Stream-fed Accretion in Intermediate Polars

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Abstract. I review the observational evidence for stream-fed accretion in intermediate polars. Recent work on the discless system V2400 Oph confirms the pole-flipping model of stream-fed accretion, but this applies only to a minority of the flow. The bulk of the flow is in the form of blobs circling the white dwarf, a state which might have been a precursor to disc formation in other IPs. I also discuss work on the systems with anomalously long spin periods, V1025 Cen and EX Hya. There are arguments both for and against stream-fed accretion in V1025 Cen, and further work is necessary before reaching a conclusion about this system.

1. Introduction

Early work on intermediate polars (IPs), taking a lead from studies of DQ Her, tended to assume the presence of an accretion disc. The accretion stream would feed the outer disc, as in non-magnetic systems, and the magnetic field would disrupt the inner disc and so channel the accretion along field lines onto magnetic polecaps. Hameury, King, & Lasota (1986) and Lasota & King (1991) presented theoretical arguments against this idea. They suggested that most IPs were discless, with the accretion stream falling until it encountered the magnetosphere directly. They argued that, observationally, discless systems would be distinguished by X-ray modulations over the orbital cycle, since in a stream-fed system the accretion sites would lie ‘beneath’ the stream, and so be localised in orbital phase.

Hellier (1991) and Hellier, Garlick, & Mason (1993) pointed out that X-ray orbital modulations can also result from obscuration of the white dwarf by structure in an accretion disc, as seen in ‘dipping’ LMXBs, and so are not exclusive to discless systems. We suggested that a better diagnostic was the presence of an X-ray pulsation at the beat frequency (ω−Ω) between the spin (ω) and orbital (Ω) frequencies. This arises because the geometry changes on the beat frequency when a magnetosphere (spinning at ω) rotates beneath a stream (orbiting at Ω). Indeed we would expect the stream to follow the field line involving least deviation from the orbital plane, and so flow to the upper magnetic pole for half the beat cycle and then flip to the lower pole for the remainder of the cycle.

Wynn & King (1992) modelled the situation and confirmed that X-ray modulations at Ω and ω−Ω are characteristic of stream-fed accretion, but also found that power could be moved from ω−Ω to 2ω−Ω for certain combinations of the system inclination and the angle between the magnetic and spin axes.
Hellier (1991; 1992) analysed X-ray lightcurves to show that all currently known IPs were dominated by X-ray pulsations at the spin period, rather than the beat period, and so argued that they were all disc-fed accretors. However, Buckley et al. (1995; 1997) then discovered the *Rosat* source V2400 Oph, which showed a strong X-ray pulsation at the 1003-sec beat period but none at the 927-sec spin period, and thus was the first secure case of discless accretion amongst the known IPs.

The 927-sec period was detected only in polarised light, and this raised the following problem for deductions based on X-ray periodicities: since many IPs show no polarised light, might we fail to detect the spin period in a non-polarised discless system, and if so might we be misinterpreting the beat cycles as spin cycles? Exactly this issue was debated in the case of BG CMi (Norton et al. 1992b; de Martino et al. 1995; Hellier 1997). New spectroscopy of V2400 Oph, reported in Hellier & Beardmore (2002), is reassuring on this point. Both the spin and the beat cycles are seen easily in the emission lines (Fig. 1), and this would leave little doubt as to their respective identities, even if we had no polarimetry. Thus V2400 Oph greatly strengthens the overall argument, since the discovery of a system showing so clearly the predicted hallmark of discless accretion confirms the validity of distinguishing between disc-fed and stream-fed accretors using the spin and beat pulses in the X-ray lightcurve.

Since nearly all well-studied IPs show both spin and beat cycles in the emission lines, we can have confidence in assigning cycles correctly and thus in applying the argument to the whole class.

![Figure 1. Fourier transforms from V2400 Oph, comparing the polarised light (data by David Buckley) with X-ray data and H\(\beta\) V/R ratios. The spin, orbital and beat frequencies are marked with the usual notation of \(\omega\), \(\Omega\) and \(\omega-\Omega\), respectively. Peaks marked ‘sp’ are windowing caused by the spacecraft orbit.](image-url)
2. Stream/disc overflow

Even in systems where a spin-cycle pulsation dominates the X-ray lightcurves, a weaker beat-cycle pulsation is often seen (e.g. Buckley & Tuohy 1989; Hellier 1991; Norton et al. 1992a; Hellier 1998). These have been interpreted as showing that most of the accretion flows through an accretion disc, but that part of the stream overflows the disc and so encounters the magnetosphere directly, giving rise to the beat-cycle modulation (e.g. Hellier 1991; 1993). The idea that overflow occurs in cataclysmic variables is supported by theoretical modelling (e.g. Lubow 1989; Armitage & Livio 1998).

Murray et al. (1999) have argued against this idea as follows. The overflowing stream cannot penetrate further in than the radius of minimum approach of a ballistic stream, $R_{\text{min}}$, so cannot connect to the magnetosphere unless $R_{\text{mag}} > R_{\text{min}}$; yet it is unclear whether a disc can form if $R_{\text{mag}} > R_{\text{min}}$, since the stream could not orbit freely around the magnetosphere. Murray et al. argue instead that spiral shocks in the inner disc might give rise to orbital sidebands of the spin frequency.

One counterargument is that a two-armed spiral would result in modulations at $2(\omega - \Omega)$, whereas a stream leads to $\omega - \Omega$, and we typically observe $\omega - \Omega$ rather than $2(\omega - \Omega)$. A second response is that in most IPs the magnetospheric radius is indeed larger than $R_{\text{min}}$. As an example, take the case of AO Psc, with orbital and spin periods of 3.59 hr and 805 sec, respectively. Deducing $R_{\text{mag}}$ by assuming that the magnetosphere corotates with a Keplerian disc at $R_{\text{mag}}$, and choosing plausible stellar masses, we find that $R_{\text{mag}} \approx 1.2 \times 10^{10}$ cm, whereas $R_{\text{min}}$ is smaller at $\approx 0.6 \times 10^{10}$ cm. Since systems like AO Psc do appear to accrete through discs, judging by the dominance of the X-ray spin pulse, the task becomes explaining disc formation in the regime where $R_{\text{mag}} > R_{\text{min}}$. Recent work on V2400 Oph (Section 4) may shed light on this.

3. FO Aqr

In turning now to individual systems, I first highlight FO Aqr as the best-studied example of a system showing disc-overflow accretion. The X-ray pulsation at the spin period is always largest, but there is often (though not always) an additional pulsation at the beat period (Hellier 1991; Norton et al. 1992a; Hellier 1993; Beardmore et al. 1998). The implication is that the overflow is variable, occurring often but not always. FO Aqr can be taken as an exemplar of the stars AO Psc, V1223 Sgr & BG CMi, which have all shown a weak beat-cycle pulsation in at least one X-ray observation (e.g. Hellier 1998).

4. V2400 Oph

V2400 Oph is at a low inclination of only $\approx 10^\circ$, so we only ever see the ‘upper’ magnetic pole (Buckley et al. 1995; Hellier & Beardmore 2002). As the stream flips to the hidden, lower pole, the X-ray flux drops, resulting in a beat-cycle pulsation which dominates the X-ray lightcurves (Fig. 2). The idea is supported by optical spectroscopy, where observed velocity changes over the beat cycle
Figure 2. Part of an RXTE X-ray observation of V2400 Oph showing an obvious beat-cycle pulsation. The Fourier transform of this observation is shown in Fig. 1. (From Hellier & Beardmore 2002.)

match well to a simulation of pole-flipping accretion, calculated for material 5–10 $R_{wd}$ from the white dwarf (Fig. 3).

However, a pole-flipping stream cannot be the whole story in V2400 Oph. In Hellier & Beardmore (2002) we concluded that much of the accretion flow is circling the white dwarf, not falling inward in a stream. The evidence is, firstly, that the X-ray beat pulse is only 25% deep. This implies that accretion is always occurring at both poles continually, so that we still see accretion when the stream flips to the lower pole, suggesting that $\sim 75\%$ of the flow does not participate in the pole flipping. Secondly, the velocity variation of the emission lines over the orbital cycle is only 6 km s$^{-1}$. Even at 10$^\circ$, the infall motion of a stream would mean that it would generate an orbital modulation of hundreds of km s$^{-1}$. Only by diluting this with material circling the white dwarf is it possible to account for the observations. A third line of argument is that while the changes in the line profile over spin and beat phases are explained by stream-fed accretion (Figs. 3 & 4), the varying components comprise only $\approx 10\%$ of the total line line, implying that most line emission comes from something other than the stream.

One possibility is that a disc is present, but this is unlikely given the non-detection of any X-ray spin pulse. Instead, we suggested (Hellier & Beardmore 2002) that the flow is in the form of diamagnetic blobs circling the white dwarf, following the theoretical analysis of King (1993) and Wynn & King (1995). The simulations by King & Wynn (1999) show that, given a range of blobs densities, the less-dense material is easily threaded and controlled by field lines, while denser blobs can cross field lines and orbit the white dwarf.

The above picture may provide the answer to disc formation in the regime $R_{mag} > R_{min}$, since it implies that dense blobs are crossing field lines, losing memory of orbital phase, and spiralling inward to accrete onto the white dwarf. If the field were somewhat lower, the drag on the blobs would be reduced, slowing their inward spiral and allowing them to accumulate. They would tend to screen the field from one another, reducing the effective field further, and so producing a runaway that would lead to disc formation.

In this regard it is notable that V2400 Oph has the highest field estimate among IPs at 9–27 MG (Buckley et al. 1995; Vâth 1997), and this might explain why it is discless. Even so, the presence of circling material suggests that it is
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5. TX Col

Most IPs have X-ray lightcurves dominated either by the spin pulse or by the beat pulse, allowing them to be interpreted as predominantly disc-fed or predominantly stream-fed systems. In TX Col, however, the two pulsations are of comparable amplitude and are variable, so that the spin-pulse is larger at some times and the beat pulse larger at others (Buckley & Tuohy 1989; Norton et al. 1997; Wheatley 1999). One possible explanation, as for FO Aqr, is variable
disc-overflow, but this time with the flow through the stream being sufficient, on occasion, to produce a beat pulse which is larger than the spin pulse.

However, it might also be possible to explain TX Col along the lines of V2400 Oph, with a combination of a stream and orbiting blobs. If a disc were on the verge of forming, the accretion flow could be hovering between the two modes, explaining the variability of the X-ray lightcurves. Arguing against this is the fact that polarisation is not seen in TX Col, suggesting that it is not among the higher-field IPs. There has been relatively little optical work published on TX Col, and further spectroscopy may be the way to resolve the issue.

6. V1025 Cen

The two stars EX Hya and V1025 Cen have exceptionally long spin periods with $P_{\text{spin}}/P_{\text{orb}} > 0.4$, whereas in all other IPs the ratio is $< 0.1$ (e.g. fig. 4 of Hellier, Beardmore, & Buckley 1998). The condition $P_{\text{spin}}/P_{\text{orb}} < 0.1$ is required for equilibrium rotation with a disc (where the field’s corotation velocity equals...
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The Keplerian velocity at $R_{\text{mag}}$ since $R_{\text{mag}}$ cannot exceed the stream’s circularisation radius, and this puts an upper limit on $P_{\text{spin}}$ (see, e.g., King & Lasota 1991). One possible explanation is that EX Hya and V1025 Cen do possess discs but are far from equilibrium, perhaps because of a drop in mass-transfer rate from which they are now recovering.

A second possibility, though, has been suggested by King & Wynn (1999). They expound a discless model for these stars in which $R_{\text{mag}}$ equals the distance to the Lagrangian point. Most of the mass-transfer stream accretes, but $\approx 10\%$ is expelled outward by the field to be swept up by the secondary. The expulsion of high-angular-momentum material balances the accretion torques and locks the system into an equilibrium at much longer spin periods than in most IPs.

In Hellier, Wynn, & Buckley (2002) we present optical spectroscopy of V1025 Cen aimed at deciding between the two models. We find that King & Wynn’s model has several successes in addition to accounting for the anomalous spin period of this system. In particular, there are correspondences between the observed line profiles over the orbital cycle and the profiles predicted by the

Figure 5. The orbital variation of the Hβ line of V1025 Cen (top) on the same scale as a simulation by Graham Wynn (bottom). The similarities include the central, lower-velocity S-wave, and a higher-velocity feature phased $\approx 0.25$ cycles earlier. See Hellier et al. (2002) for a fuller account together with Doppler tomograms.
model (Fig. 5). Further, both observed and model tomograms show the same ‘hook’-like features (Wynn 2001; Hellier et al. 2002).

However, the stream-fed model of King & Wynn (1999) is again a geometry varying with beat phase, and predicts a strong modulation of accretion rate with beat phase (see their fig. 3). The X-ray lightcurves, though, show only a spin-cycle pulsation (Hellier et al. 1998). Although a spin-cycle pulse is readily explained even in a stream-fed accretor, since views of the accretion sites vary with spin phase, the absence of any beat-cycle pulsation is a problem for any such model. A comparison of the Fourier transforms of X-ray lightcurves of V2400 Oph and V1025 Cen would suggest that the former is stream-fed and the latter disc-fed (Fig. 6).

Thus, with points both for and against the two models, further work is required to reach a conclusion about V1025 Cen. In particular, it is worthwhile exploring whether a variant of the King & Wynn model could retain the same flow near the Lagrangian point, where expulsion of material leads to the long spin period, but then give way to a disc-like flow near the white dwarf, where dependence on orbital phase is washed out.

7. **EX Hya**

Like V1025 Cen, the X-ray lightcurve of EX Hya is always dominated by a spin-cycle pulsation, pointing to disc-fed accretion. A beat-cycle pulsation has been seen only once, during an outburst (Hellier et al. 2000). The eclipse profiles during outburst showed conclusively that the accretion stream was greatly enhanced. These findings fulfilled predictions made from an earlier outburst (Hellier et al. 1989) where emission-line profiles suggested that the stream was overflowing the disc and impacting on the magnetosphere. Thus, observations
show that disc-overflow accretion occurs in EX Hya during outburst (probably owing to enhanced mass-transfer) but not in quiescence. It is currently unclear whether the enhanced mass transfer is the sole cause of EX Hya’s outbursts, or whether the enhancement is triggered by a disc instability (see Hellier et al. 2000). If the latter, it would be proof of the presence of a disc. The quiescent studies show the double-peaked lines characteristic of an accretion disc, and an S-wave compatible with arising from the bright spot where the stream hits the disc (e.g. Hellier et al. 1987). Thus, overall the observations point to the presence of a disc in EX Hya, despite the anomalous spin period. However, it should be noted that a detailed comparison of observations to the King & Wynn (1999) model has not yet been published, and could develop this debate further.

8. AE Aqr

To complete a round-up of stream-fed accretion, I mention AE Aqr. The white dwarf in AE Aqr is the fastest rotator among the secure IPs, with a period of 33 sec. The current picture is that it has no disc, and the stream is expelled from the system by the propeller effect of the rapidly spinning field (Wynn, King, & Horne). The evidence is primarily the finding that the spin-down energy of the white dwarf exceeds the accretion energy (de Jager et al. 1994), suggesting that only a small fraction of the mass-transfer stream is accreted. The small fraction that accretes is slowed by the propeller effect, presumably circling the white dwarf many times before accreting; it loses dependence on orbital phase and thus produces pulses at the spin period, although given the slow infall they are seen in soft X-rays only. Again, a detailed comparison of the observations to this model has yet to be published, so it is too early for final conclusions, but see Welsh (1999) for a review of the state of play.

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