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Magnetic Accretors in Binaries

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Abstract. I consider the angular momentum balance in binaries where the accretor has a significant magnetic field. The ejector AE Aqr provides a counterexample to most simple ideas. In particular it shows that the criterion for disc formation must involve the spin rate of the accretor, and that this rate may be subject to cycles, rather than settling to an equilibrium characterized by the magnetic fieldstrength. Angular momentum loss via magnetized disc winds can never be strong enough to affect the binary evolution significantly, but spinup of the accretor can have a marked effect. Although there is strong spin–orbit coupling in the AM Her systems, this cannot produce the orbital expansion needed to explain the low accretion rate states of these systems. Instead a mechanism intrinsic to the secondary star (such as starspots) probably interrupts mass transfer in all short–period CVs: the results are seen directly in AM Her systems, but masked by the presence of an accretion disc in most other cases.

1. Introduction

Magnetic accretors are interesting because one usually has direct information about their spin (e.g. through coherently pulsed emission) and hence the rate at which they accrete angular momentum. For an accretor of mass M_1, magnetic moment μ accreting at $\dot{M}$ we get an idea of the importance of the magnetic field from the "magnetospheric radius"

$$r_\mu \simeq 2.7 \times 10^{10} \mu_{33}^{4/7} \dot{M}_{16}^{-2/7} m_1^{-1/7} \text{ cm}, \tag{1}$$

where we have measured these quantities in units of $M_\odot$, 10^{33} G cm^3 and 10^{16} g s^{-1} and respectively. We note that a neutron star of radius 10 km and a surface field of 10^{12} G has $\mu_{33} = 10^{-3}$, while a 10^9 cm white dwarf with surface field 10^6 G has $\mu_{33} = 1$.

We can compare r_μ with the binary separation

$$a = 3.5 \times 10^{10} m^{1/3} P_{\rm hr}^{2/3} \text{ cm} \tag{2}$$

where m is the total binary mass in $M_\odot$ and $P_{\rm hr}$ the orbital period $P_{\rm orb}$ in hours. It is immediately obvious that $r_\mu << a$ for all neutron–star accretors, whereas r_μ can be of the same order as or larger than a. Thus accreting magnetic white dwarfs (magnetic CVs) allow a much richer variety of behaviour than neutron–star binaries, and I shall concentrate on them in the following, although some of my remarks will apply to neutron–star binaries also.

It is straightforward, although possibly misleading as we shall see, to classify binaries according to the relative size of r_μ and a.

(a) If $r_\mu << a$ the magnetosphere does not appear to present much of an obstacle to the accretion flow, so we would expect the formation of an accretion disc in the usual way.

(b) If $r_\mu \gtrsim a$ we expect the magnetic field to dominate the accretion flow: this inequality is thought to characterize the AM Herculis systems, in which the white dwarf spin is locked to the orbital rotation, and matter accretes largely along fieldlines.

(c) In the borderline case $r_\mu \sim a$ (the intermediate polar systems) we have a complex mixture of (a) and (b). The white dwarf spins more rapidly than the binary rotation, but it is unclear how much of an accretion disc forms.

In the following I will discuss the global angular momentum balance in the cases (a – c). However first we must examine a case suggesting that the classification itself may be a little naive.

2. AE Aquarii, the Counterexample

AE Aquarii has almost the longest orbital period $P_{\rm orb} = 9.88$ hr and the shortest spin period $P_{\rm spin} = 33$ s of any magnetic CV. The orbital period implies a wide separation a (cf eq. (2)), while the rapid white dwarf spin must imply a rather low magnetic field, as for an extensive magnetospheric radius r_μ, centrifugal forces would overcome gravity and prevent accretion. Thus we expect the inequality $r_\mu << a$ to hold more strongly for AE Aqr than for any other magnetic CV. It should therefore be the most secure member of group (a) above, and hence have a well–developed accretion disc, truncated at a small inner radius by the magnetic field. Indeed this was the conventional view of this system, until Doppler tomography by Horne, Welsh and collaborators (see Wynn, King & Horne, 1996) showed conclusively that no such disc is present. Instead the rapidly–spinning white dwarf is ejecting almost all of the matter which tries to accrete on to it. This explains the fact that the white dwarf has been known for some time to be spinning down at such a rate that the mechanical luminosity exceeds the radiative output of the system.

This remarkable discovery has several important consequences. First, the failure of the classification using r_μ and a and the fact that the ejection is powered by the white dwarf's spin energy tells us that *the criterion for disc formation involves* $P_{\rm spin}$ *as well as* $\mu, P_{\rm orb}$. Second, the extremely rapid white dwarf spin can only have resulted from from spinup via an accretion disc in the past. Evidently some interruption of the accretion occurred (a nova explosion?) and the disc was then unable to re–form. Currently the white dwarf is spinning down, and if unchecked, this process would end at the "intermediate polar" (IP) equilibrium $P_{\rm spin} \sim 0.07 P_{\rm orb}$ (King, 1993; Wynn & King, 1995). However the work of Wynn et al (1996) suggests that a disc will be able to re–form at some spin period between the current 33s and the $\sim$ 40 min. IP equilibrium value. AE Aqr evidently cycles between disc–accreting and ejection phases, and may *never* actually reach either the disc or IP equilibrium spin rates. If this is true of other magnetic CVs, attempts to deduce their fieldstrengths by using $P_{\rm spin}$ and assuming that they are close to some form of spin equilibrium may be misconceived.

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3. Systemic Angular Momentum Loss via Magnetic Fields

I shall deal below with the angular momentum budget within magnetic binaries. A related question is whether angular momentum can be lost from a binary (and thus drive its orbital evolution) using magnetic fields. In the case of the secondary star the answer to this question is affirmative: the magnetic stellar wind braking which is thought to have reduced the Sun's rotation to its current slow rate is believed to extract angular momentum from binaries containing suitable secondaries (main-sequence stars of masses $\lesssim 1 M_\odot$), since the spin of this star is closely synchronized to the orbital rotation by tides. The only magnetic *primaries* which are locked in this way are the highly magnetic white dwarfs in the AM Her binaries; here the question of angular momentum loss is controversial (King, 1985; Liebert & Stockman, 1985, Hameury, King & Lasota, 1989; Wickramasinghe & Wu, 1994).

A more general process would be angular momentum loss from magnetized accretion disc winds. This type of angular momentum loss is called "consequential" (Webbink, 1985), in that it is a consequence of mass transfer, and can only *amplify* a previously existing transfer rate driven e.g. by orbital angular momentum loss $\dot{J}_{\rm orb} < 0$ via gravitational radiation or magnetic braking of the secondary. At first sight this seems a promising mechanism: a sufficiently large extended field would offer a long lever arm, allowing large angular momentum loss with modest mass loss rates from the disc. If mass is lost in circular symmetry from the disc the angular momentum subtracts directly from that of the binary. However, we must remember that the disc cannot in the long run lose more angular momentum than it gains from the secondary star, i.e.

$$|\dot{J}_{\rm disc}| < \dot{M} j_{L_1} = \dot{M} b^2 \Omega, \tag{3}$$

where $\dot{M}$ is the accretion rate into the disc, j_{L_1} is the specific angular momentum of a particle at the L_1 point w.r.t. the accretor, b the distance of this point from the accretor, and Ω the binary frequency. We can compare this with the binary's orbital angular momentum

$$J = \frac{M_1 M_2}{M} a^2 \Omega, \tag{4}$$

so that

$$\frac{|\dot{J}_{\rm disc}|}{J} < \left(\frac{b}{a}\right)^2 \frac{M}{M_1} \frac{\dot{M}}{M_2}. \tag{5}$$

For typical mass ratios M_1/M_2 the r.h.s. is about $0.5\dot{M}/M_2$, so we see that even if the disc wind carried off *all* of the angular momentum the disc received from the secondary, this would still only amplify the mass transfer rate $\dot{M} \sim -M_2 \dot{J}_{\rm orb}/J$ by a factor of order 0.5. We can conclude that angular momentum loss via magnetized disc winds is never important in driving the orbital evolution of the binary (see King & Kolb 1995 for a detailed discussion).

4. The Angular Momentum Balance in Magnetic Binaries

The three cases (a – c) discussed in Section 1 imply very different forms of angular momentum budget within the binary.

(a) If there is a well–developed disc with a small magnetosphere well within it, the angular momentum $\dot{J}_1$ absorbed or emitted by the accretor will be small compared with the total systemic loss rate $\dot{J}_{\rm orb}$ from the binary orbit, i.e. $|\dot{J}_1| << |\dot{J}_{\rm orb}|$, since the disc matter loses most of its specific angular momentum before accreting to the magnetosphere. The angular momentum taken from the orbit and supplied to the disc by the matter overflowing through L_1 is almost all returned to the orbit via tides acting on the disc edge. Spinup of the accretor ($\dot{J}_1 > 0$) slightly raises the total rate of angular momentum loss from the orbit and thus the mass transfer rate, while spindown would slightly lower it (cf Ritter, 1985).

(b) The AM Her systems are almost all thought to be magnetically locked. The most likely candidate for the locking torque $G_{\rm lock}$ which resists the spinup of the accretor by the accretion torque (see e.g. King, 1987) is some kind of dipole–dipole (d–d) torque between the white dwarf dipole μ_1 and an intrinsic or induced dipole μ_2 on the secondary, i.e.

$$G_{\rm lock} \sim \frac{\mu_1 \mu_2}{a^3}. \tag{6}$$

As a result AM Her systems are probably the only binaries in nature in which all the components rotate truly synchronously, and tides consequently play essentially no role (cf King, Frank & Whitehurst, 1990, hereafter KFW). The most important feature of the d–d torque is that it arises from a non–central force between the two dipoles, so that spin and orbital angular momentum are coupled (the *spin* torque of one dipole on the other is *not* equal and opposite to the spin torque of the second dipole on the first, so angular momentum is conserved through an orbital torque – see KFW). This has the interesting consequence that one can in principle distinguish observationally between cases in which the secondary's rotation is braked intrinsically (magnetic stellar wind braking) and a direct torque on the orbit (gravitational radiation) by examining the orientation of the primary dipole (KFW). I discuss below another possible consequence of the spin–orbit coupling in these binaries.

(c) If the accretor rotates asynchronously (i.e. $P_{\rm spin} < P_{\rm orb}$) but there is no well–developed accretion disc, spinup ($\dot{J}_1 > 0$) of the accretor can extract a large fraction of the angular momentum given to the accretion flow (unlike the case (a) of disc accretion) and thus have a potentially dramatic effect on the mass transfer rate. Indeed, if the accretor accepts all of the transferred angular momentum the mass transfer is formally adiabatically unstable, i.e. the Roche lobe R_L shrinks faster than the stellar radius R_2. If unchecked, this would cause the mass transfer rate to rise to very large values. However, the transfer rate only reacts when the relative distance $R_L - R_2$ has decreased by a distance of order the stellar scaleheight $H \sim 10^{-4} R_2$, which takes a time of order 10^5 yr. This is about the timescale for significant spinup of the accretor also, so the spin is likely to have reached an equilibrium value at which $\dot{J}_1 \simeq 0$, quenching the instability before it takes hold. This argument does however show that we would expect to find most asynchronous accretors in discless systems spinning quite close to their equilibrium rates: slower spins are rapidly "corrected". The equilibrium rate itself can either be the IP version $P_{\rm spin} \sim 0.07 P_{\rm orb}$, where the accreted angular momentum is balanced by the secondary's recapture of high specific–a.m. matter flung out by the accretor, or the complete centrifugal expulsion of almost all the transferred mass and angular momentum. Surprisingly perhaps, the latter situation is adiabatically stable ($\dot{R}_L - \dot{R}_2 > 0$) for reasonable mass ratios, something noted by Wynn & King (1995) but regarded as a theoretical curiosity until the discovery that AE Aqr actually behaves like this.

5. Low States

The spin–orbit coupling of the AM Her systems noted in (b) above offers a tempting, but as we shall see, incorrect, explanation for another of their observed properties, namely the presence of intermittent states of low accretion rate (see e.g. Cropper 1990 for a review). For if we can inject some spin angular momentum into the orbit, we might hope to increase the binary separation enough to reduce the mass transfer rate. However this idea fails because of the magnitude ΔJ of the required angular momentum exchange. To reduce the mass transfer rate by the observed factor ~ 10 requires us to expand the Roche lobe R_L by rather more than a scaleheight H. Thus we require

$$\frac{\Delta J}{J_{\rm orb}} \sim \frac{\Delta a}{a} \gtrsim \frac{H}{a} = \frac{H}{R_2}\frac{R_2}{a} \gtrsim 2.5 \times 10^{-5}, \tag{7}$$

which must be supplied in the observed time ($\lesssim$ days) for transition to the low state in an AM Her system. To see what an extremely demanding requirement this is we need only remember that the usual orbital angular momentum loss mechanisms (magnetic braking, GR) take $\sim 10^9$ yr to reduce $J_{\rm orb}$ by a factor ~ 2 or so. The spin–orbit torque supplying ΔJ would have to be about one million times stronger than $\dot{J}_{\rm orb}$! In fact the d–d torque is only of the same order as $\dot{J}_{\rm orb}$: this is obvious from the fact that the d–d torque provides the locking torque $G_{\rm lock}$ which balances the accretion torque $\dot{J}_{\rm acc} \sim \dot{M}b^2\Omega \sim 0.5\dot{J}_{\rm orb}$.
We can conclude that the low states in AM Her systems do not result from their angular momentum balance. This is actually reassuring, in that low states are also seen in at least one IP (V1223 Sgr) and some non–magnetic CVs (the VY Scl systems) where there is no such spin–orbit coupling. Use of Occam's razor suggests that we should seek a common explanation for all types of system. In fact there is now only one possible type of explanation: since we evidently cannot make the Roche lobe R_L bigger, we must make the effective stellar radius R_2 (near L_1) smaller. This is precisely the effect of starspots: the photosphere is both lowered and made cooler, so that the scaleheight of the star is significantly reduced, and with it the transfer rate, the precise factor depending on the relative area of the spot and the region around L_1 where mass overflows. As there is no accretion disc in an AM Her system this drop is immediately reflected in the accretion luminosity.
Of course this idea has surfaced many times before, but the standard objection is to ask why such starspots only appear in AM Her and VY Scl systems, and not all CVs at similar orbital periods (and thus similar secondary spectral types). In particular one would like to know why low states are generally not observed in dwarf novae The answer to this appears to be that starspots *do* appear in these other systems, but their effects are masked by the presence of an accretion disc. In dwarf novae it is believed that the modest mass transfer rate makes the disc subject to thermal–viscous instabilities which produce the observed

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outbursts (see Cannizzo 1993 for a review), while steady systems have higher mass transfer rates that keep the whole disc in the hot (stable) state. If a starspot interrupts mass transfer in one of the latter systems, the whole disc immediately makes a transition to the cool state, as required to give a low state of a VY Scl system. Evidently the spot must disappear or move away from L_1 before the disc undergoes an outburst, as these are not observed in low states. In a dwarf nova the disc is already cool between outbursts, and as Cannizzo (1993) has emphasized, only a few precent of the total disc mass is involved in a typical outburst. Accordingly, simulations of dwarf nova discs in which the mass transfer rate is suddenly reduced by a large factor do not show low states: the outbursts continue, decaying in amplitude only quite gradually. If each outburst consumes a fraction $\epsilon << 1$ of the disc mass $M_{\rm disc}$, then after n outbursts the latter has been reduced to

$$M_{\rm disc} = (1-\epsilon)^n M_0, \tag{8}$$

where M_0 was the original mass. If for example $\epsilon = 0.03$, then even after $n = 10$ outbursts the disc mass is still 74% of M_0. It may thus be that while interruption of the mass overflow through L_1 by starspots (or indeed, some other process) is universal in CVs with $P_{\rm orb}$ less than some value (~ 4 hr?), only systems without well–developed discs, such as the AM Her systems, reveal this directly.

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Discussion

J.-P. Lasota: Is a neutron star equivalent of AE Aqr possible?

A. King: Neutron star magnetospheres are so much smaller than white dwarfs that it seems unlikely — the magnetic field must influence the dynamics at the circularisation radius, and the spin rate must be slow enough that this radius is inside the light cylinder.

U. Torkelsson: To modulate the accretion rate in an AM Her system is it really a star spot that is needed in the low state, or is it rather an open magnetic field, a coronal hole, that is needed in the high state?

A. King: Anything that tends to block or reduce the outflows from the L_1 region will do, provided of course that it is not permanently located there.

P. Szkody: There are several dwarf novae that are now known to have low states (HT Cas, BZ UMa). How do these fit into this picture?

A. King: We have still to investigate all the possibilities systematically. In particular one will get different behaviour depending on the mass transfer rate immediately preceding the low state. The systems you refer to may have rather low mass transfer rates (near the lower boundary of the disk instability strip).

C. Mauche: Would you expect that dwarf nova outbursts would switch to purely inside-out after the mass transfer rate from the secondary is switched off, whereas previously it was possible to have both inside-out and outside-in outbursts.

A. King: We have not yet checked this, but it seems plausible.

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