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SALT observations of outflows in three supersoft X-ray binaries

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Supersoft X-ray sources (SSSs) are characterized by very high soft X-ray luminosities ($\sim 10^{36}-10^{38}$ erg s^{-1}) and low effective temperatures (typically $T_{\mathrm{eff}} \sim 20-100$ eV). The high supersoft X-ray flux is derived from the nuclear burning of hydrogen on the surface of an accreting white dwarf (WD) in a binary system. Evidence for outflows have been observed in 4 canonical supersoft X-ray sources, three of which have southern declinations, i.e. CAL 83 and RX J0513.9-6951 (hereafter RXJ0513) in the LMC, and MR Vel in the Milky Way. Each source contains a massive WD accreting through an accretion disc. Signatures of outflows with velocities comparable to the WD escape velocity are present in their spectral line profiles in the form of Doppler shifted emission and P Cyg absorption. They are non-eclipsing, and the orbital inclinations of especially CAL 83 and RXJ0513 are very low, providing an unobstructed view of the approaching outflow components. CAL 83 and RXJ0513 exhibit large-scale anti-correlated X-ray and optical variability on time-scales >100 d. New SALT spectra of these three sources are presented and confirm the presence of outflows. These outflows may be driven by magnetohydrodynamic processes. Variable emission from ionized O VI appears to support the presumed temperature modulations associated with superorbital cycles.

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[†] Based on observations made with the Southern African Large Telescope (SALT).

<table>
<tr><th></th><th>CAL 83</th><th>RXJ0513</th><th>MR Vel</th></tr>
<tr><th>Luminosity</th><td>$\sim3\times10^{37}$ erg s^{-1} [2]</td><td>$\gtrsim6\times10^{37}$ erg s^{-1} [3]</td><td>$\sim4\times10^{37}$ erg s^{-1} (a) [4]</td></tr>
<tr><th>X-ray temperature</th><td>$\sim$47 eV
[2]</td><td>$\sim$40 eV
[3]</td><td>$\sim$77 eV
[4]</td></tr>
<tr><th>WD mass</th><td>$\sim$1.3 M$_\odot$ [2]</td><td>$\sim$1.3 M$_\odot$ [5]</td><td>$\lesssim$1.4 M$_\odot$ [6]</td></tr>
<tr><th>Orbital period</th><td>1.047529 ± 0.000001 d
[7]</td><td>0.762956 ± 0.000005 d
[7]</td><td>4.0287822 ± 0.0000026 d
[8]</td></tr>
<tr><th>Orbital inclination</th><td>20 – 30°
[10]</td><td>$\lesssim$7°
[11]</td><td><65° [9]
<30° [12]</td></tr>
<tr><th rowspan="2">Superorbital variability</th><td colspan="2">Exhibit quasi-periodic superorbital variability in X-ray flux of 2 to 3 orders of magnitude, anti-correlated with optical variability of $\sim$1 mag.</td><td rowspan="2">Persistent SSS.</td></tr>
<tr><td>[7]</td><td>[13]</td></tr>
<tr><th>Superorbital period</th><td>450 ± 3 d
[7]</td><td>168 ± 1 d
[7]</td><td></td></tr>
<tr><th rowspan="4">Optical spectra</th><td colspan="3">Dominated by emission lines of H I, He II, and ionized C, N and O.
Blueshifted P Cyg absorption in Balmer lines.
Widths of main emission components compatible with accretion disc emission.</td></tr>
<tr><td colspan="2">Broad Doppler shifted wings in H I and He II emission, presumably from weakly collimated outflows</td><td></td></tr>
<tr><td></td><td colspan="2">Narrow blueshifted (S$^-$) and redshifted (S$^+$) “satellite” emission features from biconical jets with velocities comparable to WD escape velocity</td></tr>
<tr><td>[10]</td><td>[11]</td><td>[9]</td></tr>
</table>

Table 1: Relevant properties of target sample from the literature, with selected references.
(a) Assuming a distance of 10 kpc to the source, although its distance is not well constrained.

1. Introduction to target sample

It was shown by [1] that the supersoft X-ray emission from many SSSs can be explained by surface nuclear burning of hydrogen on a WD accreting at $\sim10^{-7}$ M$_\odot$ yr^{-1}. The three SSSs forming part of this study have similar properties, which are summarized in Table 1.

The last detailed studies of the outflows in these sources were in the 1990s, with the exception of a paper focussing more on the ionized nebula surrounding CAL 83 [14]. Therefore, follow-up spectroscopy was undertaken with SALT. The aims were (i) to establish whether the outflows were still present, (ii) if so, to constrain their properties, and (iii) to evaluate the evolution of the CAL 83 and RXJ0513 spectra with respect to the optical low and high states as defined by OGLE photometry. The results presented here constitute a brief summary of the work of [15, Chapter 5].

The long-term variability of CAL 83 and RXJ0513 has been explained by limit cycle models where an increased accretion rate causes the WD envelope to expand due to pile-up of excess material [5, 13]. T_{eff} is now lower, and the emission peak shifts from the soft X-rays towards the ultraviolet, yielding an X-ray low, optical high state, with the optical flux further enhanced by more efficient irradiation of the disc. A decrease in the accretion rate allows the WD envelope to contract again, raising T_{eff}, shifting the emission peak back into the X-ray regime, and the source returns to an X-ray high, optical low state.

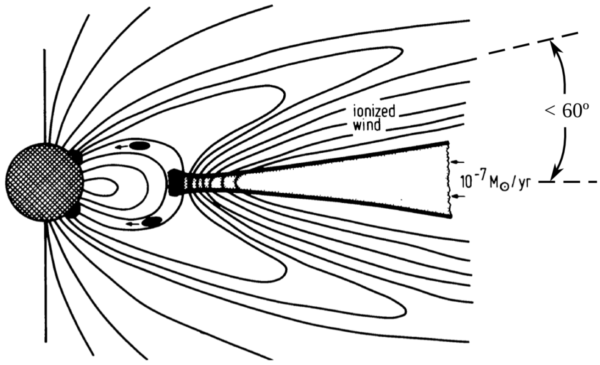

Figure 1: The Blandford & Payne model for a magnetocentrifugal wind. (Adopted from [21, Fig. 12].)

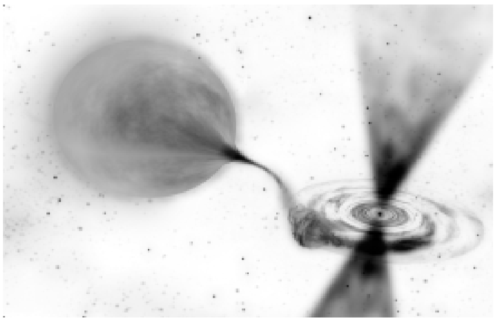

Figure 2: Outflow in a compact binary. (Image credit: Dana Berry, SkyWorks Digital/NASA-GSFC.)

2. A low-inertia magnetic accretor model for the 67 s periodicity in CAL 83

A ∼67 s X-ray periodicity was discovered in *XMM-Newton* observations of CAL 83 [15, 16]. The periodicity exhibits variability very similar to what is observed for dwarf nova oscillations (DNOs). DNOs have been explained by a low-inertia magnetic accretor (LIMA) model [17], where the periodicity arises in an equatorial belt around the WD at the inner disc boundary. The belt is loosely coupled to the WD core by a weak magnetic field ($\sim 10^5$ G), and its rotation is not synchronized with the WD spin. A similar LIMA model is proposed for the periodicity in CAL 83 [15, 18]. It is believed that the magnetic fields will be amplified as a result of differential rotation, and not be confined by the accreting gas (as illustrated for AE Aqr, see [19] and references therein).

An outflow can be driven from an accretion disc by the centrifugal force if the angle between the poloidal component of the magnetic field and the plane of the disc is less than 60° [20]. This can typically occur when the WD magnetic field is weak, and the magnetosphere is pressed inwards by the pressure associated with a high accretion rate, as shown in Fig. 1 (see also Fig. 2). The formation of magneto-centrifugally accelerated winds from an accretion disc threaded by a weak vertical magnetic field has also been shown to be a natural consequence of the existence of the magnetorotational instability, which is an almost essential element for disc accretion [22].

3. Observations with the Robert Stobie Spectrograph (RSS)

During the 2011-2013 observing cycles, a series of SALT RSS spectra were obtained: 10 of CAL 83, 5 of RXJ0513 and 2 of MR Vel. In Fig. 3, a high-state spectrum of both CAL 83 and RXJ0513 are presented, as well as a spectrum of MR Vel. The positions of all spectral lines that have ever been detected in the respective sources are indicated. The spectra exhibit similar properties as observed before, with the outflow features still visible. The Hα line profiles are plotted in terms of radial velocity in Fig. 4.

The H I and He II lines of CAL 83 exhibit broad blue wing structures extending to ∼2000 km s^{-1}, as well as P Cyg blueshifted absorption at $\gtrsim$2000 km s^{-1} in H I. The H I and He II lines of RXJ0513 also have broad asymmetric bases, and S$^-$ and S$^+$ satellite features are present at $\pm$4000 km s^{-1}. The H I lines also exhibit P Cyg profiles. The Hα emission of MR Vel also exhibits an S$^+$ feature at $+5300$ km s^{-1}, as well as P Cyg absorption. While the broad wing structures are expected to be associated with a weakly collimated outflow, the sharp satellite features presumably

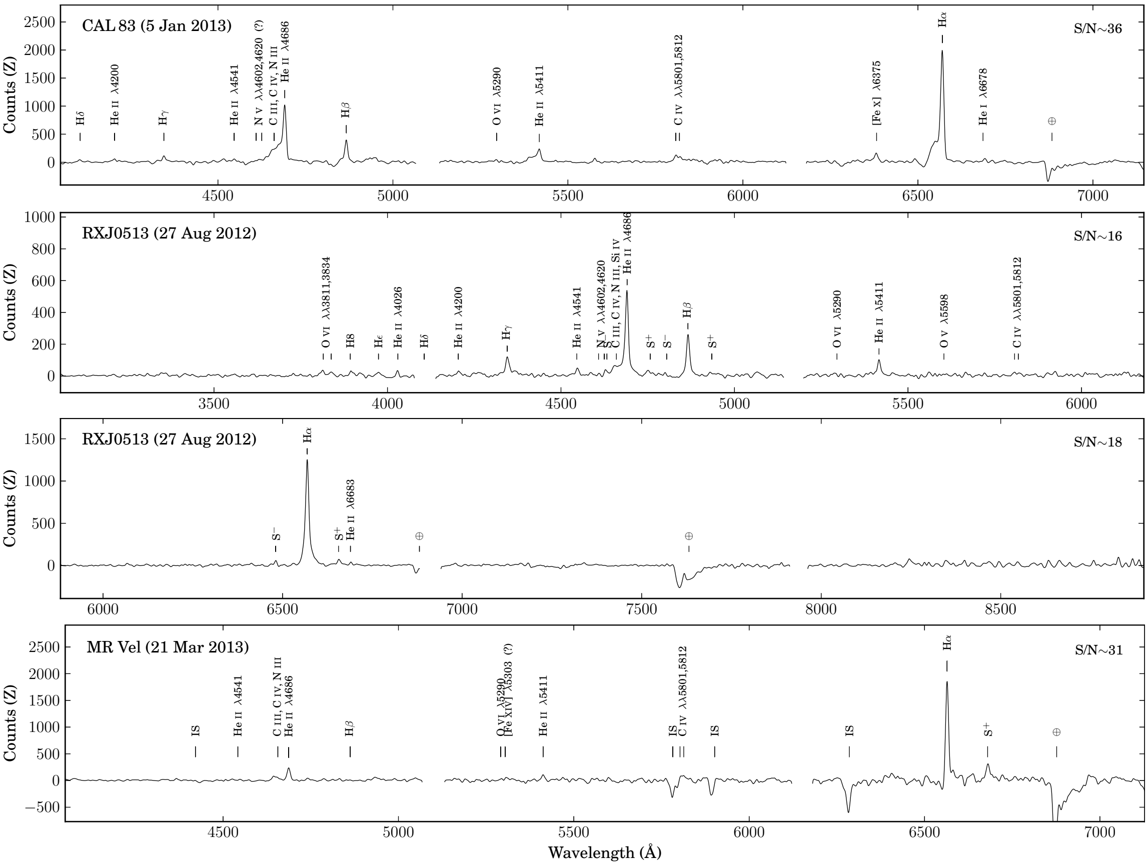

Figure 3: SALT spectra of CAL 83, RXJ0513 and MR Vel. The ⊕ symbol indicates the atmospheric A- and B-bands. "IS" marks interstellar absorption bands.

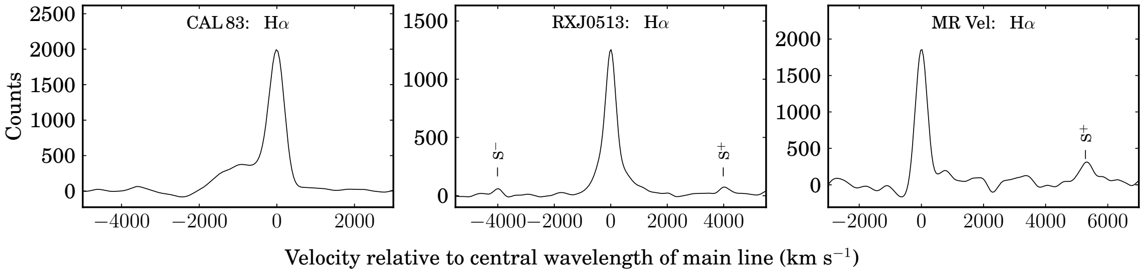

Figure 4: The Hα line profiles of the spectra in the previous figure, plotted in terms of velocity.

originate in well-collimated biconical plasma jets, with the S^- and S^+ components associated with the approaching and receding components, respectively.

Previous observations showed that S^- in RXJ0513 and MR Vel [9] are sometimes absent or even in absorption, which was also observed with SALT. With S^- in absorption, emission from the central continuum source is absorbed by optically thin material in the approaching jet. When S^- is in emission, the jet is observed along a line of sight that does not intersect the continuum source.

The presence of the S^+ Hα feature in MR Vel in the absence of the corresponding S^- feature was initially ascribed to He I λ6678 [12], but [9] found it unlikely that this feature is either

He I λ6678 or He II λ6683 emission, as no other He I lines are present in the spectrum, and the position, intensity and width of the feature are not consistent with the other He II lines in the spectrum.

A correlation of the spectral properties of CAL 83 with the OGLE light curves [23] showed that, in general, the emission line strengths and widths increase during the optical high state, which is to be expected due to the extended state of the disc and enhanced mass loss. The exception was the O VI emission, which exhibited very interesting variability. O VI emission originates in the inner disc, close to the hot WD. The general trend discovered in the SALT spectra, supported by previously published spectra, is that O VI λ5290 emission is significant during optical low states, but much weaker during optical high states. This can be readily explained by the expansion/contraction model. When the WD envelope is contracted during the optical low state, optically thin regions of the inner disc is visible, and the O VI λ5290 line is observed. This is consistent with the LIMA model, with a weak magnetic field allowing the disc to extend almost down to the WD surface. During the optical high state, the expanded envelope obscures the O VI λ5290 emission.

4. Conclusion and future work

The optical spectra of CAL 83, RXJ0513 and MR Vel exhibit strong evidence for outflows. These outflows may be radiation-driven, but are more likely to be related to magnetohydrodynamic processes, i.e. magneto-centrifugal acceleration as explained in §2. The LIMA model for CAL 83, together with the presence of the outflows and the behaviour of the O VI λ5290 emission line, are consistent with a weakly magnetized WD with a disc extending inwards almost down to the WD surface during the optical low state. Although O VI λ5290 is weak in all the available optical high state spectra of RXJ0513, an optical low state spectrum is required to establish whether the O VI emission is indeed anti-correlated with the optical flux, as in CAL 83. Follow-up work on these sources should include the application of kinematical models to constrain the outflow parameters, and their dependence on orbital phase. Current radio data of these systems only provide upper flux limits, but these systems are very suitable candidates for the possible detection of non-thermal radio emission from the outflows with MeerKAT/SKA. This could enable a better understanding of the outflows, and allow constraints on the magnetic field strengths for the first time. Recent VLA observations of dwarf novae have already lead to radio detections on μJy level (Coppejans 2015, private communication).

Acknowledgments

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