Magnetic torques between accretion discs and stars

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ABSTRACT
I show in this paper that two types of magnetic torques can appear in the interaction between an accretion disc and a magnetic accretor. There is the well-known torque resulting from the difference in angular velocity between the accretion disc and the star, but in addition there is a torque coming from the interaction between the stellar magnetic field and the disc's own magnetic field. The latter form of magnetic torque decreases in strength more slowly with increasing radius, and will therefore dominate at large radii. The direction of the disc field is not determined by the difference in angular velocity between the star and the disc as in the Ghosh & Lamb model, but rather is a free parameter. The magnetic torque may therefore either spin up or spin down the star, and the torque changes sign if the magnetic field in the disc reverses. I suggest that this mechanism can explain the torque reversals that have been observed in some disc-fed X-ray pulsars.

Key words: accretion, accretion discs – magnetic fields – MHD – stars: neutron – stars: pre-main-sequence – X-rays: stars.

1 INTRODUCTION
The interaction between a magnetic star and a surrounding accretion disc is one of the least understood aspects of accretion. At the same time it is of importance for understanding the spin evolution of objects as diverse as T Tauri stars and X-ray pulsars. The generally adopted model (Ghosh & Lamb 1979a) has been challenged by recent observations of X-ray pulsars (e.g. Nelson et al. 1997). I will discuss how the Ghosh & Lamb model fits in with current thinking regarding the angular momentum transport in accretion discs, and show that a modification of the Ghosh & Lamb model is necessary.

T Tauri stars come in two forms: classical T Tauri stars which show clear signs of having accretion discs and are slow rotators; and weak-lined (naked) T Tauri stars which are fast rotators and lack the signature of an accretion disc. The weak-lined T Tauri stars are believed to represent a later evolutionary stage, when the star has got rid of its accretion disc. Models of the rotational evolution of the T Tauri stars based on the magnetic interaction between the disc and the star have been constructed by several groups (e.g. Cameron & Campbell 1993; Cameron, Campbell & Quaintrell 1995; Armitage & Clarke 1996).

At the other end of the range of magnetic accretors are the accreting neutron stars. BATSE/CGRO has made it possible to obtain essentially daily measurements of the spin frequencies of a number of the brightest X-ray pulsars. Some of these systems are known to possess accretion discs, although other objects in the group are accreting directly from a stellar wind. I will not pay any attention to the latter objects in this paper. Nelson et al. (1997) have found that the X-ray pulsars are oscillating between periods of spin-up and spin-down. The frequency derivatives are comparable (apart from the difference in the sign) in the two states, and a typical system spends about the same amount of time in each of the two states. The length of time that a system spends in one of the states before switching to the other state differs widely between the different systems: in the case of Cen X-3 it is 10–100 d, but 4U 1626–67 has only been observed to switch once, and thus may stay for 10 yr or more in one state.

The standard model for the spin changes was presented by Ghosh & Lamb (1979b). They describe the interaction of a dipolar stellar magnetic field with a diffusive disc. The dipolar magnetic field is penetrating the disc, which winds up the magnetic field in the toroidal direction, because of the angular velocity difference between the accretion disc and the star. The corotation radius, where the angular velocities of the disc and the star are the same, plays a key role in this model. The magnetic field lines penetrating the disc inside the corotation radius spin up the star, whilst those penetrating the accretion disc outside the corotation radius brake the star. The spin evolution of the star is therefore the result of a balance between the angular momentum carried by the accreting matter from the disc to the star, the magnetic spin-up torque from the accretion disc inside the corotation radius, and the magnetic spin-down torque from the accretion disc outside the corotation radius. The position of the inner edge of the accretion disc varies with the accretion rate such that it moves closer to the star when the accretion rate increases. Thus we expect the star to spin up, or at least spin down more slowly, when the accretion rate, or...
equivalently the luminosity, is high. Wang (1987) showed, though, that the model is inconsistent in that the magnetic pressure exceeds the gas pressure of the disc outside the corotation radius, although it had been assumed that the magnetic pressure could be neglected. Wang suggested a modified mechanism for generating the toroidal magnetic field that allowed for a smoother transition between the Keplerian rotation of the disc and the stellar rotation. The magnetic field and torque are weaker outside the corotation radius in his model.

A complicated, and not yet fully solved, problem involves the position and physical properties of the boundary layer between the accretion disc and the stellar magnetosphere. Ghosh & Lamb (1979a) presented solutions for the boundary layer, but, instead of solving for the magnetic field in the disc given a certain magnetic diffusivity, they assumed a magnetic field and solved for the diffusivity. Campbell & Heptinstall (1998) and Brandenburg & Campbell (1998) have recently presented solutions for the magnetic field and velocity in the disc given a certain model for the magnetic diffusivity. The disc is terminated as the magnetic force becomes stronger than the viscous force in the disc (cf. Campbell 1992, 1997). The temperature and disc thickness increase dramatically close to the inner disc edge, and the disc is subject to a viscous instability similar to the Lightman–Eardley instability (Lightman & Eardley 1974; Lightman 1974). The torques generated in these models are unrealistically large, though, because the azimuthal magnetic fields are overestimated.

Ghosh & Lamb (1979b) calculated the torque acting on the star by integrating over the surface of the disc. This is without a doubt the most convenient approach, but it does not provide much information on how the torque is transferred to the star. To understand this problem it is necessary to obtain a solution for the structure of the magnetosphere. Simple solutions assuming no flows through the magnetosphere have been presented by Bardou & Heyvaerts (1996). It is in general assumed that the stellar magnetic field is closed, but Saifer (1998) notes that the magnetic activity of a T Tauri star will heat up the atmosphere of the star and thus produce a corona and a stellar wind. This stellar wind should not be confused with the jets, which are typically much more open than has been assumed in the past, but one must be cautious in interpreting the numerical simulations, as all of them are limited to axisymmetric flows and follow the evolution for only a few dynamical time-scales.

The purpose of this paper is to explore how a disc dynamo may affect the exchange of angular momentum between the accretion disc and the star. I compare the torque generated by the winding up of the stellar magnetic field with the torque generated by the coupling between a stellar magnetic field and a dynamo-generated magnetic field in the disc in Section 2. The existence of two different forms of magnetic torques may influence the spin evolution of the X-ray pulsars, as suggested in Section 3. Finally, my conclusions are summarized in Section 4.

2 MAGNETIC TORQUES

We can distinguish between two different ways in which the accretion disc and the star exchange angular momentum: matter flowing over from the disc to the star carries with it angular momentum, and the magnetic stress at the disc surface exerts a torque on the disc. The torque arising from the angular momentum carried by the accreting matter from the inner edge of the disc is

$$\tau = M \left(G M r_0 \right)^{1/2},$$

where $M$ is the accretion rate, $G$ the gravitational constant, $M$ the mass of the accreting star, and $r_0$ the inner radius of the disc. For the rest of this paper it is useful to write

$$r_0 = \xi r_A,$$

where $r_A$ is the Alfvén radius

$$r_A = \left( \frac{2 \pi \mu^4}{G M M_r \mu_0^2} \right)^{1/7},$$

$\mu_0$ is the permeability of free space, and $\mu$ is the magnetic dipole moment of the accreting star. To calculate $\xi$, a detailed model of the accretion disc is needed (Ghosh & Lamb 1979a), but its value is typically around 0.5 (e.g. Frank, King & Raine 1992). The torque can now be written as

$$\tau_{acc} = \left(2 \pi^2 \right)^{1/4} \xi^{1/2} \tau_0,$$

where

$$\tau_0 = \left( \frac{(G M M_r)^{1/2} \mu^3}{\mu_0^2} \right)^{1/7}.$$  

The magnetic torque is the result of the coupling between the vertical magnetic field of the star and the toroidal magnetic field in the disc. The torque acting on the upper surface of the disc can be written as

$$\tau_{mag} = 2 \pi \int_{r_1}^{\infty} \frac{B r B_z}{\mu_0} r dr,$$

where $B_z$ is the vertical magnetic field, $B_\phi$ the toroidal field and $\mu_0$ the magnetic permeability of free space. There is a similar contribution, but with the opposite sign, from the lower surface, thus angular momentum is exchanged between the disc and the star only if $B_z$ changes sign from the upper to the lower surface. This is true if $B_\phi$ is generated by the winding up of the stellar magnetic field, but it is not true for a quadrupolar magnetic field generated by a disc dynamo. Linear mean-field $\alpha$-dynamo with a positive $\alpha$-effect (e.g. Stepiński & Levy 1990; Torkelsson & Brandenburg 1994a) generate preferentially quadrupolar magnetic fields, but non-linear
αΩ-dynamo can generate a large range of different magnetic field configurations (Torkelsson & Brandenburg 1994b). It is not necessary that $B_0$ is coherent across the entire accretion disc, because, as we will see later, the magnetic torque is concentrated to the region inside $2r_0$.

2.1 The torque arising from the winding up of the stellar field in the disc

A toroidal field is generated in the disc because the angular velocities of the disc and the star match only at the corotation radius, $r_{co}$. Inside $r_{co}$ the disc rotates faster than the star so that $\Omega_0B_0 < 0$ at the upper surface of the disc, and the disc is losing angular momentum to the star, whilst $\Omega_0B_0 > 0$ outside $r_{co}$ and the disc is gaining angular momentum from the star. To calculate $\tau_0$, one must know the magnetic diffusivity in the disc (e.g. Campbell & Heptinstall 1998; Brandenburg & Campbell 1998). A simpler approach is to write $B_0 = \gamma B_\ast$, where the azimuthal pitch $\gamma \approx 3$ is assumed to be constant (e.g. Ghosh & Lamb 1979a). Obviously this approach must fail close to $r_{co}$, where the shear vanishes. Neglecting this technical complication, I calculate the torque acting on the star arising from the interaction between the stellar dipole field and the disc:

$$\tau_{\text{mag}} = 2 \times 2\pi \int_{r_{co}}^{r_0} \left( \frac{\gamma \mu^2}{\mu_0 r} r^2 dr - \int_{r_0}^{r_\ast} \frac{\gamma \mu^2}{\mu_0 r^2} r^2 dr \right)$$

$$= \frac{4\pi \gamma \mu^2}{3\mu_0 r_0^3} \left( 1 - 2 \left( \frac{r_0}{r_{co}} \right)^3 \right),$$

(7)

where $\mu$ is the magnetic dipole moment. Substituting $r_0$ from equation (2), we obtain

$$\tau_{\text{mag}} = \frac{2(16\pi)^{1/3}}{3} \gamma^{2/3} (1 - 2\omega^2) \tau_0,$$

(8)

where the ‘fastness’ parameter $\omega_0^2 = (r_0^4/GM)/(r_\ast^4/GM)$ (Elsner & Lamb 1977) is introduced.

2.2 The torque arising from the coupling between the stellar dipolar magnetic field and a dynamo-generated toroidal field in the disc

It is now widely believed that the accretion is driven by a magnetic stress that is generated by a dynamo in the accretion disc (e.g. Brandenburg et al. 1995; Matsumoto & Tajima 1995; Stone et al. 1996). The torque needed to drive the accretion is

$$\dot{M} \sqrt{GM\tau}.$$  

(9)

The magnetic torque, on the other hand, can be written as

$$\frac{2\pi^2 H}{\mu_0} B_0 B_\ast,$$

where $2H$ is the thickness of the disc. I write $B_0 = \gamma_{\text{dyn}} B_\ast$, where $\gamma_{\text{dyn}} \sim 10$ (Brandenburg 1998). Equating equations (9) and (10), the dynamo-generated toroidal field is

$$B_\ast = \sqrt{\frac{\dot{M} \gamma_{\text{dyn}} B_\ast (GM\tau)^{1/4}}{4\pi r^2 H}},$$

(11)

which falls off more slowly with $r$ than the field that is generated by the winding up of the stellar dipole field in Section 2.1. This may be a lower limit to $B_\ast$, as the work by Brandenburg & Campbell (1998) suggests that the torque in equation (10) must be much larger than the torque in equation (9) to redistribute the angular momentum exchanged with the star.

The Shakura–Sunyaev (1973) model predicts that $H Ir \approx r^{1/8}$ for a geometrically thin, optically thick disc in which the gas pressure dominates over the radiation pressure. Because this is sensitive to the opacity and equation of state, and to keep things simple, I will take $H Ir$ to be a constant. The torque arising from the coupling between the stellar field and the dynamo-generated toroidal field in the disc is then

$$\tau_{\text{mag,dyn}} = 2 \times 2\pi \int_{r_{co}}^{r_0} \frac{1}{\mu_0 r^3} B_\ast dr$$

$$= \frac{4\sqrt{3}}{5}(H Ir)^{-1/2} \left( \frac{4\pi \gamma_{\text{dyn}} \mu^2}{3\mu_0 r_0^3} (GM^2 r_0)^{1/4} \right)$$

(12)

of either sign. This can be rewritten using equation (2) as

$$\tau_{\text{mag,dyn}} = \frac{4}{5} \left( \frac{2(2\pi)^{1/3}}{12} \right)^{1/2} \gamma_{\text{dyn}}^{1/2} (H Ir)^{-1/2} \tau_0.$$  

(13)

This is in a sense an upper limit to the torque caused by the disc dynamo, as it requires the toroidal magnetic field to be aligned across the entire disc. It is common practice in accretion disc theory to assume that the typical length-scale of any turbulent quantity is of the order of the scaleheight $H$. This suggests that we should multiply the torque above with a factor $(H Ir)^{1/2}$, if the magnetic field is axisymmetric, but varies randomly in the radial direction, and by a factor $H Ir$, if it is not even axisymmetric.

The numerical simulations by Brandenburg et al. (1995) do show that the turbulence is able to generate a strong toroidal field that is nearly axisymmetric, but they do not contain any information on the radial length-scale of the magnetic field owing to the local approach of the simulations. Large-scale magnetic fields have been observed in disc galaxies (e.g. Beck et al. 1996), which suggests that they may appear in accretion discs too. Furthermore, half of the torque is concentrated inside $1.74r_0$, so it is sufficient if the magnetic field is coherent over a length-scale $\sim r_0$. The typical time-scale for reorganizing the large-scale magnetic field is comparable to the diffusive time-scale of the disc, which, I show below, is comparable to the time-scale of the observed variations in the torque of some disc-accreting X-ray pulsars.

An assumption in this and most other work on the magnetic coupling between a star and an accretion disc is that the stellar magnetic field is dipolar. In reality, the stellar field at the disc may be weakened by screening currents in the disc, or the stellar field may be partially open so that the field lines do not penetrate the disc. These effects decrease $\tau_{\text{mag}}$ more than $\tau_{\text{mag,dyn}}$, as $\tau_{\text{mag}}$ depends quadratically on the stellar magnetic field while $\tau_{\text{mag,dyn}}$ depends linearly on the magnetic field.

3 DISCUSSION: THE SPIN EVOLUTION OF DISC-ACCRETING X-RAY PULSARS

X-ray pulsars are the best laboratories for studying the exchange of angular momentum between the accretion disc and the accreting star, because the moment of inertia of a neutron star is comparatively small, and an X-ray pulsar can be timed accurately. The torque is measured from the change in spin frequency

$$\dot{\nu} = \frac{\tau}{2\pi I},$$  

(14)

where $I$ is the moment of inertia of the neutron star. Adding equations (5), (8), and (13), the spin change is

$$\dot{\nu} = 2.4 \times 10^{-14} \text{ Hz s}^{-1} I_{40}^{1/7} M_{14}^{3/2} \mu_{30}^{1/2} r ,$$  

(15)
where

\[ \dot{I} = 1.2 \xi^{1/2} + 1.2 \frac{2}{\xi} (1 - 2a^2) \pm 1.7 \left( \frac{\gamma_{\text{dyn}}}{\xi^{3/2}} \right)^{1/2} \left( \frac{H}{r} \right)^{-1/2}, \]

(16)

\[ I_{00} = \frac{1}{10^{40}} \text{ kg m}^2, \quad m = M/M_\odot, \quad M_4 = 10^{14} \text{ kg s}^{-1}, \quad \text{and} \quad \mu_{20} = \mu/10^{20} \text{ T m}. \]

The Ghosh & Lamb (1979b) model, which corresponds to the first two terms above, predicts that at a sufficiently low accretion rate the torque is spinning down the neutron star, but, as the accretion rate increases and the inner disc edge is pushed closer to the neutron star, the torque changes sign, and the spin-up torque increases with increasing accretion rate. At high accretion rates

\[ \dot{I} \propto \frac{M_4^{1/2}}{r^2}. \]

(17)

It is difficult to derive any form of similar relation when the angular momentum exchange is dominated by the coupling to a dynamo-generated magnetic field in the disc.

The number of timing data of X-ray pulsars has increased dramatically since the launch of BATSE/CGRGO. Bildsten et al. (1997) have recently presented a compilation of five years of monitoring of X-ray pulsars. Most X-ray pulsars are fed by stellar winds from their supergiant companions, and are therefore irrelevant for this paper. There are two groups of X-ray pulsars that have accretion discs. These are the Be/X-ray transients and an inhomogeneous group of binaries with steady accretion discs. The neutron stars in the Be/X-ray transients sometimes pick up an accretion disc: the time at which the periastron passage, which leads to an outburst of X-rays. The observations of transient X-ray pulsars, such as EXO 2030+375 (e.g. Reig & Coe 1998) and A0535+262, give some support to the Ghosh & Lamb model, as the X-ray pulsars spin up during the outbursts, and the spin-up rate decreases as the X-ray flux goes down, but a major uncertainty is the relation between the observed X-ray flux and the accretion rate (Bildsten et al. 1997).

The persistent X-ray pulsars with accretion discs are comparatively few and make up an inhomogeneous set. The systems that I will discuss in the following are 4U 1626–67, GX 1+4, Cen X-3 and OAO 1657–415, in which the mass-losing stars are a degenerate dwarf, a red giant, an O6-8 supergiant and an OB supergiant respectively. 4U 1626–67 had been spinning up steadily at a rate \( \dot{\nu} = 8.5 \times 10^{-13} \text{ Hz s}^{-1} \) from its discovery by Uheru (Giacconi et al. 1972) until the beginning of the BATSE observations, but it is now spinning down just as steadily at a rate \( \dot{\nu} = -7.2 \times 10^{-13} \text{ Hz s}^{-1} \) (Chakrabarty et al. 1997a). GX 1+4 is similar in the sense that it was also discovered in a state of spinning up at \( \dot{\nu} = 6.0 \times 10^{-12} \text{ Hz s}^{-1} \) (Davidson, Malina & Bowyer 1977; Nagase 1989), but since the days of Ginga (Makishima et al. 1988) it has been spinning down at \( \dot{\nu} = -3.7 \times 10^{-12} \text{ Hz s}^{-1} \). Chakrabarty et al. (1997b) have studied the correlation between the pulsed X-ray flux in the 20–60 keV band and the spin-down rate of GX 1+4. There is no clear correlation, and the largest spin-down rates seem to occur at the highest X-ray fluxes, which contradicts the Ghosh & Lamb model.

Cen X-3 shows an altogether different behaviour. On average it is spinning up at a rate \( \dot{\nu} = 8 \times 10^{-13} \text{ Hz s}^{-1} \), but BATSE revealed a lot of fine structure in its spin evolution, and it is alternating between spin-up and spin-down phases with \( \dot{\nu} = 7 \times 10^{-12} \) and \( -3 \times 10^{-12} \text{ Hz s}^{-1} \), respectively (Bildsten et al. 1997). Typically it spends 10 to 100 d in one state before switching to the other state faster than can be resolved by BATSE. OAO 1657–415 appears to be a sister system of Cen X-3, although the companion has not been identified.

The existence of two states of comparable but oppositely directed torques is not expected from the Ghosh & Lamb model. It is, though, a natural consequence, if \( \dot{I} \) is dominated by its last term, the coupling between the stellar magnetic field and the dynamo-generated field in the disc. In that case we expect the spin-up torque to be somewhat larger than the spin-down torque, in agreement with the observations.

There are two time-scales that must be explained, the time-scale over which the torque is constant, and the time-scale for reversing the torque. These time-scales are 10–100 d and less than 10 d, respectively, for Cen X-3. In the cases of GX 1+4 and 4U 1626–67, on the other hand, the torque remains constant for several years, and the sparse sampling at the time of torque reversal provides a generous upper limit for the time-scale of the torque reversal. The time-scale for reversing the torque should be the same as the time-scale for reversing the magnetic field via diffusion in my model. I assume the diffusive time-scale to be comparable to the viscous time-scale

\[ t_{\text{visc}} \sim \frac{r^2}{\nu_{\text{turb}}} = \alpha_{\text{SS}} \left( \frac{H}{r} \right)^{-2} \Omega^{-1}, \]

(18)

where \( \nu_{\text{turb}} = \alpha_{\text{SS}} H c_\iota \) is the turbulent viscosity, \( \alpha_{\text{SS}} \) the Shakura–Sunyaev (1973) parameter, and \( c_\iota \) the sound speed. The dynamo torque is so strongly concentrated in the inner part of the disc that half of the torque is due to the disc inside 1.74\( r_r \). The viscous timescale at this radius is typically less than 0.5 d.

It is much less clear what sets the time-scale over which the magnetic torque is constant. The ratios of the intervals between torque reversals and the orbital periods may be roughly comparable for Cen X-3 and GX 1+4, though only lower limits to the orbital period of the latter are known (Chakrabarty & Roche 1997). The time interval between the torque reversals is comparable to the viscous time-scale for the entire disc, which suggests that the timescale is set by the time over which the disc can support a given field configuration against diffusion. This speculation fails completely in the case of 4U 1626–67, which is the smallest of the systems that I have discussed, and yet the torque remains constant over a timescale of several years.

Some other mechanisms have been proposed to explain the transitions between spin-up and spin-down states in X-ray pulsars. van Kerkwijk et al. (1998) note that the accretion disc can be subject to a warping instability owing to the irradiation from the neutron star. This warp may be so extreme that the outer part of the accretion disc flips over and rotates in the opposite direction, which would lead to a torque reversal. Yi, Wheeler & Vishniac (1997) suggest a modification of the Ghosh & Lamb model. The torque reversals are due to small changes in the accretion rate, but the inner part of the accretion disc changes between a standard thin disc and an advection-dominated flow at the same time. The advection-dominated flow is less efficient in radiating energy, which can solve the problem of the lack of a correlation between the torque and the observed X-ray flux. A third possibility was suggested by Nelson et al. (1997). The spin-down can be explained if the disc is retrograde, which was first suggested by Makishima et al. (1988). It is difficult to see how a retrograde disc can appear in a Roche lobe overflow, but numerical simulations of accretion from winds have shown that a temporary disc rotating in the ‘wrong’ direction may appear (e.g. Fryxell & Taam 1988).

4 SUMMARY

I have shown that the torque acting between an accretion disc and an
accreting star can be enhanced by the presence of an intrinsic magnetic field in the accretion disc. The orientation of the magnetic field in the disc, and thus the direction of the magnetic torque between the disc and the star, is arbitrary, because the dynamo does not have any information on the rotation of the neutron star. In particular, it is therefore possible to reverse the torque by reversing the magnetic field in the disc. This mechanism may explain the observed torque reversals in some X-ray pulsars that are fed by accretion discs. The short time-scale for the reversals compared with the long time-scale over which the torque remains the same may be explained as the difference between the diffusive (viscous) time-scales for the inner region of the disc, to which the torque is concentrated, and the entire accretion disc. A problem with this connection is that it cannot explain the stability of the torque in the short-period X-ray binary 4U 1626–67.

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