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Face-on, stream-fed intermediate polars: An alternative model for RX J1914.4+2456 and RX J0806.3+1527

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Abstract. RX J1914.4+2456 and RX J0806.3+1527 have been proposed as double degenerate binaries with orbital periods of 569 s and 321 s respectively. An alternative model, in which the periods are related to the spin of a magnetic white dwarf in an intermediate polar system, has been rejected by other authors. We show that a face-on, stream-fed intermediate polar model for the two systems is viable and preferable to the other models. In each case, the X-ray modulation periods then represent the rotation of the white dwarf in the binary reference frame. The model explains the fully modulated X-ray pulse profiles, the X-ray spectra, the antiphase between X-ray and optical/infrared modulation, the lack of longer period modulation, and the low level of polarization. The optical spectrum of RX J0806.3+1527 suggests that Balmer series lines are present, blended with HeII lines. This is unlike the spectra of any of the known AM CVn stars and suggests that the system is not a double degenerate binary. The optical spectrum of RX J1914.4+2456 has spectral features that are consistent with those of a K star, ruling out the double degenerate models in this case. The lack of optical/infrared emission lines in RX J1914.4+2456 may be attributed to a high mass accretion rate and its face-on orientation. Its reported period decrease may be a short term spin-up episode driven by the current high $\dot{M}$. Finally we suggest that there is an observational selection effect such that the face-on intermediate polars that are detected will all have a stream-fed component, and the purely stream-fed intermediate polars that are detected will all be face-on systems.

Key words. stars: novae, cataclysmic variables – X-rays: stars – stars: individual: RX J1914.4+2456 – stars: individual: V407 Vul – stars: individual: RX J0806.3+1527 – stars: magnetic fields – stars: binaries

1. Introduction

The X-ray sources RX J1914.4+2456 (hereafter RX J1914, but now also known as V407 Vul) and RX J0806.3+1527 (hereafter RX J0806) each display a single coherent X-ray and optical modulation with a period of order several minutes and no other confirmed modulations in any waveband observed. The most widely accepted models interpret the periods as due to orbital motion in a double degenerate binary system. In this scenario, the two systems have the shortest orbital periods of any known binary star. A review of both systems is presented by Cropper et al. (2003).

In the rest of this section we summarise the observational history of the two objects and note the difficulties in reconciling their behaviour with that of double degenerate binary systems. In Sect. 2 we present simple analytical estimates of the physical properties of face-on stream-fed intermediate polars (IPs) and simulations demonstrating the accretion flow in these systems. We then consider how the various observational characteristics of RX J1914 and RX J0806 may be understood in terms of this model.

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1.1. RX J1914.4+2456

RX J1914 was identified from the *ROSAT* all sky survey as a 569 s X-ray pulsator and suggested initially to be a member of the then recently recognised class of soft IPs, with 569 s representing the spin period of a white dwarf (Motch et al. 1996). Subsequent *ROSAT* observations failed to reveal any longer periods, apparently ruling out the IP model because an orbital period modulation might be expected. The unusual X-ray pulse profile, with zero flux for half the cycle, was claimed to require a system close to 90° inclination in conflict with the lack of X-ray eclipses; a model in which the 569 s period is the beat period was also ruled out (Cropper et al. 1998). Instead, a double degenerate polar model was suggested, with a 569 s orbital period – the first magnetic analogue of the AM CVn stars (Cropper et al. 1998). Optical and infrared spectroscopy and photometry of the optical counterpart revealed that the *V*-band through to *J*-band modulations are all roughly antiphased with the X-ray modulation, that the optical and infrared spectra show no emission lines, and that the system exhibits negligible polarisation (Ramsay et al. 2000, 2002a). As this cast doubt on the double degenerate polar model, alternative interpretations were suggested including a double degenerate

Algol (direct impact accretor) system (Ramsay et al. 2002a; Marsh & Steeghs 2002) and a double degenerate electrically powered system (Wu et al. 2002). Further doubt regarding the double degenerate accretor models (polar or Algol type) was raised by the discovery that the X-ray modulation frequency of RX J1914 is increasing. If this period decrease represents a secular evolutionary trend, the observation is in direct conflict with a system which accretes via Roche lobe overflow from a degenerate star, since in that case a secular orbital period increase would be expected (Strohmayer 2002). Very recently, Strohmayer (2004) has claimed that a power spectrum of the *Chandra* X-ray data shows evidence for a sideband structure to the 569 s signal. This indicates a previously unseen longer period in the system of around ~1 h. The data also confirm the steady decrease of the 569 s period, with a frequency derivative of 6×10^{-18} Hz s^{-1}. A final piece of evidence that poses a question for all three double degenerate models was provided by a spectrum obtained by Danny Steeghs (private communication) which has spectral features that are consistent with those of a K star.

1.2. RX J0806.3+1527

RX J0806 was discovered as a 321s X-ray pulsator amongst serendipitous X-ray sources observed by the *ROSAT* HRI, and suggested as an IP (Israel et al 1999). Its X-ray modulation is remarkably similar to that of RX J1914, showing a 50% duty cycle with the flux reduced to zero between pulses and it too was suggested to be a double degenerate polar (Burwitz & Reinsch 2001; Israel et al. 2002). The faint optical counterpart (Israel et al. 1999; Burwitz & Reinsch 2001) displays an optical period coincident with that seen in X-rays and no convincing longer period (Ramsay et al. 2002b; Israel et al. 2002), although Reinsch et al. (2003) report some evidence for a possible 4700 s period in both optical and X-ray data that was also hinted at in the earlier observations. As with RX J1914, RX J0806 displays antiphased X-ray and optical pulse profiles (Israel et al. 2003a). Unlike RX J1914, the spectrum of RX J0806 shows faint, broad emission lines superimposed on a blue thermal continuum (Israel et al. 2002). Further optical spectroscopy by Reinsch et al. (2003) rules out a main sequence secondary of any spectral type, but allows the possibility that the system could contain a brown dwarf donor star. Polarimetric data obtained by Israel et al. (2003b) show that RX J0806 exhibits no circular polarization, but that linear polarization is present at a level of $1.7\% \pm 0.3\%$. It has been reported (Strohmayer 2003; Hakala et al. 2003) that RX J0806 shows a decreasing period, which if interpreted as a secular change in the orbital period would again rule out a system in which material is accreted from a degenerate companion (double degenerate polar or Algol models). However Woudt & Warner (2003) cast doubt on the measurement of this period derivative claiming that the period count is too uncertain.

2. Face-on, stream-fed intermediate polars

We use our calculations and recent results from the literature to reassess the proposal that RX J1914 and RX J0806 are face-on, stream-fed IPs. This model was considered, but rejected, for RX J1914 (Cropper et al. 1998, 2003) and for RX J0806 (Cropper et al. 2003; Israel et al. 2003a). However, we show below that their concerns are unjustified. Briefly, we suggest that 569 s and 321 s are the synodic rotation periods of magnetic white dwarfs in IPs. The data further require that the systems are seen close to face-on (i.e. at a low inclination angle) and are fed directly by the accretion stream (i.e. no accretion disc is present). As in other IPs, the magnetic axis of the white dwarf is assumed to be inclined at $\sim 10° - 30°$ to the white dwarf rotation axis, which is perpendicular to the orbital plane.

An extension of this is to suppose that RX J1914 and RX J0806 are *double degenerate* face-on, stream-fed IPs. This might be supported by the colours of RX J1914 (Ramsay et al. 2000) and the blue spectrum of RX J0806 (Israel et al. 2002) but suffers from the same problems as the other double degenerate accretor models, which we discuss below. Instead we suggest that the secondary stars are very late-type main sequence, or in the case of RX J0806 possibly a brown dwarf.

In the following subsections, we begin by reviewing the general properties of face-on, stream-fed intermediate polars and discuss the conditions required for stream-fed accretion to occur. We then show that the data on RX J1914 and RX J0806 self consistently satisfy the predictions of this model.

2.1. Stream-fed accretion

In IPs (for a general review, see Patterson 1994) the magnetospheric radius lies within the white dwarf's Roche lobe and the white dwarf spin is asynchronous with the orbit, typically $P_{\rm spin} \sim 10^3$ s and $P_{\rm orb} \sim$ a few hours. Two models for the accretion process have been suggested. (i) In most IPs, the accretion stream from the L1 point feeds a truncated accretion disc which is disrupted at the magnetospheric radius where material attaches to the field lines and follows them towards the white dwarf magnetic poles. The infalling material takes the form of arc-shaped accretion curtains standing above the white dwarf surface (Rosen et al. 1988). (ii) In some IPs however, the accretion flow attaches directly to the field lines, without passing through a disc. Close to the white dwarf, the accretion flow resulting from stream-fed accretion is similar to that resulting from disc-fed accretion, except it is considerably less extended in azimuth (e.g. Hellier & Beardmore 2002), see Fig. 1. Accretion via a combination of disc and stream is also possible in so called disc overflow accretion. In all models the accretion flow undergoes a strong shock close to the white dwarf, below which material settles onto the surface, releasing X-ray to optical emission. Since the magnetic axis is generally inclined with respect to the white dwarf spin axis, this gives rise to the defining characteristic of the class, namely pulsed X-ray (and usually optical) emission. In disc-fed IPs, this pulsation will be at the white dwarf spin period, whereas stream-fed IPs will exhibit an X-ray pulsation at the beat (synodic) period, given by

$$1/P_{\rm beat} = 1/P_{\rm spin} - 1/P_{\rm orb}. \quad (1)$$

This is due to the accretion flow flipping from one magnetic pole to the other. Disc-overflow accretion will give rise to

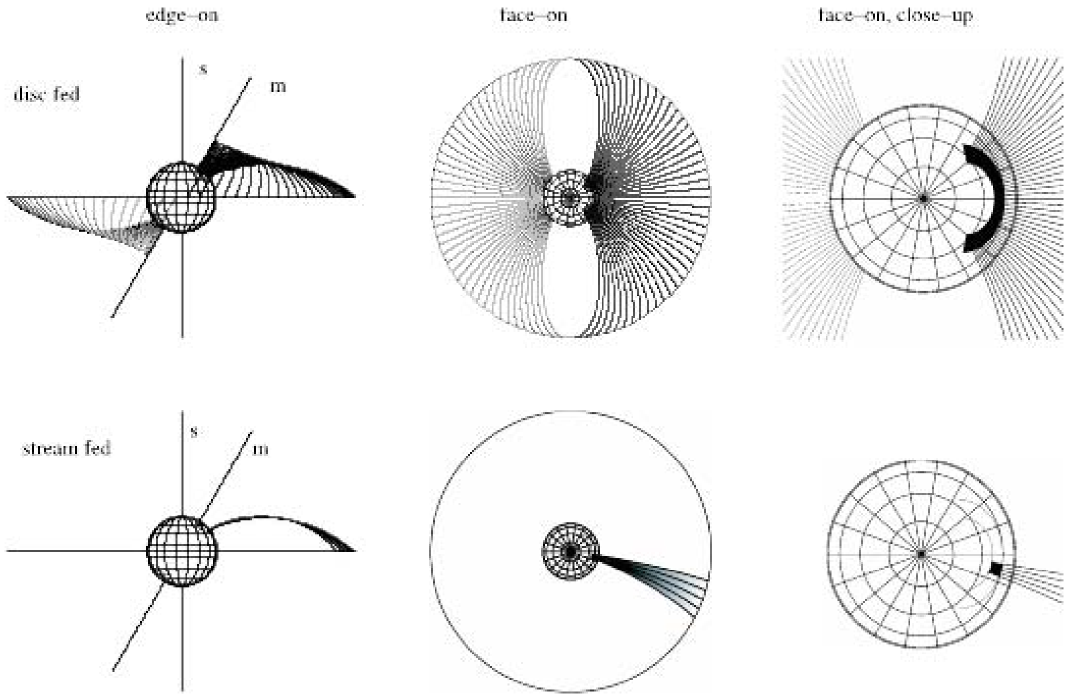

Fig. 1. Schematics illustrating the azimuthal extent of the accretion region around the upper magnetic pole on the surface of the white dwarf in an IP. *Upper panels*: disc fed accretion; *lower panels*: stream-fed accretion. Left hand panels show the accretion flow and magnetic field lines from the magnetospheric radius to the white dwarf, viewed edge-on ($i = 90°$). The orbital plane, spin axis (s) and magnetic axis (m) of the white dwarf are indicated; the magnetic axis is inclined at 30° to the spin axis in this example. Central panels show the same systems viewed face-on ($i = 0°$). The outer circle indicates the magnetospheric radius, set at five white dwarf radii here. Right hand panels show a close-up of the white dwarf surface, seen face-on, with the footprint of the accretion flow highlighted. The footprint of the flow in a stream-fed system, here shown with an azimuthal extent of ∼15°, will migrate around the white dwarf surface between the two arcs indicated.

X-ray signals at both the spin and beat periods (e.g. Norton et al. 1997; Beardmore et al. 1998).

The accretion flows in IPs have been modelled as a collection of diamagnetic blobs (e.g. King & Wynn 1999; Wynn 2000). Those blobs with a high specific orbital energy will be expelled centrifugally by the white dwarf, whilst lower energy blobs will be accreted, spinning up the white dwarf. Eventually, the white dwarf will be spinning so fast that further accretion is prevented and blobs will be ejected to be swept up by the secondary, spinning the white dwarf down. Consequently an equilibrium situation results when the rate at which angular momentum is accreted by the white dwarf is balanced by the braking effect of the magnetic torque. This results in an accretion flow which attaches to the magnetic field at around the co-rotation radius, $r_{\rm co}$ (i.e. the radius at which the magnetic field rotates at the same rate as the local Keplerian frequency).

Whether a disc-like structure forms, truncated at $r_{\rm co}$, or whether accretion is directly via a stream, depends on the relative size of the magnetospheric radius (∼the Alfvén radius, $r_{\rm a}$), which depends on the white dwarf magnetic moment, and the circularisation radius $r_{\rm circ}$ at which a circular Keplerian orbit would be established by the stream. In a purely stream-fed IP, the white dwarf has a relatively large magnetic moment and hence $r_{\rm a} > r_{\rm circ}$. This prevents a disc forming and material from the stream latches onto the field lines directly. This will initially spin-up the white dwarf so its corotation radius will reduce until equilibrium is eventually reached with $r_{\rm a} \sim r_{\rm co} > r_{\rm circ}$.

The requirement that $r_{\rm co} > r_{\rm circ}$ leads to a condition on the spin period of the white dwarf (Wynn & King 1995)

$$P_{\rm spin} > P_{\rm orb}(0.500 - 0.227\log_{10} q)^6(1+q)^2 \qquad (2)$$

where $q = M_2/M_1$ is the mass ratio of the system. Since the spin periods of both RX J1914 and RX J0806 are relatively short, this implies that the orbital periods must be relatively short too. In the limiting case for stability against thermal timescale mass transfer ($q \sim 1$), $P_{\rm beat} = 569$ s implies $P_{\rm orb} < 2.37$ h for RX J1914 and $P_{\rm beat} = 321$ s implies $P_{\rm orb} < 1.33$ h for RX J0806. If q is smaller than this, the upper limit on the orbital period of each system is even shorter. This indicates that for RX J1914 and RX J0806 to be stream-fed they must have orbital periods below the period gap and a reasonably high mass ratio.

2.2. X-ray modulation

In a stream-fed IP, assuming a dipole magnetic field geometry, the magnetic field lines from the inclined dipole will intercept the incoming accretion stream with a varying aspect angle as the white dwarf rotates. After locking on to the field lines, the accretion flow will preferentially follow the "downhill" direction to the nearest magnetic pole and the accretion stream will flip from one pole to the other twice per rotation of the white dwarf (e.g. Norton 1993). The upper (visible) pole accretes for half the rotation cycle of the white dwarf, whilst the lower (hidden) pole accretes for the other half, giving rise to

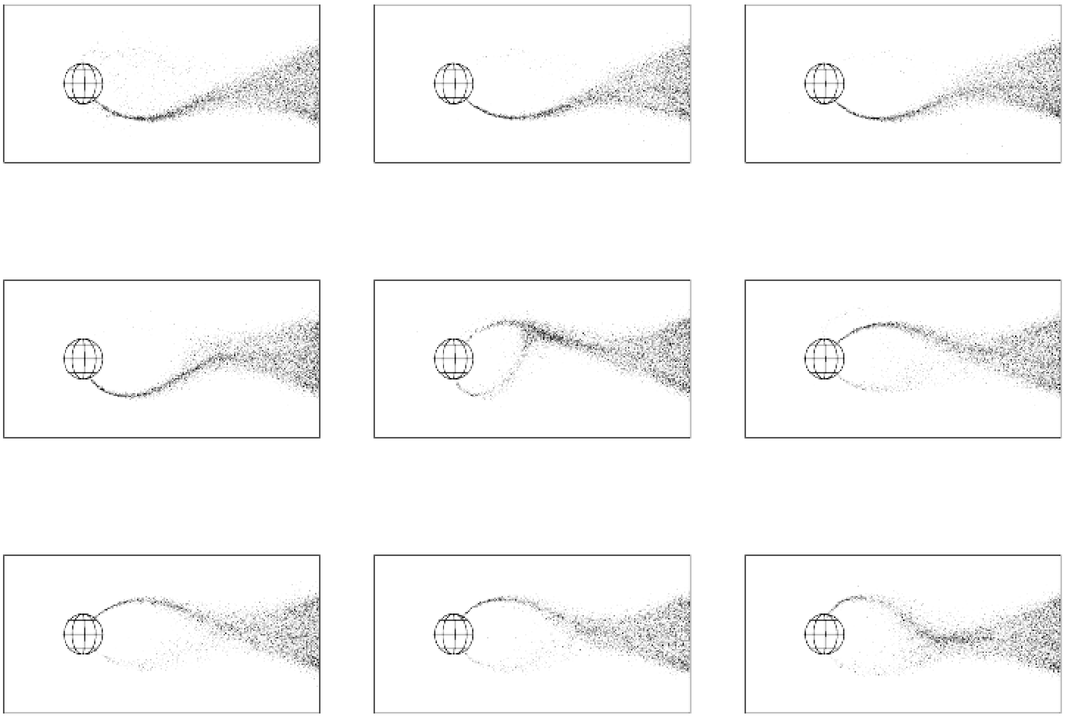

Fig. 2. Stream-fed accretion simulations for a system with $P_{\rm orb}$ = 1.5 h. The system is here shown edge-on (i = 90°) and rotated to 20° after eclipse centre. The panels span a single beat cycle and are equally spaced in beat phase, running from top left to bottom right. With reference to the phasing shown in Fig. 3, phase zero occurs around the time of the central panel. Note that in this simulation the lower pole accretes preferentially and is only rarely free from accretion. This is entirely dependent on initial conditions, as the preference for one pole or the other depends on the phase and angle at which the stream and field first come into contact at the magnetosphere.

an X-ray modulation on the beat period. As an example, we show in Fig. 2 a simulation of stream-fed accretion flow in a system with parameters appropriate to RX J1914 or RX J0806, following the prescription of King & Wynn (1999) and Wynn (2000). We emphasise that this is merely illustrative to demonstrate that a stream-fed accretion flow is possible for the system parameters applicable to these objects.

The lack of any other X-ray periods is understandable in this model. There will be no modulation at the spin period of the white dwarf since there is nothing which has a structure or a visibility which varies at this period. We note that Reinsch et al. (2003) report there is a possible ~4700 s period present in both X-ray and optical data from RX J0806, and that Strohmayer detects a sideband structure in the X-ray power spectrum of RX J1914 indicating a period close to ~1 h. These could represent the orbital periods of the systems and their values are consistent with our prediction that $P_{\rm orb}$ < 1.33 h for RX J0806 and $P_{\rm orb}$ < 2.37 h for RX J1914.

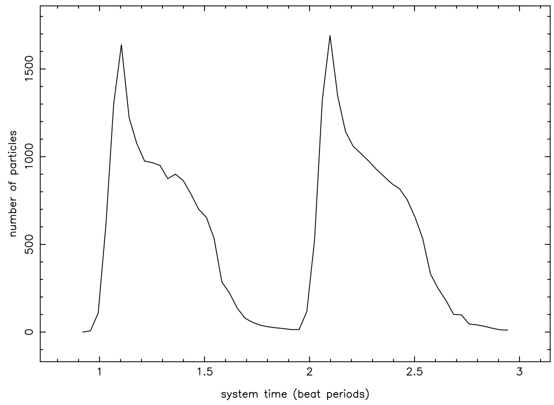

Fig. 3. Results of the stream-fed accretion model illustrated in Fig. 2, showing the number of "particles" accreted by the upper pole as a function of beat phase. For a face-on system, this will be similar to the X-ray lightcurve.

Cropper et al. (1998) rejected the face-on, stream-fed IP model for RX J1914 on the grounds that the X-ray emission from the upper pole would not drop to zero when the stream feeds the lower pole, because the travel time of the accreting material is of the same order as the 569 s period, and also because they thought it unlikely pole-switching can produce the required sharp rise times seen in the X-ray pulse profile. Our simulations indicate that the pole-switching is complete and rapid (Fig. 3), with rise and fall times for the number of particles accreted of order ~0.1 in beat phase. Thus when the system is viewed face-on, the X-ray lightcurve will also be fully modulated with a sharp rise and fall. We recognise that the profile in Fig. 3 does not exactly mimic the X-ray pulse profiles of RX J1914 and RX J0806, but emphasise this merely shows an illustrative accretion duty cycle. Precisely what the X-ray flux duty cycle would be depends on the details of the shock front at the impact site, the radiative transfer process and other considerations beyond this simple model. Nonetheless, it is apparent that a face-on, stream-fed IP model can produce an X-ray modulation similar to those observed, and rejection of the model on these grounds is not justified.

The simulations in Fig. 2 indicate that the field effectively dams the flow of matter at certain phases and then allows a burst of accretion as each pole rotates close to the stream. This effect is responsible for the sharp spike seen in Fig. 3 at the beginning of each cycle of accretion onto the upper pole. The steepness of the rise and fall shown in Fig. 3 may be understood as follows. The free fall time onto a white dwarf from 10^{10} cm (the typical distance at which material might be expected to attach to field lines) is ~100 s. However, the time by which the "turn-off" at the upper pole is delayed as a result of the free-fall time is the same as the delay in the subsequent "turn-on" at the same pole and a duty cycle of ~50% can result. Hence the rapid rise and fall is essentially independent of the free-fall time. The rise and fall time *does* depend on the azimuthal extent of the stream. The width of the accretion stream is initially set by the nozzle at the L1 point (see Eq. (5)) which in this case is of order 10^9 cm. The stream width is roughly constant from here to the magnetospheric radius and will determine the range of azimuth over which material attaches to the field lines. Since material then follows the field lines down to the white dwarf surface, this range in azimuth will be maintained, although the linear extent of the stream is greatly reduced (Fig. 2) as the field lines converge. The azimuthal extent of the arc which forms the footprint of the accretion flow on the white dwarf surface (Fig. 1) will therefore reflect the original azimuthal extent of the stream. As Fig. 3 shows, a stream with initial width of ~10^9 cm still gives rise to a sharp rise and fall in the X-ray pulsation.

The rise time of the observed X-ray pulse profiles in both RX J1914 (Cropper et al. 1998) and RX J0806 (Burwitz & Reinsch 2001) extends over <0.15 in phase, indicating an azimuthal stream extent of <50°. Hellier & Beardmore (2002) show that observations of the stream-fed IP V2400 Oph are consistent with a model in which the azimuthal extent of the accretion stream is around 20°.

V2400 Oph is the clearest example of a stream-fed IP previously known (Buckley et al. 1995, 1997; Hellier & Beardmore 2002) although FO Aqr (Beardmore et al. 1998) and TX Col (Norton et al. 1997) have each been seen to switch between predominantly disc-fed and predominantly stream-fed accretion modes on timescales of years or months. V2400 Oph is also a low inclination system with $i < 10°$ (Buckley et al. 1997). In this case, the X-ray pulse is roughly sinusoidal and, unlike the case of RX J1914 and RX J0806, does not go to zero flux for half the cycle. In order to explain this modulation, Hellier & Beardmore (2002) were forced to postulate the existence of a ring of material around the white dwarf which accretes continuously onto both poles. It is only by invoking this non-stream element to the accretion that they were able to justify the fact the the X-ray flux in V2400 Oph does not drop to zero.

2.3. X-ray spectra

Both RX J1914 and RX J0806 have X-ray spectra that are well fitted by simple blackbody models with temperatures of 43 eV (Motch et al. 1996; Cropper et al. 1998) and 64 eV (Israel et al. 2003a) respectively. Neither object shows evidence for the hard X-ray component seen in other IPs, and on these grounds Israel et al. (2003a) rejected the IP interpretation of RX J0806. However, unlike other IPs, the X-ray emitting regions in RX J1914 and RX J0806 are fuelled purely by a stream-fed accretion flow. This means that the accretion footprint is much smaller than in the case of disc-fed systems. We also suggest that both systems have relatively high accretion rates (see Sect. 2.9). Given these constraints it is more likely that the accreting material becomes buried beneath the white dwarf surface before releasing X-rays (Frank et al. 1988). The outcome of such an accretion mode is a blackbody X-ray spectrum, as observed in these systems. In the other stream-fed system, V2400 Oph, part of the flow is disc-fed (Hellier & Beardmore 2002) and so will have a conventional flow, producing hard X-ray bremsstrahlung emission from beneath a shock situated above the white dwarf surface.

2.4. Optical and infrared modulation

The azimuthally concentrated footprint of the accretion stream on the white dwarf surface will migrate around the magnetic pole to follow the incoming stream (Fig. 1), as the field lines which have captured the flow change on the synodic spin period (Norton 1993). We suggest this will leave behind a heated trail on the white dwarf surface which will be a source of optical/infrared blackbody radiation. The upper magnetic pole of the white dwarf will be heated by the accretion flow for half the rotation period. When the stream flips to the lower pole, the heated trail will be completely exposed and the optical to infrared emission from the whole of this heated region will be seen. As long as some part of the optical to infrared emission from the heated trail is absorbed by the flow whilst the accretion stream is feeding the upper pole, then a residual optical to infrared modulation will remain and be antiphased with the X-ray.

To assess the viability of this scenario for RX J1914, we assume $P_{\rm orb} \sim 2$ h, so the secondary star has $M_2 \sim 0.2\,M_\odot$, $R_2 \sim 0.2\,R_\odot$ and $T_2 \sim 3000$ K. In order to have $r_{\rm co} > r_{\rm circ}$ (Eq. (2)), this orbital period requires $q \sim 0.6$, so we assume for the white dwarf, $M_1 \sim 0.3\,M_\odot$ and therefore $R_1 \sim 1.25 \times 10^9$ cm. For illustrative purposes we further assume that the heated trail left behind after the stream has flipped to the lower pole has a temperature of order 10^5 K and occupies an area on the white dwarf of order 0.2% of its surface. This area is ~ a few times the hotspot area in polars (Warner 1995) since it is the *trail* of a stream we must consider here, not the stream footprint area itself. We then assume that when the stream is feeding the upper pole, one-fifth of the heated trail is obscured by the stream itself. Then, in the V-band, the ratio of blackbody flux from the obscured part of the heated trail to that from the secondary star plus contributions from elsewhere in the system (assumed to be comparable to that from the secondary star) is of order 15%, in agreement with the ~15% modulation observed in the V-band flux (Ramsay et al. 2002a). A similar calculation and conclusion applies to RX J0806, although here the secondary star is likely to be even fainter and so contribute even less light (Reinsch et al. 2003).

The X-ray spectrum of RX J1914 is best fit by a blackbody of temperature 43 eV (Motch et al. 1996; Cropper et al. 1998), corresponding to $T \sim 5 \times 10^5$ K. We assume this to be the temperature of the stream footprint, with an area ~0.04% of the white dwarf surface, whilst material is feeding the visible pole. The ratio of the X-ray flux in the *ROSAT* band (0.1–2 keV) from blackbodies at temperatures of 5×10^5 K and 10^5 K, with the cooler one occupying five times greater area, is about 150. Therefore the heated trail left behind after the stream has flipped to the lower pole would indeed give rise to an X-ray modulation with an amplitude of close to 100%, as observed (Cropper et al. 1998). Once again, a similar result may be obtained for RX J0806.

2.5. Optical spectra

The optical spectrum of RX J0806 shows faint, broad emission lines which are claimed to be mostly those of the HeII Pickering series (Israel et al. 2002), i.e. transitions from $n = 5, 6, 7, 8...$ to 4. However, the lines corresponding to even terms of the series are all stronger than those of the odd terms. The most likely explanation for this is that the even lines are each blended with those of the Balmer series which occur within 2 Å in each case (HeII Pickering $\beta \sim$ Hα, HeII Pickering $\delta \sim$ Hβ, etc.). This is unlike the spectra of any of the known AM CVn stars (e.g. Marsh et al. 1991; Groot et al. 2001; Ruiz et al. 2001). None of these interacting double degenerate systems show any evidence for hydrogen and none of them show the HeII Pickering series. Any hydrogen in the precursor to an AM CVn system is believed to be lost during the two common envelope phases that are necessary to achieve the close orbit. If RX J0806 is a double degenerate with an orbital period of 321 s, it too should have lost all its hydrogen. The shortest orbital period possible for a system with a degenerate hydrogen-rich donor star is ~30 min (Rappaport et al. 1982). Hence the presence of hydrogen in the spectrum of RX J0806 argues against the three double degenerate binary models for this system.

Similar blending of Balmer lines with HeII lines has been seen in the outburst spectra of the soft X-ray transient XTE J2123–058 (Hynes et al. 2001). In quiescence XTE J2123–058 has a well-studied late K dwarf absorption spectrum with Hα emission from the accretion disc (Casares et al. 2002; Tomsick et al 2002); no abundance anomalies have been reported. Hence normal abundance material can produce a spectrum resembling that of RXJ0806 if the physical conditions are appropriate. In Sect. 2.3 we showed that the stream-fed IP model predicts a small accretion footprint and high mass transfer rate, hence at the impact site on the white dwarf these systems are expected to have more extreme physical conditions than other IPs, and indeed the resemblance of the RX J0806 spectrum to that of the accreting neutron star in XTE J2123–058 is not unexpected.

As noted earlier, the fact that the optical spectrum of RX J1914 has spectral features that are consistent with those of a K star (Steeghs, private communication) poses a question for the double degenerate models for that system too.

A remaining issue to consider is the lack of emission lines in the optical and infrared spectra of RX J1914 (Ramsay et al. 2002a). In conventional (disc-fed) CVs, the emission lines are presumed to originate in the accretion disc itself, from the bright spot where a stream impacts the disc, from a corona above the disc, or (in the case of some UV lines) from a wind emanating from the system (Warner 1995). Clearly, a stream-fed IP would not be expected to exhibit emission lines from such locations. However, the disc-less polars also exhibit emission lines, and here the line emission is attributed to the accretion stream itself. A similar origin for emission lines might be expected in stream-fed IPs. The majority of the line emission in polars arises near the base of the accretion stream where the stream material is photoionized by the UV and X-ray flux from below the shock (Warner 1995). For the accretion stream in RX J1914, we have already suggested that the stream material has a significant optical depth to the optical/infrared continuum from the heated trail on the white dwarf surface, so it will have an even greater optical depth to optical/infrared emission lines.

To estimate the optical depth of the stream, we first calculate its optical depth as it emerges through the L1 point. Here, the width of the stream may be approximated by

$$W \sim c_s P_{\rm orb}/2\pi \quad (3)$$

and the density at this point is given by

$$\rho \sim \dot{M}/c_s W^2. \quad (4)$$

So assuming $T \sim 3000$ K, $P_{\rm orb} \sim 2$ h, the sound speed $c_s \sim 10^6$ cm s^{-1} and the mass transfer rate $\dot{M} \sim 10^{17}$ g s^{-1} (see Sect. 2.9), we have $W \sim 10^9$ cm and $\rho \sim 10^{-7}$ g cm^{-3}. Using the grid of low temperature opacities presented by Alexander & Ferguson (1994), this combination of temperature and density corresponds to an opacity at the L1 point of $\kappa \sim 0.03$ cm^2 g^{-1}. Hence the optical depth at the L1 point, given by

$$\tau = \kappa\rho W \quad (5)$$

is $\tau \sim 3$. Since the stream is essentially confined from here down to the white dwarf surface, it will become more concentrated as the field lines converge near to the magnetic poles. At the white dwarf surface, the width of the stream is $W \sim 10^7$ cm and the density will therefore increase to $\rho \sim 10^{-3}$ g cm^{-3}. Assuming that the opacity obeys $\kappa \propto \rho^{1/2}$, the opacity will therefore be ~100× higher at the base of the stream (for constant temperature along the stream). The optical depth at this point is then $\tau \sim 3 \times 10^4$, and the base of the accretion stream will indeed be extremely optically thick.

Allowing for the fact that the base of the accretion stream near to the white dwarf will be hotter than at the L1 point, the opacity will not be less than $\kappa \sim 0.3$ cm^2 g^{-1} which is the limit imposed by electron scattering at high temperatures. Even this opacity corresponds to $\tau \sim 3 \times 10^3$ for the density and width of the stream at this point. Furthermore, in a face-on system with a magnetic axis angle of a few tens of degrees, this region will always be viewed through parts of the stream that are further out, and hence cooler and more optically thick. So it is unlikely that any emission lines will be seen from a stream-fed, face-on IP with a high mass transfer rate.

2.6. Radial velocity variations

As noted above, even though emission lines are suppressed in RX J1914, the accretion stream in a stream-fed IP may be a source of optical emission lines. Close to the white dwarf where these are emitted, the velocity of the material is likely to be of order ~1000 $\mathrm{km\,s^{-1}}$, and unless the system is seen precisely at an inclination of 0°, radial velocity shifts of these lines would be observable and vary on the orbital period of the system. However, the current data on the lines in RX J0806 are too poor to reveal such motions, and no emission lines are seen in RX J1914 anyway. This suggests a test of the IP model, in that detailed radial velocity studies of the emission lines in RX J0806 should reveal a longer orbital period modulation.

2.7. Polarization

The lack of polarization seen in RX J1914 (Ramsay et al. 2002a) is consistent with the IP interpretation, as the majority of IPs have lower magnetic field strengths than polars and do not exhibit polarized emission. Only 5 out of ~25 confirmed IPs have been seen to emit polarized light. Similarly, the recent detection of linear polarization at the 1.7% level in RX J0806 (Israel et al. 2003b) is in agreement with the level of polarization seen in the few IPs that do reveal polarized emission. However, this low level and its lack of variation is also consistent with the polarization being interstellar in origin.

2.8. Period change

As noted above, IPs are expected to evolve towards an equilibrium spin period with $r_{\rm co} \sim r_{\rm a}$ and a continuum of equilibrium spin rates exists with spin periods varying as a function of orbital period and white dwarf magnetic moment (Wynn 2000; Norton et al. 2003). However, on short timescales (~years) random spin-up or spin-down episodes may be expected due to fluctuations in the mass transfer rate. Amongst other IPs, some are seen to be spinning down and others to be spinning up (e.g. Patterson 1994), with the $\dot{P}$ of FO Aqr having been observed to change sign over the last few years.

If the periods in RX J1914 and RX J0806 arise from rotating magnetic white dwarfs, then the recent measurements by Strohmayer (2002, 2003, 2004) and Hakala et al. (2003) imply that the white dwarfs in each system are spinning up. (Although, as already noted, Woudt & Warner (2003) suggest that the period derivative in RX J0806 is ambiguous.) Even if the period derivatives are confirmed, the few year span over which these measurements were obtained does not necessarily reflect a secular period derivative of the magnetic white dwarf. The reported rate of change of frequency in RX J1914 corresponds to $\dot{P} \sim 2 \times 10^{-12}$ s s^{-1} (Strohmeyer 2004) whilst that in RX J0806 corresponds to $\dot{P} \sim 6 \times 10^{-11}$ s s^{-1} (Hakala et al. 2003; Stromayer 2003). These are comparable with those seen in other IPs (Patterson 1994) and the spin up timescales are $P_{\rm spin}/\dot{P} \sim 9 \times 10^6$ years and $\sim 2 \times 10^5$ years respectively. These are typical for a white dwarf and therefore are consistent with an IP model. It is entirely feasible that the period changes represent temporary spin-up episodes, and the systems are accreting via a stream with a long term white dwarf spin rate equal to its equilibrium value. Such a temporary spin-up phase may be the result of a large mass accretion rate which in turn is due to magnetic activity on the secondary. The magnetic field of the secondary may dominate the flow near the L1 point if the region of the secondary star near the L1 point is magnetically active (Barrett et al. 1988).

2.9. Mass accretion rate

The measured spin-up rate may be used to estimate the mass accretion rate in RX J1914. As above we assume $P_{\rm orb} \sim 2$ h, $M_2 \sim 0.2\ M_\odot$, $M_1 \sim 0.3\ M_\odot$ and $R_1 \sim 1.25 \times 10^9$ cm. The orbital separation of the two stars is therefore $a \sim 4.4 \times 10^{10}$ cm and the distance from the white dwarf to the L1 point is

$$b = a(0.500 - 0.227 \log_{10} q) \sim 2.4 \times 10^{10}\ \mathrm{cm}. \tag{6}$$

The moment of inertia of the white dwarf is

$$I = \frac{2}{5} M_1 R_1^2 \sim 3.75 \times 10^{50} \mathrm{g\ cm^2}. \tag{7}$$

With a frequency derivative of $\dot{f} = 6 \times 10^{-18}$ Hz s^{-1} (Strohmayer 2004), the implied mass transfer rate is

$$\dot{M} = \frac{\dot{f} I P_{\rm orb}}{b^2} \sim 3 \times 10^{16}\ \mathrm{g\ s^{-1}} \sim 5 \times 10^{-10}\ M_\odot\ \mathrm{yr^{-1}}. \tag{8}$$

This may be compared with the mass accretion rate derived from the X-ray spectral properties. RX J1914 has an X-ray spectrum best fit by a blackbody with a temperature of 43 eV (Motch et al. 1996; Cropper et al. 1998). The emitted blackbody flux is therefore $F_{\rm BB} = 3.5 \times 10^{18}$ erg cm^{-2} s^{-1}. If we assume the accretion stream impacts the white dwarf over an area of ~0.01% of its surface area as in polars (Warner 1995), the blackbody accretion luminosity is $L_{\rm BB} \sim 7 \times 10^{33}$ erg s^{-1} which corresponds to an accretion rate $\dot{M} \sim 2 \times 10^{17}$ g s^{-1} $\sim 3 \times 10^{-9}\ M_\odot$ yr^{-1} in rough agreement with the estimate from the spin-up rate.

These mass accretion rates are relatively high for an IP and support the suggestion that a dense accretion stream is responsible for suppressing the line emission in RX J1914. We note that the density of the stream is enhanced over that in a conventional disc-fed IP with the same $\dot{M}$, since the flow in the stream-fed case is concentrated in a region which extends over only a few tens of degrees in azimuth around the magnetic pole compared with the 180° extent of an accretion curtain in a disc-fed IP (Fig. 1).

2.10. Probability of detection

Of the four models proposed to explain RX J1914 and RX J0806, three have potential difficulties relating to how likely it is that such systems are detectable. In the double degenerate Algol model the parameter space imposed by the geometric constraints on the system is rather confined (Marsh & Steeghs 2002; Ramsay et al. 2002b). In the electric star model the predicted lifetime of the phase is only $\sim 10^3$ years (Wu et al. 2002). However, the system can undergo many cycles of this behaviour and so can appear as an electric star at many epochs

(Cropper et al. 2003). This is therefore not a serious difficulty for the model.

The apparent problem with the face-on, stream-fed IP model is that only ~1.5% of all IPs would be expected to have an inclination angle $i < 10°$. Since V2400 Oph is already suggested to be such a system, further examples would not necessarily be expected amongst the 25 or so confirmed IPs in the absence of selection effects. However, it may be that the constraint on inclination angle necessary to produce a fully modulated X-ray pulse profile can be relaxed somewhat. King & Shaviv (1984) and Wynn & King (1992) show that, based on geometric considerations only, the upper magnetic pole remains constantly visible, and the lower pole is never seen, as long as:

$$i + m < 90° - \beta \tag{9}$$

where m is the angle between the dipole magnetic axis and the spin axis of the white dwarf and β is the angle subtended at the magnetic axis by the X-ray emitting region. As noted earlier, m is typically ~10°−30°, and β will be similar. Based on this simple geometry, inclination angles of up to several tens of degrees would still give rise to a fully modulated X-ray pulse in the case of stream-fed accretion.

The fact that all three IPs with a substantial stream-fed component are close to face-on may not be unexpected though. In a stream-fed IP seen at high inclination, both poles would be visible at some times during the beat cycle, and little modulation would occur as the disappearance of one pole is compensated by the reappearance of the other. Therefore there is an observational bias against high inclination stream-fed systems and in favour of low inclination stream-fed systems.

The fact that all three face-on IPs have a stream-fed component is not surprising either, since a purely disc-fed face-on IP would display no X-ray modulation. The structure and visibility of the X-ray emitting upper pole would remain constant throughout the spin cycle of the white dwarf in such a case. Therefore any face-on disc-fed IPs would almost certainly go un-recognised because X-ray variability is the usual key to the identification of an IP.

In conclusion, the only purely stream-fed IPs that will display an X-ray modulation are those that are seen close to face-on, and the only face-on IPs that will display an X-ray modulation are those in which at least some of the accretion arrives at the white dwarf without first flowing through a disc.

3. Conclusions and predictions

It is difficult to see how the double degenerate models are viable given the observation of hydrogen lines in the spectrum of RX J0806 (Israel et al. 2002) and the spectral features consistent with those of a K star seen in RX J1914 (Steeghs, private communication). If the period decreases seen in RX J1914 (Strohmayer 2002) and RX J0806 (Strohmeyer 2003; Hakala et al. 2003) are confirmed, and do indeed represent secular changes in the period, this too would rule out accretion from a degenerate donor star and the identification of the periods as orbital in nature. We note though that such period changes may also be understood in terms of magnetic cycles on the donor star, so this evidence is not compelling. The lack of polarization in RX J1914 and low level polarization in RX J0806 are a problem for the double degenerate polar model, whilst the geometrical constraints argue against the double degenerate Algol model.

For both RX J1914 and RX J0806, the X-ray pulse profiles, X-ray spectra, lack of other modulation periods, antiphased optical/infrared modulation, and level of polarization may be understood in terms of a face-on, stream-fed intermediate polar model. The implied orbital periods in each case are below the period gap (RX J1914: $P_{\rm orb} < 2.37$ h; RX J0806: $P_{\rm orb} < 1.33$ h), and the mass ratios (M_2/M_1) are relatively high. In the case of RX J1914, the lack of spectral lines and the observed rate of period decrease may all be attributed to a current phase of high mass accretion rate, with $\dot{M} \sim 10^{17}$ g s^{-1}. The possible detection of sideband structure in the X-ray power spectrum of RX J1914 (Strohmayer 2004) and the possible long period X-ray modulation in RX J0806 (Reinsch et al. 2003) each suggest that the originally detected short period is related to a white dwarf spin period rather than an orbital period. Finally, the preferential detection of stream-fed systems with a low inclination angle may be the result of observational selection effects.

If the face-on stream-fed IP model is correct, then the emission lines seen in RX J0806, and any which are ever detected from RX J1914, should exhibit no sinusoidal radial velocity variations at the 321 s or 569 s periods, but may show modulation at a longer orbital period. If, instead, 321 s and 569 s do represent orbital periods in double degenerate binaries then sinusoidal radial velocity variations should be present at these periods. In the face-on, stream-fed IP model, there may be a kinematic signature of the flipping accretion stream in any lines which are found. For half the beat cycle, the stream flows essentially towards the observer before turning to crash onto the upper, facing, magnetic pole of the white dwarf. For the other half of the beat cycle, the stream flows away from the observer, before turning to crash onto the lower, hidden, magnetic pole. This stream-flipping may lead to velocity variations of spectral lines. Any variation would be at the 569 s or 321 s period in the two systems but would not be a simple sinusoidal modulation.

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