.18. We observe the second in 2008 June, with a frequency of 292.05 ± 1.11 cycles d^{-1} ($P = 296$ s) and a g' amplitude of 1.25 per cent ± 0.18.

In GW Lib, we observe an additional modulation in luminosity with a period of ∼2.1 h. This has been detected before, but not in all previous observations. The origin of this modulation is unclear: it is apparently unrelated to the orbital period. We find this modulation to vary over the course of our observations in phase and/or period. We suggest that this is an accretion-related phenomenon associated with the accretion disc. A similar variation is apparent in some of the post-outburst data, but we believe this is most likely to be an orbital modulation.

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