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Dead discs, unstable discs and the stars they surround

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Abstract. Strong stellar magnetic fields significantly alter the behaviour of surrounding accretion discs. Recent work has demonstrated that at low accretion rates a large amount of mass can remain confined in the disc, contrary to the standard assumption that the magnetic field will expel the disc in an outflow (the "propeller regime"). These "dead discs" often become unstable, causing cycles of accretion onto the central star. Here I present the main predictions of this model, and argue that it provides a good explanation for the peculiar behaviour seen in several accreting sources with strong magnetic fields. I will focus in particular on three accreting millisecond X-ray pulsars: SAX J1808.4-3658, NGC 6440 X-2 and IGR J00291+5934. These sources all show low-frequency quasi-periodic oscillations consistent with a variable accretion rate, as well as unusual outburst patterns that suggest gas is confined in the inner disc regions during quiescence.

1 Introduction

How does the presence of a strong stellar magnetic field affect the behaviour of gas surrounding it? In the inner regions of the accretion flow the magnetic field disrupts the disc and channels the gas onto the magnetic pole of the star. The coupling between the field and the disc can also allow angular momentum exchange between the two, changing the spin rate of the star.

The interaction between the disc and the magnetic field is usually divided into two distinct regimes: the standard accreting regime and the 'propeller' regime. The division depends on whether the 'magnetospheric' radius, $r_{\rm m}$ (the point where the magnetic field is strong enough to disrupt the disc), is located inside or outside the 'co-rotation radius', $r_{\rm c}$ – where the Keplerian period of the disc equals the rotation rate of the star. If $r_{\rm m} > r_{\rm c}$ accretion onto the star is inhibited, because the fast-spinning magnetosphere presents a centrifugal barrier to accretion. In the accreting regime, angular momentum is added to the star, which spins up, while in the propeller regime, the star-disc coupling that prevents accretion also transfers angular momentum from the star to the disc, spinning the star down.

Observations of magnetospherically accreting sources reveal a much more complicated phenomenology than suggested by the simple accretion/ejection picture. For example, many magnetically-accreting systems (both compact stars and protostars) show large variability on a wide variety of timescales, some of which may be attributed to various instabilities in the disc-field interaction that lead to a variable accretion rate onto the star. These are both predicted analytically and confirmed with numerical simulations of accretion onto a magnetosphere (e.g. [1–4]).

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In this report I present recent work studying the interaction between the disc and field in the 'propeller' regime, which leads to a different disc density solution from the standard accreting one and predicts bursts of episodic accretion on to the star, on timescales similar to those seen in some bursting sources. This work is outlined in more details in [5–7]. In the second half of the report, I present an overview of the growing list of astronomical objects showing variability that could be caused by this instability, focusing on NGC 6440 X-2, an accreting millisecond pulsar that shows large $\sim$ 1s variability and was recently studied in detail in the context of this model.

2 Accretion at low $\dot{M}$: forming a 'dead disc'

The truncation radius of the disc, $r_{\rm m}$, depends on the strength of the magnetic field, the amount of mass in the inner parts of the disc and the details of the disc-field coupling [5]. The corotation radius, $r_{\rm c}$, depends only on the spin rate of the star. Of these four parameters, only the amount of material in the inner disc usually changes on timescales likely to be observable, and thus determines whether the system is in a 'propeller' or 'accreting' state.

It is generally assumed that once $r_{\rm in} > r_{\rm c}$, the interaction between the disc and the magnetic field will completely expel the mass at $r_{\rm m}$ in an outflow, with the spinning magnetic field likened to a propeller flinging matter out of the system [8]. However recent work suggests this does not always happen: if the disc is truncated very close to $r_{\rm c}$ the energy exchange between the field and the disc is not large enough to launch an outflow, and the majority of the mass remains confined in the disc [1, 5].

This modified interaction between the disc and the field, which prevents material from accreting but does not expel it, changes the disc's surface density profile from the standard accreting one to a solution known as a "dead disc" [9]). In a dead disc, $r_{\rm m}$ is located where the rate of angular momentum being injected into the disc by the magnetic field balances the rate at which the disc can transport it outwards. The inner radius is thus determined by the **amount of mass** in the disc, rather than the accretion rate through it. More mass in the inner parts of the disc means that the disc can transport more angular momentum outwards, efficiently spinning the star down. If there is a net accretion rate through the disc (with matter continuing to move inwards from the disc's outer regions) accretion onto the star itself can become unstable, and manifest as episodic bursts of accretion.

3 Episodic Accretion Bursts

The accretion instability works as follows. The mean accretion rate through the disc is initially low enough that the disc cannot overcome the centrifugal barrier at $r_{\rm m}$. The rapid rotation of the magnetic field thus acts more as a dam than a propeller, and matter in the inner disc piles up. As more material piles up, the pressure from the material in the disc increases and the inner edge moves inwards. Once crosses inside $r_{\rm c}$, though, the centrifugal barrier disappears and the accumulated material is quickly dumped onto the star.

The properties of the instability are determined by the mean accretion rate onto the star, the width of the coupling between the star and disc, and the radial extent around co-rotation around which the disc moves from accreting to non-accreting. These three variables determine whether the instability appears [5], its period, and the shape and duty cycle of the accretion burst. Figure 2 shows some sample bursts.

In [7] we found two distinct regions of instability, shown in figure 2. In the first region (left panel), accretion proceeds as outlined above, and accretion onto the star is mostly suppressed while matter builds up. The period of the outburst increases with decreasing mean accretion rate, since a lower

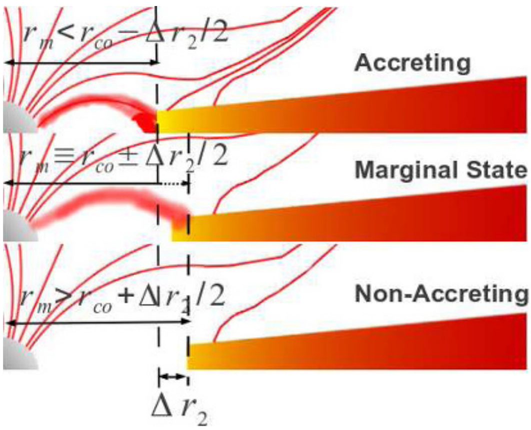

Figure 1. Schematic picture of accretion instability. Top: initially mass accretes freely onto the star. Middle: as $\dot{M}$ drops through the disc, the inner edge of the disc begins to recede, and a centrifugal barrier from the disc-field interaction appears. Top: Accretion is temporarily blocked by the star's rapidly spinning magnetic field as material piles up to drive another outburst. The whole instability takes place on timescales $0.01 - 100T_{\rm visc}$, where $T_{\rm visc}$ is the viscous timescale at the inner edge of the disc.

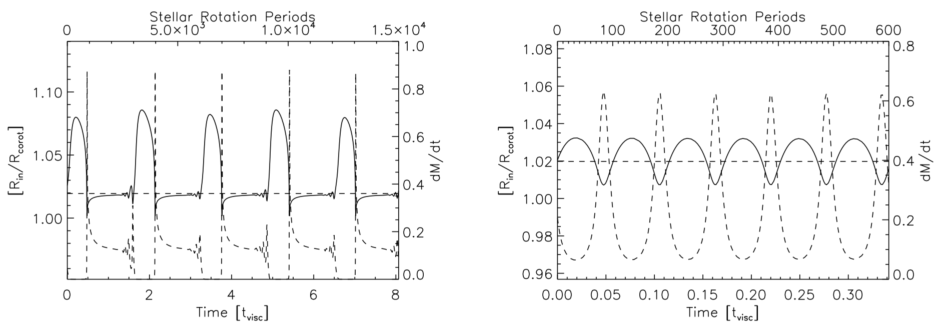

Figure 2. Accretion instability observed in our simulations. The solid line shows the change in disc inner radius, while the dashed line shows the change in accretion rate onto the star with respect to $\dot{m}_{\rm c}$, the accretion rate that would put $r_{\rm m}$ at $r_{\rm c}$.. **LEFT**: The low-frequency region of instability. The disc moves through distinct periods of outburst and quiescence and the outburst profile takes the form of a relaxation oscillator. **RIGHT**: The high-frequency region of instability. In addition to a much higher frequency of oscillation, the instability has a smoother outburst profile, and accretion continues even during the low phase of the instability.

accretion rate requires a longer time to build up enough material in the disc to power an outburst. The period of the outbursts can vary over four orders of magnitude, from $\sim 0.1 - 100T_{\rm visc}$, where $T_{\rm visc}$ is the viscous evolution timescale at $r_{\rm c}$. The outburst shape also changes substantially with changing accretion rate, although it is most sensitive to the details of the disc-field interaction (our other two parameters). The outburst profile is typically a relaxation oscillator, with an initial spike followed by a longer tail, although higher-frequency oscillations within the outburst are also frequently observed.

The second region of instability (right panel) occurs when the mean accretion rate is high enough to keep $r_{\rm m}$ close to $r_{\rm c}$. The instability has a much higher frequency than the first region (with periods between $\sim 0.01 - 1T_{\rm visc}$, and the disc continues to accrete (although at a much lower rate) throughout the instability. The shape of the outburst also changes, with a smooth transition between high and low accreting states. Since this instability occurs exactly around the transition between accreting and non-accreting states, the detailed properties of the instability are likely sensitive to the way in which

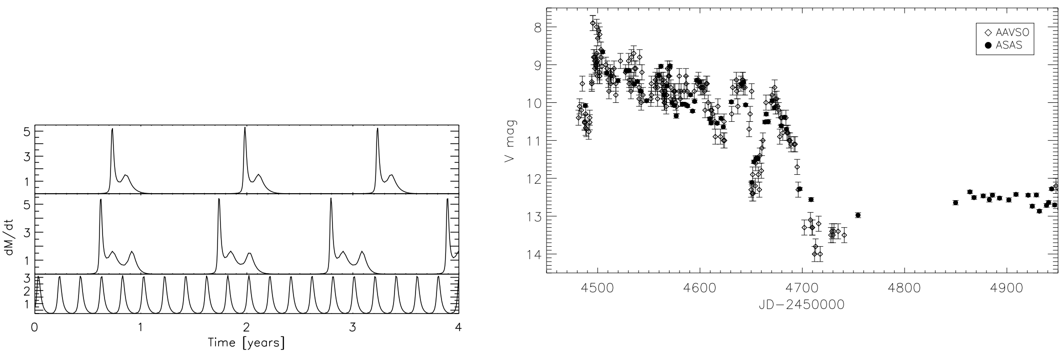

Figure 3. Left: Accretion bursts from magnetic field-disc instability. The accretion rate onto a protostar vs. time for three different average accretion rates, increasing top to bottom. [5] Right: 2008 outburst from EX Lupi. The observations start after the beginning of the outburst (∼ 4500) and continue until the return to quiescence (∼ 4710). The accretion burst structure (with quasi-periodic variations during the outburst), burst duration and intensity all qualitatively match theoretical expectations [12].

the transition takes place, which in our simulation is parameterized by two numerical parameters. Several sources, both accreting milli-second X-ray pulsars [10, 11] and protostars (e.g. [12–14]), show variability whose timescale and amplitude suggest they are caused by the instability outlined above. In [11], we argued that a careful study of the variability can be used to constrain the properties of disc-field interaction itself. I outline these findings more below.

4 Observations of Episodic Accretion and Dead Discs

4.1 EX Lupi and other EXors: extreme versions of a larger class?

EXors are a type of TTauri star which show outbursts that recur on a timescal of several years [15, 16]. The 2008 outburst from the EXor prototype star, EX Lupi, was the object of intense observational study [12, 17–19], resulting in a large data set to test against theoretical models. Recent work has also suggested that the EXor phenomenon could be a (brief) evolutionary phase common to most young stars [6], and an extreme version of a more widespread behaviour[13]. This view is supported by new survey results (e.g. [20, 21]) that report frequent large luminosity variations in young forming stars.

Several EXor outbursts appear to this picture [12–14, 14]. Figure 2 shows outbursts for different average accretion rates from [5][left] and the 2008 EX Lupi light curve [right]. EX Lupi's outburst increased 10x in luminosity, lasted ∼ 300 days with quasi-periodic variations of ∼ 35 days, roughly as predicted by [5] ([12]).

4.2 NGC 6440 X-2 and other MSPs

NGC 6440 X-2 is a transient millisecond X-ray pulsar first detected in 2009 [22] when it went into a series of unusually short (2-5 day) and weak outbursts with an unusually short recurrence time (∼ month). Further analysis revealed a strong quasi-periodic variability at a frequency of about 0.5-1 Hz. Both the frequency and the source's luminosity when it appears are similar to the 1 Hz QPO seen in another MSP, SAX J1808.4-3658 [10]. This timescale is much longer than the 4.8ms spin period of the star, suggesting the modulation is not caused by the star's rotation, but instead is driven by variations in the accretion disc.

There are several indications that the 1Hz variability is driven by a changing accretion rate (as opposed to say, obscuration). Pulsations at 4.8ms are seen wherever the QPO is seen, indicating continuous channelled accretion. There is also stronger variability at higher energies, which, given that the flux from the surface is expected to dominate the emission (from an accretion shock onto the surface), suggests the accretion rate onto the star itself is changing [11].

If the mechanism outlined above is operating in NGC 6440 X-2, then the properties of the system (the frequency of the QPO, the luminosity at which it appears, the spin period of the star) allow constraints to be placed on the extent of the disc-field coupling. [11] suggest that the extent of the coupled region (which connects the star to the disc) is only of the order of 1km, only 3% of the star's co-rotation radius. This is in sharp contrast to older pictures of magnetospheric accretion (e.g. [23]), which posit an extended connected region between the field and the disc, but in line with more recent analytic work and simulations that suggests a more limited connection between the disc and the star.

The short recurrence time for the outbursts of NGC 6440 X-2 might also be caused by the presence of a dead disc. Outbursts in accretion discs are thought to be powered by the ionization instability, in which mass builds up in the outer regions of the disc until the temperature rises enough to ionize hydrogen. This sudden increase in optical depth (from free electrons) drives a large temperature increase and increased accretion rate through the disc (see, e.g. [24] for a review). The details of ionization-driven outbursts depend *inter alia* on the surface density profile of the disc, which is altered from the standard one in a dead disc, and may affect the duration of outbursts, allowing for weaker outbursts to occur at shorter recurrence times. This picture is currently very qualitative; more work is needed to make quantitative predictions.

Similarly uncertain is how a strong stellar magnetic field might interact with a radiatively-inefficient accretion flow, believed to operate in sources at very low luminosity [25]. The simplest model of an ADAF requires a very strong propeller effect to be operating in neutron stars in quiescence [26], but recent work demonstrates that this is highly implausible for sources such as Cen X-4 that are believed to have low magnetic fields[27]. This may suggest strong outflows launched in the accretion flow; alternately the disc-field interaction may act to inhibit the formation of an ADAF solution.

5 Conclusions

The interaction between a strong stellar magnetic field and an accretion disc can produce a much more varied observational appearance than the traditional 'accretion/propeller' picture would predict. In particular, the interaction can lead to episodic outbursts of accretion through a mis-match between the accretion rate at large distances and the inhibition of accretion at the disc's inner edge. These accretion cycles have the correct amplitude and duration for variable accretion seen in a variety of systems with strong magnetic fields.

Further work is needed to explore how the disc-field interaction might couple to processes further out in the disc, such as the formation of a radiatively inefficient flow, or the onset of an ionization-driven outburst of accretion.

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