The magnetic SW Sextantis star RX J1643.7+3402

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ABSTRACT

We present time-resolved spectroscopy and circular spectropolarimetry of the SW Sex star RX J1643.7+3402. We find significant polarization levels exhibiting a variability at a period of 19.38 ± 0.39 min. In addition, emission-line flaring is found predominantly at twice the polarimetric period. These two findings are strong evidences in favour of the presence of a magnetic white dwarf in the system. We interpret the measured periodicities in the context of our magnetic accretion model for SW Sex stars. In contrast with LS Pegasi – the first SW Sex star discovered to have modulated circular polarization – the polarization in RX J1643.7+3402 is suggested to vary at 2(ω − Ω), while the emission lines flare at (ω − Ω). However, a 2ω interpretation cannot be ruled out. Together with LS Peg and V795 Her, RX J1643.7+3402 is the third SW Sex star known to exhibit modulated circular polarization.

Key words: accretion, accretion discs – magnetic fields – polarization – binaries: close – stars: individual: RX J1643.7+3402 – novae, cataclysmic variables.

1 INTRODUCTION

The ROSAT X-ray source RXJ1643.7+3402 (AAVSO 1640+34) was identified as a cataclysmic variable (CV) by Mickaelian et al. (2002). Based on spectroscopic and photometric data, they classified this object as a member of the SW Sex family. In spite of their effort to determine its orbital period, two possible candidates from the power spectra of the Hα radial velocity curves, namely 2.575 h and 2.885 h, were suggested. In addition, they found a photometric period of 2.595 h which they identified as a superhump modulation, as well as rapid variations in the V-band light curve with a time-scale of ∼15 min.

In the same year, Patterson et al. (2002) measured a reliable value for the orbital period, 2.893 44(34) h, in agreement with one of the values suggested by Mickaelian et al. (2002). This places the system within the period gap, a region in the period distribution of CVs (between approximately 2 and 3 h) in which a dearth of systems is observed. Patterson et al. also reported two additional periodicities found in the light curve of RXJ1643.7+3402: 2.807 h and 4.05 d, which they interpret as a negative superhump and the wobble period of the accretion disc, respectively. Moreover, a quasi-periodic oscillation with a period near 17 min (very close to that previously reported by Mickaelian et al.) was also observed. On the other hand, Patterson et al. (2002) confirmed the SW Sex membership of RX J1643.7+3402 on the basis of its spectroscopic behaviour and photometric variability.

The SW Sex stars form a group of CVs firstly defined by Thorstensen et al. (1991). Their original definition was later updated at the light of new observational and theoretical knowledge (see e.g. Martínez-Pais, Rodríguez-Gil & Casares 1999; Rodríguez-Gil et al. 2007 for a review). Briefly (i) they show a strong absorption component in the Balmer and He i lines usually detectable along a fraction of the orbit and reaching maximum depth around orbital phase ~0.4–0.5, when it moves from positive to negative velocities. The relative intensity of this component increases with the line excitation level, even dominating the line profile in He i. (ii) They also show a high-velocity emission S-wave, which is stronger in the blue wing of the Balmer lines and reaches its extreme negative velocity at orbital phase ~0.4–0.5. (iii) As a consequence of the complex structure of the emission lines, the Balmer radial velocity curves are delayed with respect to the white dwarf motion. (iv) Most of them (68 per cent; see Rodríguez-Gil et al. 2007) cluster at the upper edge of the period gap with orbital periods in the range ~3–4 h.

The magnetic origin of the SW Sex phenomenology has been claimed by several authors (Williams 1989; Casares et al. 1996; Martínez-Pais et al. 1999). It was only after the discovery of variable circular polarization in the non-eclipsing systems LS Peg (Rodríguez-Gil et al. 2001, hereafter P01) and V795 Her (Rodríguez-Gil et al. 2002), and the X-ray pulsation in LS Peg at exactly the polarimetric frequency (Buskall, Wheatley & Osborne 2005), that the presence of a magnetic white dwarf has become a primary ingredient in defining the nature of this class of CV.

RX J1643.7+3402 (J1643) is the brightest non-eclipsing SW Sex star known (and one of the brightest CVs at V ≃ 12.6). This, together

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with the restrictive signal requirements of time-resolved spectropolarimetry, makes it the best candidate for probing the presence of a magnetic white dwarf by means of circular polarimetry measurements. Besides, the lack of eclipses ensures an inclination angle small enough to guarantee a good visibility of the white dwarf along the whole orbital cycle. For this reason, we decided to undertake a spectropolarimetric study on this system similar to our pioneering work on LS Peg (P01), which provided a positive result: the detection of variable circular polarization at a period of 29.6 (±1.8) min.

2 OBSERVATIONS AND DATA REDUCTION

Two data sets (spectroscopic and spectropolarimetric) are presented in this paper. Both were obtained using the blue arm of the Intermediate dispersion Spectrograph and Imaging System mounted on the 4.2-m William Herschel Telescope at the Roque de los Muchachos Observatory on La Palma. Spectra of Cu–Ne–Ar comparison lamps were obtained every ~30–40 min in order to secure an accurate wavelength calibration. Data reduction was performed using IRAF, while wavelength calibration and most of the subsequent analyses made use of Tom Marsh’s MOLLY package.

Regarding the pure spectroscopic data, a total of 114 spectra were acquired on 2002 May 21 using the R600B grating and a 1-arcsec slit width. This gave a spectral resolution of 1.7 Å [full width at half-maximum (FWHM)] in the λ3600–5350 spectral range. The data were reduced in a standard way, i.e. by applying bias and flat-field corrections, sky subtraction and the optimal extraction procedure described by Horne (1986). Once the spectra were wavelength-calibrated, their wavelength scale was re-sampled into an uniform velocity scale and then normalized to their continuum.

The spectropolarimetric data (2003 July 1) were acquired using a λ/4 plate above the slit and a Savart plate below it. This configuration produces two different images on the detector, corresponding to the ordinary and the extraordinary ray, respectively. The exposures were performed alternating two positions of the λ/4 plate differing by 90°. A total of 44 images were acquired at each position angle of the quarterwave plate, each lasting between 120 and 150 s. We used the R300B grating which covered the spectral range λ3800–7430 at a 3.4 Å resolution. Reduction of the spectropolarimetric data was performed according to the procedure described in P01. The extraction of the ordinary and extraordinary spectra from the images taken at both positions of the λ/4 plate provided a total of 4 × 44 = 176 spectra, from which the spectral density of the $P_V = V/I$ Stokes parameter can be obtained following the procedure described in Tinbergen & Rutten (1992).

In addition to the spectropolarimetric information contained in the 2003 data, it is possible to recover the (non-calibrated) flux distribution by just coadding the ordinary and extraordinary spectra on each frame. We therefore obtained a total of 88 spectra which were later rebinned and rectified in the same way as the 2002 data.

3 VARIABLE CIRCULAR POLARIZATION

Once the $P_V$ spectra were obtained (see Section 2), we measured the circular polarization level on different continuum windows.

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$P_V$–HJD curves were subsequently constructed for which Scargle periodograms were computed. The best results (i.e. the strongest peaks in the periodograms) were found for redder continuum regions, especially in the range λ5960–6850 after masking out the atmospheric and interstellar features. It must be noted, however, that no polarization was detected in the emission lines. Actually, neither He II nor He I λ6678 (the lines included in the working range) is present in the $P_V$ spectra.

In Fig. 1, we show the circular polarization curve for the selected continuum region. The Scargle periodogram (Scargle 1982) is clearly dominated by a sharp peak at ~75 d$^{-1}$ for which a Gaussian fit yielded a frequency of 74.3 ± 1.5 d$^{-1}$ (a period of 19.38 ± 0.39 min; the quoted uncertainty is half the FWHM of the fitting Gaussian). In order to check the significance of this periodicity, we performed a Monte Carlo test by generating 10$^6$ white-noise time series, i.e. random, zero-mean normal distributions of data with the same sampling as our $P_V$ data. A Scargle power spectrum was subsequently computed for each white-noise time series, and a statistic was performed among them. Thus, for example, the 4σ level indicated in Fig. 1 is the power level for which 99.99 per cent of the computed power spectra have values below it. We can therefore say that the probability of a random time series having a peak in its periodogram exceeding this level is 0.01 per cent or, in other words, a peak having a power greater than this value has a probability of at least 99.99 per cent of being true. This unambiguous detection of variable circular polarization in J1643 is a clear sign of magnetic accretion in the system. Fig. 1 shows the circular polarization data folded on both the 19.38-min period and twice that value. The reason for this will be explained in what follows.
Circular polarization in RX J1643.7+3402

Figure 2. Top panel: continuum-subtracted, trailed spectra diagrams in the vicinity of Hγ, Hβ, He II λ4686 and He I λ4922 from the 2002 May data. Emission-line flaring is apparent in all the lines, especially in He II λ4686. Black represents emission. Bottom panel: same for the 2003 July data but including Hα. The grey levels of the Hα trailed spectra have been adjusted to enhance the high-velocity S-wave. The blank space corresponds to a bad weather interval. Orbital phases for both sets of data were calculated from the orbital period reported by Patterson et al. (2002) under the assumption of maximum blue excursion of the high-velocity S-wave occurring at ϕ = 0.45 (see e.g. Rodríguez-Gil et al. 2007).

4 EMISSION-LINE VARIABILITY

Magnetic accretion can give rise to variations of the emission lines at a period related with that of the circular polarization variability. This is the case in, e.g., the intermediate polar CV (IP) PQ Gem (Pirola, Hakala & Coyne 1993; Rosen, Mittaz & Hakala 1993; Potter et al. 1997) and the SW Sex star LS Peg (P01). In Fig. 2, we present the Hγ, Hβ, He II λ4686, He I λ4922 and Hα trailed spectra diagrams constructed from the pure spectroscopic data (2002 May) and the spectropolarimetric data (2003 July) after subtracting the continuum. Emission-line flaring at a short time-scale (∼10–20 min) is clearly visible, especially in the 2002 data. Apart from LS Peg, these variations have been observed in the emission lines of other four SW Sex stars (see Rodríguez-Gil et al. 2007, and references therein), and are also seen in the optical spectra of other IPs, such as FO Aqr (Marsh & Duck 1996). By analogy to IPs, the emission-line flaring present in the SW Sex stars has been connected to the spin period of a magnetic white dwarf (P01; Patterson et al. 2002).

In order to search for coherent signals in the lines of J1643 and to study a possible link with the circular polarization period, we constructed radial velocity and equivalent width (EW) curves which were subjected to a period analysis. We will focus on the 2003 July spectropolarimetric data, as J1643 could have been on a different accretion state during the 2002 observations. Nevertheless, we also analysed the 2002 radial velocity and EW curves for comparison.

The radial velocities of the emission lines were obtained by cross-correlation of the line profile with a Gaussian template having a FWHM similar to the linewidth. This technique provided better results (i.e. stronger main peaks in the periodograms) than the double-Gaussian approach of Schneider & Young (1980).

4.1 He II λ4686 and the Bowen blend

In Fig. 3, we show the He II λ4686, Bowen blend, Hα and Hβ Scargle periodograms computed from the 2003 radial velocity and EW curves.

The He II λ4686 power spectra do not exhibit a peak at the circular polarization frequency (ωpol). Instead, the radial velocities present the strongest peak (> 3σ) at 65.9 ± 2.0 d⁻¹, which we identify with ωpol - Ω1, where Ω = 8.3 d⁻¹ is the orbital frequency. The Scargle periodogram of the He II λ4686 EW curve is dominated by a peak centred at ωEW = 36.7 ± 2.0 d⁻¹, which has a significance much in excess of the 4σ level. The fact that its frequency is almost exactly ωpol/2 indicates that the circular polarization is not modulated at...
Figure 3. Left-hand panel: Scargle periodograms of the 2003 He \textsc{ii} \lambda 4686, Bowen blend, H\alpha and H\beta radial velocity curves. Right-hand panel: same for the EW curves.

4.2 Balmer lines

Both the Balmer radial velocity and EW curves are dominated by the orbital motion. The strongest peak in the H\alpha and H\beta periodograms (H\gamma showed the same features and is not shown) corresponds to twice the orbital frequency (2\Omega), and the second strongest is found at \omega_{pol}/2. Note that the EW periodograms were computed from the EW curves after removing the orbital modulation to illustrate the effect of detrending.

4.3 The 2002 data periodograms

We have performed the same period analysis on the 2002 pure spectroscopic data. The Scargle periodograms are presented in Fig. 4. It is clear from the figure that the 2002 data portrait a different scenario. The He \textsc{ii} \lambda 4686 radial velocities also show a significant peak at \omega_{pol}/2, but the strongest peak seen in 2003 at \omega_{pol} - \Omega is absent. The \omega_{pol}/2 frequency is also the dominant one in the Balmer radial velocity periodograms (only H\beta is shown in Fig. 4) after subtracting the original orbital modulation. The Balmer velocities also show a peak very close to \omega_{pol} at 70.4 \pm 3.0 d^{-1}. With regard to the Bowen-blend velocities, a peak at 20.2 \pm 3.0 d^{-1} shows power in excess of 3\sigma.

The He \textsc{ii} \lambda 4686 EWs are dominated by a modulation at 2\Omega. The periodogram shown in Fig. 4 was constructed after removing the orbital modulation. The 2002 periodogram shows a cluster of peaks centred at 36.3 \pm 3.0 d^{-1}, which we identify as \omega_{pol}/2. The flanking peaks are located at 28.2 \pm 3.3 and 44.9 \pm 3.4 d^{-1}. Their respective distances to the central one at \omega_{pol}/2 are consistent with the orbital frequency (\Omega). On the other hand, a peak at 31 d^{-1} dominates the Bowen-blend EWs, while one at 47.3 \pm 3.5 d^{-1} is the strongest observed in the Balmer EW periodograms. These are consistent, within the errors, with the peaks observed in the He \textsc{ii} \lambda 4686 EW periodogram.

The only frequency clearly common to both the 2002 and 2003 data sets is \omega_{pol}/2. The remaining (i.e. \sim 20, \sim 28 and \sim 45 d^{-1}) are not significant frequencies in the 2003 circular polarization data. Perhaps the most intuitive association would be \omega_{pol}/2 - \Omega and \omega_{pol}/2 + \Omega, respectively. Finally, we found no explanation for the \sim 20 d^{-1} frequency observed in the Bowen radial velocities.
5 DISCUSSION

5.1 The magnetic nature of RX J1643.7+3402

Several authors have provided clues of the presence of magnetic white dwarfs in the SW Sex stars (see e.g. Casares et al. 1996; Martínez-Pais et al. 1999; Patterson et al. 2002; Rodríguez-Gil & Martínez-Pais 2002). Direct confirmation of magnetism in a particular system would require at least one of the two following observational facts: (1) the presence of coherent pulsations related to the white dwarf spin period and/or to the orbital period and, mainly, (2) the detection of variable circular polarization. The observation of modulated circular polarization is an unambiguous proof as it implies the direct detection of a relatively strong magnetic field. It is clear from our results that the presence of an asynchronously rotating magnetic white dwarf in J1643 is beyond any doubt: the detection of variable circular polarization and emission-line flaring (which introduces oscillations in both the EWs and the radial velocities) is a solid proof. J1643 is therefore the second SW Sex star in which a magnetic white dwarf has been discovered by means of spectropolarimetric techniques.

5.2 The observed periodicities in the magnetic scenario

Our discovery of the first SW Sex star showing modulated circular polarization, LS Peg, led us to propose a magnetic model (P01) in which the periodicities found in this work can be interpreted. Briefly, due to the high accretion rate, the gas stream coming from the secondary star overflows the disc and hits the magnetosphere of the white dwarf, which is assumed to extend up to the corotation radius. From this point on, the gas couples to the magnetic field lines, eventually shocking against the white dwarf surface and forming accretion columns above the magnetic poles. The resulting X-ray radiation irradiates other structures of the system which can reprocess the high-energy radiation into optical wavelengths. For example, in the intermediate polar CVs periodicities at a frequency $\omega - \Omega$ (with $\omega$ as the white dwarf spin frequency) are usually detected due to the irradiation of structures anchored to the orbit (disc, secondary star, etc.; Warner 1986).

According to our magnetic model, and by analogy with LS Peg and intermediate polars, the emission lines should be flaring at $\omega - \Omega$ as the white dwarf magnetosphere is connected to the overflown gas stream which provides information about the orbital motion. Therefore, we would identify $\omega_{\text{EW}} = 36.7 \pm 2.0$ d$^{-1}$ with $\omega - \Omega$. However, in this scenario the actual circular polarization would be modulated at $2(\omega - \Omega)$. This has two problems: first, the circular polarization is not modulated at a fundamental frequency, but at a first harmonic; and secondly, its frequency is related to $\omega - \Omega$, instead of $\omega$.

Modulations at the first harmonic of the spin frequency have been observed in the bona fide intermediate polar CV, PQ Gem. In this system, the relative dominance of the first harmonic with respect to the fundamental frequency depends on the wavelength range. In the X-ray regime, Mason et al. (1992) observed a dip at medium energies (2–6 keV) in their Ginga data, which produced a double-humped light curve when folded on the spin frequency, $\omega$. A periodogram of those data would therefore have provided the strongest peak at $2\omega$. In optical wavelengths, Potter et al. (1997) noted that both the circular polarization and the light curves were dominated by oscillations at $2\omega$ towards red wavelengths. The authors explain the double-waved I-band circular polarization curve as a dip in the negative circular polarization due to absorption or scattering of the cyclotron emission by the gas stream. On the other hand, the polar CV, V1432 Aql (Rana et al. 2005), shows the same phenomenology (i.e. polarization modulated at twice the white dwarf spin frequency). It is worth mentioning that this system is not...
synchronized, so it constitutes a valuable example to explain the evolution of magnetic CVs. Rana et al. interpret this periodicity as due to the double-peaked shape of the white dwarf spin-modulated curve. Overall, these findings are not unexpected as cyclotron radiation dominates in the red and, therefore, interaction with the accretion structures can make this kind of behaviour more notable.

The second problem is the most fundamental question: is \( \omega_{\text{GW}} = \omega_{\text{pol}}/2 \) in J1643 the actual spin frequency (\( \omega \)) or the beat frequency (\( \omega - \Omega \))? With the data at hand and the lack of X-ray and ultraviolet light curves, and circular polarization data in 2002, answering to this question proves very difficult. Although we cannot rule out a disc-fed configuration (i.e. \( \omega \)), the circular polarization would be modulated at the beat period with two maxima and two minima per cycle, i.e. at \( 2(\omega - \Omega) \), if our stream-fed model holds. In this regard, it is widely accepted that both the X-ray emission and the circular polarization in intermediate polars show variation at the spin frequency (or its first harmonic as we discussed above). But Buckley et al. (1997) observed the X-ray emission of the intermediate polar V2400 Oph modulated at \( \omega - \Omega \) as a result of variable accretion rate with the rotation of the magnetic field. In our SW Sex magnetic model, accretion along the magnetic field lines on to the white dwarf surface only takes place when the field encounters the gas stream. Therefore, optically thick conditions for cyclotron radiation emission are only met every synodic period as seen by the gas stream. As a result, the circular polarization can be varying at \( \omega - \Omega \) or its harmonics.

Assuming a one solar-mass white dwarf, the corotation radius (with \( P_{\text{pol}} = 1900 \) s) is \( \sim 2.3 \times 10^5 \) km, and the corresponding free-fall velocity is \( \sim 1000 \text{ km s}^{-1} \). Therefore, the time-scale to refill the portion of the stream swept by the magnetic field is \( \sim 200 \) s, short enough to ensure that during the time elapsed between two consecutive passes of the field by the stream (\( \sim 1000 \) s), it can be actually refilled.

In the described accretion scenario, the white dwarf spin frequency would then be \( \sim 45 \text{ d}^{-1} \). Peaks very close to this frequency (\( >3\sigma \)) are observed in both the He \( \lambda \lambda 4686 \) and Balmer periodograms constructed from the 2002 EW curves, but no sign of this frequency is found in the 2003 spectropolarimetric data. The different behaviour seen in the 2002 and 2003 data likely points to the changes in the accretion mode in J1643, and reflects the importance of spectropolarimetry: circular polarization and emission-line variability can be compared as they are obtained simultaneously. Imaging polarimetry can be the only way to measure fainter objects, but in that case, time-resolved spectroscopy has to be performed as close in time as possible to avoid data contamination by accretion mode changes.

### 6 CONCLUSIONS

We have found significant circular polarization levels modulated at a period of 19.4 (\( \pm 0.4 \)) min, which we interpret as half of the beat period between the white dwarf spin period and the orbital period. In addition, the variation of the EWs and radial velocities of the He \( \lambda \lambda 4686 \) and Balmer lines shows a predominant period at the beat period. All this phenomenology confirms the existence of a magnetic white dwarf in J1643, a characteristic that may be common to the SW Sex stars.

The interpretation of the observed frequencies was based on our magnetic model of an overflowing gas stream striking the white dwarf’s magnetosphere at approximately the corotation radius, inside which the material accretes along the magnetic field lines. This model was also proposed by us for LS Peg, another SW Sex star in which emission-line flaring and variable circular polarization were also detected. However, in the case of J1643, the frequency at which the polarization varies can be \( 2(\omega - \Omega) \), whilst for LS Peg it is \( \omega \). However, it is also possible that the polarization in J1643 is modulated at \( 2\omega \), while the EWs are at \( \omega \). We are not able to address an unambiguous conclusion with the data presented in this paper.

Our results demonstrate that performing polarimetric measurements of other SW Sex stars is crucial to test the impact of magnetism within the class. Especially interesting are non-eclipsing systems since, following our model, in eclipsing ones the disc may be intercepting the light coming from the regions near the white dwarf surface. However, the results will depend on the system geometry. In fact, several eclipsing systems are known to exhibit emission-line flaring (BT Mon, DW UMa), and these should also be observed using polarimetric techniques.

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