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Multiwavelength variability in CAL 83⋆

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Abstract. CAL 83 is a supersoft X-ray source in the LMC that exhibits multiwavelength variability on a wide range of time-scales. The optical magnitude shows quasi-periodic variability with a period of ~450 d, an orbital modulation of just more than a day, and also possible QPOs associated with an accretion disc. The X-ray lightcurves exhibit large-amplitude modulations, including periodicities ranging from 67 s to hours. The X-ray variability is accompanied by temperature changes, and is anti-correlated with the optical behaviour.

Key words. Stars: individual: CAL 83 — X-rays: binaries — White dwarfs — Stars: oscillations — Accretion, accretion discs

1. Introduction

Supersoft X-ray sources (SSS) are highly luminous, with bolometric luminosities of the order $\sim 10^{37}$ erg s^{-1}. They are “supersoft” because their X-ray emission peaks at low-energy X-rays, typically between ~15 and 80 eV (see e.g. the review of Kahabka & van den Heuvel 2006). The X-ray emission observed in SSS can be explained by nuclear hydrogen burning on the surface of an accreting white dwarf (WD) (Van den Heuvel et al. 1992).

As illustrated in Fig. 2 of Hachisu & Kato (2001), the nature of the H burning on the WD surface is determined by the WD mass $M_{\rm WD}$ and the accretion rate $\dot{m}_{\rm acc}$. For material consisting of 70% H, $\dot{m}_{\rm acc} \sim (3.7\text{-}7.6) \times 10^{-7}\,(M_{\rm WD}/{\rm M}_{\odot} - 0.40)\ {\rm M}_{\odot}\,{\rm yr}^{-1}$ can sustain steady H shell burning.

For lower $\dot{m}_{\rm acc}$, steady burning is not possible, but shell flashes trigger nova outbursts. For $\dot{m}_{\rm acc}$ above the steady burning regime, H burning can take place in a thin shell around the WD, while excess material piles up to form an extended envelope, with part of the envelope blown off in an optically thick wind.

CAL 83 is a close binary supersoft source in the LMC. It has long been considered the prototype of persistent SSS, but is in fact highly variable. In this paper, its known multiwavelength variability is summarized, and new results based on *XMM-Newton* data are presented.

2. Long-term variability

CAL 83 exhibits pronounced brightness changes (~1 mag) in the optical. These modulations are quasi-periodic with a period of ~450 d (Rajoelimanana et al. 2013, hereafter R13). Since its discovery, CAL 83 has been observed 8 times during X-ray off-states, coinciding with optically high states. The X-ray luminosity during the on-state observations is also variable. R13 presented new results

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on this anti-correlated optical and X-ray variability, as well as a review of previously published results.

The anti-correlation between the optical and X-ray flux may be caused by changes in $\dot{m}_{\rm acc}$. A small increase in $\dot{m}_{\rm acc}$ will cause excess material to pile up, increasing the WD photospheric radius, as well as the irradiation of the accretion disc and the rate of inward flow through the disc. The shift of the WD spectrum towards longer wavelengths, as well as the increased irradiation and resulting emission of reprocessed radiation from the disc (and the disc wind?) will cause a decrease in the X-ray luminosity and an increase in the optical luminosity (also see Greiner & Di Stefano 2002 and references therein). Once the excess material has been drained, or the mass transfer rate from the secondary decreases, the contraction in the WD photosphere shifts the emission peak to soft X-rays again.

3. Other optical variations

The orbital modulation in the optical lightcurve was refined by R13 to 1.047529(1) d (with a ~0.1 mag semi-amplitude).

Photometrical observations with the Sutherland High-Speed Optical Camera (SHOC) on the SAAO 1.9-m Telescope in April 2013 revealed quasi-periodic modulations at frequencies $\lesssim$1 mHz (as summarized in Odendaal et al. 2015). They are most probably quasi-periodic oscillations (QPOs) from the disc.

Optical spectra reveal broad wing structures in the He II and Balmer emission lines, as well as P Cyg profiles in the Balmer lines. These structures are variable, and probably originate in a wind/jet from the disc, which is possibly precessing at a period of ~69 d (Crampton et al. 1987).

4. The ~67 s X-ray pulsation

The *XMM-Newton* archive contains 19 on-state and 4 off-state observations of CAL 83. In 7 of the on-state observations, we discovered a ~67 s X-ray pulsation (Odendaal et al. 2014). However, it is not completely stable, exhibiting a spread of up to ~3 s from the median.

If this is related to the WD rotation, then its variability needs to be explained. We may be observing the WD rotation through an extended envelope surrounding it. The rotation of the nuclear burning envelope may not be quite synchronized with the WD spin, with these layers "slipping" on the fast rotating WD surface, modulating the observed period.

Alternatively, the pulsation may be associated with g-mode oscillations, driven by the ϵ-mechanism, i.e. due to an instability caused by thermonuclear reactions (e.g. Saio 2013).

5. The 38.4 min X-ray pulsation

From a NLTE analysis of *Chandra* observation 1900 and *XMM-Newton* observation 0123510101 of CAL 83, Lanz et al. (2005) obtained $M_{\rm WD} \sim 1.3 \pm 0.3$ M$_\odot$ and a photospheric radius 2.5 times that of the degenerate core.

Schmidtke & Cowley (2006) (hereafter SC06) performed a detailed timing analysis of these 2 observations, and discovered a period of ~38.4 min in the *Chandra* lightcurve. They ascribed this periodicity to non-radial pulsations of the accreting WD.

Non-radial g-mode WD pulsations first became known in single WDs, where they are detected in the optical and UV (e.g. Córsico 2009). They are often multi-periodic and often stable on time-scales of years. Non-radial pulsations have also been observed in dwarf novae (e.g. Warner & Woudt 2005).

More recently, pulsations on time-scales of several minutes have also been observed in X-rays from accreting WDs with surface H burning. Drake et al. (2003) found a strong periodic signal of ~41.7 min in the nova V1494 Aql, together with a suite of periods from 8.8 to 57.7 min. Ness et al. (2003) reported a ~22.1 min pulsation in V4743 Sgr, with two weaker harmonic overtone periods at 11.1 and 7.5 min. The 38.4 min pulsation in CAL 83 may be of a similar origin.

Since the paper of SC06, another 18 on-state observations of CAL 83 were obtained with *XMM-Newton*. We took another close look at these archival observations to investi-

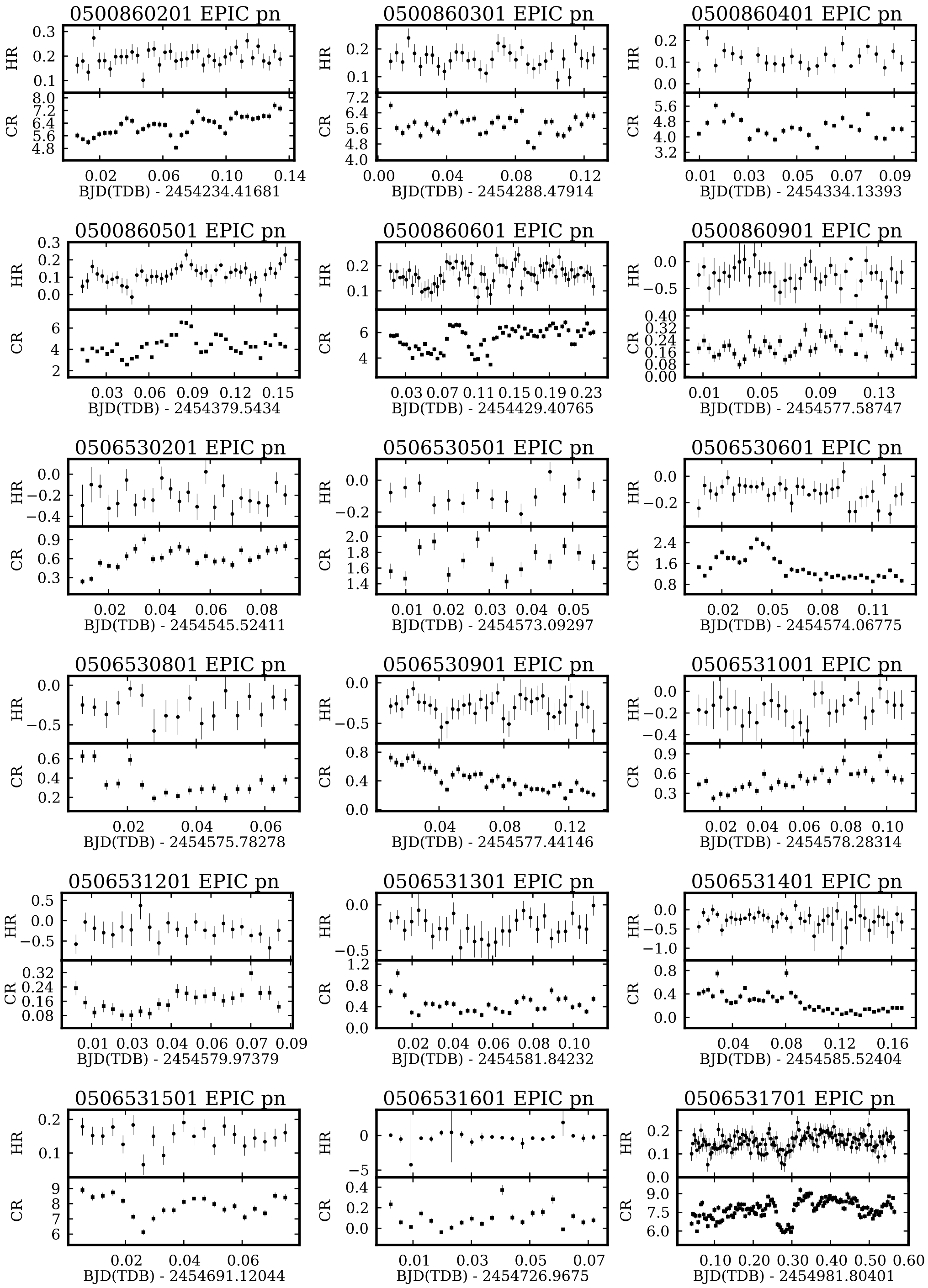

Fig. 1. *XMM-Newton* X-ray lightcurves of CAL 83 during 2007-2009. For each plot, the bottom panel represents the EPIC pn count rate (in the 0.15–2.5 keV band) and the top panel the EPIC pn hardness ratio (see text for definition). Each data point represents a 300 s bin.

gate variability on time-scales of several minutes to hours.

6. Recent *XMM-Newton* lightcurves

The observations were calibrated with the SAS Version 13.0.1. Broadband (0.15–2.5 keV) EPIC lightcurves with barycentric corrections were extracted. Soft (0.15–0.25 keV), hard (0.25–2.5 keV) and hardness ratio lightcurves were also created. The hardness ratio was defined as HR = (H–S)/(H+S), with S and H the soft and hard count rates respectively.

6.1. Hardness ratio correlations

The broadband and HR lightcurves are shown in Fig. 1 for the EPIC pn detector. The lightcurves exhibit significant variability. It is also evident that the count rate (CR) and hardness ratio (HR) seem to follow the same trends for many of the observations.

To quantify this correlation, the Spearman linear rank-order correlation coefficient r_s was utilized, (Press et al. 2007, p. 749). r_s describes the correlation between two simultaneous lightcurves and can vary between -1 (complete anti-correlation) and $+1$ (complete correlation), with 0 indicating no correlation. The Spearman coefficients correlating the CR and HR for each observation in Fig. 1 respectively were calculated, and are listed in Table 1 together with their statistical significances.

A correlation between CR and HR was confirmed above a 99.73% significance level for observations 0500860401, 0500860501, 0500860601 and 0506531701, and at a lower level in some of the other observations. The only negative r_s values were obtained for 0506531201 and 0506531601, where the count rates were extremely low, but the significance levels of these anti-correlations are also low.

Table 1 also gives the average pn CR and average pn HR for each observation, and these are plotted in Fig. 2. Here one can also see a trend according to which observations with high average CRs also have high average HRs, which agrees with the findings of R13. For this correlation, r_s=0.909, with a 99.999983% significance. We can conclude that, in general, an

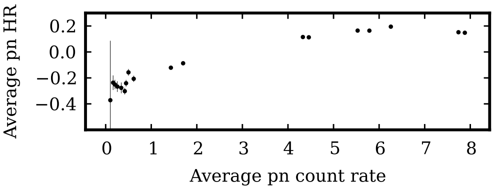

Fig. 2. The average EPIC pn hardness ratio versus the average EPIC pn count rate for the CAL 83 observations listed in Table 1.

increase in the X-ray count rate is accompanied by an increase in temperature. It has already been proposed that the superorbital modulations (§2) are related to temperature changes, but it now appears that a correlation between X-ray flux and temperature can also be found on time-scales of minutes to hours.

6.2. Lomb-Scargle analysis

For each observation, a combined EPIC lightcurve in the 0.15–2.5 keV range was created by obtaining a weighted average of the mos1, mos2 and pn lightcurves. Lightcurves with a wide range of bin sizes were created, and detrending was performed by subtracting different low-order polynomial functions.

A comprehensive Lomb-Scargle (LS) analysis (with the Starlink PERIOD package[1]) was performed to search for periodic behaviour in the X-ray lightcurves at periods longer than the known ~67 s (15 mHz) pulsation. Many of the observations had significant peaks at frequencies below 2 mHz. The statistical significance levels were determined by performing Monte Carlo significance tests. The LS periodograms for the observations exhibiting periodic behaviour are shown in Fig. 3. These periodograms were produced using a bin size of 50 s, with long term trends removed by subtracting a second-order polynomial fit.

The peaks in Fig. 3 that have a >99.73% significance level are marked, and listed in Table 2. It should be noted that the indicated peaks were also visible for the other bin sizes and detrending variants, and there were no sig-

[1] www.starlink.ac.uk/docs/sun167.htx/sun167.html

Table 1. *XMM-Newton* observations of CAL 83 from 2007 to 2009. The average EPIC pn count rate and hardness ratio is given for each observation. The Spearman correlation coefficient r_s between the pn count rate and hardness ratio lightcurves (see Fig. 1) is also given, together with its significance level.

Observation	Start date & time (UT)	Average pn CR	Average pn HR	Spearman coefficent r_s	Significance level (%)
0500860201	2007-05-13 22:03:32	6.257 ± 0.031	0.195 ± 0.005	0.320	94.9713
0500860301	2007-07-06 23:31:52	5.786 ± 0.031	0.164 ± 0.006	0.487	99.7000
0500860401	2007-08-21 15:11:21	4.457 ± 0.032	0.113 ± 0.007	0.580	99.7627
0500860501	2007-10-05 23:49:21	4.327 ± 0.024	0.115 ± 0.006	0.548	99.9826
0500860601	2007-11-24 21:10:14	5.529 ± 0.022	0.165 ± 0.004	0.598	99.999989
0500860901	2008-03-21 02:10:24	0.204 ± 0.006	-0.251 ± 0.036	0.019	9.3808
0506530201	2008-03-20 00:33:22	0.615 ± 0.013	-0.207 ± 0.024	0.292	83.4068
0506530501	2008-04-16 12:32:01	1.699 ± 0.026	-0.087 ± 0.016	0.168	45.0144
0506530601	2008-04-17 13:40:13	1.431 ± 0.015	-0.121 ± 0.011	0.227	81.6993
0506530801	2008-04-19 06:43:35	0.342 ± 0.012	-0.277 ± 0.041	0.323	80.8932
0506530901	2008-04-20 22:38:43	0.419 ± 0.009	-0.302 ± 0.026	0.121	52.4060
0506531001	2008-04-21 18:47:57	0.500 ± 0.012	-0.157 ± 0.026	0.356	94.2082
0506531201	2008-04-23 11:20:22	0.163 ± 0.008	-0.237 ± 0.056	−0.463	97.4067
0506531301	2008-04-25 08:13:32	0.448 ± 0.010	-0.241 ± 0.026	0.221	76.0228
0506531401	2008-04-29 00:40:23	0.257 ± 0.006	-0.267 ± 0.041	0.189	78.7418
0506531501	2008-08-12 14:50:27	7.881 ± 0.046	0.148 ± 0.006	0.371	90.2642
0506531601	2008-09-17 11:10:21	0.102 ± 0.007	-0.372 ± 0.458	−0.194	59.9341
0506531701	2009-05-30 08:00:48	7.741 ± 0.017	0.152 ± 0.002	0.536	>99.999999

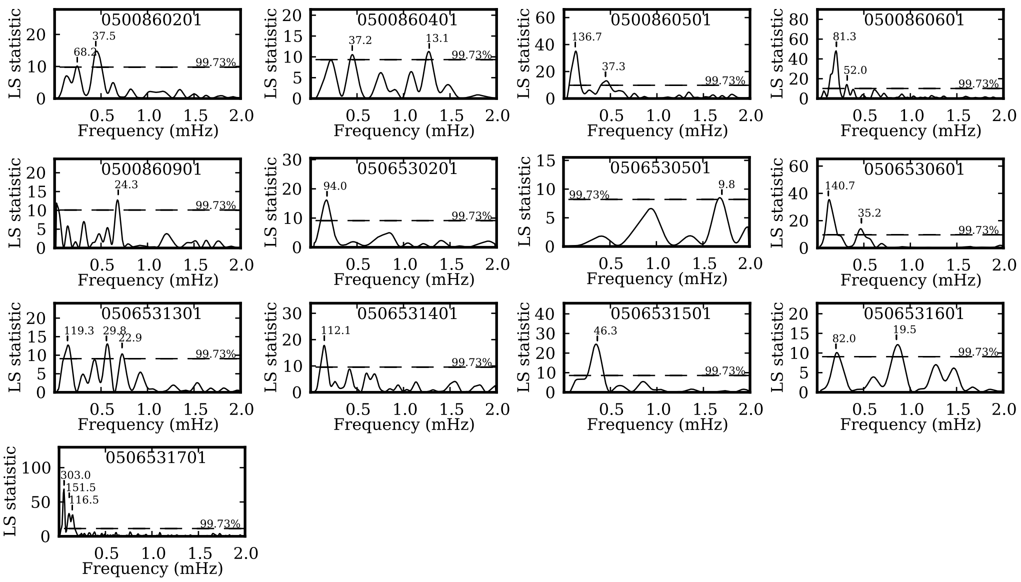

Fig. 3. Lomb-Scargle periodograms of those combined EPIC lightcurves that exhibit significant peaks. The lightcurves had a binning of 50 s and were detrended by subtracting a 2nd-order polynomial fit. The 99.73% significance level is indicated. Each significant peak has been marked with its period in minutes.

Table 2. Periodicities detected at a >99.73% significance level in the periodograms (Fig. 3) of the combined EPIC lightcurves.

Observation	Pulsation periods (in minutes)		
0500860201	68.2±12.5;	37.5±3.8	
0500860401	37.2±5.8 ;	13.1±0.7	
0500860501	136.7±46.9;	37.3±3.4	
0500860601	81.3±10.3;	52.0±4.2	
0500860901	24.3±1.5		
0506530201	94.0±39.2		
0506530501	9.8±0.7		
0506530601	140.7±58.6;	35.2±3.5	
0506531301	119.3±49.7;	29.8±3.0;	22.9±1.8
0506531401	112.1±28.5		
0506531501	46.3±10.4		
0506531601	82.0±34.2;	19.5±1.9	
0506531701	303.0±61.2;	151.5±15.2;	116.5±9.0

nificant peaks in the background periodograms at these positions.

It is interesting to note that 5 of the periodograms has a peak at the same position (within error bars) as the 38.4 min reported by SC06. There are also peaks at other periods, and often several simultaneous peaks. We think that these transient periodicities are also related to non-radial g-mode pulsations as discussed in §5, possibly driven by nuclear burning instabilities. The multiple peaks may represent harmonic periods. These are preliminary results and will be investigated in more detail. We also need to explain the wide range of and variability in the observed pulsations. We believe, though, that the unstable and ever-changing accreted layers on the WD surface in CAL 83 can be expected to yield a much more variable series of pulsations to be triggered than in WD systems without H burning or accretion.

7. Conclusions

The optical and X-ray variability of CAL 83 on various time-scales has been reviewed. The count rates and hardness ratios of the recent *XMM-Newton* X-ray lightcurves have been explored, and it was found that the significant modulations in the count rates are often correlated with the hardness ratio variations. The X-ray modulations also exhibit periodic behaviour, with pulsation periods ranging from ∼10-300 minutes. The possibility that these pulsations are associated with non-radial WD pulsations is currently being explored.

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