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An adapted LIMA model for the 67 s periodicity in the supersoft X-ray source CAL 83

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Supersoft X-ray sources constitute a class of astronomical objects characterized by extremely high X-ray luminosities and low effective temperatures, typically 20-100 eV. The canonical model for these sources involves a white dwarf accreting from a more massive companion in a binary system at a very high rate. The high soft X-ray luminosity is derived from steady or quasi-steady nuclear burning of accreted hydrogen in a shell on the white dwarf surface. CAL 83 in the Large Magellanic Cloud (LMC) is often considered to be the prototype of the SSS class. CAL 83 exhibits large-scale anti-correlated X-ray and optical variability on a superorbital time-scale of $\sim$450 d, which has been explained by cyclic changes of the white dwarf envelope between a contracted high-temperature and an expanded low-temperature state. A detailed periodic analysis of the *XMM-Newton* lightcurves of CAL 83 has revealed a variable X-ray modulation with a period of $\sim$67 s. This oscillation was detected in all the X-ray high state lightcurves obtained during the 2000-2009 time period, as well as in the X-ray low state lightcurve with the highest count rate. The model proposed to explain the behaviour of this oscillation is related to the low-inertia magnetic accretor (LIMA) model described in the literature to explain the observed properties of dwarf nova oscillations (DNOs). In this model, the $\sim$67 s modulation originates in an equatorial belt-like structure in the envelope at the boundary with the inner accretion disc, with the belt weakly coupled to the white dwarf core via a $\sim 10^5$ G magnetic field.

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1. Introduction

Supersoft X-ray sources (SSSs) emit most of their energy in the soft X-ray band, with $\gtrsim$90% of the unabsorbed photon flux below 0.5 keV (see e.g. the review of [1]). They have very high luminosities, typically of the order of $\sim 10^{37}$ erg s^{-1}. It has been shown that the soft X-ray spectrum of many SSSs can be explained by the nuclear burning of accreted hydrogen on the surface of a white dwarf in a binary system with an accretion rate of $\dot{m}_{\rm acc} \gtrsim 10^{-7}$ M$_\odot$ yr^{-1} [2].

CAL 83 is often considered to be the prototypical close binary supersoft source, and has an orbital period of 1.047529 ± 0.000001 d [3]. X-ray spectral fits indicate a white dwarf (WD) primary with mass $\sim$1.3 M$_\odot$ and luminosity $\sim 3.4\times 10^{37}$ erg s^{-1} [4]. This fascinating source exhibits variability in various wavebands on various time-scales. A review of its properties is provided by [5], while [6] considered the source variability.

CAL 83 exhibits long-term quasi-periodic modulations in the optical ($P \sim 450$ d), cycling between an optical low state and an optical high state [3]. Several X-ray off-states have been observed during optical high states, while the X-ray high states were observed during optical low states. This long-term anti-correlation between X-ray and optical flux are also observed in another LMC SSS, namely RX J0513.9-6951, albeit with a shorter cycle period of $\sim$168 d. A similar model could explain the behaviour of both sources. It has been suggested that the X-ray high, optical low state is associated with the WD photosphere being in a contracted state (higher effective temperature), while the X-ray low, optical high state correspond to an expanded WD photosphere (lower effective temperature) due to an enhanced accretion rate [7, 8, 9].

There are 23 observations of CAL 83 in the *XMM-Newton* Science Archive (obtained 2000 to 2009). A systematic search for short time-scale periodicities in all these observations revealed a $\sim$67 s X-ray periodicity (indicated by $P(\sim 67$ s$)$) in several of these lightcurves [10]. This periodicity is variable in nature: it disappears and reappears on time-scales of hours, and on similar time-scales the period typically varies with $\sim$3 s to either side of the median value of $\sim$67 s.

There are several indications that CAL 83 has already passed through a long period of mass accretion onto the primary WD: (i) The WD is massive [4]. (ii) The low ratio of H to He II and CNO emission in the optical spectra indicate an evolved donor of which the outer layers have already been stripped by accretion [11]. (iii) Calculations of the time-dependent properties of ionization nebulae around SSSs indicate that CAL 83 has been radiating at a time-averaged luminosity of $\gtrsim 3\times 10^{37}$ erg s^{-1} for at least the past $\sim 10^5$ years [12]. This poses the possibility that the WD in CAL 83 may have been spun up to a short spin period by accretion torques.

However, if $P(\sim 67$ s$)$ represents the WD rotation period, the $\sim$3 s drift still has to be explained. It was thus suggested that the WD rotation may be observed through a well developed envelope, the rotation of which is not quite synchronized with that of the rapidly spinning WD, resulting in a slippage of the layers on the WD surface, and a spread in the observed periodicity [10]. However, a closer investigation into the nature of this periodicity has also shown that its characteristics are remarkably similar to those of dwarf nova oscillations (DNOs) (see also the independent remarks of [13]). DNOs are quasi-periodic modulations observed in dwarf novae (DNe) during outburst, and also in novalike variables, i.e. in cataclysmic variables (CVs) with "high" accretion rates ($\gtrsim 10^{-9}$ M$_\odot$ yr^{-1}), but not in intermediate polars (e.g. [14]).

The favoured interpretation for DNOs is that they originate from a region close to the surface

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of a WD with a magnetic field too weak to enable rigid body rotation of the core and exterior region, but strong enough to control accretion close to its surface. This is known as the low-inertia magnetic accretor (LIMA) model ([15] and references therein).

In this paper, a similar LIMA model is proposed for $P(\sim 67\text{ s})$ in CAL 83, based on the preliminary discussion of [16], Chapter 4. In §2, some properties of $P(\sim 67\text{ s})$ itself are highlighted [10, 16], while §3 presents a summary of the existing LIMA model for DNe. In §4 the relevance of a similar model in CAL 83 is discussed, followed by the conclusion in §5.

2. The 67 s X-ray periodicity in CAL 83

Among the 23 *XMM-Newton* observations of CAL 83, 4 were performed during an X-ray off-state. The 19 on-state observations can be separated into 2 groups, with 8 X-ray "bright" states where the EPIC pn count rate was > 5 counts s^{-1}, and 11 X-ray "faint" states with an EPIC count rate < 2 counts s^{-1}. A comprehensive Lomb-Scargle (LS) timing analysis was performed for all the X-ray lightcurves. This discussion will focus on the EPIC pn results, since this is the most sensitive X-ray detector of *XMM-Newton*.

A power peak around 15 mHz ($\sim$67 s) was found in the periodograms of all the X-ray bright observations, and also in the X-ray faint observation with the highest count rate[1]. Modulation semi-amplitudes in the 2.5-8.6% range were determined for $P(\sim 67\text{ s})$. The power and period of the peak varied from one observation to the next, and multiple peaks were sometimes observed. Therefore each observation was subdivided into shorter segments, each 2245 s long, with the centre of each segment displaced by $\sim$600 s in time relative to the centre of the previous one.

An LS analysis was performed for each segment, yielding for each observation a series of periodograms in the form of a moving average. Such a dynamic periodogram is shown in Fig. 1 for observation 0500860601 on 24 November 2007. For each segment, the strongest peak between 13.5 mHz (74.1 s) and 16.5 mHz (60.6 s) was identified, and its corresponding period and significance level over white noise (determined with Monte Carlo simulations) are also given *if* the peak significance is >95.45%. The variability of the peak on time-scales of hours is obvious. The dynamic periodograms of the other observations exhibited similar behaviour.

The degree of coherence of a periodicity P is often described by the quantity $Q = |dP/dt|^{-1}$, i.e. fast changes in the period yield a small Q. For the coherent WD spin period in the intermediate polar DQ Her, $Q \sim 10^{12}$ (e.g. [17]). The value of Q for $P(\sim 67\text{ s})$ was calculated from the two longest observations (0500860601 and 0506531701), and was typically a few times 10^2.

3. Dwarf nova oscillations and the LIMA model

DNOs typically have periods in the $\sim$5-40 s range, with variation amplitudes of <1% in the optical waveband [14]. However, they have also been observed in X-rays, with much larger modulation amplitudes, reaching up to 100% of the X-ray flux. DNO periods are variable, with Q typically in the 10^3 to 10^7 range. DNOs also exhibit a period-luminosity relation, i.e. the period is slightly shorter at higher luminosity, associated with a higher $\dot{m}_{\text{acc}}$. Small "jumps" in the period are

[1] The non-detection of the peak in the other faint observations may simply imply that the signal was too low for the periodicity to be detected, and not necessarily that the periodicity was inherently absent at these epochs.

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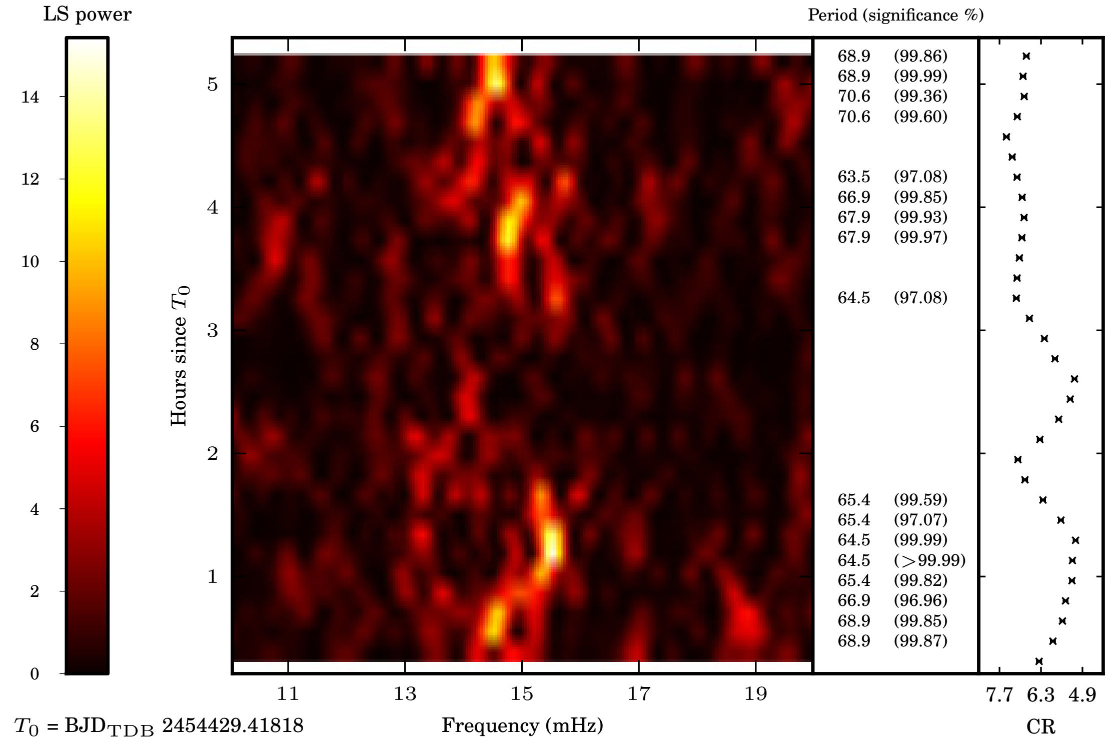

Figure 1: Dynamic LS periodogram of the EPIC pn data of observation 0500860601 of CAL 83, illustrating the variability in the value of $P(\sim 67$ s). The colour represents the LS power, and if a peak was detected between 13.5 and 16.5 mHz at a >95.45% significance level, the corresponding period in seconds and its significance percentage are given. The error in the period values is ± 1 s. The BJD$_{\mathrm{TDB}}$ reference represents the start of the observation. The broadband (0.15-1 keV) EPIC pn count rate (CR) is also plotted.

also observed. $P(\sim 67$ s) in CAL 83 is therefore slightly longer, and the continuous variability in the period somewhat more rapid than is typically expected for DNOs (according to the Q-values).

The WD rotation period in DQ Her has been studied by [17], who argued that the clock-like stability of the WD rotation in intermediate polars must be due to rigid-body rotation of the WD, with the WD magnetic field as the mechanism coupling the stable clock of the core to the exterior regions. It was shown that the minimum magnetic field required to transmit an observed spin-up rate of $\dot{\Omega}_* \approx 10^{-15}$ s^{-2} from the outer regions to the core is $\sim 10^5$ G.

A weaker magnetic field will not be able to rigidly couple the accretion torque to the interior, allowing the accumulation of an equatorial belt at the inner disc boundary, rotating rapidly at the local Keplerian velocity, i.e. faster than the WD core. Instead of the period of the equatorial belt (P_{b}) being exactly equal to the local Keplerian period (P_{K}), P_{b} may be somewhat longer due to its inertia [18], and magnetic coupling to the WD. This concept was initially suggested by [19], and developed into the LIMA model to explain the DNO phenomenon [15, 18].

The equatorial belt probably contains a mass of $< 10^{-10}$ M$_\odot$. The DNO period-luminosity relation can be explained by the inner disc radius moving further inward as $\dot{m}_{\mathrm{acc}}$ increases, yielding a shorter P_{b} for the equatorial belt. As $\dot{m}_{\mathrm{acc}}$ decreases in the final stages of the outburst, the inner disc boundary moves outward quickly, resulting in a fast outward centrifugal acceleration of the wound-up belt. Angular momentum is removed from the belt as gas is propellered outwards,

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rapidly spinning down the belt, increasing both the associated radius and $P_{\rm b}$.

Magnetic field lines connecting the belt and the inner disc will be wound up, until reconnection occurs after differential rotation of $\sim 2\pi$, relieving the tension in the field lines ([15] and references therein). Latitudinal variations in rotational period may be present in the belt, with the period increasing at higher latitudes towards the spin period of the underlying primary. Magnetohydrodynamic turbulence caused by reconnection may cause "accretion curtains", from which gas can be fed through accretion arcs at different latitudes. The discontinuous DNO period jumps are too rapid to be explained by spin-up/spin-down of the belt, but may be related to reconnection events.

Many accretion arcs would usually be involved simultaneously, and if they are spread out over different latitudes, a coherent oscillation may not be observable. The actual detection of DNOs may only be because of the coincidental domination of one or two of the arcs.

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4. An adapted LIMA model for the 67 s periodicity

We propose that $P(\sim 67\ \rm s)$ in CAL 83 might also originate in a similar equatorial region around the WD. It should be noted that the conditions on the surface of the WD in an SSS is significantly different from those on the surface of a WD in a DN. The accretion rate in DNe during outburst is typically $\lesssim 10^{-8}\ \rm M_\odot\ yr^{-1}$, compared with $\gtrsim 10^{-7}\ \rm M_\odot\ yr^{-1}$ in SSSs. As a result, the WD in an SSS is enshrouded by an extended envelope, with a radius up to 2-3 times larger than that of the WD core [20], with hydrogen burning in a shell close to the surface.

The outer limit for the equatorial belt in CAL 83 will be approximated by $R_{\rm b2} \sim 7\times 10^8$ cm, which is the WD photospheric radius measured from X-ray spectral fits [4]. The Keplerian radius corresponding to $P_{\rm K} = 67$ s is 2.7×10^9 cm, while $P_{\rm K}$ at $R_{\rm b2}$ is only $\sim$9 s. A belt with rotation period $\sim$67 s at $R_{\rm b2}$ thus rotates more slowly than the local Keplerian velocity, presumably due to its loose coupling to a WD core with an even longer rotation period. By the same reasoning as [17], and by considering the mass, radius, accretion rate and expected spin-up rate $\dot{\Omega}_*$ specifically for CAL 83, it can be shown that a WD surface magnetic field of the order $B_1 \lesssim 10^5$ G would allow the existence of a non-corotating belt structure at $R_{\rm b2}$ (similar to what was found for DQ Her).

Assuming that $P(\sim 67\ \rm s)$ originates from asymmetric emission from an equatorial belt, we will now investigate the possibility that the modulations in the period may arise from the spin-up and spin-down of the belt. The maximum required belt spin-up rate $\dot{\Omega}_{\rm b}$ to explain the modulations was estimated from the dynamic periodograms to be $\dot{\Omega}_{\rm b} \sim 1.8\times 10^{-6}\ \rm s^{-2}$. The specific angular momentum of the belt magnetically linked to the WD is estimated by $R_{\rm b2} v_{{\rm b},\phi}$, where $v_{{\rm b},\phi} = 2\pi R_{\rm b2}/P_{\rm b}$ is its azimuthal velocity. The spin-up rate $\dot{\Omega}_{\rm b}$ of the belt can thus be expressed as $\dot{\Omega}_{\rm b} = \dot{m}_{\rm acc}\left(2\pi R_{\rm b2}^2/P_{\rm b}\right) I_{\rm b}^{-1}$, yielding a maximum belt inertia of

$$I_{\rm b} \sim 1.6\times 10^{41}\left(\frac{\dot{m}_{\rm acc}}{10^{-7}\ \rm M_\odot\ yr^{-1}}\right)\left(\frac{\dot{\Omega}_{\rm b}}{1.8\times 10^{-6}\ \rm s^{-2}}\right)^{-1}\left(\frac{R}{7.0\times 10^8\ \rm cm}\right)^{2}\left(\frac{P_{\rm b}}{67\ \rm s}\right)^{-1}\ \rm g\ cm^2\ , \tag{4.1}$$

which is almost 10 orders of magnitude smaller than that of the WD itself.

The critical envelope mass required for the ignition of nuclear burning is $\sim 9\times 10^{-7}\ \rm M_\odot$ for a 1.3 $\rm M_\odot$ WD accreting at $\sim 10^{-7}\ \rm M_\odot\ yr^{-1}$, which can be considered as a lower limit for the envelope mass for nuclear burning to occur [21, 22]. Assuming that the geometry of the equatorial belt can be approximated by an annular cylinder around the WD, with central axis perpendicular to the orbital plane, one can now proceed to estimate $m_{\rm b}$, i.e. how much of the envelope mass is actually contained in the belt. The outer radius of the cylinder is taken to be $R_{\rm b2}$, and the inner radius as $R_{\rm b1} \sim 4 \times 10^8$ cm, representing the WD radius according to the Hamada-Salpeter relation [23] (although $R_{\rm b1}$ is probably larger than this). This yields $m_{\rm b} \sim 2.5 \times 10^{-10}$ M$_\odot$, therefore the equatorial belt constitutes only a small fraction of the total envelope mass.

Considering the extended, "fuzzy" nature of the WD envelope in SSSs, this scenario seems quite plausible. An equatorial belt at the envelope-disc boundary may have a rotational period of ∼67 s, while accreted layers closer to the WD may be rotating with slightly longer periods, yielding differential rotation between these weakly coupled layers at different radial distances. In such a case it is more likely that the inner radius of the belt is significantly larger than the WD radius. Increasing $R_{\rm b1}$ up to almost $R_{\rm b2}$ (implying a thin shell at this radius) yields $m_{\rm b} \sim 1.6 \times 10^{-10}$ M$_\odot$, i.e. the presumed thickness of the shell does not change the resulting mass significantly.

Due to the relative weakness of the magnetic field, the flow of material in the equatorial belt will be ram pressure dominated. Assuming that the WD rotation period is noticeably longer than that of the belt, the belt will carry the footpoints of the originally poloidal field lines (frozen into the belt plasma) around its orbit, winding up the field lines and creating a substantial toroidal field component $B_{{\rm b},\phi}$ in the vicinity of the belt (e.g. [24]). According to [15], the toroidal field generated in the belt for DNe is $B_{{\rm b},\phi} \sim 2 \times 10^5$ G for an original poloidal WD field of $\sim 10^5$ G.

As $B_{{\rm b},\phi}$ grows, reconnection of the increasingly stretched magnetic field lines through the tearing mode instability ([25], Chapter 6) may cause the ejection of "bubbles" containing magnetic loops. These magnetic bubbles carry a significant amount of angular momentum, and are therefore centrifugally expelled towards outer regions of the belt, possibly expanding the effective outer radius of the belt, corresponding to a slightly longer observed period (closer to 70 s).

Alternatively, the rapid changes in $P(\sim 67$ s$)$ within a single observation may be caused by the same mechanism proposed to explain the discontinuous jumps in the DNOs: the channelling of the accretion flow onto different accretion arcs in the belt as a result of magnetic reconnection. In such a case, the disappearance and reappearance of the period on time-scales of hours may be due to the accretion being channelled dominantly onto latitudes with the same period at some epochs (well-defined peak observable), with accretion onto a wide range of latitudes with different periods at other epochs (well-defined peak not observable). If spin-up and spin-down is not the primary cause of the modulations in $P(\sim 67$ s$)$, the upper limit imposed on the inertia earlier in this section would not be so strict, and a larger fraction of the envelope mass could form part of the belt.

5. Conclusion

A detailed period analysis of the archival *XMM-Newton* lightcurves of CAL 83 revealed a variable X-ray modulation with a period of ∼67 s. This periodicity was detected in all the X-ray high state lightcurves, and in the X-ray low state lightcurve with the highest count rate.

The preliminary model proposed to explain the behaviour of this periodicity is related to the LIMA model developed by [18] and [15] to explain the observed properties of DNOs. In this model, the ∼67 s periodicity originates in a belt-like structure in the envelope at the boundary with the inner accretion disc, which is weakly coupled to the WD core by a WD magnetic field with a

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strength of $\sim 10^5$ G. The variability in the $\sim$67 s period might be caused by a combination of spin-up/spin-down of the equatorial belt and magnetic reconnection mechanisms. The LIMA model has been well described for dwarf novae, but a more detailed theoretical investigation of the properties of a similar model in supersoft X-ray binaries with their much higher accretion rates and more massive envelopes should be conducted, and constitutes some very interesting follow-up work.

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