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ROSAT observations of RX J1712.6 − 2414: a discless intermediate polar?

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ABSTRACT

We present *ROSAT* observations of the newly discovered polarized intermediate polar, RX J1712.6 − 2414. Whereas the polarimetry establishes the white dwarf spin period to be 927 s, we show that the X-ray variations occur at the 1003-s *synodic* (i.e., beat) period. This period is also sometimes seen in both the optical photometry and the radial velocities. New filtered polarimetry of RX J1712.6 − 2414 establishes a strong wavelength dependence in the circular polarization variations. We argue that these new observations support the contention that RX J1712.6 − 2414 is a discless accreting system, and the first clear case amongst the asynchronous intermediate polars.

Key words: accretion, accretion discs – stars: individual: RX J1712.6 − 2414 – stars: magnetic fields – novae, cataclysmic variables – white dwarfs – X-rays: stars.

1 INTRODUCTION

Intermediate polars (IPs), sometimes called DQ Herculis systems (see a recent review by Patterson 1994) are magnetic cataclysmic variables CVs, but unlike the other members of the magnetic subclass, i.e., the polars (e.g. Cropper 1990), the white dwarf's rotation is *not* orbitally synchronized. Spin and orbital periods typically differ by an order of magnitude. Early speculation that the longer period asynchronous IPs evolve into the shorter period synchronous polars, after loss of sufficient orbital angular momentum (e.g. Chanmugam & Ray 1984; King, Frank & Ritter 1985), has largely been contradicted observationally. It was proposed that IPs were the asynchronous analogues of the polars, and were predominantly discless systems because of their similar magnetic moments (Hameury, King & Lasota 1986). However, it appears that IPs have systematically lower magnetic field strengths than polars, which is evidenced by the presence of accretion discs and mostly null detections of polarization (e.g. Hellier 1991, 1992; Wickramasinghe, Wu & Ferrario 1991). The presence of strong magnetic fields in polars is manifested by the degree of circularly polarized optical and infrared emission (up to ~60 per cent; Hakala et al. 1994), and in many cases magnetic field strengths in the range 8–75 MG have been measured directly from either cyclotron lines or Zeeman features (e.g. Cropper 1990; Bailey 1995). In contrast, only three of the ~15 IPs (the exact numbers of IPs are somewhat dependent on the classification criteria adopted) have a measurable circular polarization (Cropper 1986; Penning, Schmidt & Liebert 1986; West, Berriman & Schmidt 1987; Stockman et al. 1992; Piirola, Hakala & Coyne 1993; Buckley et al. 1995). Such low polarizations must imply lower magnetic field strengths (Wickramasinghe et al. 1991), despite invoking dilution effects in an attempt to hide the polarization (Chanmugam & Ray 1984).

Strong evidence has also accumulated that IPs contain accretion discs, and the subsequent limits placed on the magnetospheric radii (e.g. Patterson 1994; Warner 1995) also imply that IPs have weaker magnetic fields. The evidence includes observations of eclipses, rotational disturbances and bright-spot s-waves (see Hellier 1991), all of which require the presence of a disc. Additional evidence for disced accretion comes from the apparent absence, or low amplitude, of X-ray periodicities corresponding to certain orbital sidebands (Hellier 1992). This contrasts with the predictions for discless accretion made by Wynn & King (1992) that there would be substantial power in X-ray light curves at the $\omega - \Omega$ and $2\omega - \Omega$ frequencies (where ω is the spin and Ω the orbital frequency respectively).

Observations therefore strongly support the notion that IPs accrete predominantly via a disc, and that they must have weaker magnetic fields than their relatives, the polars. Recent theoretical discussion also support this picture (e.g. King & Lasota 1991; Wickramasinghe et al. 1991).

In this paper we present results of a time-series analysis of *ROSAT* PSPC observations of RX J1712.6 − 2414. These results convincingly support the notion that RX J1712.6 − 2414 is a discless accretor, the first clear case amongst the asynchronous IPs. This suggestion was already made by Buckley et al. (1995) on the basis of optical polarimetric, photometric and spectroscopic evidence. Whereas the circular polarimetry varied at a period of 927 s, the photometric and radial velocity variations, when detectable, occurred at a longer period, at either 1003 or 1027 s (each a 1 cycle d^{-1} alias of the other). Buckley et al. concluded that the 927-s polarization period reflected the spin period of the white dwarf, whereas the other period corresponded to the synodic frequency (i.e., the $\omega - \Omega$ sideband). New polarization data, also presented here, show that, contrary to earlier suggestions, the circular polarization is wavelength-dependent, increasing in sign and amplitude to longer wavelengths. The implications for the discless model as applied to RX J1712.6 − 2414 are discussed.

2 X-RAY PERIODICITY

RX J1712.6 − 2414 was observed by the *ROSAT* satellite in 1991 July with the Position Sensitive Proportional Counter (PSPC). The total accumulated integration time was ~25 000 s, spanning ~1.5 d. The data were analysed using the PROS software package, and background-subtracted light curves were produced using circular and annular extraction apertures, centred on RX J1712.6 − 2414, for source and background respectively. The data were corrected for dead-time and vignetting effects. A time-series analysis of the resultant 0.5–2.0 keV X-ray light curves was then performed using both the discrete Fourier transform and phase-dispersion minimization techniques on unequally spaced data. The resulting periodograms both show a dominant periodicity at 1003.4 s, and at aliases (Fig. 1, middle panel) produced by the data-sampling window function, resulting from the ~90-min satellite orbit. This result unambiguously establishes that the X-ray variations are modulated at the synodic period, rather than at the spin period, which is detected only in the polarization variations (Fig. 1, top panel). The X-ray pulse fraction is ~40 per cent, as seen in the light curve folded on the 1003-s synodic period (Fig. 2). We performed a Fourier fit to these data, and derived an amplitude of 15.5 ± 1.2 per cent for the synodic period.

A frequency spectrum of the data pre-whitened by the synodic frequency reveals power close to the $\omega + \Omega$ sideband frequency, and its alises. No other significant peaks are detected in the power spectrum, either at the harmonics of

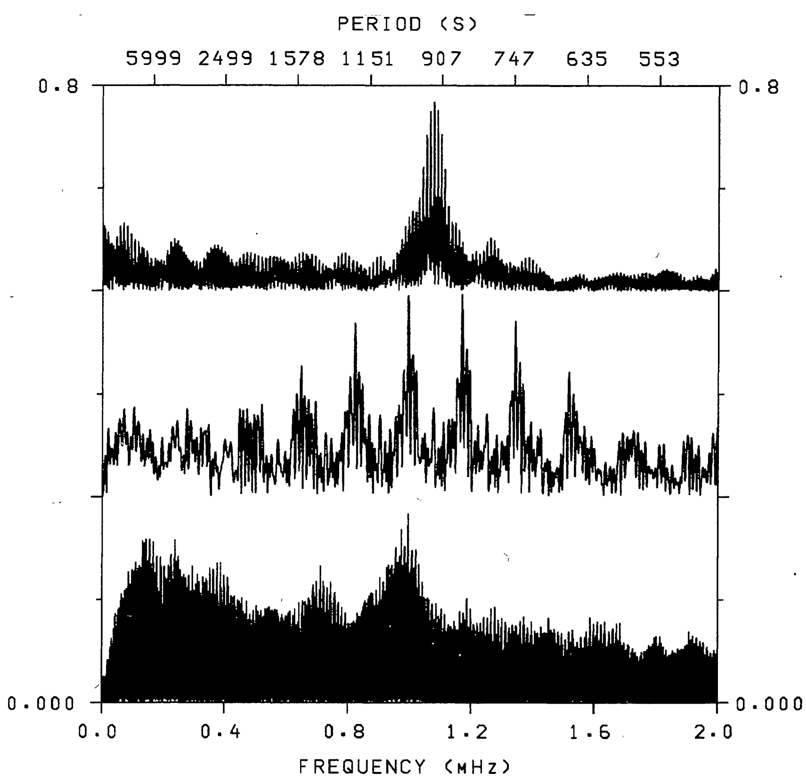

Figure 1. Comparison of DFT periodograms for RX J1712.6 − 2414: circular polarization (top), X-ray (middle), high-speed photometry (bottom). The polarization varies at the 927-s spin period, while X-ray and optical variations occur at the 1003-s synodic period.

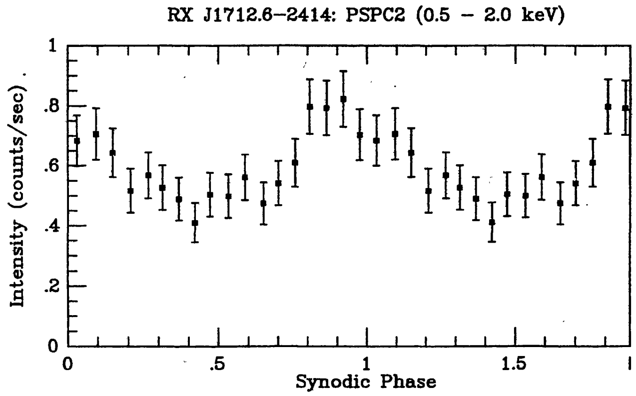

Figure 2. Phase-binned PSPC X-ray light curve at the 1003-s synodic period.

$\omega-\Omega$ or at the $2\omega-\Omega$ sideband frequency. A tantalizing peak is seen near the spin frequency (~ 1.1 mHz) in Fig. 1, but the folded light curve appears to be quite irregular. More significant, however, is the fact that pre-whitening failed to reveal the spin period conclusively, and we place an upper limit of ~ 4 per cent on its amplitude.

3 X-RAY SPECTRUM

Spectral models were fitted to the phase-binned *ROSAT* X-ray spectra, covering the region 0.1–2.4 keV, and corresponding to phase maximum and minimum of the 1003-s synodic period. All spectra were consistent with an unconstrained thermal bremsstrahlung of temperature $kT>3$ keV. The lower limit is a result of the relative insensitivity of the PSPC instrument to such high temperatures. The spectra and model fits at the maxima and minima of the 1003-s period are shown in Fig. 3. All models were consequently fixed in temperature ($kT=10$ keV), with the free parameters being the degree of absorption (N_H) and normalization factor. A summary of the spectral modelling results is presented in Table 1. The variations are consistent with a varying normalization, although there is marginal evidence for decreased absorption at flux maximum. These spectral properties are characteristic of all but three IPs, the exceptions being the so-called *ROSAT* 'soft IPs' (Haberl & Motch 1995; Motch & Haberl 1995; see also Section 5.1). Previous phase-resolved X-ray spectral studies (e.g. Norton & Watson 1989) have shown that these variations arise from an accretion region on the white dwarf subjected to a combination of varying observed emitting area and variable photoelectric absorption.

4 FILTERED POLARIMETRY

Previously reported polarimetry of RX J1712.6−2414 (Buckley et al. 1995) was mostly in photomultiplier-defined 'white light', with a few brief observations in *V*, *R* and *I*. Because of the wavelength-dependent nature of circular polarization, further filtered observations were obtained of RX J1712.6−2414 to investigate this aspect in more detail. These observations were conducted on 1996 May 14 to 18 using the UCT Polarimeter (Cropper 1985) on the SAAO 1.9-m telescope. The instrument was run in the usual Stokes mode, which delivered both linear and circular polarization measurements every 50 s. Simultaneous intensity data were obtained at a 10-s resolution. Sky-background measurements were taken every ~ 20–30 min. The observations we report here were obtained using two broad filters: a 'red' filter using 1.0 mm of Schott OG570 glass, and a 'blue' filter using 1.0 mm of BG38. Data taken with the red filter cover the wavelength region ~ 5600 to 9000 Å (effective wavelength ~ 7000 Å), while the blue filter covers ~ 3200 to 7000 Å (effective wavelength ~ 4700 Å).

Both sets of data were reduced in a similar manner, involving defining the zero-point offsets from observations of standard stars (HD 160529 and 147084), and background subtraction using spline interpolation. The circular polarization and intensity measurements were then subjected to a period anlaysis using a discrete Fourier transform. For both data sets we confirm the previous result (Buckley et al. 1995) that the polarization period is 927 s, and that no power is detected at the synodic, or any other sideband, frequency. This is also the case for the polarized fluxes, deduced from determining the product of the intensity and V/I values. Least-squares sinusoidal fits, which well describe the polarization variations (see Buckley et al. 1995), gave the following results for V/I: mean $= -2.82\pm0.04$ per cent (red), -0.90 ± 0.03 per cent (blue); amplitude $=0.82\pm0.06$ per cent (red), 0.42 ± 0.04 per cent (blue).

5 DISCUSSION

5.1 Discless accretion and 'soft' IPs

If the magnetic fields in IPs are sufficiently strong to prevent an accretion disc from forming, then direct accretion from the mass-transferring stream occurs (e.g. Hellier et al. 1989). There are observational consequences for this mode of accretion, the major one being that the X-rays should be modulated predominantly at the synodic frequency, $\omega-\Omega$ (e.g. Mason, Rosen & Hellier 1988; Hellier 1991; Wynn & King 1992), or even possibly at the $2\omega-\Omega$ sideband (Wynn & King 1992). Before the discovery, reported here, of synodic X-ray variability in RX J1712.6−2414, only one IP, TX Col, exhibited an X-ray synodic periodicity dominating (in hard X-rays at least) the spin modulation (Buckley & Tuohy 1989). Mason et al. (1988) first proposed that this object may be the first clear example of direct discless accretion. The situation, however, is not clear-cut. While there is evidence for synodic optical and X-ray periods in several IPs, it is also apparent that these same systems contain discs. It also appears that the sideband signatures are not necessarily stable features. For example, in FO Aqr, while the sideband period was detected in *Ginga* observations (Norton et al. 1992), it was not seen in earlier *EXOSAT* data (Hellier 1992). The reverse is the case for TX Col, where recent optical (Sullivan, Buckley & Thomas 1995) and hard X-ray (*ASCA*; Wheatley 1996) photometry revealed no sign of the synodic period.

The properties of some IPs have led to the suggestion of a 'hybrid' model, involving both disced and discless accretion (e.g. Hellier et al. 1989; Hellier 1993; Hellier, Garlick & Mason 1993). Such a model has a component of the accretion stream flowing above and below the disc, impacting it close to the inner radius, near the magnetosphere. This

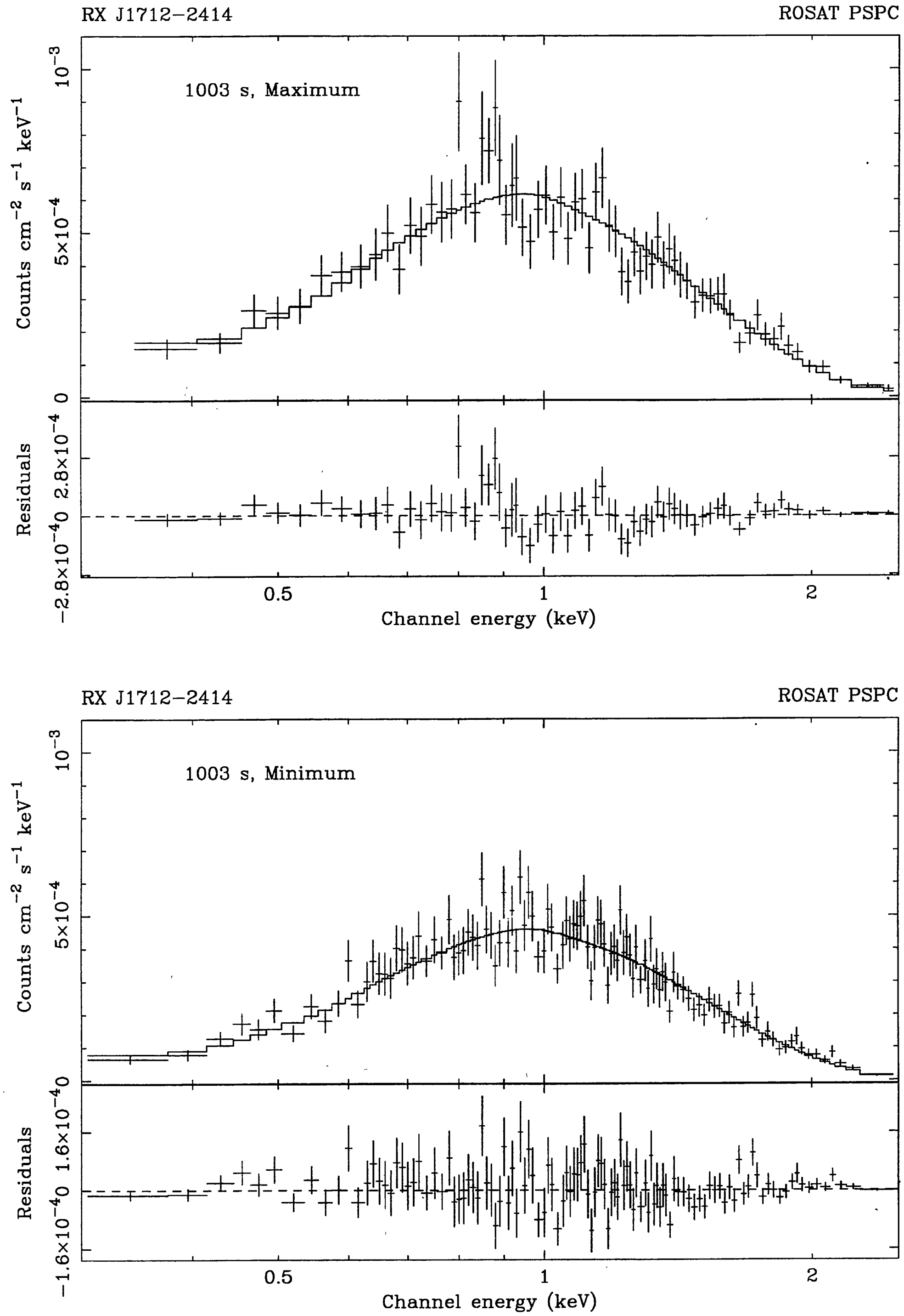

Figure 3. Thermal-bremsstrahlung model fits to the PSPC spectra of RX J1712.6 − 2414 at maximum and minimum of the 1003-s synodic period.

'stream overflow' model has been successful in explaining both the behaviour of the optical emission lines and the orbital modulation of the X-rays, as a result of photoabsorption by material in the stream and impact sites. Some non-magnetic CVs also show evidence for stream overflows; for example, the class of nova-like CVs called SW Sex stars (Thorstensen et al. 1991) are subject to peculiar line-absorption effects. These occur at orbital phases nearly $\sim 180°$ from the eclipse, and are clearly not associated with the conventional disc bright spot. The phasing and amplitude of the anomalously high-velocity s-waves are also consistent with stream–disc overflow.

The recent discovery from the *ROSAT* EUV and soft X-ray surveys of several IPs exhibiting properties not before observed in the class may mean that at last there are some true 'intermediate' polars: asynchronous systems with mag-

Table 1. Bremsstrahlung spectral fits to RX J1712.6 – 2414.

Phase[1]	kT (keV)	$N_H(10^{20}\ cm^{-2})$	Flux[2]	χ^2_r
Max:	10	4.4 (+1.4, -1.2)	1.08×10^{-11}	0.9
Min:	10	6.8 (+1.4, -1.1)	0.79×10^{-11}	1.1

[1]of the 1003-s synodic (beat) period.
[2]erg cm^{-2} s^{-1} in the 0.1–2.4 keV band.

netic field strengths similar to the polars. One of these properties is the presence of a true separate soft X-ray component (Haberl et al. 1994; Haberl & Motch 1995), akin to the 20–40 eV soft blackbody component so ubiquitous amongst the polars. It is interesting to note that Wickramasinghe et al. (1991) predicted that discless IPs would be strong EUV sources. It has yet to be demonstrated whether these new 'soft' IPs are candidates for discless accretion. In the case of RX J1712.6 – 2414, there is no indication of a separate 'soft' spectral component, and it seems that the X-ray spectrum is well described by a simple thermal-bremsstrahlung model.

The other hitherto rare observation for an IP is the detection of polarization, for which there are now two systems showing relatively strong (for an IP), spin-modulated, circular polarizations: PQ Gem (– 2.7 per cent; Piirola et al. 1993) and, the subject of this study, RX J1712.6 – 2414 (– 5.1 per cent; Buckley et al. 1995).

5.2 The X-ray behaviour

We have demonstrated that the X-ray variations in RX J1712.6 – 2414 occur at a period of 1003 s, which was previously seen in both the optical photometry (Fig. 1, bottom panel) and radial velocities (Buckley et al. 1995), although an alias at 1027 s could not be ruled out at the time. This period is demonstrably different from the 927-s polarization period (see Fig. 1, top panel), and we argue that it has to be the synodic period of the system. Intuitively, we expect that the rotation of the magnetic field of the white dwarf will be manifested in polarization variations at the same period. The 927-s polarization period must therefore correspond to the spin period. The alternative, that the 1003-s period is in fact the spin period, would require that the polarization varies at $\omega + \Omega$ sideband frequency, which is highly unlikely. In the optically thick regime for cyclotron emission, the magnetic field variation dominates the behaviour of the circular polarization (e.g. Wickramasinghe 1988). Therefore, even if the X-ray-producing shock is modulated at a *different* frequency (e.g., synodic), the polarization frequency will be determined by the rotation of the magnetic field itself, which is anchored to the white dwarf.

From the X-ray data we unambiguously identify the synodic period to be 1003.299 ± 0.003 s (the more precise value follows from the optical photometry of Buckley et al. 1995), while the 927.66 ± 0.41 s polarization period corresponds to the spin period. The orbital period of RX J1712.6 – 2414 must therefore be 3.42 ± 0.02 h.

RX J1712.6 – 2414 is the first IP for which the dominant X-ray periodicity occurs at the $\omega - \Omega$ synodic frequency. Indeed, we find it difficult to show that there is *any* power at the spin frequency (the spin amplitude is $\lesssim 4$ per cent). This is compelling evidence that RX J1712.6 – 2414 is a discless accretor, or at the very least that the bulk of the accretion is discless. This hypothesis is made stronger by the behaviour of the optical emission lines, and the radial velocity and photometric variations, all of which were very suggestive of discless accretion (Buckley et al. 1995). Indeed, a recent discless simulation study by Garlick (1996) confirms the essential features of the model for RX J1712.6 – 2414 developed by Buckley et al. The system has to be viewed nearly pole-on, and only one of the accreting poles is directly observed, although the line-emitting gas recently threaded by the magnetic field at the magnetosphere must be streaming towards both poles. Also, the dipole tilt angle has to be quite small so as to hide large velocity amplitude variations at the synodic period. The tilt is enough, however, to modulate the accretion on to the respective magnetic poles at the synodic period. The $\sim$30–40 per cent pulse fraction indicates that the pole we can see is always accreting some gas, which is expected for a modest tilt angle. Wickramasinghe et al. (1991) have postulated that asynchronous discless systems will accrete over a wide range of magnetic longitude, perhaps as high as $\Delta\psi \sim 360°$. This implies a fractional area possibly as high as $f \sim 0.01$. The lack of an X-ray spin modulation in RX J1712.6 – 2414 could therefore be a consequence of the low inclination, where this extended accretion region on the white dwarfs surface, or most of it, is always in view.

The strong, energy-independent, X-ray modulation at the synodic period is a result of the modulation of the accretion rate on to the magnetic pole that we see (the other is always hidden). Over one synodic cycle, 30–40 per cent of the accreting material is directed more to one pole than the other. This is because the magnetosphere acts as a 'gate', through which some of the material from the accretion stream is preferentially directed to the nearer magnetic pole.

5.3 The polarization behaviour and magnetic field

We now discuss the nature of the polarization variations. Contrary to earlier conclusions (Buckley et al. 1995) based on 'white light' and some limited filtered observations, there does appear to be a significant increase of the polarization towards longer wavelengths. The discrepancy was probably due to some overly simplified assumptions regarding the effective wavelength of the white-light polarimetry, which cannot be treated in such a manner. While a full analysis of the filtered polarimetry, and more recently obtained spectropolarimetry, is beyond the scope of this paper, it importantly confirms the expected nature of IP polarization. The increasing polarization redwards is similar to BG CMi (West et al. 1987) and PQ Gem (Piirola et al. 1993).

If RX J1712.6 – 2414 is indeed a discless accretor, we can use the following formulation for the limit on the magnetic moment (Wickramasinghe et al. 1991; Warner 1995), namely

$$\mu_{33} > 0.3[P_{\rm orb}({\rm h})]^{7/6}[M_1({\rm M}_\odot)]^{5/6}(\dot{M}_{17})^{1/2}. \quad (1)$$

This is derived from the condition that disc formation is prevented when the distance at which the accretion stream couples to the magnetic field is greater than the circularization radius (e.g. Warner 1995). The ratio of $r_{\min}$ (the minimum distance at which the ballistic accretion stream approaches the white dwarf) to r_{L1} (the mean white dwarf Roche lobe radius) normally enters the equation. However, this ratio is determined by the mass ratio, $q(=M_2/M_1)$, and we have simply adopted the condition that $q<1$. From equation (1) we derive $\mu_{33}\gtrsim 1.3$ G cm^3 for an orbital period of 3.4 h, a white dwarf mass of 1.0 $M_\odot$ and an accretion rate of $\dot{M}_{17}=1$, which is typical for an IP above the period gap (Warner 1995). In this case the magnetic field needs to be stronger than 7.8 MG for a disc not to form. This limit is weakened if either the mass or mass-transfer rate is less than these adopted values. Our measured polarized fluxes imply that the field strength is probably in excess of 8 MG (Buckley et al. 1995), although Väth (1997) finds from his modelling that field strengths in the region 9 to 27 MG are required for likely ranges of M_1 and $\dot{M}$. These values are all consistent with the notion of a discless system.

We can also place an upper limit on the magnetic field from the condition of asynchronism (e.g. Patterson 1994),

$$B_6 < 2.15(M_1)^{3.1}[P_{\rm orb}({\rm h})]^{2.8}. \qquad (2)$$

For the same mass (1.0 $M_\odot$) and period, we derive an upper limit of ~ 66 MG for the system to be asynchronous. However, lower fields could also synchronize the system if $\dot{M}$ were significantly lower than that determined from the empirical relation. Recently, Buckley & Shafter (1995) were forced to make this very conclusion for the synchronized, extremely long-period polar ($P_{\rm orb}=8$ h) RX J0515.6+0105.

We conclude from the above arguments that a discless accretion scenario is also supported on theoretical grounds, when consideration is made of the limits imposed by both the asynchronism condition and the relatively weak field required for a disc to be present. The observed circular polarization is in direct conflict with such a low-field scenario. The lack of a detectable X-ray spin pulse supports the discless hypothesis, although the windowing of the frequency spectrum makes it difficult to detect. It is still possible that a weak, spin-modulated component to the X-ray power spectrum is present, beyond our detection threshold. Such a component could arise from a residual disc, or an associated azimuthally symmetry structure (e.g. Hameury et al. 1986). Although we cannot rule these out, the fact remains that the power in the synodic phase is $\gtrsim 14\times$ the spin power (from the upper limit). This must imply that the bulk of the accretion is proceeding directly on to the magnetosphere, rather than passing through an azimuthally symmetric structure (e.g., a disc), which removes all knowledge of the orbital phase of the accreting material.

6 CONCLUSION

We have shown from a *ROSAT* observation of RX J1712.6−2414 that the dominant soft X-ray modulation occurs at the synodic period, and not the spin period as in all other IPs. This is strong evidence for discless accretion, or at least that the major component of the accretion is via direct injection into the magnetosphere. Although we do not detect a spin modulation, the ~ 4 per cent limit placed on its amplitude does not rule out the possibility of its existence. The spectral variation is consistent with a fixed temperature and absorbing column, and a varying normalization. Such an energy-independent variation could arise from varying the accretion rate on to the magnetic poles. This 'accretion gating', is consistent with a discless accretion scenario. New filtered polarization observations show a strong dependence of the circular polarization as a function of wavelength, doubling in amplitude from 4700 to 7000 Å. This is the same behaviour as that seen in the other two polarized IPs, BG CMi and PQ Gem. Attempts at modelling the polarized fluxes with cyclotron models have so far resulted in field strengths in excess of 8 MG. Such values are entirely consistent with the condition for discless accretion, provided that the following limits apply: $q<1$, $M_1<1.0\,M_\odot$ and/or $\dot{M}_{17}<1$.

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