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RX J2115–5840: confirmation of a new near-synchronous polar

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ABSTRACT

Following the suggestion of Schwope et al that the magnetic cataclysmic variable RX J2115–5840 maybe a near-synchronous polar, we obtained optical polarimetry of this system over a 2 week period. From a power spectrum of the circular polarimetry data we determine that the spin period of the white dwarf and the binary orbital period which differ by 1.2 percent. RX J2115–5840 is thus the fourth near synchronous polar and has the shortest spin-orbit beat period: 6.3 days. By folding the data on spin, beat and orbital periods we find evidence that the accretion stream is directed towards opposite magnetic poles as the stream precesses around the white dwarf on the spin-orbit beat period. The phasing requires that the accretion flow must be directed onto the same magnetic field line at all spin-orbit beat phases implying that at some phases the flow must follow a path around the white dwarf before accreting. This is difficult to reconcile with simple views of how the accretion stream attaches onto the magnetic field of the white dwarf.

Key words: binaries: individual: RX J2115–5840, EUVE 2115–58.6, stars: magnetic fields - stars: variables

1 INTRODUCTION

EUVE 2115–58.6 was discovered during the *EUVE* all sky survey (Bowyer et al 1996) and also during the *ROSAT* all sky survey (RX J2115–5840, Voges et al 1997). From optical spectra, Craig (1996) suggested that RX J2115–5840 is a magnetic Cataclysmic Variable (mCV). Further spectroscopic observations by Vennes et al (1996) suggested an orbital period (P_o) of 110.8 min or an alias at 102.8 min. Optical polarimetry obtained by Schwope et al (1997) showed variable circular polarisation of up to 15 percent, indicating that it is a member of the polar sub-class of mCVs. In these systems the accreting white dwarf has a sufficiently strong magnetic field to lock the spin of the white dwarf into synchronous rotation with the binary period. The bulk of the accretion luminosity is liberated at X-ray/EUV wavelengths.

Schwope et al (1997) also suggested that the orbital period differs with respect to the spin period of the white dwarf by $\sim 1\%$. They concluded that the spectroscopic period of 110.8 min represents the binary orbital period, while the photometric period of 109.84 min or 109.65 min represents the spin period of the white dwarf (P_s). If confirmed, this would make RX J2115–5840 the fourth near-synchronous polar and the first one below the 2–3 hr orbital period gap. Therefore to determine if RX J2115–5840 is indeed near-synchronous, we obtained white light polarimetric observations covering 2 weeks.

2 OBSERVATIONS

RX J2115–5840 was observed in white light using the SAAO 1.9m telescope and UCT Polarimeter (Cropper 1985) between 1997 July 29 and 1997 August 11. Data were obtained on 10 nights over this interval although the total amount of data obtained on each night varied. Conditions ranged from photometric to non-photometric. Sky measurements were obtained every 15–25 mins and subtracted from the source measurements by a polynomial fit to the sky data. Polarised and non-polarised standard stars (Hsu & Breger 1982) and calibration polaroids were observed at the beginning of the night to set the position angle offsets and efficiency factors.

3 RESULTS

The white light intensity data are similar to those shown in Schwope et al (1997) in that unlike most polars they do not show large photometric variations, although humps

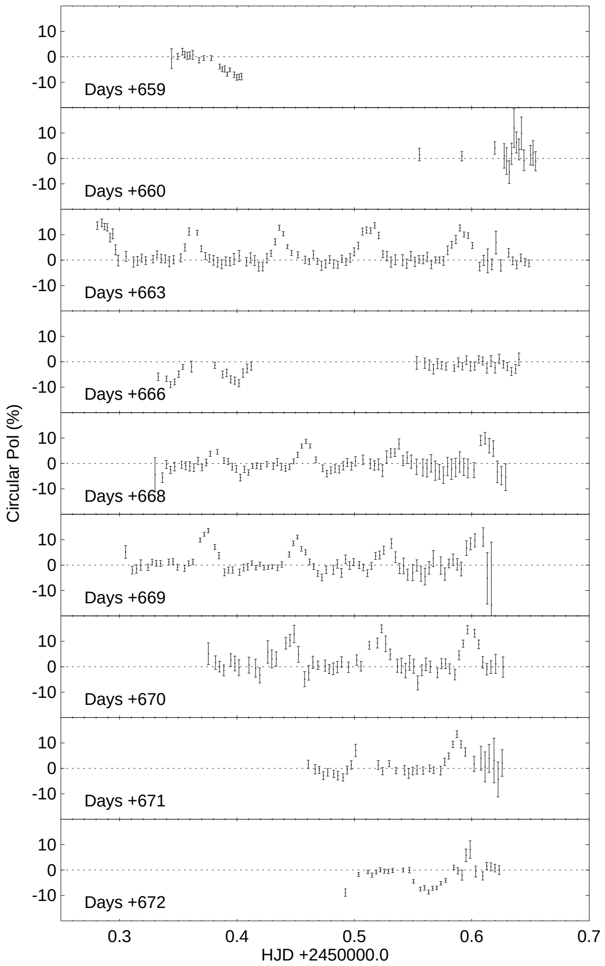

Figure 1. The circular polarisation data. The label in the left hand of each panel indicates the HJD +2450000.0.

were seen in some of the data sets. We recorded low levels (typically 3–4 percent) of linear polarisation. In this paper, however, we concentrate on the circular polarisation data since the intensity data were compromised to some extent by non-photometric conditions on some nights. The circular polarisations are shown in Fig. 1. For most of the observation the circular polarisation is either close to zero or shows positive excursions which follow the intensity curve at some epochs. However, there are occasions when negative circular polarisation is seen (HJD 2450000+ 659, 666 and 672). Similar behaviour was seen by Schwope et al (1997), although they had circular polarisation from short sections of data on only 3 days.

In fully synchronised polars, the spin period of the white dwarf is equal to the binary orbital period. In these systems the circular polarisation curves are broadly repeatable from cycle to cycle since the accretion flow is directed onto the same accretion pole(s). These observations showing modulated circular polarisation of positive polarity at some epochs and negative polarity at other epochs suggests that RX J2115–5840 is not fully synchronised.

While a Discrete Fourier Transform (DFT) may not be the optimum method to analyse intensity or polarisation curve of a near-synchronous polar since there may be phase shifts between the curves for each pole, we use a DFT for this first stage of our investigation. Fig. 2 shows the amplitude spectrum of the circular polarisation data without subtracting the mean. The highest amplitude peak corresponds to a period of 110.889 mins – similar to the spectroscopic period of 110.8 mins reported by Vennes et al (1996). Moving higher in frequency, the next peak in amplitude corresponds to a period of 109.547 mins – similar to the shorter of the two possible optical photometric periods, 109.84 and 109.65 mins, reported by Schwope et al (1997).

We take the periods 110.889 and 109.547 found from our DFT to represent the binary orbital frequency, Ω, and the spin frequency of the white dwarf, ω, respectively. A side band frequency $2\omega-\Omega$ corresponding to a period of 108.237 mins is then very close to an amplitude peak at 108.38 mins in the DFT (this side band frequency is prominent in the near-synchronous polar BY Cam: Mason et al 1998). At much lower frequencies, the spin-orbit beat frequency $\omega-\Omega$, which corresponds to a period of 6.28 days, is within the FWHM of the highest amplitude peak seen at the lowest frequencies (7.05 days). The next two highest frequencies in the DFT (1.19 and 0.88 days) are aliases of this spin-orbit beat frequency.

So far we can therefore account for the principle amplitude peaks in the DFT at frequencies lower than 0.0002 Hz. Moving to the first harmonics of the proposed spin and orbital periods (close to 0.0003 Hz), we find that twice our proposed spin frequency, 2ω, corresponds exactly with a prominent amplitude peak. The prominent peak at 3.02442×10^{-4} Hz (=55.107 mins) is the $\omega+\Omega$ side-band frequency. We also detect the 3ω harmonic and the $4\Omega-3\omega$ side-band frequency

To test our proposed values of P_o = 110.889 mins and P_s = 109.547 mins, we pre-whitened the circular polarisation data with these two frequencies (and their second and third harmonics), the $2\omega-\Omega$ side band frequency (P =108.38 mins), the $4\Omega-3\omega$ side band frequency (P=114.956 mins) and the more $\omega\pm\Omega$ side band frequencies (shown in the lower panel of Fig. 2). All frequencies which have an amplitude greater than 1 percent have been removed. This implies that if any other frequencies are present in the amplitude spectrum then they are present at a low level. We show in Table 1 the peak amplitudes of all the frequencies we can distinguish, together with their equivalent periods. We note that not all of the frequencies quoted in Table 1 are necessarily significant (it is difficult to assign significance levels to amplitude peaks). We have merely noted those combinations of spin and orbital frequencies which coincide with a peak in the amplitude spectrum.

4 THE BEAT PERIOD

To make a more detailed investigation of the circular polarisation data we folded the circular polarimetry on the proposed spin period. The top panel of Fig. 3 shows that for over half the spin cycle the circular polarisation is close to zero, while for the remainder of the cycle, there are positive or negative excursions at approximately the same spin phase. If we fold the circular polarimetry on the proposed orbital period (the middle panel of Fig. 3) we find similarly that the circular polarisation is close to zero while there are

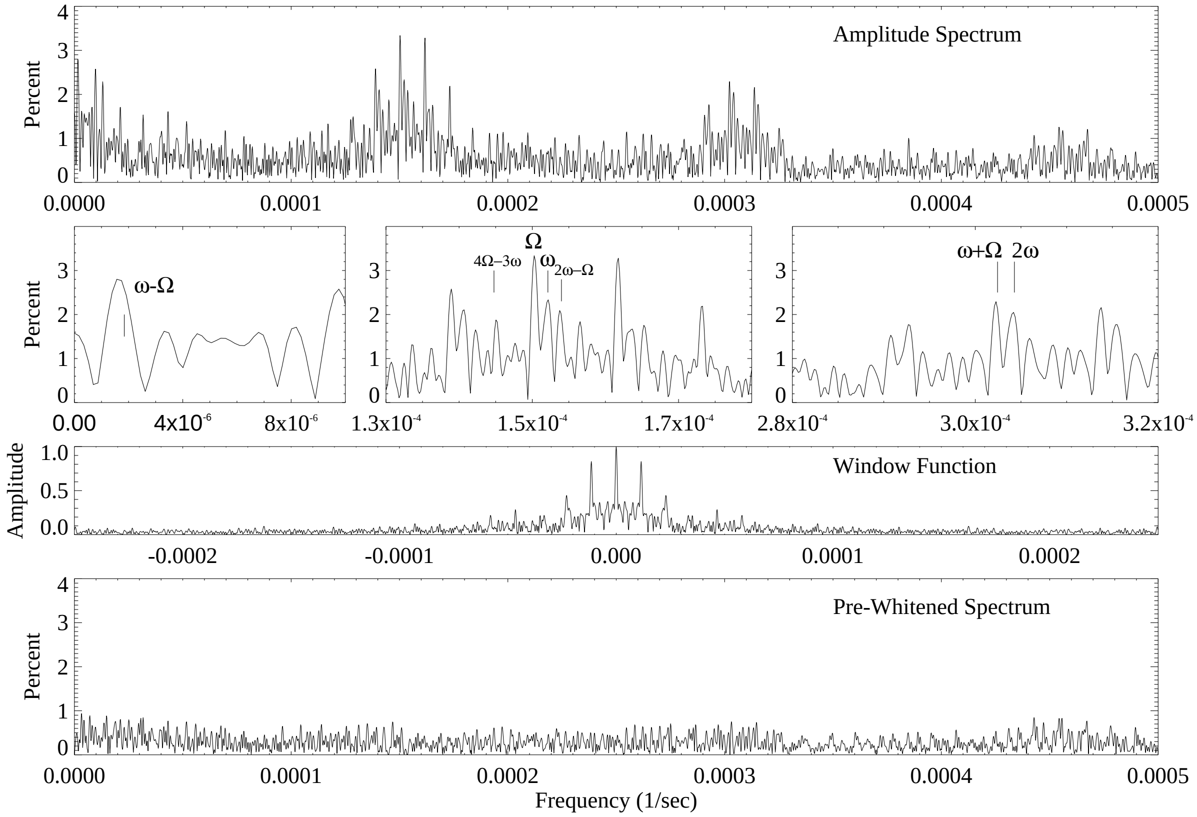

Figure 2. From the top: the amplitude spectrum of the circular polarisation data; the amplitude spectrum in greater detail over three frequency intervals; the window function and the pre-whitened spectrum (see text for details).

Frequency	Hz	Period (min)
Ω	1.502993×10^{-4}	110.889
3Ω	4.543406×10^{-4}	36.683
ω	1.521423×10^{-4}	109.547
2ω	3.041679×10^{-4}	54.794
3ω	4.559762×10^{-4}	36.552
$\omega-\Omega$	1.6276×10^{-6}	10238
$\omega+\Omega$	3.022470×10^{-4}	55.143
2ω-Ω	1.539853×10^{-4}	108.235
4Ω-3ω	1.449825×10^{-4}	114.956

Table 1. The frequencies in the amplitude spectrum which we can distinguish: we show the frequency in Herz and its equivalent period in mins. We do not necessarily claim that all of these frequencies are significant.

phases of alternate positive and negative circular polarisation.

To determine if these positive and negative excursions were observable on the 6.28 day spin-orbit beat period we folded the circular polarisation on this period. The bottom panel of Fig. 3 shows the folded data (phase zero was arbitrarily chosen to be 24500659.0, the start of our observation). Although there is a good deal of variability due to spin variations at shorter time scales, the mean level of circular polarisation is negative at $\phi_{(\omega-\Omega)}$ ~0.07 and 0.17 while it increases at later phases.

To examine variations in the circular polarisation data over the spin-orbit beat period, we folded and binned each section of data which corresponded to a discrete beat phase on the proposed spin period of the white dwarf – 109.547 mins (Fig. 4). As expected from Fig. 3, at phases $\phi_{(\omega-\Omega)}$ ~0.07 & 0.17 the mean circular polarisation is negative. The polarisation curve shows a negative excursion lasting approximately half the spin cycle, while other spin phases the polarisation is close to zero. At $\phi_{(\omega-\Omega)}$=0.20 the polarisation is not significantly modulated. At other beat phases a prominent positive hump is seen in the folded spin polarisation curves, the peak of which advances in phase as $\phi_{(\omega-\Omega)}$ increases.

5 POLE-SWITCHING

In polars the accretion flow leaves the secondary star on an initially ballistic trajectory, couples onto the magnetic field of the white dwarf primary and is directed below and/or above the orbital plane before it is channeled onto the surface of the white dwarf. In fully synchronous polars, the accretion flow is locked with respect to the binary orbital rotation frame and the bulk of the accretion flow is thought to be directed onto the prefered magnetic pole of the white dwarf. However, in the case of near-synchronous polars, the accretion flow rotates around the magnetic field of the white dwarf on the timescale of the spin-orbit beat period. This has the effect that the accretion flow will be directed preferentially onto first one then the other magnetic pole of the white dwarf. At two phases of the spin-orbit beat period we expect that the flow will be equally directed onto both poles. This 'pole-switch' will manifest itself most obviously in the circular polarisation curves where the polarisation

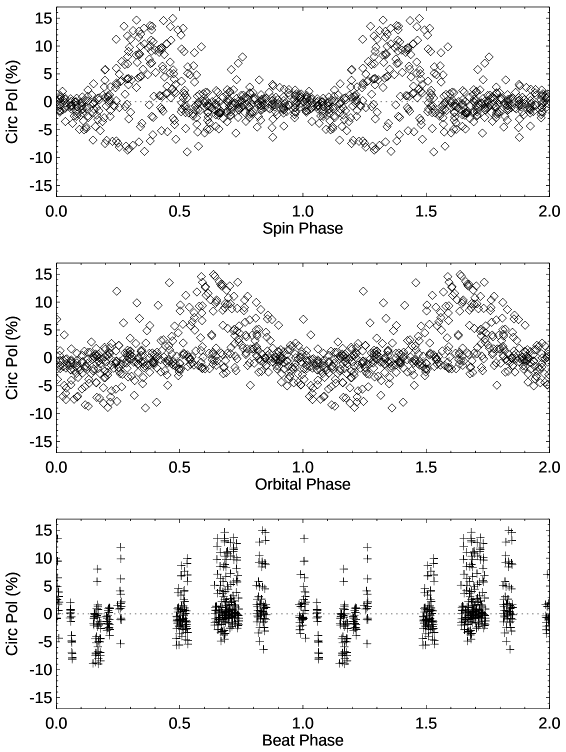

Figure 3. The circular polarisation folded on the spin period, 109.55 mins, (top panel); folded on the orbital period (middle panel), folded on the orbital-spin beat period, $\omega - \Omega = 6.28$ days. Phase zero was arbitrarily chosen to be HJD = 2450659.0.

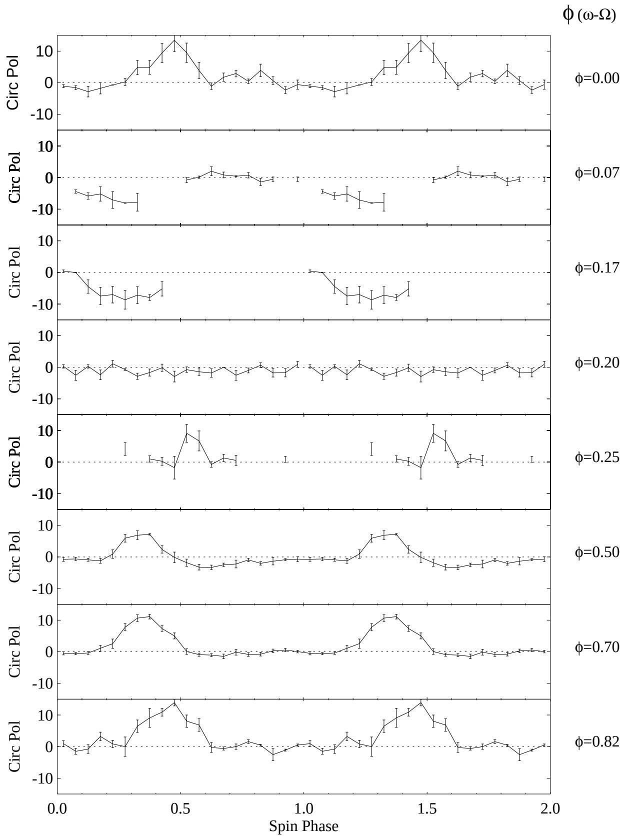

Figure 4. The circular polarisation data folded and binned on the proposed spin period of the white dwarf, 109.547 mins, as a function of the spin-orbital beat period of 6.28 days. The beat phase is shown at the right hand side.

will change sign after the accretion flow has 'switched' poles. This is seen in Fig. 4 where at $\phi_{(\omega-\Omega)}$ ~0.00 the polarisation is modulated with a positive hump, but at $\phi_{(\omega-\Omega)}$ ~0.07 and 0.17 it is modulated with a negative hump. Further, at $\phi_{(\omega-\Omega)}$ ~0.20, the accretion flow is directed equally towards both magnetic poles and the net polarisation is zero. We expect that between $\phi_{(\omega-\Omega)}$ ~0.00 and 0.07 the net polarisation will also be zero. In a system where the spin axis and the magnetic axes are both orthogonal to the binary plane then it is possible that the accretion flow will be directed equally onto both magnetic poles of the white dwarf and pole-switching will not occur.

To make an estimate of the angle that the spin axis makes with the magnetic axis (m) and the binary inclination (i) we examine the predicted power spectra of the more rapidly rotating analogues of the near-synchronous polars – the intermediate polars (those mCVs where typically $P_s = 0.1P_o$). A number of authors have predicted the power spectra of the light curves of IPs (Warner 1986, Wynn & King 1992 and Norton, Beardmore & Taylor 1996). The detection or non-detection and relative strength of the individual components in power spectra of IPs are dependent on a range of factors, for example whether the system is discless or is stream-fed, whether the accretion regions are directly opposite each other, i, m, the angle the accretion regions subtend (β) around co-latitude m and so on. It is more difficult to invert this process and obtain values for i, m etc, from the power spectra: we can, however, make some general remarks. Wynn & King (1992) show that for low i and low m (where $i+m < 90^\circ - \beta$ holds) only the spin-orbit frequency $\omega - \Omega$ and its even harmonics will be detected. This is clearly not the case in RX J2115–5840 and it is likely that this system has high i and high m and obeys the condition $i+m > 90^\circ + \beta$. We should caution that in polars there are less sites for reprocessing radiation compared to IPs since there is no accretion disc.

We now examine two possible accretion scenarios: one in which the accretion flow is directed onto one or other footprint of the same set of magnetic field lines at all spin-orbit beat phases and the other in which the flow is directed onto roughly diametrically opposite field lines at different beat phases (see Fig 5). In the first scenario we would expect the positive and negative circular polarisation humps in the spin folded circular polarisation data (the top panel of Fig. 3) to be seen at roughly similar spin phases. In the second scenario we would expect to observe positive and negative polarisation humps at distinct spin phases. The first scenario is consistent with Fig. 3.

We now consider the orbitally folded circular polarisation data. For the first scenario we would expect the positive circular polarisation hump to advance in phase as the white dwarf precesses. When the flow is directed onto the other pole, the negative circular polarisation hump will be roughly 180° out of phase with the positive polarisation hump. In contrast, the second scenario would give positive and negative humps at roughly the same orbital phase. Again the first scenario is consistent with Fig. 3.

It is clear that the scenario in which the accretion flow is directed onto roughly diametrically opposite points as we

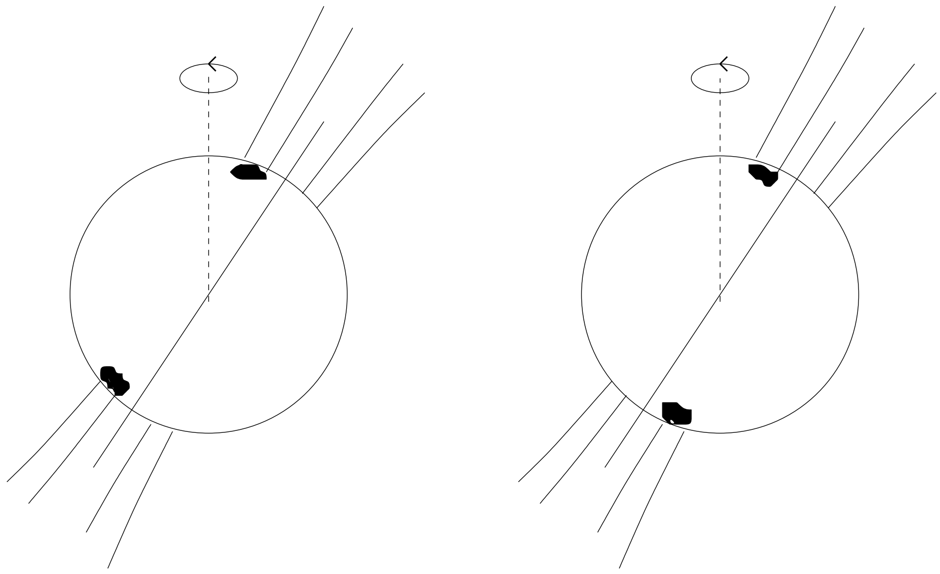

Figure 5. Our two accretion scenarios. In the left hand panel we show our first scenario in which the accretion flow is directed onto one or other footprint of the same set of magnetic field lines at all spin-orbit beat phases. The right hand panel shows our second scenario in which the flow is directed onto a diametrically opposite set of field lines at different beat phases. The spin axis of the white dwarf is shown as a dotted vertical line.

move in spin-orbit beat phase is not consistent with the circular polarisation data. Rather the data are consistent with the accretion flow being directed onto the same field line at all spin-orbit beat phases. This leads to the conclusion that at some spin-orbit beat phase the accretion flow must follow a path around the white dwarf to accrete onto the white dwarf rather than accrete onto the field lines in the most direct possible way. This may be possible if one magnetic pole was much stronger than the other: Schwope et al (1997) suggest that one pole is strong in the EUV while the other is stronger in hard X-rays which is consistent with this view. This would imply that there is large dipole offset or equivalently that the magnetic field is more complex than a dipole field. It is also possible that the magnetic field is distorted perhaps as a result of the accretion stream-magnetic field interaction.

As the accretion flow precesses around the white dwarf it will attach onto different magnetic field lines and the accretion region on the white dwarf will gradually shift, mainly in magnetic longitude, around the magnetic axis of the white dwarf (Geckeler & Staubert 1997). This manifests itself in the spin-folded data: the peak of the positive modulation advances in spin phase as we increase in beat phase (Fig. 4). However, since the peak of the positive and negative circular polarisation humps differ by only 0.2 spin cycles this implies that the upper and lower accretion regions are fixed to within $\sim 70°$ in magnetic longitude. More detailed modelling of the variations of the circular polarimetry will require additional data, preferably simultaneously with X-ray observations.

6 THE NEAR-SYNCHRONOUS POLARS

The near-synchronous polars provide the best opportunity to investigate the magnetic field structure of the white dwarf: we can see directly the effect of the orientation of the magnetic field on the way the accretion flow threads onto the field. This threading process, which is not well understood, determines most of the subsequent emission processes at the surface of the white dwarf in both X-rays and the optical. In the near-synchronous systems, if we can sample the spin-orbit beat period sufficiently, we are able (from modelling the polarisation) to determine the accretion structures at each orientation of the field, on a timescale in which other parameters such as the mass transfer rate do not change very significantly.

RX J2115–5840 is the fourth near-synchronous polar to be discovered. (We note that Mukai 1998 proposes an alternative model for V1432 Aql in which it is an intermediate polar with a spin period of ∼67 min and an orbital period of 202 min). The first three such systems (Table 2) had orbital periods which clustered closely around 200 mins giving rise to some speculation that such an orbital period was special in some way for these objects. The discovery of RX J2115–5840 with an orbital period of 110 mins suggests that it is not.

Of the four currently known near-synchronous polars, V 1432 Aql (RX 1940–10; Watson et al 1995, Friedrich et al 1996, Geckeler & Staubert 1997) and BY Cam (Silber et al 1997, Mason et al 1998) have beat periods of weeks which makes it difficult to obtain sufficient polarimetric coverage. V 1500 Cyg has a shorter beat period of 8 days – but the semi-amplitude of the circular polarisation is only 1.5% (Stockman, Schmidt & Lamb 1988). We now have a system, RX J2115–5840, which although relatively faint $V \sim$17–18

Star	P_s (mins)	P_o (mins)	$P_o - P_s/$ P_o	$P_s - P_o$ (days)
V1432 Aql	202.507	201.940	-0.28%	–49.5
BY Cam	199.330	201.258	0.96%	14.5
V 1500 Cyg	197.502	201.043	1.79%	7.8
RX J2115–58	109.547	110.889	1.21%	6.3

Table 2. The near-synchronous polars - the spin period of the white dwarf, (P_s), the orbital period, (P_o) and the spin-orbit beat period ($P_s - P_o$).

(a similar brightness to V 1500 Cyg), has a beat period which is short enough, 6.3 days, to obtain sufficient polarimetric coverage over the beat period. Such coverage will allow us to determine, in principle, the magnetic field structure of this system.

7 ACKNOWLEDGMENTS

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