Magnetically modulated accretion in T Tauri stars

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ABSTRACT

We examine how accretion on to T Tauri stars may be modulated by a time-dependent ‘magnetic gate’ where the inner edge of the accretion disc is disrupted by a varying stellar field. We show that magnetic field variations on time-scales $\ll 10^5$ yr can modulate the accretion flow, thus providing a possible mechanism both for the marked photometric variability of T Tauri stars and for the possible conversion of T Tauri stars between classical and weak line status. We thus suggest that archival data relating to the spectrophotometric variability of T Tauri stars may provide an indirect record of magnetic activity cycles in low-mass pre-main-sequence stars.

Key words: stars: formation – stars: T Tauri – stars: rotation – stars: magnetic fields – accretion discs

1 INTRODUCTION

The relationship between classical and weak line T Tauri stars (henceforth CTTs and WTTs) remains an open question in the study of pre-main-sequence stellar evolution. Whilst a number of spectral diagnostics suggest that CTTs are associated with material close to the stellar photosphere, it is not all clear whether the weak line systems (which lack such signatures) are necessarily devoid of circumstellar material at all radii and are thus, permanently and irreversibly, truly naked systems. The strongest argument that this is not the case is provided by the observation that a number of T Tauri systems have been observed to switch between strong and weak line status on a time-scale of decades (Herbig & Bell 1988). Since this time-scale is considerably less than even the fastest (dynamical) time-scale associated with any reservoir of material at large radius it is clear that, in these systems, the transition between CTT and WTT status is controlled by processes close to the star. By implication, therefore, at least some stars classified as WTTs must be indistinguishable on the large scale from some CTTs. Further support for this view is provided by the overlap in stellar parameters between the WTTs and CTTs as a class, both in terms of their location on the Hertzprung-Russell (HR) diagram and in terms of their angular momentum per unit mass. Furthermore the detection of spectral excesses in some WTTs at submillimetre or near-infrared wavelengths has been claimed as evidence that some systems are ‘weak’ in terms of their circumstellar material close to the star but are nevertheless associated with matter at large radii (Strom et al. 1989; Beckwith et al. 1990), although this claim remains controversial (Walter et al. 1992).

In this paper we propose a simple mechanism that can allow systems to switch between weak line and strong line status, and may also give rise to the pronounced photometric variability of T Tauri stars on a time-scale of decades. We argue that variations in both the lines and continuum are related to accretion processes close to the star, and that these are modulated by a time-dependent magnetic ‘gate’ at the inner edge of an accretion disc. In this model the disc is disrupted by the magnetic field of the central star at a distance of a few stellar radii; material can, however, only flow down the field on to the star if the star is rotating more slowly than the local Keplerian frequency of the disc at the magnetosphere. If, therefore, the field is variable, the changing location of the magnetosphere can give rise to alternating phases of storage of material in the disc and of accretion on to the star. We thus suggest that the variability pattern of T Tauri stars may provide indirect evidence of the cycles of magnetic activity in pre-main-sequence stars, analogous to the similar record inferred from chromospheric variations of main-sequence dwarfs (Baliunas 1988).

In Section 2 we set out the model in more detail, estimating the field strengths and variability time-scales for which the magnetic gate would work in the way outlined above. In Section 3 we discuss the model in relation to a variety of observational parameters of T Tauri stars.

2 THE MODEL

In this section we set out the model of magnetically coupled T Tauri-disc systems and derive the conditions under which
such a model can modulate the accretion flow on to the central star.

We assume that the central star possesses an ordered magnetic field on large scales whose axis is aligned with the rotation axis of the star. Furthermore, following Ghosh & Lamb (1973), and subsequent authors we assume that the field is able to penetrate the disc as a result of a variety of micro-instabilities that ensure efficient mixing between the field and disc plasma. Apart from a narrow region around corotation between disc and star, the mismatched angular velocity between field lines (corotating with the star) and Keplerian disc material ensures that the field exerts a torque on the disc, transferring angular momentum from/to the disc respectively inward/outward of corotation.

In such a situation, a disc of material flowing inwards under the action of viscosity is first significantly perturbed by the field at radius $r_m$ where the magnetic torque becomes comparable with the local viscous torque (Bath et al. 1974, Campbell 1992). (Note that, owing to the ordering of the magnitude of the viscous torque per unit volume and the thermal and dynamical energy densities in accretion discs, such a criterion is satisfied when the magnetic pressure is negligible compared with either the thermal or ram pressure in the disc; one can therefore use unperturbed disc structure equations in the estimation of $r_m$.) For steady-state disc flow around a star of mass $M_*$, at accretion rate $\dot{M}$, the differential torque across an annulus of width $dr$ is given by

$$\frac{dG_\nu}{dr} = \frac{\dot{M}}{2} \left( \frac{GM_*}{r} \right)^{1/2},$$

where $G_\nu$ denotes the torque due to viscous processes in the disc. The corresponding differential magnetic torque is

$$\frac{dG_m}{dr} = r^2 B_\phi B_z,$$

where $B_z$ and $B_\phi$ are the vertically averaged poloidal and toroidal components of the field respectively. Equating these quantities, the magnetospheric radius then satisfies

$$B_z B_\phi|_{r_m} = \frac{\dot{M}}{2} \left( \frac{GM_*}{r_m} \right)^{1/2}.$$

We follow previous authors (e.g. Cameron & Campbell 1993; Königl 1991) in assuming that, whatever the chaotic field structure near the stellar surface, the residual poloidal field at several stellar radii is approximately dipolar:

$$B_z|_{z=0} = B_\ast \left( \frac{r_*}{r} \right)^3,$$

(where $B_\ast$ is the equatorial dipole field at the stellar surface, $r_\ast$) and that, moreover, the equilibrium poloidal field threading the disc is close to its unperturbed value (Ghosh & Lamb 1973, Campbell 1992). Evaluation of the toroidal field, however, requires several adjustments about the processes determining the equilibrium value of $B_\phi$ in a shearing velocity field. Whereas the mechanism for the generation of toroidal field is uncontroversial (i.e. differential rotation between the footpoints of field lines anchored respectively on the star and disc), a number of mechanisms have been suggested for limiting the growth of $B_\phi$, including reconnection of twisted field lines in the magnetosphere (Livio & Pringle 1992), magnetic buoyancy or turbulent magnetic diffusion in the disc (Campbell 1992, Romanova, Lovelace & Bisnovatyi–Kogan 1993) or else the action of a poorly specified anomalous resistivity, whose role is to dissipate $B_\phi$ on a time-scale comparable to the Alfvén crossing time of the disc height (Ghosh & Lamb 1973). Here we assume that magnetic reconnection in the magnetosphere is the dominant limiting process, which implies $B_\phi \sim B_\ast$ since, away from corotation, $B_\phi$ is both generated and destroyed on a dynamical time-scale. Thus equation (3) becomes

$$B_z^2|_{r_m} = \frac{\dot{M}}{2} \left( \frac{GM_*}{r_m^3} \right)^{1/2}.$$

It is immediately apparent that this expression is within a numerical factor of order unity of that obtained if one calculates the field strength required to dominate magnetically a spherical inflow of the same $M$ (Davidson & Ostriker 1973), thus justifying, to order of magnitude, earlier works that have applied the spherical Alfvén radius in the context of disc accretion (e.g. Königl 1991). A particularly convenient aspect of this result is that $r_m$ depends only on the field strength and $\dot{M}$:

$$r_m = \left( \frac{2B_\ast^2 r_\ast^3}{(GM_*)^{1/2} \dot{M}} \right)^{2/7},$$

and is independent of the internal structure of the disc giving rise to this steady-state accretion rate $\dot{M}$.

We now consider the response of such a magnetically coupled star-disc system to cyclical variations in the field strength of the central star. According to equation (3) such changes produce cyclical variations in the magnetospheric radius $r_m$. At strong field phases of the cycle, $r_m$ may lie outside the radius of corotation between disc and star, $r_\Omega$, so that the action of the field is then to impart angular momentum to the disc. At such phases, therefore, material is held up in the disc by the strong magnetic torques at its inner edge and is unable to flow down the field on to the star. As the field subsequently reduces, material can again flow inwards under the action of viscosity; once inside $r_\Omega$ the magnetic torques change sign so that disc material can be decelerated and again flow on to the star. Thus modulation of the field can give rise to an intermittent accretion pattern, with strong field phases in which material is stored in the disc alternating with weak field phases in which the stored material flows on to the star.

Several criteria have to be satisfied, however, in order for this process to operate in the way outlined above. Since the modulation of accretion depends on the alternate displacement of $r_m$ inward and outward of corotation it is necessary, for order-unity field variations to achieve this effect, that $r_\Omega$ is close to the mean value of $r_m$. Secondly, it is also necessary that the field variations are sufficiently rapid for variations of $r_m$ to occur at approximately constant $r_\Omega$. Below we consider each of these issues in the context of T Tauri stars.

For a star rotating with period $P_\ast$, the corotation radius is

$$r_\Omega = \left( \frac{GM_\ast P_\ast^2}{4\pi^2} \right)^{1/3}.$$

Thus (comparing equations 3 and 6) it is evident that, for parameters typical of classical T Tauri stars ($\dot{M} \sim 10^{-7} M_\odot$ year$^{-1}$, $P_\ast \sim 1$ year, $r_\ast \sim 1$ AU), $r_\Omega$ will be close to $r_m$ in the disc regime for $B_\phi$ much less than $B_\ast$. This suggests that the action of the field is only significant when there is a strong field phase in the cycle, at which point material is held up in the disc by the strong magnetic torques at its inner edge as material flows radially inwards under the action of viscosity. Such conditions are well satisfied by models of T Tauri stars.
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3 DISCUSSION

In the previous section we showed that, for field strengths of a few hundred gauss, order-unity variations of the field on timescales \( t \lesssim 10^5 \) yr would strongly modulate the accretion flow on to the central star. Further characterization of the time-dependent flow and associated photometric variability requires detailed hydrodynamic modeling (Armitage et al., in prep). The main implications of this conclusion are, first, that spectrophotometric variations of T Tauri stars may thus provide a record of the magnetic activity cycle of T Tauri stars and, secondly, that at least some weak line systems are interconvertible with strong line systems. We examine each of these issues below.

The temporal behaviour of magnetic fields in T Tauri stars is not known, apart from the rapid variations deduced (by analogy with solar chromospheric/coronal flares) from short-time-scale ultraviolet (Worden et al. 1981) and X-ray (Montmerle et al. 1983, 1993) flares in these objects. Further analogy with magnetic activity in main-sequence stars leads one to anticipate that T Tauri magnetic fields would also be variable on a range of longer time-scales, as witnessed by the chromospheric variations of late-type dwarfs (time-scales \( \sim 10 \) yr; Baliunas 1988) and the history of intermittent activity on longer time-scales contained in the sunspot record. The qualitative similarity between the convective dynamos believed to be responsible for magnetic fields in both main-sequence and pre-main-sequence low-mass stars leads one to anticipate a similarly variable pattern in T Tauri stars.

Pronounced variability, on a range of time-scales, is one of the defining characteristics of T Tauri stars as a class. Apart from the rapid flares alluded to above, which may be interpreted as localized surface phenomena on the star, it is hard to avoid the conclusion that this variability is related to variable accretion on to the star since, in the absence of accretion, it is difficult to envisage what processes in the stellar interior could account for such large-amplitude variations in the bolometric output of the star on these time-scales. Variable accretion can result either from magnetic variations (as described here) or else from variable flow in the accretion disc, although it is not at all obvious why the accretion flow should be intrinsically intermittent on these time-scales. We note that the hypothesis that T Tauri variability reflects the stars’ magnetic activity opens up the possibility of using the photometric variability record of T Tauri stars as a diagnostic of magnetic activity cycles in T Tauri stars, in much the same way as chromospheric variations are used in main-sequence stars. However, whereas the latter record only extends back a few decades, and for a limited sample of stars that have been deliberately monitored for this purpose, published photometry for T Tauri stars, together with archival plate material, means that a database extending back over a century is available for a large sample of stars.

We next turn to the question of the interconvertibility of strong and weak line T Tauri stars. The strongest evidence for the possibility of switching between the two states is provided by the half a dozen systems in the Herbig & Bell (1988) catalogue, for which it is noted that their current designation as weak or strong line does not accord with the results of objective prism surveys in previous decades. Since these remarks do not relate to systematic monitoring programmes they cannot be used to derive duty cycles, but just illustrate that such transitions can occur on timescales of decades. Further plausibility arguments about the possible interconversion of WTTs and CTTs depend on the overlap in properties (apart from those indicative of material flow at small radii) between the two classes of object. It is well known, for example, that CTTs and WTTs co-exist in the same region of the HR diagram (apart from a WTT-only region near the main-sequence), thus arguing against a simple picture in which a universal clock controls
an irreversible transition of stars from WTT to CTT status. The rotational properties of CTTs and WTTs also overlap: whereas the WTTs rotate faster as a class (Bouvier et al. 1993; Edwards et al. 1993), about half of them have angular momenta that overlap with the CTTs. Since the slow rotation of T Tauri stars is commonly attributed to a history in which they have been braked by magnetic coupling to associated discs (Königl 1991; Cameron & Campbell 1993), the low angular momentum WTTs have probably undergone a similar history of disc braking. Such data suggest a picture in which objects classified as WTTs are a mixture of genuinely naked systems (devoid of material at all radii) and those that, retaining a reservoir of circumstellar material, are capable of being resuscitated as strong line systems.

The above picture suggests some correlations between the diagnostics of material at small radii and the rotational properties of T Tauri stars. For example, if the low angular momentum T Tauri stars have evolved to a state of rotational quasi-equilibrium (i.e. if the time-averaged magnetospheric radius is close to corotation, so that the the spinup and spindown torques exerted by disc material nearly cancel) then the magnetic field should disrupt the disc out to larger radii in more slowly rotating systems, thus increasing the volume of the region of quasi-spherical infall. Since Hα emission is believed to arise from material flowing nearly radially near the star (e.g. Calvet & Hartmann 1992) one would therefore anticipate a larger Hα flux in slowly rotating systems of given accretion rate, since the solid angle intercepted by inflowing material is larger than in more rapidly rotating systems. On the other hand, the range of rotation periods among CTTs may indicate that these systems have not all evolved to a state in which the magnetosphere lies at corotation; in this case the time-averaged magnetosphere would lie outside corotation in more slowly rotating systems, thus reducing the fraction of the cycle during which accretion can occur. Since (see Section 2) accretion on to the star does not occur when the magnetosphere is outside corotation it follows that, in a magnetic cycle, the fraction of the cycle for which accretion can occur is lower for rapidly rotating systems. Thus in this case, also, one would expect weaker diagnostics of accretion close to the star for more rapidly rotating stars. It is notable that these predictions are borne out by the observed decline in the ratio of Hα (indicative of material close to the star) to excess K magnitude (indicative of the reservoir of material at larger radii) with increasing stellar rotation (Bouvier et al. 1993).

Finally we note that such a model is not unique in predicting a variety of spectral energy distributions according to the inner radius to which the disc extends. The possibility of systems that are ‘weak’ on small scales and ‘strong’ on large scales has been recognized by various authors who have sought to identify spectral ‘gaps’ in some T Tauri stars as clearing of the inner disc by planetary formation (e.g. Marsh & Mahoney 1992). Such a picture does not, however, unlike the variable magnetic disc model described here, allow the reversible exhaustion/replenishment of material on small scales as suggested by the variability data described above.

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