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CAL 83 — The Prototypical Close Binary Supersoft X-ray Source in the LMC: A Short Review

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CAL 83 is a luminous supersoft X-ray binary that is often considered the prototype of its class. It is believed to contain an accreting white dwarf with surface hydrogen burning, and has an orbital period of $\sim$1 day. X-ray spectroscopy indicates a massive white dwarf with luminosity $\sim 10^{37}$ erg s^{-1} and effective temperature $\sim$46 eV. The rich optical spectrum provides evidence of a precessing accretion disc with an associated outflow, as well as a surrounding ionization nebula. The system exhibits X-ray to optical variability on time-scales of $\gtrsim$1 min to $>$1 year. A brief review of this intriguing binary in the Large Magellanic Cloud is presented.

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1. Introduction

Supersoft sources (SSSs) are extremely soft, high-luminosity X-ray emitters, with typical effective temperatures of a few hundred thousand Kelvin, and bolometric luminosities of $L_{\rm bol}$ $\sim$$10^{36}$-$10^{38}$ erg s^{-1}, close to the Eddington limit for a solar-mass object (e.g. [1]). The first luminous SSSs were discovered in the Large and Small Magellanic Clouds (LMC and SMC) with the *Einstein Observatory* [2, 3], and further observations during the *ROSAT* all-sky survey [4] and subsequent pointed observations established SSSs as a new class of objects.

CAL 83 was the brightest X-ray point source discovered in the Columbia Astrophysics Laboratory *Einstein* survey that is not associated with a Galactic foreground star or a background AGN, with a luminosity of a few times 10^{36} erg s^{-1} in the 0.15-4.5 keV band. A blue object with magnitude $B \sim 16.8$ was identified as the optical counterpart [5]. Due to the similarities of its optical properties to that of low-mass X-ray binaries, this was initially the favoured model for CAL 83, i.e. a system containing an accreting neutron star or black hole [6, 7, 8, 9, 10].

However, Van den Heuvel *et al.* [11] proposed instead that many SSSs consist of a white dwarf (WD) in a binary system, with the energy released by the nuclear burning of accreted hydrogen on the WD surface responsible for the high X-ray luminosity. The accretion rate required to sustain nuclear burning is very high ($\sim$$10^{-7}$ M$_\odot$ yr^{-1}), and can be sustained if the donor is more massive than the WD.

Photometrical observations showed the orbital period to be around 1 day [7, 8, 12, 13]. The most recent value was obtained from the analysis of OGLE III data spanning 2001-2009, i.e. 1.047529 ± 0.000001 d [14]. The folded light curve is quasi-sinusoidal in shape, with no observed eclipses, indicating a relatively low binary inclination.

During the past two and a half decades since its discovery, observational studies of CAL 83 have proven it to be a very fascinating source, the exact nature of which is everything but clear-cut. In this paper, a short review is presented, focussing on its properties in the X-ray to optical wavebands. Little is known at longer wavelengths: In the near-infrared, weak H emission and only a marginal detection of the Ca II infrared triplet were reported [12]. ATCA radio observations indicated an upper limit of <0.12 mJy at wavelengths of 3.5 cm and 6.3 cm [15].

2. The X-ray spectrum

The supersoft nature of the X-ray emission from CAL 83 was confirmed by observations with *EXOSAT* in 1983 and 1985 [6, 7], *ROSAT* in 1990-1991 [4, 16, 17], *BeppoSAX* [18] and *ASCA* [19].

Initially, blackbody models provided satisfactory fits to the low-resolution X-ray spectra. However, the absorbing neutral hydrogen column density $N_{\rm H}$ along the line of sight was uncertain, as it would include interstellar absorption not only in the Galactic foreground, but also in the LMC, as well as any intrinsic absorption in the binary itself. Blackbody fits with different $N_{\rm H}$ yielded very different values for $kT_{\rm eff}$ and $L_{\rm bol}$.

Modelling of the Lyα absorption in the *HST* UV spectrum indicated that $N_{\rm H} = (6.5 \pm 1.0) \times 10^{20}$ cm^{-2} along the line of sight to CAL 83, which is consistent with the best fit value of $\sim$$7\times10^{20}$ cm^{-2} obtained from a WD model atmosphere analysis of the *ROSAT* spectrum [20]. This value is in good agreement with the Galactic foreground hydrogen absorption, indicating that CAL 83 must be on the near side of the LMC, and that no highly significant neutral hydrogen absorption occurs within the source itself.

Later it came to light that a blackbody fit tends to overestimate the WD luminosity, because actual WD atmospheres emit a larger fraction of their total energy in the soft X-ray band than a blackbody with the same temperature. Therefore a WD model atmosphere fit to an X-ray spectrum with a certain flux will translate to a lower value of the integrated bolometric luminosity than a blackbody fit, and this will also lead to an underestimation of the WD mass. Also, after the first high-resolution spectra ($\sim$0.05 Å) of CAL 83 obtained with *XMM-Newton* [21] and *Chandra* became available, it was obvious that the fine structure of the spectrum, including various absorption features, can not be fit by a smooth continuum spectrum to a high degree of accuracy.

Various authors performed fits of WD atmosphere models with varying degrees of sophistication to the low-resolution CAL 83 spectra [18, 20, 22, 23, 24]. LTE models assume local thermodynamic equilibrium, while the NLTE (non-LTE) models also incorporate departures from LTE.

The most recent investigation involved detailed NLTE model atmosphere analysis of the first high-resolution X-ray spectra of CAL 83: an *XMM-Newton* RGS spectrum (23 April 2000, obs ID 0123510101) in combination with a *Chandra* LETG spectrum (15 August 2001, obs ID 1900) [25]. The best fit parameters when fixing $N_{\rm H}$ to 6.5×10^{20} cm^{-2} are $\log g = 8.5 \pm 0.1$, where g is the WD surface gravity, $kT_{\rm eff} = 46 \pm 2$ eV, photospheric radius $R = (6.96 \pm 0.70) \times 10^{8}$ cm and $L_{\rm bol} = (3.4 \pm 1.1) \times 10^{37}$ erg s^{-1}. These values correspond to a WD mass in the 1.0-1.4 M$_{\odot}$ range, and this was the first direct spectroscopic evidence that the WD in CAL 83 is massive.

It should be noted that the layers of accreted, hydrogen-burning material on the surface of a WD in a SSS presents conditions quite different from that on the surface of a WD without accretion. In fact, an accreting, hot WD with steady surface nuclear burning will have a photospheric radius 2 to 3 times larger than that of a cool WD [23].

3. Anti-correlated long-term X-ray and optical variability

It was originally thought that CAL 83 is a persistent X-ray source, but it has since been observed during an X-ray off-state on the following dates: 28 April 1996 (*ROSAT*, [26, 27]), 29-30 November 1999 (*Chandra*, [28]), 3-4 October 2001 (*Chandra*, [25]), 2 January - 18 March 2008 (*Swift*, [29, 30]), 16 January, 10 March, 11 April and 16 April 2008 (*XMM-Newton*, [14]).

Different models explaining the X-ray off-states in terms of a decrease [31] or increase [22] in the accretion rate have been proposed. The 1992-1999 MACHO light curve exhibited variability of $\lesssim$1 mag, and upon correlation with the epochs of the X-ray on- and off-state observations, it was found that each of the observed X-ray off-states was during an optical high state, while each X-ray on-state observation was during a lower optical state [28].

This anti-correlation was confirmed by comparing the OGLE light curve with the more recent (2007-2009) *XMM-Newton* observations [14]. The long-term optical variability was found to be quasi-periodic ($P \sim 450$ d), and the X-ray on (optical low) state has a length of $\sim$200 d. This implies $M_{\rm WD} \sim$ 1.32-1.38 M$_{\odot}$. Applying blackbody fits to the *XMM-Newton* spectra indicated a slightly higher X-ray temperature during the X-ray high states than during the X-ray low states.

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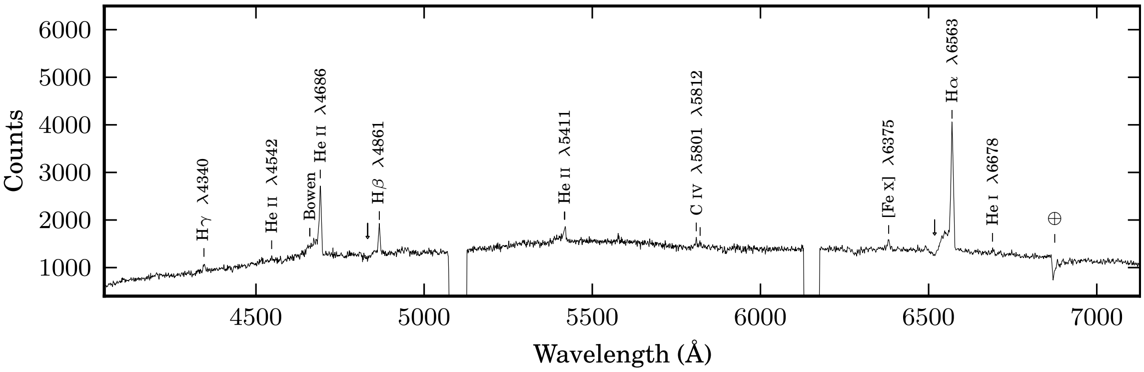

Figure 1: SALT RSS spectrum of CAL 83 on 5 January 2013. The resolution is ∼3.8 Å. Arrows indicate the Hα and Hβ P Cyg absorption features. The ⊕ indicates the atmospheric B-band.

The anti-correlation can be explained by a qualitative model where an increase in the accretion rate causes an increase in the WD photospheric radius, lowering kT_{eff} and shifting the emission peak towards the extreme UV, causing an X-ray off-state and increasing the optical luminosity [14, 28, and references therein]. The irradiation of the disc increases, also enhancing the optical luminosity. After the accretion rate decreases again, the WD photosphere contracts and the source enters an X-ray high, optical low state again. Possible reasons for a modulation in the mass transfer rate may be: (i) attenuation when a magnetic star spot on the secondary passes over the L_1 point, or (ii) the attenuation of the mass transfer from the secondary by a strong wind from the X-ray source stripping off the outer layers of the secondary.

4. The optical and UV spectrum

4.1 The central source

The optical spectrum of CAL 83 contains emission lines typical of an accretion disc. The most prominent features are the Balmer and He II emission lines [6, 7, 8, 32, 33, 34, 35, 36]. These lines have variable broad wing structures extending to several thousand km s^{-1} from the main component. The wings are sometimes observed to be blueshifted, and sometimes redshifted relative to the main component. A wind or weakly collimated jet from an accretion disc precessing with a period of ∼69 d could be responsible for the variable wing structures [7]. Although this is not yet well established, it is in good agreement with theoretical predictions [37]. P Cyg profiles in the Balmer lines provide additional support for the outflow scenario. A spectrum obtained with the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT) is shown in Fig. 1, exhibiting blueshifted wing structures[1].

Unfortunately, the donor star is too faint to establish its spectral type. Several of the papers above determined the radial velocity semi-amplitude of the He II λ4686 emission line to be in the 30-40 km s^{-1} range, leading to the conclusion that the secondary must be significantly less massive than the WD, which contradicts the model of Van den Heuvel *et al.* [11]. However, this mass

[1] Proposal ID: 2012-2-RSA_UKSC-006. PI: A. Odendaal

function determination assumes that the He II line provides an exact measure of the WD orbital motion, which would only be true if the distribution of its emission was perfectly symmetrical about the WD. A stellar wind is expected to blow from the heated side of the donor, and Van den Heuvel *et al.* [11] argued that the He II λ4686 emission line originates from the interaction between this wind and a wind from the WD/disc, and that its radial velocity semi-amplitude is much smaller than the actual value for the WD.

The optical spectrum also contains evidence of ionized carbon and nitrogen, including the Bowen blend at ~4660 Å, and also He I λ6678, [Fe X] λ6375 and O VI emission lines at 3811, 3834 and 5290 Å. The ratio of hydrogen emission to He II and CNO emission is relatively low [7]. This serves as evidence of CNO cycling in the donor star, indicating an evolved donor of which the outer layers have already been stripped by accretion and possibly winds from the X-ray source.

Ultraviolet spectra obtained with the *IUE* during 1984-1987 showed emission lines of N V λ1240, Si IV λ1403 and He II λ1640, as well as several interstellar absorption features [7, 38]. In January 1987, the UV flux was higher by a factor of 2 to 3, and ESO observations showed that this coincided with an optical high state. The shape of the UV/optical continuum indicated emission from an accretion disc rather than pure stellar emission. Modelling of the spectral energy distribution also showed that the observed optical and UV flux can be explained very well by a combination of the WD spectrum, the accretion disc with the reprocessing of radiation and disc flaring included, and also some emission of reprocessed radiation from the heated side of the donor star [39].

From the *HST* GHRS spectrum, the N V λ1239 and λ1243 resonance doublet lines were determined to have a FWHM of ~1 Å, and red wings extending to ~+800 km s^{-1} [20]. These lines are expected to originate from the disc, and the small widths indicate that the orbital inclination is relatively low. The red wing structures may have the same origin as the blue- or redshifted wing of the He II λ4686 emission.

Eleven observations with *FUSE* showed that the UV flux is modulated by the orbital period, and that the radial velocity semi-amplitude of the O VI λ1032 emission line is 23 ± 6 km s^{-1}, similar to that of He II λ4686 [13]. However, the relative phasing of these lines are not the same, therefore they probably originate in different parts of the system. They also do not have the same phasing as the photometric orbital light curve.

4.2 The ionization nebula

From a theoretical investigation, it was predicted that SSSs should be surrounded by ionized regions, with the central X-ray emitter as the ionizing source [40] . Evidence of forbidden oxygen emission from an extended region was indeed found in the optical spectra, and an [O III] λ5007 image confirmed the presence of an ionized nebula around CAL 83 [41]. Detailed spectroscopic studies showed [O III], [O I], [N II], [Si II], He II λ4686 and Balmer emission from a nebula with a dense inner region (~5-10 cm^{-3}) with a typical radius of ~7.5 pc and a more diffuse outer region extending to ~20 pc [36, 42].

The mass contained in the inner nebula was estimated to be ~150 $M_\odot$, while the material ejected from the binary system itself (e.g. by an accretion wind) should only be of the order of ~1 $M_\odot$. Therefore the nebula is primarily caused by the ionization of the local ISM by the supersoft X-rays from CAL 83. Calculations of the time-dependent properties of ionization

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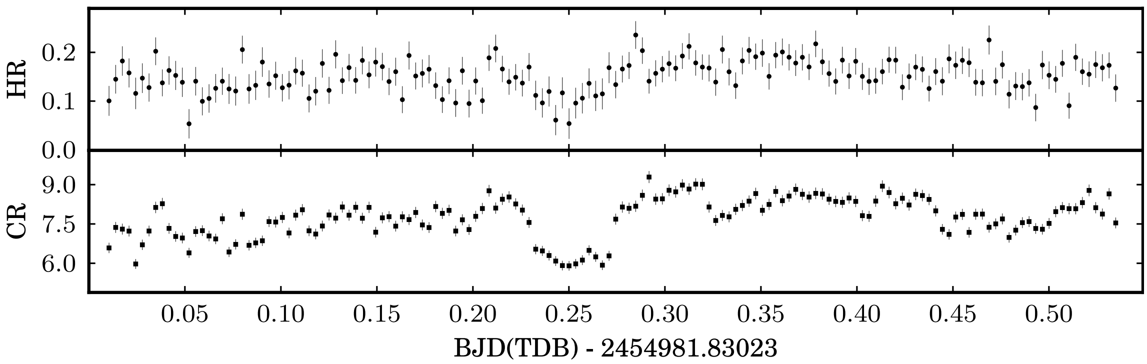

Figure 2: EPIC pn hardness ratio (top) and count rate (bottom) light curves of *XMM-Newton* observation 0506531701 of CAL 83.

nebulae around SSSs indicated that CAL 83 has been radiating at a time-averaged luminosity of $\gtrsim 3\times10^{37}$ erg s^{-1} for at least the past $\sim 10^5$ years, with any luminosity variations taking place on time-scales $\lesssim 2\times10^3$ yr [43].

5. Short time-scale variability

5.1 Optical magnitudes

Variability of a few tenths of a magnitude on time-scales of 2 h or less were reported [6, 7, 8]. We performed differential photometry with the Sutherland High-speed Optical Camera (SHOC) on the SAAO 1.9-m Telescope, and our Lomb-Scargle (LS) analysis revealed significant peaks in the $\lesssim$1 mHz region in some of the periodograms [44]. Their positions are not constant and they have broad profiles. We ascribe these to quasi-periodic oscillations associated with the accretion disc around the WD.

5.2 X-ray modulations on time-scales of several minutes

A 38.4 min pulsation was discovered in *Chandra* observation 1900, which was not present in *XMM-Newton* observation 0123510101 [45]. It was ascribed to non-radial g-mode pulsations in the WD, similar to those that have recently been observed in some novae. We performed a LS analysis on the 18 more recent *XMM-Newton* observations (proposal IDs 050086 and 050653), and found variable peaks above a 99.73% significance level in 13 of the light curves, ranging from $\sim$10 to $>$100 minutes [46]. Five of the periodograms have a peak at the same position (within error bars) as the 38.4 min pulsation, and several different peaks are often present in the same periodogram. These transient periods may also be ascribed to non-radial g-mode pulsation in the WD, driven by the ε-mechanism, i.e. instabilities caused by thermonuclear reactions (e.g. [47]), but more detailed modelling is needed to explain their variable nature.

We also quantified the correlation between the count rate and hardness ratio for all the light curves by making use of the Spearman linear rank-order correlation coefficient, and established a significant correlation ($>$99.73%) for 4 observations, indicating that higher count rates are associated with a higher source temperature even on short time-scales (e.g. Fig. 2)[46].

5.3 The ∼67 s pulsation

In 7 of the 19 on-state *XMM-Newton* observations, a ∼67 s X-ray pulsation was discovered [48]. There is significant variability in the period, exhibiting a spread of up to ∼3 s from the median of ∼67 s. If this period is related to the WD rotation, its variability needs to be explained. One possibility is that we may be observing the WD rotation through an extended H-burning envelope, with these layers "slipping" on the fast rotating WD surface, with their rotation not quite synchronized with the WD spin. An alternative interpretation is that this pulsation is also related to non-radial oscillations of the WD.

6. Summary

Observational evidence indicates that CAL 83 contains a massive WD that has already passed through a long period of mass accretion from a companion star, of which the mass has not been determined conclusively. It appears that the mass transfer rate from the companion undergoes cyclic modulations, causing the quasi-periodic superorbital modulation in the optical magnitude that is anti-correlated with the long-term changes in the X-ray flux. While the optical modulation is well defined by the MACHO and OGLE light curves, X-ray monitoring (e.g. with *Swift*) is needed to better define the shape of the long-term X-ray light curve.

It has already been proposed that these superorbital modulations are related to temperature changes, but a correlation between X-ray flux and hardness ratio can also be found on time-scales of minutes to hours. X-ray oscillations on time-scales of a few minutes and more are probably associated with non-radial WD pulsations. This possibility needs to be explored by modelling the pulsation modes that can be expected from the accreting WD.

The optical and UV properties are consistent with emission from an accretion disc, with a wind or a jet with a large collimation angle originating from the disc. This outflow may be radiation-driven, but if the WD has a short spin period, the ejection of accreting blobs from the fast rotating WD magnetosphere is also a possibility. Obtaining optical spectra spread over a few months should shed more light on the possible jet precession.

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DISCUSSION

JIM BEALL: Is the Doppler shifted line you see evidence for disk rotation or more likely from a jet?

ALIDA ODENDAAL: The broadened main components of the emission lines indicate emission from an accretion disc, albeit with some contribution from the heated side of the secondary. However, the additional broad wing structures and P Cyg features are displaced from the main components by several thousand km s^{-1}, comparable to the WD escape velocity. Therefore the Doppler shifted wings that we see are most probably the result of a jet with a large collimation angle from the inner accretion disc.

DMITRY BISIKALO: Do you have any information about the value of the magnetic field in the system?

ALIDA ODENDAAL: No, there has not been a direct measurement of the WD magnetic field strength, e.g. by means of polarimetry. However, if the 67 s pulsation represents the WD spin period, then (i) the detection of the spin period indicates inhomogeneous emission from the WD surface, perhaps due to the accretion flow being channelled onto the polar caps by the magnetic field, and (ii) it indicates that the WD has been strongly spun up by disc torques during its lifetime, which can take place much more effectively in the presence of a magnetic field.

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