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YY Draconis and V709 Cassiopeiae: two intermediate polars with weak magnetic fields

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Abstract. We present data from long *ROSAT* HRI observations of the intermediate polars YY Dra and V709 Cas which show that V709 Cas, like YY Dra, exhibits a double-peaked X-ray pulse profile. Neither system shows evidence for X-ray beat period or orbital modulation, so both must be disc-fed accretors seen at low inclination angles. We argue that the short spin periods of the white dwarfs in these objects indicate that they have weak magnetic fields, so the radius at which material is captured by the field lines is relatively small. Consequently the footprints of the disc-fed accretion curtains on the white dwarf surface are large. The optical depths to X-ray emission within the accretion curtains are therefore lowest in the direction along the magnetic field lines, and highest in the direction parallel to the white dwarf surface, such that the emission from the two poles conspires to produce double-peaked X-ray pulse profiles. We emphasise that such a pulse profile is *not* a unique indicator of two-pole accretion however. Indeed, two-pole accretion onto smaller regions of the white dwarf surface may be considered the 'normal' mode of behaviour in a disc-fed intermediate polar with a longer white dwarf spin period (and therefore a higher field strength), resulting in a single-peaked pulse profile.

Collating data on other intermediate polars, we may classify them into two subsets. Fast rotators, with relatively weak fields, show double-peaked pulse profiles (AE Aqr, DQ Her, XY Ari, GK Per, V709 Cas, YY Dra, V405 Aur), whilst slower rotators, with larger fields and therefore larger magnetospheres, have been seen to exhibit an X-ray beat period modulation at some time (FO Aqr, TX Col, BG CMi, AO Psc, V1223 Sgr, RX J1712.6–2414).

Key words: stars: individual: V709 Cas – stars: individual: YY Dra – stars: magnetic fields – stars: novae, cataclysmic variables – X-rays: stars

1. Introduction

Intermediate polars are semi-detached interacting binaries in which a magnetic white dwarf accretes material from a Roche-lobe filling, usually late-type, main sequence companion star. The accretion flow from the secondary proceeds towards the white dwarf either through an accretion disc, an accretion stream, or some combination of both (known as disc overflow accretion), until it reaches the magnetospheric radius. Here the material attaches to the magnetic field lines and follows them towards the magnetic poles of the white dwarf. The infalling material that originates from an accretion disc takes the form of arc-shaped accretion curtains, standing above the white dwarf surface. At some distance from this surface, the accretion flow undergoes a strong shock, below which material settles onto the white dwarf, releasing X-rays as it cools by thermal bremsstrahlung processes. Since the magnetic axis is offset from the spin axis of the white dwarf, this gives rise to the defining characteristic of the class, namely X-ray emission pulsed at the white dwarf spin period. If any of the material accretes directly from an accretion stream, the proportion falling onto each pole of the white dwarf will vary according to the rotation phase of the white dwarf in the reference frame of the binary. Consequently, stream-fed (or disc overflow) accretion will give rise to X-ray emission that varies with the beat period, where $1/P_{\rm beat} = 1/P_{\rm spin} - 1/P_{\rm orbit}$. About twenty confirmed intermediate polars are now recognized with a similar number of candidate systems having been proposed. Comprehensive reviews of various aspects of their behaviour are given by Patterson (1994), Warner (1995), Hellier (1995; 1996) and Norton (1995).

2. Observational histories

2.1. YY Draconis

The 16th magnitude star YY Dra was discovered in 1934 and originally mis-classified as an Algol-like system. Detected as an X-ray source by *Ariel V* (3A 1148+719) and *Einstein* (2E 1140.7+7158), it was subsequently reclassified as a cataclysmic variable (see the discussions in Patterson et al. 1992 and Patterson & Szkody 1993 for the history of this source). Optical radial velocity observations by Friend et al. (1988) revealed its orbital period as 3.97 hr, whilst time resolved infrared spectroscopy by Mateo et al. (1991) yielded estimates of other system parameters. The intermediate polar nature of YY Dra was eventually recognised by Patterson et al. (1992), who discovered optical photometric modulation at periods of about 265 s and 275 s. Indications of sub-harmonics at periods of 529 s and

550 s suggested that the spin period of the white dwarf might actually be 529 s, and that 550 s was the beat period between the orbital and spin periods (ie. the spin period of the white dwarf in the binary reference frame). The dominant signals at the shorter periods indicated that the pulse profile is ‘double-peaked’.

A series of short X-ray observations of YY Dra with the *ROSAT* PSPC and HRI (Patterson & Szkody 1993; Beuermann & Thomas 1993; Reinsch et al. 1995) confirmed the earlier findings and revealed the following periods: 529.2 s (1990, PSPC all sky survey); 265 s (1991, PSPC); 264 s (1992, HRI); 264.6 s and 530.9 s (1993, PSPC). These authors concluded that the true spin period of the white dwarf was around 530 s, that the presence of a dominant signal at half this period indicates that the system usually accretes onto both poles of the white dwarf, and that the emission sites are nearly identical.

Subsequent Hubble Space Telescope spectroscopy of YY Dra (Haswell et al. 1997) established a more accurate white dwarf spin period of 529.31 s, by combining their detection of UV pulsations at a period of 264.71 s with the previous detections referred to above. A beat period of 273 s was also detected and attributed to reprocessing of the X-ray pulse in a structure fixed in the orbital frame. Haswell et al. determined a precise orbital period of 3.968976 hr and calculated the system parameters, including an inclination angle of 45°.

2.2. V709 Cassiopeiae

This source was recognised as an intermediate polar by Haberl & Motch (1995), following its detection in the *ROSAT* All Sky Survey as RX J0028.8+5917. A follow up 18 ksec pointed observation with the *ROSAT* PSPC revealed a pulse period of 312.8 s and a conventional ‘hard’ intermediate polar X-ray spectrum. Motch et al. (1996) subsequently noted that RX J0028.8+5917 was probably coincident with previously catalogued sources detected by *HEAO-1* (1H 0025+588), *Uhuru* (4U 0027+59) and *Ariel V* (3A 0026+593), and identified the X-ray source with a 14th magnitude blue star, V709 Cas. The optical spectra of this star show radial velocity variations with periods of either 5.4 h or 4.45 h, the two being one day aliases of each other (Motch et al. 1996). One of these periods is assumed to be the orbital period of the system.

3. *ROSAT* HRI observations and results

3.1. YY Draconis

Here we report details of the longest X-ray observation yet of YY Dra. It was made with the *ROSAT* High Resolution Imager (Zombeck et al. 1995) and comprises 56.6 ksec on source between 1996 May 22 23:54 UT and 1996 May 25 06:27 UT. A lightcurve at 10 s time resolution was constructed by using the Starlink *Asterix* software (Allen & Vallance 1995) to optimally extract data from a region 0.68 arc min in radius, centred on the source. Background subtraction was carried out using the data from a nearby region of sky, and the resulting lightcurve is shown in Fig. 1 at a lower time resolution. The lightcurve is broken-up by the 90 minute satellite orbit and has a mean count rate of 0.40 c s^{-1}.

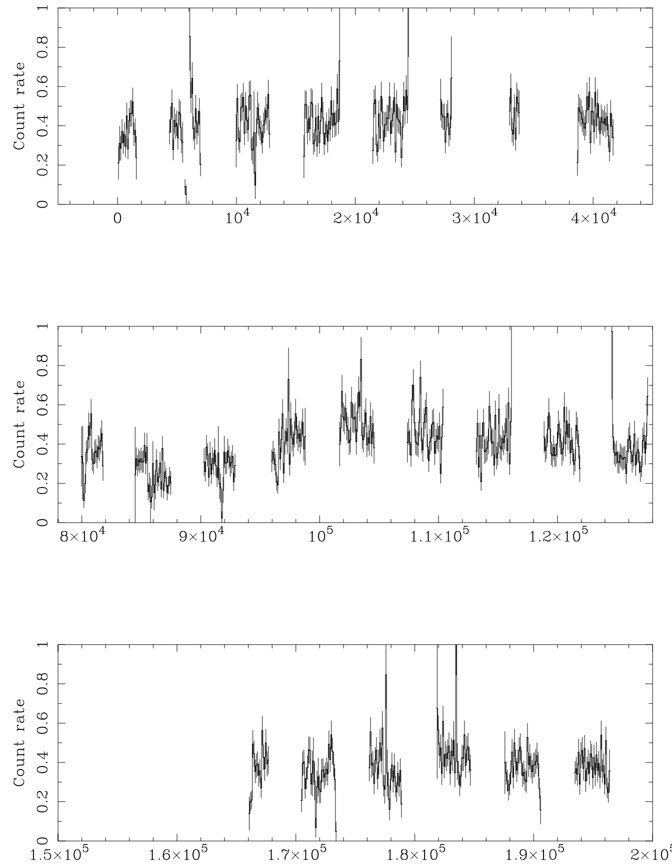

Fig. 1. The *ROSAT* HRI lightcurve of YY Dra at a time resolution of 100 s. There are no data in the time intervals between those illustrated in each panel.

To analyse the lightcurve we used the 1-dimensional CLEAN algorithm in the implementation of H.J. Lehto. This is particularly suited to time series which are irregularly sampled and in which multiple periodicities may be present. Fig. 2 shows the resulting raw power spectrum, window function, and CLEANed power spectrum. The only significant signal detected is at a frequency corresponding to a period of (264.7 ± 0.1) s, and may be identified with the first harmonic of the white dwarf spin frequency described earlier. Other spikes in the power spectrum, at a level of 10^{-4} c^2 s^{-2} or lower, do not correspond to any known system period, or combination of periods, and are presumed to be due to noise. The power at the first harmonic of the spin frequency is 3.9×10^{-4} c^2 s^{-2} which corresponds to an amplitude of 0.040 c s^{-1}. (Nb. The amplitude is equal to twice the square root of the CLEANed power.) The modulation therefore has a fractional amplitude of 10%.

We note that no significant power is detected at either the orbital period or the beat period of the system, or at any harmonics and sidebands of either of their corresponding frequencies, in these data. In particular, the two peaks with power of $\sim 10^{-4}$ c^2 s^{-2} at frequencies of about 2×10^{-4} Hz (Fig. 2) are *not* coincident with any harmonics of the orbital frequency;

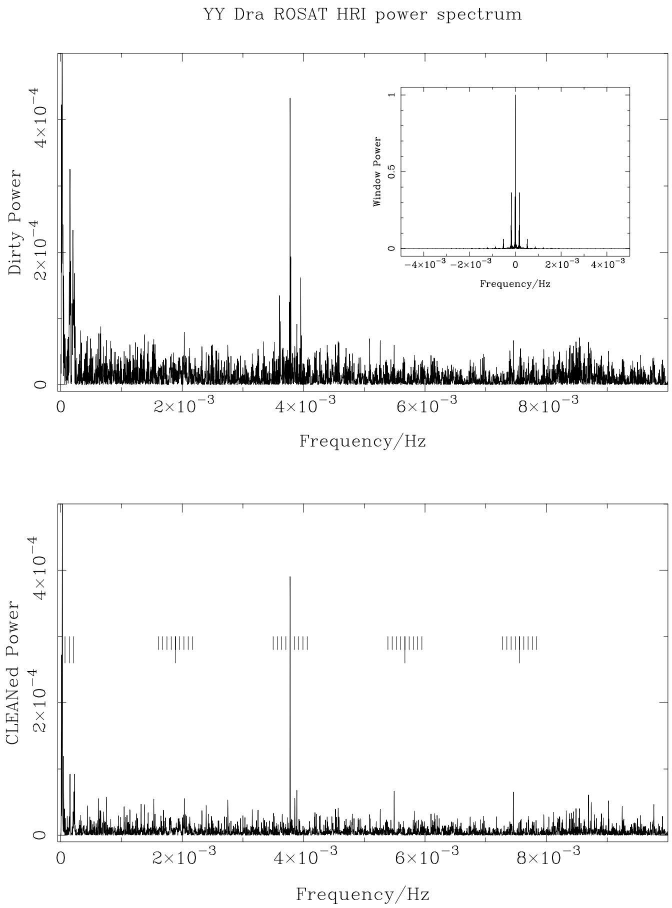

Fig. 2. The power spectrum of the *ROSAT* HRI lightcurve of YY Dra. The upper panel shows the raw power spectrum with the window function inset. The lower panel shows the CLEANed power spectrum. Tick marks show the expected locations of the orbital and spin frequencies, along with some of their sidebands and harmonics.

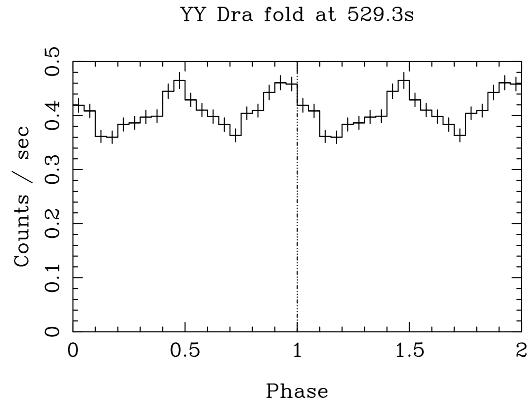

Fig. 3. The *ROSAT* HRI lightcurve of YY Dra folded at a period of 529.3 s. Phase zero is arbitrary, and the profile is shown repeated over two cycles.

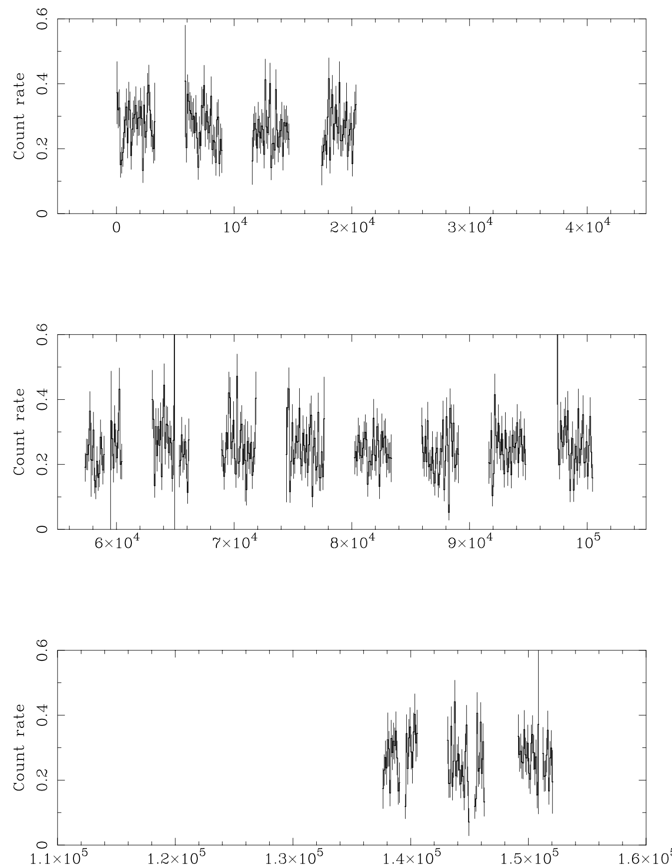

Fig. 4. The *ROSAT* HRI lightcurve of V709 Cas at a time resolution of 100 s. There are no data in the time intervals between those illustrated in each panel.

nor is the broad dip in the lightcurve around 9×10^4 s (Fig. 1) believed to be related to any orbital phenomenon.

The limit on the power at the actual spin period of YY Dra (529.3 s) is $< 10^{-5}$ c^2 s^{-2}, corresponding to a limiting amplitude in the light curve of < 0.006 c s^{-1}, and a limiting fractional amplitude of less than 1.5%. However, given the abundance of 'noise' peaks with power of the order of 5×10^{-5} c^2 s^{-2}, a more realistic estimate of the limiting fractional amplitude is around 3.5%. The data folded at the white dwarf spin period are shown in Fig. 3. From this, it is clear that the pulse profile can be described as 'double-peaked' with two similar peaks per cycle separated by about 0.5 in phase. Since the power at this period is clearly very small, it is not surprising that the difference between the two peaks is negligible.

3.2. V709 Cassiopeiae

As with YY Dra, we report details of the longest X-ray observation yet of V709 Cas, made with the *ROSAT* HRI. The observation comprises 43.3 ksec on source between 1998 Feb 15 14:31 UT and 1998 Feb 17 08:45 UT. Again using the Starlink *Asterix* software, data were optimally extracted from a region 0.65 arc min in radius, centred on the source, in order to construct a time series at 10 s resolution. Background subtraction was carried out using the data from an adjacent region of blank sky and the resulting light-curve, shown in Fig. 4 at a lower time resolution, has a mean count rate of 0.26 c s^{-1}.

As above, we used the 1-dimensional CLEAN algorithm to analyse the light-curve and Fig. 5 shows the results. We detect signals at frequencies corresponding to the previously identified spin period and its first and second harmonics. Using the accurately determined frequency of the second harmonic we calculate a more precise value for the spin period than previously measured, namely (312.78 ± 0.03) s. The power at the fundamental frequency is 8.8×10^{-4} c^2 s^{-2} which corresponds to an amplitude of 0.059 c s^{-1}. The modulation therefore has a fractional amplitude of 23% and the data folded at a period of 312.78 s are shown in Fig. 6.

As with YY Dra, we note that no significant power is detected at either the orbital period (whether 5.4 hr or 4.45 hr) or the beat period of the system, or at any harmonics and sidebands of the frequencies corresponding to either period. The limit to the power at any other period is of the order of 10^{-5} c^2 s^{-2}, corresponding to a limiting fractional amplitude of about 2.5%.

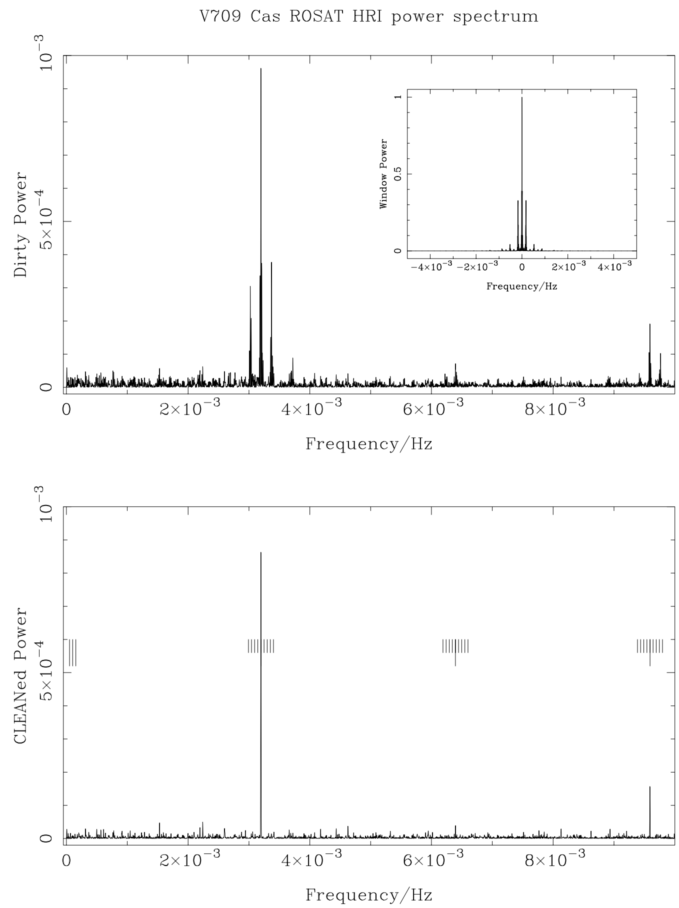

Fig. 5. The power spectrum of the *ROSAT* HRI lightcurve of V709 Cas. The upper panel shows the raw power spectrum with the window function inset. The lower panel shows the CLEANed power spectrum. Tick marks show the expected locations of the spin and orbital frequencies (assuming an orbital period of 5.4 hr), along with some of their sidebands and harmonics.

4. Discussion

4.1. Similarities and differences

The results from these X-ray observations of YY Dra and V709 Cas are clearly very similar. Both systems show a single, relatively short pulse period, at 264.7 s and at 312.78 s respectively, and neither system shows any evidence for orbital or beat period modulations. The absence of an orbital modulation in YY Dra is not surprising, given the relatively low inclination of the system, and suggests that our view of the white dwarf is not obscured by material located elsewhere in the binary system. The similar absence of orbital modulation in V709 Cas suggests that the inclination angle of this system too is quite low. The absence of a signal in the X-ray power spectrum at the beat frequency (or any related sideband frequency) of either system implies that both YY Dra and V709 Cas must accrete predominantly via a disc rather than directly from a stream (Mason et al. 1988; Hellier 1991; Wynn & King 1992; Norton 1993). Consequently the accreting material has lost all knowledge of the orbital phase by the time it impacts the white dwarf.

The similarities in pulsation behaviour between the two systems are rather more subtle. The spin period of the white dwarf in YY Dra is believed to be *twice* the period observed in its power spectrum, and so the resulting spin pulse profile is double-peaked with two similar maxima (Fig. 3). Conversely there is no evidence to suggest that the spin period of the white dwarf in V709 Cas is anything other than the dominant period seen in its power spectrum. Nonetheless we would argue that the pulse profile of V709 Cas (Fig. 6) is also ‘double-peaked’. The only difference between it and the pulse profile of YY Dra is that the two maxima in the case of V709 Cas are separated by only about one-third of the pulse cycle, rather than half the pulse cycle in the case of YY Dra. The secondary minimum in the V709 Cas pulse profile is therefore ‘filled-in’ somewhat by the proximity of the two peaks. So, whilst the power spectrum of YY Dra is dominated by the first harmonic of the spin frequency (ie. $2/P_{\rm spin}$), that of V709 Cas is dominated by the fundamental and the second harmonic (ie. $1/P_{\rm spin}$ and $3/P_{\rm spin}$).

4.2. Double-peaked pulse profiles as an indicator of a weak magnetic field

When compared with many other intermediate polars, the ‘unusual’ feature of both YY Dra and V709 Cas is that they display double-peaked pulse profiles. Amongst the rest, the only other intermediate polars that have shown similar behaviour are AE Aqr, DQ Her, V405 Aur, GK Per and XY Ari (the latter two only have double peaked pulse profiles in quiescence and change to single-peaked pulse profiles during outburst). What these systems have in common is that they all have relatively short white dwarf spin periods. As noted above, the periods of YY Dra and V709 Cas are about 529 s and 313 s, whilst those of the other five systems listed are about 33 s, 142 s, 545 s, 351 s and 206 s respectively. All other confirmed intermediate polars have white dwarf spin periods in excess of 700 s.

It is believed that most intermediate polars exist in a state of equilibrium rotation (eg. Warner 1996), that is to say the accretion disc is disrupted at the radius where the Keplerian period of the disc is equal to the rotation period of the white dwarf. Now, if this is the case, then a short spin period implies that the white

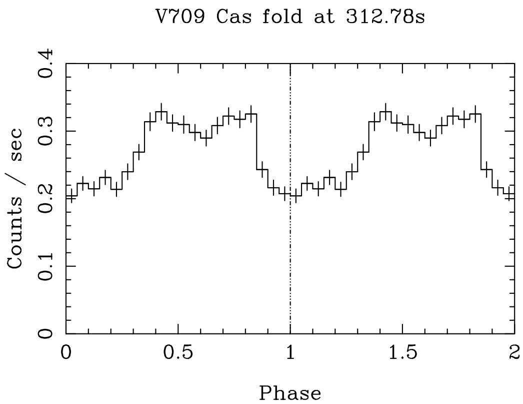

Fig. 6. The *ROSAT* HRI lightcurve of V709 Cas folded at a period of 312.78 s. Phase zero is arbitrary and the profile is shown repeated over two cycles.

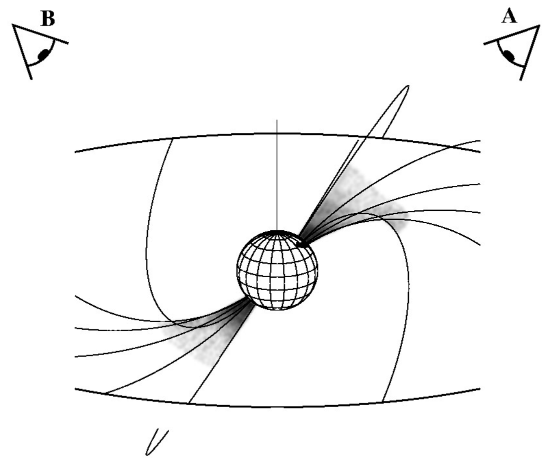

Fig. 7. Schematic diagram showing an intermediate polar with a relatively high magnetic field. Attenuation of the X-rays is greatest along the magnetic field lines (up the accretion curtains), and least parallel to the white dwarf surface (across the accretion curtains). When viewed from B, X-ray pulse maximum is seen, and when viewed from A, X-ray pulse minimum is seen.

dwarf has a weak magnetic field. In fact, the magnetic moment of the white dwarf is proportional $P_{\rm spin}^{7/6}$ and it has been calculated that YY Dra, V405 Aur and XY Ari each have magnetic moments of about 10^{32} G cm^3, for example (Warner 1996). So, as pointed out by Hellier (1996) and Allan et al. (1996), the implication is that a short white dwarf spin period, and hence a weak magnetic field, is what determines the presence of a double-peaked pulse profile.

The common interpretation of a double-peaked spin pulse profile is to say that the system is undergoing two-pole accretion, and this is indeed the interpretation previously placed on YY Dra (eg. Patterson & Szkody 1993). However, this is a simplistic interpretation since a double-peaked pulse profile *is not* a unique indicator of two-pole accretion. If it were then it would imply that single-peaked pulse profiles are the result of one-pole accretion. Whilst this is probably true in the phase-locked polar systems which undergo stream-fed accretion, it is unlikely to occur in a disc-fed intermediate polar system. In this case material from the inner edge of the disc is as likely to be channelled to one pole as the other, and two-pole accretion is the normal way in which such a system will accrete. As pointed out by Hellier (1996) and Allan et al. (1996), two-pole disc-fed accretion *does not* generally produce a double-peaked pulse profile, although it can in some circumstances. Indeed, two-pole disc-fed accretion is believed to be the 'normal' mode of behaviour in intermediate polars, yet both single-peaked and double-peaked pulse profiles are seen. It is important that the paradigm which states 'single-peaked profile equals one-pole accretion; double-peaked profile equals two-pole accretion' is put to rest for intermediate polars. We describe below how both types of pulse profile can be produced by two-pole disc-fed accretion, depending on the strength of the magnetic field.

4.3. Two-pole disc-fed accretion producing a single-peaked pulse profile

Many intermediate polars, such as the canonical system AO Psc (Hellier et al. 1991), show a single-peaked pulse profile resulting from two-pole disc-fed accretion. With a relatively strong magnetic field, the accreting material attaches to the field lines whilst still quite distant from the white dwarf, as shown in Fig. 7. This results in relatively small emission regions, whose 'vertical optical depth' (up the accretion curtain, along the magnetic field lines) is greater than their 'horizontal optical depth' (across the accretion curtain, parallel to the white dwarf surface). So in this case minimum attenuation of the X-ray flux (minimum photoelectric absorption and electron scattering) occurs when the emission region is seen from the side. Hence, when the 'upper pole' (ie. the one in the hemisphere of the white dwarf above the orbital plane as we observe it) points away from the observer, then pulse maximum is seen (Fig. 7 viewpoint B), and when it points towards the observer, pulse minimum is seen (Fig. 7 viewpoint A). The contribution to the modulation from the lower pole is *in phase* with that from the upper pole, since when the upper pole is pointing towards the observer, the lower pole will generally be occulted. Conversely, when the upper pole is pointing away from the observer, the lower pole is viewed essentially from the side too, and so its flux adds to the pulse giving a maximum.

Single-peaked, roughly sinusoidal, pulse-profiles are seen in many intermediate polars, and so two-pole disc-fed accretion can be considered as the 'normal' mode of behaviour in these systems.

4.4. Two-pole disc-fed accretion producing a double-peaked pulse profile

In contrast to the above, Hellier (1996) and Allan et al. (1996) suggest that a double-peaked pulse profile can result if the vertical optical depth (up the accretion curtain) is *lower* than the horizontal optical depth (across it). As they point out, if the white dwarfs in systems showing a double-peaked pulse profile

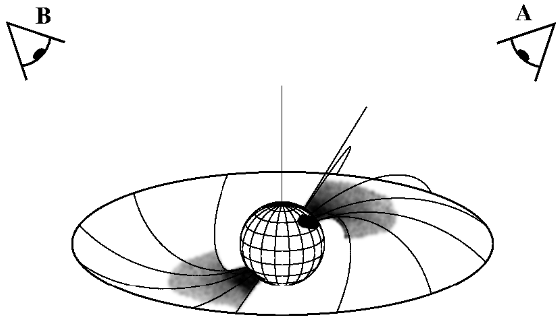

Fig. 8. Schematic diagram showing an intermediate polar with a relatively low magnetic field. Attenuation of the X-rays is greatest parallel to the white dwarf surface (across the accretion curtains), and least along the magnetic field lines (up the accretion curtains). X-ray pulse maxima are seen when the system is viewed from both A and B.

have a relatively weak magnetic field, then material threads onto the field lines much closer to the white dwarf, and the accretion area is relatively large, as shown in Fig. 8. With a large enough footprint to the accretion curtain, this optical depth reversal will be inevitable. This is reminiscent of the large accretion area model suggested by Norton & Watson (1989).

Now when the upper pole points towards the observer, maximum flux is seen from it, so giving the first peak in the pulse profile (Fig. 8 viewpoint A). The contribution to the modulation from the lower pole is *in anti-phase* with that from the upper pole since, when the upper pole is pointing towards the observer, the lower pole will generally be occulted, and when the upper pole is pointing away from the observer, the lower pole is at its most visible, so giving a second peak in the pulse profile (Fig. 8 viewpoint B). A relatively large accretion area may also account for the fact that emission from the lower pole is seen even at the relatively low inclination angle of 45° in YY Dra.

An alternative way of producing a double-peaked pulse profile from two-pole accretion may be to have *tall* accretion regions, and this could also conceivably be the result of a weak magnetic field. The shock height is proportional to the size of the accreting area (eg. Frank et al. 1992), so the likelihood is that the accretion regions in intermediate polars with a weak magnetic field are both wide and tall. Even if the accretion region is not wide enough for the vertical optical depth to be lower than the horizontal optical depth, it may be tall enough for each accretion region to not entirely disappear over the rim of the white dwarf. With tall accretion regions whose vertical optical depths are greater than their horizontal optical depths (as in a conventional accretion curtain) therefore, when the upper pole points away from the observer, the lower pole is viewed essentially from the side, and so its flux adds in phase to the first flux maximum of the cycle. But, when the upper pole points towards the observer (giving minimum flux), the lower pole *may still be visible* and so give rise to a second flux maximum in the cycle.

Having said this, the height of the accretion region also depends inversely on the mass accretion rate. In most intermediate polars, the mass accretion rate is probably not low enough for the accretion region to have an appreciable height and so make this scenario feasible. The one exception is probably EX Hya which has an accretion rate about ten times lower than most other intermediate polars, and consequently an accretion shock height of about one white dwarf radius. In that case though, the upper pole is continuously visible and partial occultation of the lower pole is the main cause of the single-peaked spin pulse profile (Allan et al. 1998).

In summary, either wide or tall accretion regions could give rise to a double-peaked pulse profile, and both could be the result of a relatively weak white dwarf magnetic field. Such double-peaked pulse profiles might therefore be expected to arise in intermediate polars whose white dwarfs have relatively short spin periods.

4.5. A subset of intermediate polars with weak magnetic fields

Allan et al. (1996) discussed the cases of V405 Aur, AE Aqr and YY Dra in support of the theory outlined above, whilst Hellier (1996) also mentioned DQ Her and XY Ari in addition to those three. As further support for this theory we can now add V709 Cas to the list of sources and we also note that GK Per, with a spin period of 351 s, has displayed a double-peaked pulse profile on some of the occasions it has been observed.

The data presented earlier demonstrate that V709 Cas follows the pattern as an intermediate polar with a short spin period displaying a double-peaked pulse profile. The fact that the two maxima in its pulse profile appear more closely spaced than those of YY Dra is most probably due to an asymmetry in the locations of the upper and lower magnetic poles. This may be caused by a dipole magnetic field which is offset from the centre of the white dwarf, for instance. If the two poles are not separated by 180°, then the times at which maximum flux is seen from the two poles will not be separated by 0.5 in phase either.

GK Per only exhibits its double-peaked pulse profile in quiescence (Norton et al. 1988; Ishida et al. 1992), and shows a single-peaked pulse profile when in outburst (Watson et al. 1985). A similar situation exists in XY Ari, which also shows a double-peaked pulse profile when the system is in quiescence (*Ginga* observation: Kamata & Koyama 1993; *RXTE* observation: Hellier 1997), but a single-peaked pulse profile when in outburst (Hellier et al. 1997). We suggest that the cause of the changing pulse profile may be the same in both cases, and can be understood in the light of the model outlined earlier, following the explanation given by Hellier et al. (1997). The radius at which the accretion disc is truncated is proportional to (amongst other things) $\dot{M}^{-2/7}$ (eg. Frank et al. 1992). Since the disc already extends fairly close to the white dwarf in both these systems, due to the relatively weak magnetic field, during outburst the increased mass accretion rate will cause the accretion disc to extend even closer to the white dwarf before it is truncated. Hellier et al. (1997) suggest that in XY Ari the accretion disc then hides the lower pole from view, and a single-peaked pulse profile remains, produced by modulation of the X-ray flux from the upper pole only. Now, XY Ari is an eclipsing system, with $i = 82^\circ$ (Hellier 1997), whilst the inclination of GK Per is believed to be within the range $46^\circ < i < 73^\circ$ (Reinsch 1994).

In XY Ari the accretion disc extends to within four white dwarf radii of the white dwarf during outburst (Hellier et al. 1997). So, if the lower pole in GK Per is also hidden during outburst, the implication is that the accretion disc must extend even closer to the white dwarf in that case.

If the model outlined in Sect. 4.4 is correct, then we would expect *all* short period intermediate polars to display double-peaked pulse profiles. The seven systems described above comprise the only *confirmed* intermediate polars with a spin period below about 700 s. However, there are also three systems that have been proposed as intermediate polars which would fall within this subset if their classifications are confirmed.

The first of these systems is V533 Her, and although it has never exhibited X-ray pulsations, it has been suggested that it is an intermediate polar on the basis of optical photometry which shows a stable 63 s period that appears and disappears with a timescale of years (Patterson 1994). As a short period, weak magnetic field system, we might expect its X-ray spin pulse profile to be double-peaked, if such a pulsation is ever detected. In this case the previously identified pulse period may in fact represent half the true spin period of the white dwarf. A similar re-assessment of the spin period of DQ Her has recently been made (Zhang et al. 1995) resulting in the identification of its spin period as 142 s, twice the value previously assumed.

The other two proposed intermediate polars are both recently discovered systems by *ROSAT*. RX J0757.0+6306 has an optical photometric modulation with a period of 511 s which may represent the spin period of the white dwarf (Tovmassian et al. 1998). However, no X-ray pulsation at this period has been detected and the classification as an intermediate polar has yet to be confirmed. RX J1914.4+2456 displays an X-ray 'pulsation' with a period of 569 s, but Cropper et al. (1998) suggest that this may be a double degenerate polar, rather than an intermediate polar, and so the period represents the orbital period of the system rather than the spin period of a white dwarf. If either of these systems do turn out to be intermediate polars, we predict that their pulse profiles may turn out to be double-peaked also.

4.6. Beat frequency signals

None of the seven systems that show double-peaked pulse profiles has shown evidence for beat frequency signals in their X-ray emission. Such a signal is generally taken as a signature of stream-fed or disc-overflow accretion, and may therefore be confined to the intermediate polars with higher magnetic field strengths. This is to be expected, as the accretion flow becomes attached to the magnetic field lines at larger distances from the white dwarf when the magnetic field is stronger. The further from the white dwarf, the more chance there is that some of the accretion flow is still constrained to travel as an accretion stream, so the greater the likelihood of a signature of stream-fed accretion in the X-ray power spectrum.

All the intermediate polars that have exhibited X-ray beat period signals have relatively long white dwarf spin periods. FO Aqr with a spin period of 1254 s showed a strong beat period during a *Ginga* observation in 1988 and in an *ASCA* observation in 1993, although it was absent during a second intervening *Ginga* observation in 1990 (Norton et al. 1992a; Beardmore et al. 1998). TX Col with a spin period of 1911 s showed a strong beat period in an *EXOSAT* observation in 1985 and also in a *ROSAT* HRI observation from 1995, however it was absent from an *ASCA* observation in 1994 (Buckley & Tuohy 1989; Norton et al. 1997). The case of BG CMi is more controversial. Here an 847 s period detected during a 1988 *Ginga* observation was interpreted by Norton et al. (1992b) as the *true* spin period, implying that the previously detected 913 s X-ray pulsation was at the beat period. Even more radically, Patterson & Thomas (1993) have suggested that the true spin period is 1693 s, with the 913 s X-ray pulse then corresponding to a frequency of $(2/P_{\rm spin} - 1/P_{\rm orbit})$. In either interpretation the strong X-ray pulse is an indicator of a stream-fed accretion component, but the case for this is not yet proved one way or the other. The two systems AO Psc and V1223 Sgr, with spin periods of 805 s and 745 s respectively, both showed tentative evidence for beat periods in *EXOSAT* data from 1983–1985 (Hellier 1992), although later observations with *Ginga*, *ROSAT* and *ASCA* failed to detect any (Taylor et al. 1997; Hellier et al. 1996). Finally, the recently discovered intermediate polar RX J1712.6–2414 displays an X-ray pulsation only at the beat period of 1003 s, with no signal at the 927 s spin period of the white dwarf (Buckley et al. 1997). Furthermore, RX J1712.6–2414 and BG CMi are two of the three intermediate polars from which polarized emission has been detected (Buckley et al. 1995; Penning et al. 1986; West et al. 1987), which is another signature of a strong magnetic field. The correlation between X-ray beat periods, strong magnetic fields and long white dwarf spin periods is clearly apparent.

We therefore suggest that other intermediate polars with long white dwarf spin periods and strong magnetic fields might be expected to exhibit X-ray beat periods at some time in their lives. A prime candidate to search for such effects may be PQ Gem with a spin period of 833 s (Mason et al. 1992), since this is the third system for which polarized emission has been detected (Piirola et al. 1993). Observations with *Ginga* and the *ROSAT* PSPC failed to detect an X-ray beat period signal, but the upper limits to the amplitudes of such a modulation were 5% and 20% respectively (Duck et al. 1994), so it cannot be ruled out. Moreover, as the observations of FO Aqr and TX Col demonstrate, beat period signals can appear or disappear on a timescale of a few years, so may yet be found in PQ Gem.

5. Summary

We have presented data obtained with the *ROSAT* HRI which constitute the most sensitive X-ray observations yet of the intermediate polars YY Dra and V709 Cas. In common with some previous observations of YY Dra, the power spectrum of its X-ray lightcurve shows a signal only at a frequency corresponding to 264.7 s, which is *half* the spin period of the white dwarf. The X-ray spin pulse, with a period of 529.3 s, therefore exhibits a double-peaked profile in which the two peaks are similar and separated by about 0.5 in phase. The power spectrum of the X-ray lightcurve of V709 Cas shows a signal at a frequency corresponding to 312.8 s, the previously determined spin period, and also at the first two harmonics of this frequency. The harmonics enabled us to measure the spin period more accurately as (312.78 ± 0.03) s. When folded at this period, the pulse profile of V709 Cas displays a structure that is also double-peaked, although the maxima are separated by only about 0.3 in phase, and the secondary minimum is somewhat filled-in. There is no evidence for X-ray modulation at either the orbital period or the beat period of either system, so each must be disc-fed and seen at a relatively low inclination angle.

To allay a common assumption, we have emphasised that a double-peaked pulse profile is *not* a unique indicator of two pole accretion, and that either single-peaked *or* double-peaked pulse profiles can arise when accretion occurs onto both poles of the white dwarf. Following Hellier (1996) and Allan et al. (1996), we have explained that the two possibilities are related to the spin period of the white dwarf. A short white dwarf spin period is an indicator of a relatively weak magnetic field, which in turn gives rise to relatively large footprints of the accretion curtains on the white dwarf surface. Conversely, a long white dwarf spin period indicates a somewhat stronger magnetic field, which means that the footprints of the accretion curtains are smaller. In the first case the relative optical depths across and along the accretion curtain conspire to produce a double-peaked pulse profile, whilst in the second case a single-peaked pulse profile is the result. We trust that this will lay to rest the widely accepted paradigm that single-peaked X-ray pulse profiles are the result of single pole accretion whilst double-peaked X-ray pulse profiles are the only result of two pole accretion.

There are now seven intermediate polars with short spin periods which display double-peaked pulse profiles and must therefore have weak magnetic fields: AE Aqr, DQ Her, XY Ari, V709 Cas, GK Per, YY Dra and V405 Aur. None of them exhibit X-ray beat periods, so stream-fed or disc overflow accretion does not occur in these systems. Conversely, the six systems which have shown X-ray beat periods at some time all have long spin periods and must have stronger magnetic fields: FO Aqr, TX Col, BG CMi, AO Psc, V1223 Sgr and RX J1712.6–2414. We conclude that double peaked X-ray pulse profiles are an indicator of a white dwarf with a relatively weak magnetic field, whilst X-ray beat periods are an indicator of a white dwarf with a relatively strong magnetic field.

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References

Allan A., Horne K., Hellier C., et al., 1996, MNRAS 279, 1345
Allan A., Hellier C., Beardmore A.P., 1998, MNRAS 295, 167
Allen D.J., Vallance R.J., 1995, Starlink User Note/98.6, Rutherford Appleton Laboratory
Beardmore A.P., Mukai K., Norton A.J., Osborne J.P., Hellier C., 1998, MNRAS 297, 337
Beuermann K., Thomas H.-C., 1993, Adv. Space Res. 13, 115
Buckley D.A.H., Tuohy I.R., 1989, ApJ 344, 376
Buckley D.A.H., Sekiguchi K., Motch C., et al., 1995, MNRAS, 275, 1028
Buckley D.A.H., Haberl F., Motch C., Schwarzenberg-Czerny A., Sekiguchi K., 1997, MNRAS 287, 117
Cropper M., Harrop-Allin M.K., Mason K.O., et al., 1998, MNRAS 293, L57
Duck S.R., Rosen S.R., Ponman T.J., et al., 1994, MNRAS 271, 372
Frank J., King A.R., Raine D.J., 1992, Accretion power in astrophysics. 2nd edition, Cambridge University Press
Friend M.T., Martin J.S., Smith R.C., Jones D.H.P., 1988, MNRAS 233, 451
Haberl F., Motch C., 1995, A&A 297, L37
Haswell C.A., Patterson J., Thorstensen J.R., Hellier C., Skillman D.R., 1997, ApJ 476, 847
Hellier C., 1991, MNRAS 251, 693
Hellier C., 1992, MNRAS 258, 578
Hellier C., 1995, In: Buckley D.A.H., Warner B. (eds.) ASP Conf. Ser. Vol. 85, Proc. Cape Workshop on Magnetic CVs. Astron. Soc. Pac., San Francisco, p. 185
Hellier C., 1996, In: Evans A., Woods J.H. (eds.) Cataclysmic Variables and Related Objects. Kluwer Academic Publishers, Dordrecht, p. 143
Hellier C., 1997, MNRAS 291, 71
Hellier C., Cropper M., Mason K.O., 1991, MNRAS 248, 233
Hellier C., Mukai K., Ishida M., Fujimoto R., 1996, MNRAS 280, 877
Hellier C., Mukai K., Beardmore A.P., 1997, MNRAS 292, 397
Ishida M., Sakao T., Makishima K., et al., 1992, MNRAS 254, 647
Kamata Y., Koyama K., 1993, ApJ 405, 307
Mason K.O., Rosen S.R., Hellier C., 1988, In: White N.S., Filipov L.G. (eds.) The Physics of Compact Objects. Pergamon Press, Adv. Space Res., 8 (2), 293
Mason K.O., Watson M.G., Ponman T.J., et al., 1992, MNRAS 258, 749
Mateo M., Szkody P., Garnavich P., 1991, ApJ 370, 370
Motch C., Haberl F., Guillout P., et al., 1996, A&A 307, 459
Norton A.J., 1993, MNRAS 265, 316
Norton A.J., 1995, In: Buckley D.A.H., Warner B. (eds.) ASP Conf. Ser. Vol. 85, Proc. Cape Workshop on Magnetic CVs. Astron. Soc. Pac., San Francisco, p. 285
Norton A.J., Watson M.G., 1989, MNRAS 237, 853
Norton A.J., Watson M.G., King A.R., 1988, MNRAS 231, 783
Norton A.J., Watson M.G., King A.R., Lehto H.J., McHardy I.M., 1992a, MNRAS 254, 705
Norton A.J., McHardy I.M., Lehto H.J., Watson M.G., 1992b, MNRAS 258, 697
Norton A.J., Hellier C., Beardmore A.P., et al., 1997, MNRAS 289, 362
Patterson J., 1994, PASP 106, 209
Patterson J., Szkody P., 1993, PASP 105, 1116
Patterson J., Thomas G., 1993, PASP 105, 59
Patterson J., Schwartz D.A., Pye J.P., et al., 1992, ApJ 392, 233
Penning W.R., Schmidt G.D., Liebert J., 1986, ApJ 301, 881
Piirola V., Hakala P., Coyne G.V., 1993, ApJ 410, L107
Reinsch K., 1994, A&A 281, 108
Reinsch K., Beuermann K., Hanusch H., Thomas H.-C., 1995, In: Buckley D.A.H., Warner B. (eds.) ASP Conf. Ser. Vol. 85, Proc. Cape Workshop on Magnetic CVs. Astron. Soc. Pac., San Francisco, p. 115
Taylor P., Beardmore A.P., Norton A.J., Osborne J.P, Watson M.G., 1997, MNRAS 289, 349

Tovmassian G.H., Greiner J., Kroll P., et al., 1998, A&A 335, 227
Warner B., 1995, Cataclysmic Variable Stars. Chap. 7, Cambridge University Press
Warner B., 1996, Ap&SS 241, 263
Watson M.G., King A.R., Osborne J.P., 1985, MNRAS 212, 917
West S.C., Berriman G., Schmidt G.D., 1987, ApJ 322, L35
Wynn G.A., King A.R., 1992, MNRAS 255, 83
Zhang E., Robinson E.L., Stiening R.F., Horne K., 1995, ApJ 454, 447
Zombeck M.V., David L.P., Harnden F.R., Kearns K., 1995, Proc. SPIE 2518, 304