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The role of the disc magnetization on the hysteresis behaviour of X-ray binaries

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ABSTRACT

We present a framework for understanding the dynamical and spectral properties of X-ray binaries, where the presence of an organized large-scale magnetic field plays a major role. Such a field is threading the whole accretion disc with an amplitude measured by the disc magnetization $\mu(r, t) = B_z^2 / (\mu_0 P_{\text{tot}})$, where P_{tot} is the total, gas and radiation, pressure. Below a transition radius r_J , a jet emitting disc (JED) is settled and drives self-collimated non-relativistic jets. Beyond r_J , no jet is produced despite the presence of the magnetic field and a standard accretion disc (SAD) is established. The radial distribution of the disc magnetization μ adjusts itself to any change in the disc accretion rate \dot{m} , thereby modifying the transition radius r_J .

We propose that a SAD-to-JED transition occurs locally, at a given radius, in a SAD when $\mu = \mu_{\text{max}} \simeq 1$ while the reverse transition occurs in a JED only when $\mu = \mu_{\text{min}} \simeq 0.1$. This bimodal behaviour of the accretion disc provides a promising way to explain the hysteresis cycles followed by X-ray binaries during outbursts.

Key words: accretion, accretion discs – black hole physics – MHD – ISM: jets and outflows – X-rays: binaries.

1 INTRODUCTION

In the last 10 yr, different studies have shown that during periods of strong activity X-ray binaries (XRBs) follow an hysteresis cycle in the hardness–intensity diagram (hereafter HID), the X-ray equivalent of the colour–magnitude diagrams used in the optical range (Miyamoto et al. 1995; Barret & Olive 2002; Nowak, Wilms & Dove 2002; Maccarone & Coppi 2003; Rodriguez, Corbel & Tomsick 2003; Corbel et al. 2004; Zdziarski et al. 2004; Belloni et al. 2005; Remillard & McClintock 2006). The archetype of HID has been reported in Fig. 1 in the case of GX 339–4 during its 2002/2003 outburst. The system transits from radio-loud (jet-dominated) hard states (HSs) at the right-hand side in the figure to radio-quiet (disc-dominated) soft states (SSs) at the left-hand side. Such transitions occur at a luminosity generally a factor of a few larger than during the SS–HS transitions back to the initial state. This hysteresis cycle clearly indicates that the accretion rate cannot be the unique physical parameter that controls the spectral evolution of these systems, and the fact that at some point XRBs produce collimated jets (as probed by flat radio spectra) points towards the other physical parameter: the magnetic field.

In a previous paper (Ferreira et al. 2006, hereafter F06), we presented a new model to explain the different spectral states observed

in black hole (BH) XRBs that assumes the presence of a large-scale vertical magnetic field B_z (of the same polarity everywhere) anchored in an accretion disc. The central regions have a multi-flow configuration consisting of an outer standard accretion disc (SAD) down to a transition radius r_J and an inner magnetized jet emitting disc (JED) below r_J . The JED drives a self-collimated non-relativistic magnetohydrodynamical (MHD) jet surrounding, when conditions for pair creation are met, a ultrarelativistic pair beam on its axis. We also assume the presence of a hot thermal corona at the base of the jet that is likely part of the JED itself (Petrucci et al. 2006, Petrucci et al., in preparation). This model provides a promising framework to explain the canonical spectral states of BH XRBs mainly by varying r_J and \dot{m}^1 independently. The HSs then correspond to large r_J , while SSs correspond to small r_J . This transition radius is observationally identified as the usual ‘disc inner radius r_{in} ’ determined from spectral fits. Indeed, the JED is transferring most of the released accretion power into the jets: the blackbody spectrum is therefore dominated by the outer SAD.

However, this model did not address the cause of the transitions between the various spectral states, namely what really drives the variations of r_J . This directly translates to the fundamental question: what are the physical conditions to have a JED, that is, to produce a

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¹ $\dot{m} = \dot{M} / \dot{M}_{\text{edd}}$ with \dot{M} the accretion rate and $\dot{M}_{\text{edd}} = L_{\text{edd}} / c^2$ with L_{edd} the Eddington luminosity and c the speed of light.

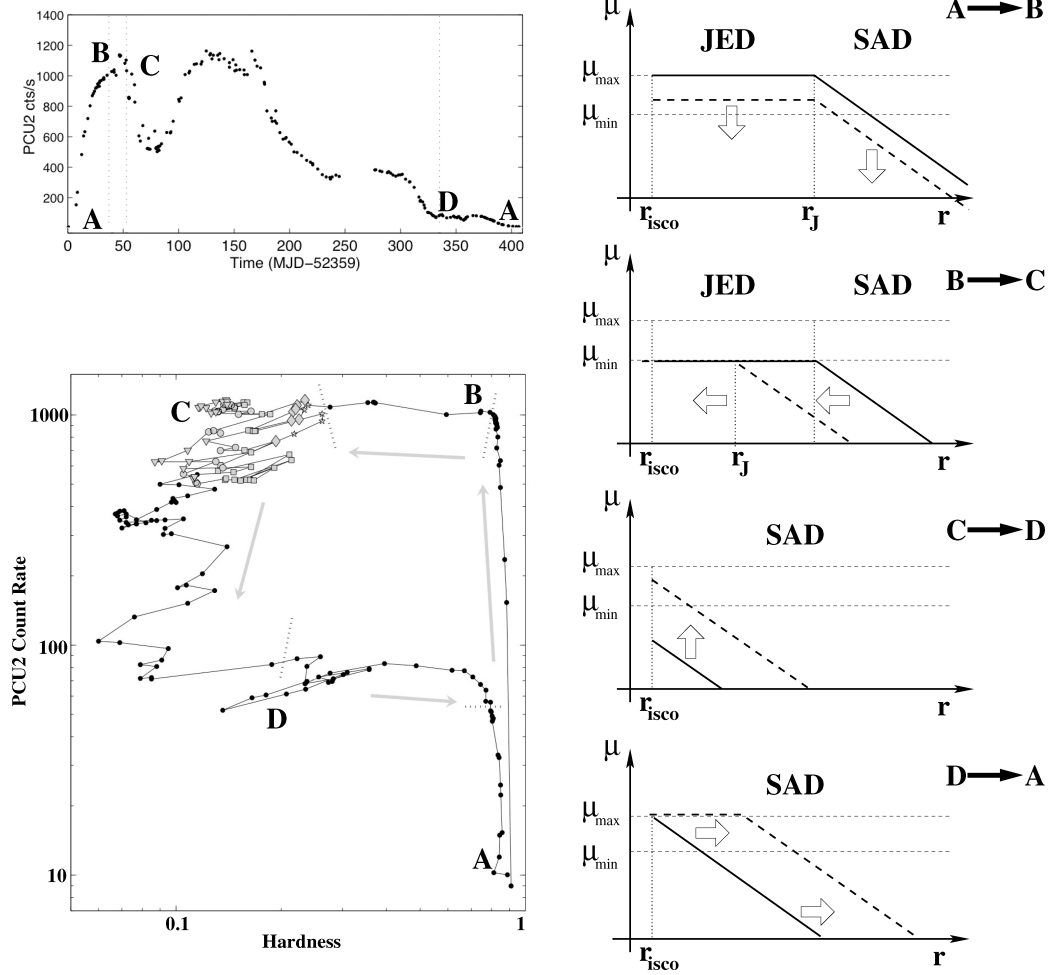


Figure 1. Left-hand panel: light curve and HID followed by GX 339–4 during its 2002–2003 outburst (from Belloni et al. 2005). Right-hand panel: sketch of the expected evolution of the radial distribution of the disc magnetization $\mu(r)$ during an outburst with hysteresis. In each plot, the solid line represents the initial (for each part of the HID) radial distribution of the disc magnetization, while the dashed one shows its evolution. See Section 3 for more details.

large-scale MHD jet from an accretion disc? This points out to the important local parameter called the disc magnetization

$$\mu(r, t) = \frac{B_z^2}{\mu_0 P_{\text{tot}}}, \quad (1)$$

where $P_{\text{tot}} = P_{\text{gas}} + P_{\text{rad}}$ includes the plasma and radiation pressures.² The disc magnetization is a fundamental parameter in accretion–ejection physics and, as shown analytically by Ferreira & Pelletier (1995) and Ferreira (1997), and numerically by, for example, Casse & Keppens (2002) and Zanni et al. (2007), it has to be close to unity (i.e. the magnetic field must be close to equipartition) to produce super-Alfvénic jets. We here address the crucial role of the disc magnetization in the spectral evolution of XRBs. We show that its expected variation during the outburst, coupled with that of the accretion rate, can explain the hysteresis cycle across the HID.

2 THE DISC MAGNETIZATION

The reason why the disc magnetization has to be close to unity to produce steady-state jets is twofold. On one hand, the magnetic

field is vertically pinching the accretion disc so that a (quasi-) vertical equilibrium is obtained only, thanks to the gas and radiation pressure support. As a consequence, the field cannot be too strong. However, on the other hand, the field must be strong enough to accelerate efficiently the plasma right at the disc surface so that the slow-magnetosonic point is crossed smoothly. These two constraints can only be met with fields close to equipartition. Quantitatively, analytical self-similar calculations show that μ has to lie between $\mu_{\text{min}} \simeq 0.1$ and $\mu_{\text{max}} \simeq 1$ for a stationary jet from a Keplerian disc to exist (Ferreira & Pelletier 1995, see e.g. fig. 2 in Ferreira 1997). The existence of a limited range in μ is a key point in our interpretation of the hysteresis cycle.

In our framework, a large-scale, organized vertical magnetic field B_z is threading the whole accretion disc. There have been some claims in the literature that such a field could not be maintained in a SAD (see e.g. Lubow, Papaloizou & Pringle 1994). In fact, the magnetic field distribution is given by the interplay between advection and diffusion, namely Ohm’s law. It turns out that in a SAD in a stationary state, this equation gives $B_z \propto r^{-\mathcal{R}_m}$ with $\mathcal{R}_m \simeq \mathcal{R}_e \simeq 1$. As a consequence, one can reasonably expect $\mu(r)$ to be a decreasing function of the radius (cf. equation 4 of F06). On the other hand, in a JED one has roughly $B_z \propto r^{-5/4}$ (Ferreira & Pelletier 1995) and μ remains constant with the radius. In consequence, a reasonable radial distribution of μ should look

² Note that μ differs from the inverse of the usual plasma β parameter which compares the magnetic pressure to the gas pressure only.

like the one plotted on top of Fig. 1, namely constant (but in the range $\mu_{\min}-\mu_{\max}$) in the JED, located between the disc innermost stable circular orbit (ISCO) r_{ISCO} and r_J , and decreasing in the SAD beyond r_J .

Now, the evolution in time of the disc magnetization $\mu(r, t)$ is a far more complex issue. Since $P_{\text{tot}} \propto \dot{m}$, one gets $\mu \propto \dot{m}^{-1} B_z^2$. It means that its temporal evolution is governed by the evolution of both B_z and $\dot{m}(t)$. Although the origin of the variations in the disc accretion rate $\dot{m}(t)$ during an outburst is relatively well understood (e.g. Lasota 2001), the evolution of $B_z(t)$ is more speculative. One of the reasons is that B_z could itself be a function of the disc accretion rate. Different scenarios have been proposed (e.g. King et al. 2004; Tagger et al. 2004) but the problem is very tricky and no detailed calculation has emerged so far. In this context, and given the large uncertainties on the physical processes governing the evolution of the magnetic field with \dot{m} , we make the zeroth-order approximation that the variation in the accretion rate is the dominant cause of the variation in μ . In other words, we assume here that $\mu(r, t)$ anticorrelates with the accretion rate.

One last issue is what determines the transition radius r_J in a disc that is threaded everywhere by a large-scale B_z field? In a SAD, the origin of the turbulence is commonly believed to arise from the magnetorotational instability or MRI (Balbus & Hawley 1991; Lesur & Longaretti 2007). However, the MRI requires the presence of a weak magnetic field and is quenched when the field is at equipartition. Thus, while a SAD works well at $\mu \ll 1$, there is no known solution when $\mu \gtrsim 1$. On the other hand, as said before, a steady-state JED can establish only around a rather limited range in disc magnetization, namely $\mu_{\min} \lesssim \mu \lesssim \mu_{\max}$.

These facts lead us to make the following conjecture that, at a given radius,

- (i) a SAD-to-JED transition occurs when $\mu = \mu_{\max} \simeq 1$;
- (ii) a JED-to-SAD transition occurs when $\mu = \mu_{\min} \simeq 0.1$.

As we will see in the next section, this conjecture provides a plausible scenario for the hysteresis cycle observed in BH XRBs.

3 TEMPORAL EVOLUTION OF BH XRBs

It is commonly believed that BH XRBs generally evolve along an hysteresis cycle during their outbursts, following a counter-clockwise sequence A–B–C–D like the one reported in Fig. 1, before turning back to their initial state at the end of the outburst. The HS and SS correspond to the A–B and C–D parts of this diagram, respectively. The horizontal branches, B–C and D–A, correspond to the intermediate states (hereafter ISs) whose spectral and timing properties are relatively complex (e.g. Corbel et al. 2004; Fender et al. 2004a; Belloni et al. 2005). This is especially the case during the high IS (hereafter HIS, Homan & Belloni 2005; Belloni et al. 2005) that corresponds to the top horizontal branch where the system luminosity is high. During its evolution along this horizontal branch, the system may enter in a flaring state associated with radio and X-ray flares and/or superluminal sporadic ejections (e.g. Sobczak et al. 2000; Hannikainen et al. 2001; Fender, Belloni & Gallo 2004b). This spectral evolution goes also with a quenching of the radio emission, signature of the disappearance of the jet component. During the bottom horizontal branch (the low IS, hereafter LIS) and the turning back of the system to its initial state, the radio emission is detected again, meaning that the ejection structure has been rebuilt.

We detail below our interpretation of this hysteresis cycle as a consequence of our conjecture on the disc magnetization $\mu(r, t)$. We give also some estimates of the expected time-scales involved at the different phases of the cycle. In the accretion disc, the shortest dynamical time-scale dealt with is the Keplerian orbit time, namely $\tau_D(r) = 2\pi/\Omega_k = 0.1(m/10)(r/50 r_g)^{3/2}$ s, where m is the BH mass in solar mass units and $r_g = GM/c^2$ the gravitational radius. In the following, we take $m = 10$ and consequently $r_g = 1.5 \times 10^6$ cm.

Let us start at a HS located at the bottom of the HID right-hand branch (point A in Fig. 1). This state is usually seen as a SAD being interrupted at typically $r_{\text{in}} \sim 100 r_g$. Within our framework, this is perfectly consistent with a JED settled from r_{ISCO} up to $r_J = r_{\text{in}}$ and driving self-collimated non-relativistic jets (seen as persistent radio features). Within the JED μ is roughly constant and we assume that at the beginning of the outburst $\mu = \mu_{\max} \simeq 1$. Let us now consider an increase in the disc accretion rate \dot{m} (an outburst) triggered by, for instance, a disc instability at some outer radius $r_{\text{out}} \gg r_J$ (e.g. Lasota 2001). A front defined by a rise in P_{tot} (hence a decrease in μ) propagates then radially inwards eventually reaching r_J . As for the SAD, the JED adapts itself locally on a dynamical time-scale (a few τ_D) by lowering μ . This adaptation will affect the whole JED extension on a time-scale roughly equal to $\tau_{\text{acc, JED}}$, the accretion time-scale in the JED. Since the accretion radial velocity $u_r^{\text{JED}} \sim \Omega_K h$ in a JED (Ferreira 1997), this time is even shorter than that of the front propagation in the outer SAD. For instance, one gets $\tau_{\text{acc, JED}}(100 r_g) \simeq \tau_D(100 r_g)r/h \simeq 30$ s (using a disc aspect ratio $h/r = 0.01$, Shakura & Sunyaev 1973). This time-scale is much shorter than the time-scale of the ascendent phase of an outburst, which is typically of the order of several days between states A and B. Thus, during the ascendant motion of the XRB along the right-hand branch from A to B, μ should only decrease within the whole JED without any change in r_J : no spectral state transition is expected.

If the rise in \dot{m} is such that $\mu(r_J)$ decreases below the critical value μ_{\min} , then the XRB arrives at point B. Any subsequent increase in the accretion rate will then produce an outside-in JED-to-SAD transition starting from the outer part of the JED. The transition radius r_J decreases and both the MHD jet and the corona extension shrink. The XRB enters the HIS, between B and C. Since r_J is decreasing, the time-scale for the system evolution along the top branch becomes more and more rapid, in agreement with observations (e.g. Belloni et al. 2005).

Formally, the end of the top branch should be reached around point C when $r_J = r_{\text{ISCO}}$, that is, when the JED has completely disappeared and the whole disc adopts a radial structure akin to the standard disc model. However, we expect this situation to be quite variable, probably even before $r_J = r_{\text{ISCO}}$. Indeed, an important large-scale (open) magnetic field is present, providing a magnetic torque helping the MRI to drive accretion. However, it is not clear whether jets can be formed or not. In fact, the only calculations that actually proved that steady ejection can take place from a disc were done with a self-similar ansatz. Implicitly, this assumes that the radial extension of the jet emitting region is large. This is consistent with the physical interpretation that the disc material must be first radially accreting fast before being lifted up by the plasma pressure gradient and magneto-centrifugally accelerated at the disc surface by the Lorentz force. What will happen when $r_J \gtrsim r_{\text{ISCO}}$ only? Our guess is that the MHD jet structure will probably be oscillating between life and death. Accordingly, persistent radio jets should thus disappear even before point C is reached. Besides, in our framework, we also expect luminous systems to enter a flaring state as soon as the conditions for a strong pair production in the MHD funnel

are fulfilled,³ resulting in sporadic ultrarelativistic blob ejections. This could explain why this HID region seems to harbour complex variability phenomena (e.g. Nespoli et al. 2003; Belloni et al. 2005).

In C, the system enters the so-called SS. The disappearance of the MHD jet would explain the quenching of the radio emission generally observed at this stage (e.g. Corbel et al. 2003; Fender et al. 2004b). Then whatever the accretion rate does, and following our conjecture, the JED cannot reappear along the left-hand vertical branch unless $\mu(r_{\text{ISCO}})$ reaches $\mu_{\text{max}} \sim 1$. The descent from C to D must then correspond to a decrease in intensity, that is, mainly to a decrease in the accretion rate itself, with no spectral state transition. This is the beginning of the fading phase of the outburst. In our simple picture, the decrease in the disc accretion rate produces an outside-in decrease in P_{tot} leading to an increase in μ . Point D then corresponds to the situation when $\mu(r_{\text{ISCO}}) = \mu_{\text{max}}$.

This initiates the inside-out rebuilding of the accretion-ejection structure along the low horizontal branch. Note that the accretion rate must still be decreasing. However, it does not require a strong decrease in \dot{m} to build up again a JED on a significant extension (hence jets observable in radio and a change in the hardness ratio). Indeed, as said before, the steady-state radial distribution of the vertical magnetic field is steeper in a SAD ($B_z \propto r^{-\mathcal{R}_m}$, with $\mathcal{R}_m \simeq 1$) than in a JED ($B_z \propto r^{-5/4}$). As a consequence, μ may become greater than unity in the innermost disc regions with only a slight decrease in \dot{m} . There is no known steady-state disc solution at these large values of magnetization. We expect such a strong field to diffuse away outwardly in the outer SAD so that a maximum value of $\mu = 1$ can be maintained in the inner JED-like regions. Providing a time-scale is out of the scope of this Letter as it would require to take into account the whole process of the magnetic field redistribution. However, this time is probably shorter than (in the JED) or comparable to (in the SAD) the accretion time-scale. We thus expect a rather fast inside-out rebuilding of the JED with reappearance of the self-collimated electron-proton jet and the hot corona. This marks also a spectral state transition as the SAD emission is receding when going back to point A, at the end of the outburst.

4 DISCUSSION AND CONCLUSION

We present a scenario where the spectral states of X-ray binaries depend on the transition radius r_J between an inner accretion-ejection structure and an outer SAD (F06). We propose in this Letter that the variation in r_J is mostly controlled by the evolution of the accretion rate \dot{m} and the disc magnetization μ .

We made the conjecture that a SAD-to-JED transition will locally occur when μ reaches a maximum value $\mu_{\text{max}} \simeq 1$, whereas a JED-to-SAD transition requires a much lower μ : analytical estimates show that it could happen around $\mu_{\text{min}} \simeq 0.1$. It was shown that such a simple framework is enough to explain the dynamical and spectral behaviours of XRBs, providing moreover a dynamical basis for the hysteresis cycles observed in the HIDs. The exact values taken for the limits μ_{min} and μ_{max} may not be strictly equal to those chosen here as they were derived from self-similar calculations (Ferreira 1997). However, this is not crucial as the main element is the existence of such an interval. It is noteworthy though that these values are compatible with our present understanding of disc physics: there are neither SAD solutions with large-scale fields

beyond equipartition, nor JED solutions at much lower fields. However, a precise examination of the dynamical transitions between a JED and a SAD solution and vice versa remains to be done in order to assess the conjecture made here.

Interestingly, this scenario gives a physical constraint on the existence of a hysteresis cycle in a given source during an outburst. Indeed, the magnetization has to decrease necessarily below μ_{min} in the whole accretion disc during the flare. This translates into the condition that, at a given time during the burst, $\mu(r_{\text{ISCO}})$ has to become smaller than μ_{min} . If it is not the case, the source should oscillate between HS and SS with an inner JED never disappearing. Cyg X-1 could be in this situation. It is known to transit from HS to SS and reversely at the same accretion rate $\dot{m} \sim 0.01$ (e.g. Smith et al. 2002; Zdziarski et al. 2002). It is persistent in X-ray but also in radio, even if the radio emission is weaker in its softest states (Brocksopp et al. 1999 and references therein, Pandey et al. 2006). This suggests that ejection is always present. On the other hand, the strong disc signature in the SS implies that r_J is close to r_{ISCO} . Thus, for some reasons, in this object the accretion-ejection structure keeps stable even for low values of r_J . That could be linked to the fact that it is a high-mass X-ray binary system as already proposed by Smith et al. (2002) and Maccarone & Coppi (2003).

GRS 1915+105 has also a peculiar behaviour that does not match the one described in Section 3. This source is generally believed to accrete close to its Eddington limit and to stay preferentially at the top of the HID. Its ‘hard’ states would correspond to the right-hand part of the top branch while its SSs are generally observed in the left-hand part of the top branch, after the so-called jet line (Fender et al. 2004b). The flare states are observed when the source oscillates around this line. In our view, in this region of the HID the JED competes with the SAD with $r_J \sim r_{\text{ISCO}}$. The magnetic field keeps trying to re-adjust itself in the inner disc region to agree with one of the two disc solutions. This might produce the complex variability pattern exhibited by this source during outbursts (Belloni et al. 2000; Fender & Belloni 2004). Moreover, close to the ISCO the time-scales controlling the system are of the order of fractions of a second, in agreement with the rapid variability that characterizes this peculiar object.

Maccarone & Coppi (2003) and Zdziarski & Gierliński (2004) provided several other suggestions for the hysteresis behaviour of XRBs but without going much into details (see critical discussion in Meyer-Hofmeister, Liu & Meyer 2005). In fact, it seems that the most-detailed model so far is the disc evaporation model (Meyer-Hofmeister et al. 2005 and references therein). In this model, the efficiency of the SAD evaporation critically depends on the external photon field. In the SS for instance, there is mainly a Compton cooling and not much evaporation. The spectral state transitions would then be triggered at different accretion rates simply because of history, hence of a different Comptonizing spectrum (see their fig. 2). Although the physics of jet production is not included in this model, taking into account radiative effects in order to explain the HID hysteresis sounds quite reasonable and could, in principle, be integrated in our framework. In our case, however, the hysteresis has a dynamical explanation based on the disc magnetization and a two-temperature disc never settles in. Since ejection processes are known to be important in the XRB global energy budget, our suspicion is therefore that evaporation is not the main driver.

As a final note, we stress that if one is to explain self-collimated jets in XRBs, then large-scale magnetic fields in the inner regions of accretion discs must be taken into account. Their presence is both compatible with SAD physics and provides a simple and promising framework to explain hysteresis cycles. In our view, the magnetic

³ This would correspond to the jet line defined by Fender et al. (2004b), see F06 for more details.

flux available in discs is therefore a fundamental and unavoidable ingredient for modelling XRBs. Also, there is no reason why it should not vary from one system to another. Since changing the amount of magnetic flux changes the transition radius r_T , the characteristic value of \dot{m} (hence luminosity) associated with each spectral state transition is also modified. This picture becomes even more complex if accreting material is advecting magnetic flux from the secondary. Indeed, taking into account the advection of a large-scale magnetic fields within the disc introduces a whole new set of variable phenomena.

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