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Supersoft X-Ray Source CAL 83: A Possible AE Aqr-like System

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Abstract

CAL 83 is a close binary supersoft X-ray source in the Large Magellanic Cloud. A ∼67 s periodicity detected in supersoft X-rays is most probably associated with the spin period of a highly spun-up white dwarf (WD). The variability in the period is ascribed to the obscuration of the WD by the hydrogen burning envelope surrounding it, rotating with a period that is close to, but not quite synchronized with, the WD rotation period. Optical spectra obtained with SALT exhibit accretion disc emission lines with broad wing structures and P Cyg profiles, indicating mass outflows. Timing analysis of photometrical observations performed at the South African Astronomical Observatory (SAAO) revealed variable signals at ≤1 mHz which are thought to be associated with quasi-periodic oscillations from an accretion disc. The short spin period inferred for CAL 83 can be the result of spin-up by accretion disc torques during a long mass transfer history, placing this source on a similar evolutionary track as the cataclysmic variable AE Aqr.

Keywords: stars: individual: CAL 83 - binaries: close - white dwarfs - stars: oscillations - stars: winds, outflows - stars: evolution.

1 Introduction

Supersoft X-ray sources (SSS) are highly luminous in the supersoft X-ray band, with >90% of the unabsorbed X-ray flux being below ∼0.5 keV. These sources were first discovered by the *Einstein X-ray Observatory* and *ROSAT* (see Kahabka & van den Heuvel (2006) and references therein).

Van den Heuvel et al. (1992) (hereafter vdH92) showed that the low effective temperatures and high luminosities of SSS can be explained by the nuclear burning of hydrogen on the surface of a white dwarf (WD) accreting from a binary companion (the close binary SSS model). The accretion rate required for steady nuclear burning is $\sim 1 - 4 \times 10^{-7}$ $M_\odot$ yr^{-1}. Such a high accretion rate can be sustained if the companion mass is comparable to or greater than the WD mass, as this will cause the Roche lobe of the donor to shrink and drive mass transfer on the thermal time-scale of the donor.

CAL 83 is a close binary SSS in the Large Magellanic Cloud. However, it is not a persistent X-ray source and several X-ray off-states have been observed, with long-term optical variability anti-correlated with the long-term X-ray variability, as described by e.g. Rajoelimanana et al. (2013). These authors also derived a refined orbital period of 1.047529(1) d for CAL 83 from OGLE-III photometry. The inclination has been estimated to be in the $i = 20 - 30°$ range (see Cowley et al. (1998) and references therein, hereafter Co98). Lanz et al. (2005) used NLTE models during a combined analysis of *XMM-Newton* and *Chandra* data, and their results indicate a massive WD ($M_{\rm WD} \sim 1.3 \pm 0.3\,M_\odot$). Schmidtke & Cowley (2006) found a periodic signal of 38.4-minutes in the *Chandra* LETG data of CAL 83, which they ascribed to possible non-radial pulsations in the accreting WD.

The optical spectrum of CAL 83 is characterized by Balmer and He II accretion disc emission lines (Co98 and references therein). The He II λ4686 emission line has a broad, variable wing structure that has also been observed in some of the Balmer lines. In each particular spectrum, these wing structures are either all towards the blue side of the main components of these emission lines, or all towards the red side. According to Crampton et al. (1987) (hereafter Cr87), this may be associated with the slow precession of an accretion disc with outflows through either wind or a weakly collimated jet.

The ∼67 s X-ray periodicity is briefly summarized in §2.1 (a detailed discussion is provided in Odendaal et al. 2014). Preliminary results of the analysis of optical data are presented in §2.2 and §2.3. After this discussion, the possible evolutionary scenario of CAL 83 is brought into context with that of the CV AE Aqr in §3, followed by the conclusions in §4.

2 CAL 83: Observations and Results

2.1 The ∼67 s X-ray pulsation

The *XMM-Newton* archive contains 23 observations of CAL 83, 4 of which were during an X-ray off-state. A systematic search for short time-scale periodicities that may be associated with the WD spin was performed on the 19 on-state light curves. The Starlink PERIOD[1] package was used to obtain a Lomb-Scargle (LS) periodogram of each light curve.

A power peak at a period of 66.8 ± 0.4 s was discovered at a $> 99.9999\%$ significance level in the periodogram of the EPIC PN light curve of observation 0506531501, and at a lower significance level in 6 of the other PN periodograms. In 3 of these observations, 1 of the MOS light curves also exhibited a weak ∼67 s periodicity. The LS periodogram of observation 0506531501, as well as the light curve folded on the 66.8 s period, are shown in Fig. 1.

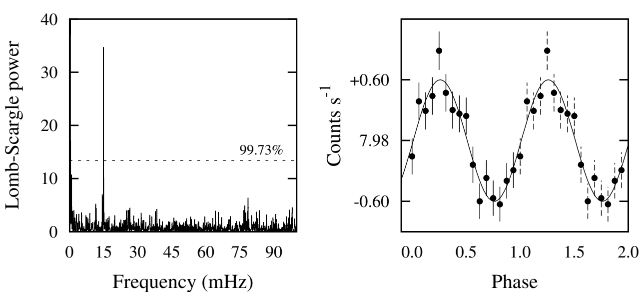

Figure 1: Lomb-Scargle periodogram (left) and folded light curve (right) of CAL 83 *XMM-Newton* dataset 0506531501 PN. Both the periodogram and folded light curve display a significant 66.8 s oscillation.

The overall significance of this detection, considering the PN datasets of all 19 the on-state observations, is $\geq 3\sigma$. The detected period exhibits a spread of ± 3 s around ∼67 s between different observations, and even within a single observation. This variability cannot be explained by Doppler shifts due to WD orbital motion.

The long-term presence of the pulsation suggests its association with the WD spin, although the variation in the detected period complicates matters. It is possible, however, that we are observing the WD spin, but through an extended envelope around the accreting WD. According to Ibragimov et al. (2003), the photospheric radius in a steady nuclear burning SSS may have a radius 2-3 times the radius of the WD itself. The spread in the observed period can possibly be explained by the envelope not being quite synchronized with the WD, resulting in a slippage effect and associated variation in the pulsation period.

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

2.2 Optical spectroscopy with SALT

A series of optical spectra of CAL 83 has been obtained with the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT), using the pg0900 grating to obtain a resolution of $R \sim 1500$. These spectra show similar characteristics to those discussed in §1, with strong Balmer and He II emission lines. The velocity widths of these lines indicate emission from regions compatible with an accretion disc around the WD. These lines also exhibit blue wing structures extending to ∼2000 km s^{-1} from the line centres, supporting the existence of a wind or weakly collimated jet in the system. P Cyg profiles are also evident in the Hα and Hβ lines, serving as further evidence of mass outflow. Shown in Fig. 2 are the Hα and Hβ profiles from a spectrum obtained on 2 February 2013.

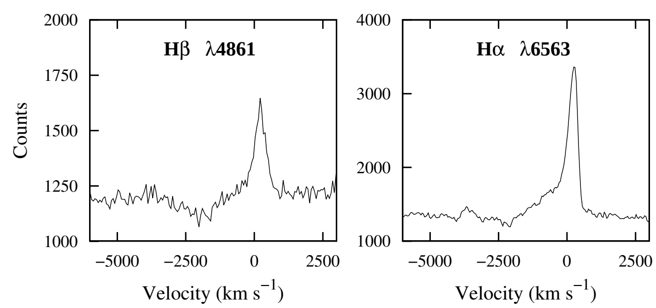

Figure 2: Hβ and Hα profiles of CAL 83, obtained with SALT on 2 Feb 2013.

For $M_{\rm WD} \sim 1.3\,{\rm M}_\odot$, the WD radius is $R_{\rm WD} \approx 4 \times 10^8 (M_{\rm WD}/1.3\,{\rm M}_\odot)^{-0.8}$ cm (see Eracleous & Horne 1996 and references therein). The mass function can be determined if the semi-amplitude (K_1) of a spectral line originating close to the WD is known. Although the orbital coverage of the SALT spectra was not adequate to calculate a new K_1, various values have been reported in the literature. Adopting $K_1 \sim 35$ km s^{-1}, $i \sim 25°$ (see Co98) and $P_{\rm orb} = 1.047529$ d, the mass function is $4.7 \times 10^{-3}\,{\rm M}_\odot$, and a secondary mass of $M_2 \sim 0.61\,{\rm M}_\odot$ is obtained, yielding a mass ratio $q = M_2/M_{\rm WD} \sim 0.47$. However, this value of K_1 was derived from the radial velocity modulation of the He II λ4686 disc emission line, and this line would only represent the WD orbital motion if the He II emission was distributed symmetrically about the WD. As discussed by e.g. Kaitchuck et al. (1994), there are some problems with this assumption, compromising the mass function calculation.

2.3 Fast photometry with SHOC

In April 2013, fast photometrical observations were obtained with one of the Sutherland High-speed Optical

Cameras (SHOC2) on the SAAO 1.9-m Telescope at Sutherland. These cameras have been commissioned recently, and are optimized for high time resolution photometry. A clear filter was used for the CAL 83 observations, and with this sensitive instrument, exposure times in the 0.5-5 s range were adequate, depending on observing conditions.

Aperture photometry was utilized to obtain light curves, and the CAL 83 light curves were corrected by performing differential photometry using 4 comparison stars. The Starlink PERIOD package was used to perform a LS analysis. The LS periodograms of CAL 83 did not reveal any significant pulsation at the inferred spin period of ∼67 s or at higher frequencies.

However, some of the CAL 83 periodograms exhibited a significant peak in the region just below 1 mHz. These peaks have broadened profiles, and their positions do not stay constant. In Fig. 3, the LS periodogram of the SHOC observation on 15 April 2013 is presented, showing a peak at 1168 ± 214 s. The light curve folded on this period is also shown. This observation had a total length of 3245 s, and the light curve was binned to 20 s for this analysis. These peaks are ascribed to quasi-periodic oscillations associated with the accretion disc around the WD.

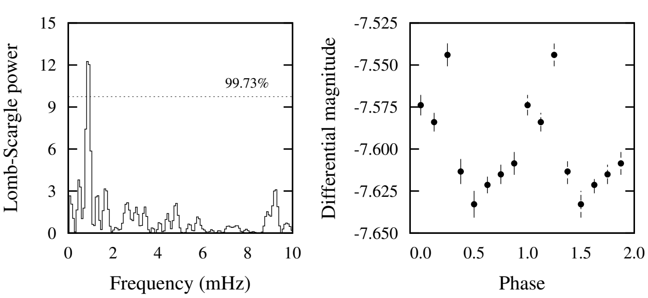

Figure 3: SHOC periodogram and light curve folded on the detected period of 1168 ± 214 s (obtained on 15 April 2013).

These quasi-periods at ≤ 1 mHz may be the Keplerian periods of blobs of material orbiting the WD in the accretion disc, or possibly beat periods between the presumed spin period of $P_* \sim 67$ s and blobs orbiting in the inner regions of the disc. Assuming that the 1168 ± 214 s periodicity is a Keplerian period, the associated Keplerian radius is $46\,R_{\rm WD}$. On the other hand, it may be a beat period between $P_* \sim 67$ s and a Keplerian period of ∼71 s associated with blobs orbiting at $\sim 7\,R_{\rm WD}$. Adopting the orbital parameters in §2.2 yields a circularization radius of $\sim 150\,R_{\rm WD}$, supporting the compatibility of both the Keplerian radii above with emission from the accretion disc.

3 The Evolution of CAL 83: An AE Aqr Analogue?

AE Aqr is a nova-like variable with a short WD spin period (33.08 s), and a long orbital period (9.88 h). A review of the multi-wavelength properties of AE Aqr is provided by Meintjes, Odendaal and van Heerden elsewhere in this volume. It has been shown by Meintjes (2002) and Schenker et al. (2002) that the properties of this source indicate a high mass transfer history, during which AE Aqr could have been a supersoft source. During this phase, accretion disc torques would have been able to spin-up the WD to such a short rotation period.

The probable association of the ∼67 s period in CAL 83 with a short WD spin may place this source on a similar evolutionary path as AE Aqr. Evidence indicating that CAL 83 has already passed through quite a long mass transfer history does indeed exist. The high WD mass, just below the Chandrasekhar limit, is one of the factors supporting an extended period of mass accretion. However, with the WD being more massive than the WD in AE Aqr, it may be driven over the Chandrasekhar limit before entering the CV stage.

Emission lines of ionized carbon, nitrogen and oxygen are present in the optical and UV spectra of CAL 83, and as remarked by Cr87, the low ratio of H to He II and CNO lines indicate a donor with an H-poor envelope. Therefore the secondary may already have shed most of its envelope during a long period of mass transfer to the WD, with CNO cycling resulting in the observed line ratios. Assuming that the secondary mass is as low as $\sim 0.61\,{\rm M}_\odot$ (see §2.2), the Roche lobe of the secondary should be $R_2 \sim 1.7\,{\rm R}_\odot$. As the secondary has to be in contact with its Roche lobe for Roche lobe overflow, this implies a donor that is too large for its mass, possibly an evolved star that has lost a large fraction of its envelope, also supporting the long mass transfer history.

The thermal time-scale is of the order $\tau_{\rm th} \leq 5 \times 10^7\,(M_2/0.61\,{\rm M}_\odot)^{-2}\,(R_2/1.7\,{\rm R}_\odot)^{-1}$ yr (e.g. Meintjes 2002 and references therein), while the spin-up time-scale corresponding to a $\sim 1.3\,{\rm M}_\odot$ WD accreting from a disc extending to its surface is $\tau_{\rm s-u} \leq 10^7$ yr (e.g. Wang 1987). These time-scales are comparable, showing that the WD in CAL 83 could have been spun-up to a short spin period if it has been in the supersoft phase with its characteristic high mass transfer rates for a sufficiently long time.

To sustain a $\tau \sim 10^7$ yr mass transfer, $q > 5/6$ is required for a conservative process, as described by the vdH92 model. However, evidence indicating significant mass and accompanied angular momentum losses is present in the optical spectra, suggesting a non-conservative mass transfer process. Given the possible WD spin period of ∼67 s, the outflow mechanism may be the ejection of accreting material by a similar magnetospheric propeller mechanism as in AE Aqr. For non-conservative mass transfer, the Roche lobe will shrink according to the relation

$$\frac{\dot{R}_{\mathrm{L},2}}{R_{\mathrm{L},2}} = -\frac{\dot{M}_2}{M_2}\left[\frac{5}{3} - 2\,(1-\alpha)\,q - \frac{2}{3}\frac{q\alpha}{1+q} - 2\eta\frac{M_2\,(GM_{\mathrm{WD}}R_{\mathrm{circ}})^{1/2}}{J_{\mathrm{orb}}}\right] + \frac{2\dot{J}}{J}\,, \tag{1}$$

where α and η represent the fraction of mass and angular momentum transferred through L_1 that is lost from the system (e.g. Meintjes 2002). Therefore, for CAL 83, mass transfer that can sustain nuclear burning is perhaps only possible in the phase when the evolved donor is expanding, with significant angular momentum loss contributing substantially in keeping the Roche lobe in contact with the donor. This will be explored more quantitatively in the future.

4 Conclusion

It has been shown that CAL 83 exhibits a transient ∼67 s X-ray periodicity. This is expected to be associated with the WD spin period, which would make it one of the shortest known spin periods in the white dwarf binary population. Results from optical data support the scenario of accretion through an accretion disc, creating the possibility of the WD being spun-up by disc torques during an extended period of mass accretion, similar to what happened during the evolution of AE Aqr. Optical spectra also present evidence of mass outflows in CAL 83, which can be related to the ejection of accreting blobs from a fast rotating WD magnetosphere or accretion disc winds. However, many questions about this fascinating source still remain unanswered, and detailed follow-up studies are essential.

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DISCUSSION

MARIKO KATO: How do you determine the secondary mass for CAL 83? Is it really so small? I expect $q \geq 1$ to explain anti-correlation with X-ray.

ALIDA ODENDAAL: The radial velocity semi-amplitude of the He II λ4686 line was used to calculate

$M_2 \sim 0.61\,M_\odot$, which is only valid if the He II emission is uniformly distributed around the WD. This assumption can be highly problematic (e.g. Kaitchuck et al. 1994), therefore this approach does not yield a conclusive M_2. A more reliable WD radial velocity profile may be obtained by constructing Doppler tomograms for the emission lines.

MARGARETHA PRETORIUS: Is there a radio detection of CAL 83?

ALIDA ODENDAAL: No, but an upper limit of < 0.12 mJy at 3.5 and 6.3 cm was determined by Fender, Southwell and Tzioumis (1998) from data obtained with the Australia Telescope Compact Array.