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

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Accepted 1998 October 6. Received 1998 October 2; in original form 1998 May 20

ABSTRACT

Following the suggestion of Schwope et al. that the magnetic cataclysmic variable RX J2115–5840 may be 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 differ by 1.2 per cent. RX J2115–5840 is thus the fourth near-synchronous polar and has the shortest spin–orbit beat period: 6.3 d. 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 on to 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 on to the magnetic field of the white dwarf.

Key words: accretion, accretion discs – binaries: close – stars: individual: RX J2115–5840 – stars: magnetic fields – novae, cataclysmic variables – white dwarfs.

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. 1996). 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 polarization of up to 15 per cent, 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 ~1 per cent. They concluded that the spectroscopic period of 110.8 min represents the binary orbital period, while the photometric period of 109.84 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 h 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 South African Astronomical Observatory (SAAO) 1.9-m telescope and University of Cape Town (UCT) Polarimeter (Cropper 1985) between 1997 July 29 and 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 min and subtracted from the source measurements by a polynomial fit to the sky data. Polarized and non-polarized 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 were seen in some of the data sets. We recorded low levels (typically 3–4 per cent) of linear polarization. In this paper, however, we concentrate on the circular polarization data since the intensity data were compromised to some extent by non-photometric conditions on some nights. The circular polarizations are shown in Fig. 1. For most of the observation the circular polarization either is close to zero or shows positive excursions which follow the intensity curve at some epochs. However, there are occasions when negative circular polarization is seen (HJD 245 0000+ 659, 666 and 672). Similar behaviour was seen by Schwope et al. (1997), although they had circular polarization from short sections of data on only 3 days.
The frequency is prominent in the near-synchronous polar BY Cam: to an amplitude peak at 108.38 min in the DFT (this sideband frequency of the white dwarf, \( q \)) corresponding to a period of 6.28 d, is within the FWHM of the highest amplitude peak seen at the lowest frequencies (7.05 d). The next two highest frequencies in the DFT (1.19 and 0.88 d) are aliases of this spin–orbit beat frequency.

So far we can therefore account for the principal 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, \( 2\omega \), corresponds exactly with a prominent amplitude peak. The prominent peak at 3.0244 Hz (55.107 min) is the \( \omega + \Omega \) sideband frequency. We also detect the 3\( \omega \) harmonic and the 4\( \Omega - 3\omega \) sideband frequency.

To test our proposed values of \( P_\omega = 110.889 \) min and \( P_\Omega = 109.547 \) min, we pre-whitened the circular polarization data with these two frequencies (and their second and third harmonics), the \( 2\omega - \Omega \) sideband frequency (\( P = 108.38 \) min), the \( 4\Omega - 3\omega \) sideband frequency (\( P = 114.956 \) min) and the \( \omega - \Omega \) sideband frequencies (shown in the lower panel of Fig. 2). All frequencies that have an amplitude greater than 1 per cent 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 that 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 that coincide with a peak in the amplitude spectrum.

4 THE BEAT PERIOD

To make a more detailed investigation of the circular polarization 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 polarization 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 polarization is close to zero while there are phases of alternate positive and negative circular polarization.

To determine if these positive and negative excursions were observable on the 6.28-d spin–orbit beat period, we folded the circular polarization on this period. The bottom panel of Fig. 3 shows the folded data (phase zero was arbitrarily chosen to be 245 0659.0, the start of our observation). Although there is a good deal of variability owing to spin variations at shorter time-scales, the mean level of circular polarization is negative at \( \phi_{(\omega - \Omega)} \approx -0.07 \) and 0.17, while it increases at later phases.

To examine variations in the circular polarization data over the spin–orbit beat period, we folded and binned each section of data that corresponded to a discrete beat phase on the proposed spin period of the white dwarf – 109.547 min (Fig. 4). As expected from Fig. 3, at phases \( \phi_{(\omega - \Omega)} \approx -0.07 \) and 0.17 the mean circular polarization is negative. The polarization curve shows a negative excursion lasting approximately half the spin cycle, while at other spin phases the polarization is close to zero. At \( \phi_{(\omega - \Omega)} = 0.20 \) the polarization is not significantly modulated. At other beat phases a prominent positive hump is seen in the folded spin polarization 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 on to the magnetic field of the white dwarf primary, and is directed below and/or above the orbital plane before it is channelled on to 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 on to the preferred 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 time-scale of the spin–orbit beat period. This has the effect that the accretion flow will be directed preferentially on to 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 on to both poles. This ‘pole-switch’ will manifest itself most obviously in the circular polarization curves where the polarization will change sign after the accretion flow has ‘switched’ poles. This is seen in Fig. 4 where at $f_{\Omega-\Omega} \approx 0.00$ the polarization is modulated with a positive hump, but at $f_{\Omega-\Omega} \approx 0.07$ and 0.17 it is modulated with a negative hump. Further, at $f_{\Omega-\Omega} \approx 0.20$, the accretion flow is directed equally towards both magnetic poles and the net polarization is zero. We expect that between $f_{\Omega-\Omega} \approx 0.00$ and 0.07 the net polarization will also be zero. In a system where the spin axis and the magnetic axis are both orthogonal to the binary plane then it is possible that the accretion flow will be directed equally on to 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 (IPs) (those mCVs where typically $P_s \approx 0.1P_o$). A number of authors have predicted the power spectra of the light curves of IPs (Warner 1986; Wynn & King 1992; 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 that the accretion regions subtend ($\beta$) around colatitude $n$, and the relative strength of the $\Omega$- and $\omega$-components.

### Table 1

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Hz</th>
<th>Period (min)</th>
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<tbody>
<tr>
<td>$\Omega$</td>
<td>$1.502993 \times 10^{-4}$</td>
<td>110.889</td>
</tr>
<tr>
<td>$3\Omega$</td>
<td>$4.543406 \times 10^{-4}$</td>
<td>36.683</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$1.521423 \times 10^{-4}$</td>
<td>109.547</td>
</tr>
<tr>
<td>$2\omega$</td>
<td>$3.041679 \times 10^{-4}$</td>
<td>54.794</td>
</tr>
<tr>
<td>$3\omega$</td>
<td>$4.559762 \times 10^{-4}$</td>
<td>36.552</td>
</tr>
<tr>
<td>$\omega-\Omega$</td>
<td>$1.6276 \times 10^{-6}$</td>
<td>10238</td>
</tr>
<tr>
<td>$\omega+\Omega$</td>
<td>$3.022470 \times 10^{-4}$</td>
<td>55.143</td>
</tr>
<tr>
<td>$2\omega+\Omega$</td>
<td>$1.539853 \times 10^{-4}$</td>
<td>108.235</td>
</tr>
<tr>
<td>$4\Omega-3\omega$</td>
<td>$1.44825 \times 10^{-4}$</td>
<td>114.956</td>
</tr>
</tbody>
</table>
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 fewer sites for reprocessing radiation compared with IPs, since there is no accretion disc.

We now examine two possible accretion scenarios: one in which the accretion flow is directed on to 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 on to roughly diametrically opposite field lines at different beat phases (see Fig. 5). In the first scenario we would expect the positive and negative circular polarization humps in the spin-folded circular polarization 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 polarization humps at distinct spin phases. The first scenario is consistent with Fig. 3.

We now consider the orbitally folded circular polarization data. For the first scenario we would expect the positive circular polarization hump to advance in phase as the white dwarf precesses. When the flow is directed on to the other pole, the negative circular polarization hump will be roughly 180° out of phase with the positive polarization 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 on to roughly diametrically opposite points as we move in spin–orbit beat phase is not consistent with the circular polarization data. Rather, the data are consistent with the accretion flow being directed on to 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 on to the white dwarf rather than accrete on to the field lines in the most direct way possible. 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 on to 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 peaks of the positive and negative circular polarization humps differ by only 0.2 spin cycles, this implies that the upper and lower accretion regions are fixed to within $\sim 70^\circ$ 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 in which the accretion flow threads on to 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 polarization) to determine the accretion structures at each orientation of the field, on a time-scale on 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 that clustered closely around 200 min, 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 min suggests that it is not.

Of the four currently known near-synchronous polars, V1432 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 make it difficult to obtain sufficient polarimetric coverage. V1500 Cyg has a shorter beat period of 8 d – but the semi-amplitude of the circular polarization is only 1.5 per cent (Stockman, Schmidt & Lamb 1988). We now have a system, RX J2115–5840, which although relatively faint, V ~ 17–18 (a similar brightness to V1500 Cyg), has a beat period which is short enough, 6.3 d, 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.

ACKNOWLEDGMENTS

We thank the Director of SAAO, Dr R. Stobie, for the generous allocation of observing time, and we are grateful to Dr D. O’Donoghue for the use of his period analysis software.

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