Mem. S.A.It. Vol. 78, 340

Memorie della

The spatial structure of the coronae of T Tauri stars

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Abstract. Our present understanding of the coronal structure of T Tauri stars is fragmentary and observations in different wavelength regimes often appear to give contradictory results. X-ray data suggest the presence of magnetic loops on a variety of scales, from compact loops of size less than a stellar radius, up to very large loops of up to 10 stellar radii which may connect to the disk. While some stars show a clear rotational modulation in X-rays, implying distinct bright and dark regions, many do not. This picture is complicated by the accretion process itself, which may contribute to the X-ray emission. The location of the inner edge of the accretion disk and the nature of the magnetic field there are still hotly-contested issues. Accretion indicators often suggest the presence of discrete accretion funnels. This has implications for the structure of the corona, as does the presence of an outflowing wind. All of these factors are linked to the structure of the magnetic field, which we are now beginning to unravel through Zeeman-Doppler imaging. In this review I will describe the present state of our understanding of the magnetic structure of T Tauri coronae and the impact this has on this early evolutionary stage.

Key words. Stars:coronae

1. Introduction

T Tauri stars represent a fascinating phase in stellar evolution. It is during this period, when stars of intermediate to low mass contract onto the main sequence, that planets may form in the disks around these stars. Two outstanding questions remain however about this phase in stellar evolution. The first is the rate at which material can accrete from this disk onto the star. This influences the lifetime of the disk and so sets the challengingly brief timescale for planet formation. The second question is the mechanism by which these stars lose angular momentum. Most T Tauri stars are fairly slow rotators, despite their contraction and the possible gain in angular momentum associated with accretion of material from a surrounding disk.

The nature of the stellar magnetic field is central to both of these questions. Until quite recently, most of the interest in the magnetic structure of T Tauri stars centered around the interaction of the stellar field with the accretion disk. Most work focussed on the mechanisms by which the stellar magnetic field might truncate the inner edge of the disk and on the nature of the torque balance between the star and the disk. The theoretical structure for this grew out of studies of accretion onto compact objects and hence the assumption of a strong, dipolar field seemed natural (Königl 1991; Collier Cameron & Campbell 1993; Shu et al. 1994).

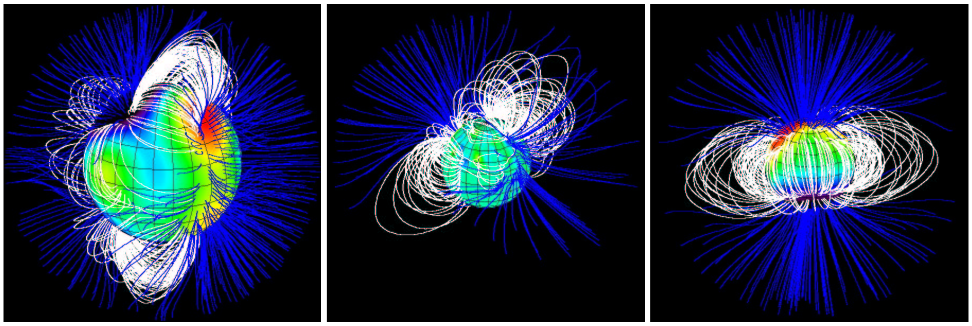

Fig. 1. Field structures for the 15 $M_\odot$ star Tau Sco (left), the 1 $M_\odot$ star AB Dor (middle) and the 0.3 $M_\odot$ star V374 Peg (right) extrapolated from Zeeman-Doppler surface magnetic maps (Donati et al. 2006b; Donati et al. 1999; Donati et al. 2006a).

The magnetic field strength at the stellar surface was obtained by taking the value at the inner edge of the disk (the main region of interest) and extrapolating back to the surface, assuming some simple field geometry. Although these different approaches yielded predictions for the stellar surface magnetic field strength that varied by different scaling factors (depending on the details of the assumed coupling between the star and the disk) they typically predicted surface field strengths of 0.1-5 kG. The requirement that the system be in torque balance also lead to an inner disk that was truncated close to the Keplerian co-rotation radius.

The last few years have, however, seen great advances in our knowledge of the surface magnetic fields of T Tauri stars. Zeeman-Broadening measurements can now be used to measure mean fields on the stellar surface (Johns-Krull et al. 2004; Valenti & Johns-Krull 2004a; Yang et al. 2005). This gives distributions of local field strengths on the stellar surface that may be as high as 6kG. The results are similar on both accreting and non-accreting T Tauri stars and show little correlation with either the values predicted by theory, or with the stellar rotation rotation rate or Rossby number.

A complementary approach is to use circular polarisation measurements either in photospheric lines (presumably formed across the whole stellar surface) or the Helium λ5876 emission line believed to form in the accretion shock (Yang et al. 2006). Polarisation measurements taken at a range of rotation phases can then be used to provide information on the structure of the magnetic field both across the surface and in the accretion shock. The low circular polarisation measured in photospheric lines rules out the presence of a global dipole, suggesting perhaps a complex field that may be locally very intense, but which is organised into small enough scales that the individual polarisations cancel out. In comparison, the strong, rotationally modulated polarisation in the Helium emission lines suggests that the field associated with accretion is much simpler with few reversals in sign. This is no doubt to be expected, since it is the largest-scale field lines that will interact with the disk and these are likely to have the simplest structure. The nature of the star-disk interaction will clearly depend on the structure of the whole coronal field, and in particular the degree to which the complexity that seems apparent at the stellar surface may have died away by the time the coronal field reaches the inner edge of the disk.

2. Coronal field structures

We can gain some insight into the possible types of coronal field by taking as examples main sequence stars of different masses. For a high-mass star, the radiative interior may be expected to generate magnetic fields (if at all) by a different type of dynamo action from a solar-mass star which has an outer convective

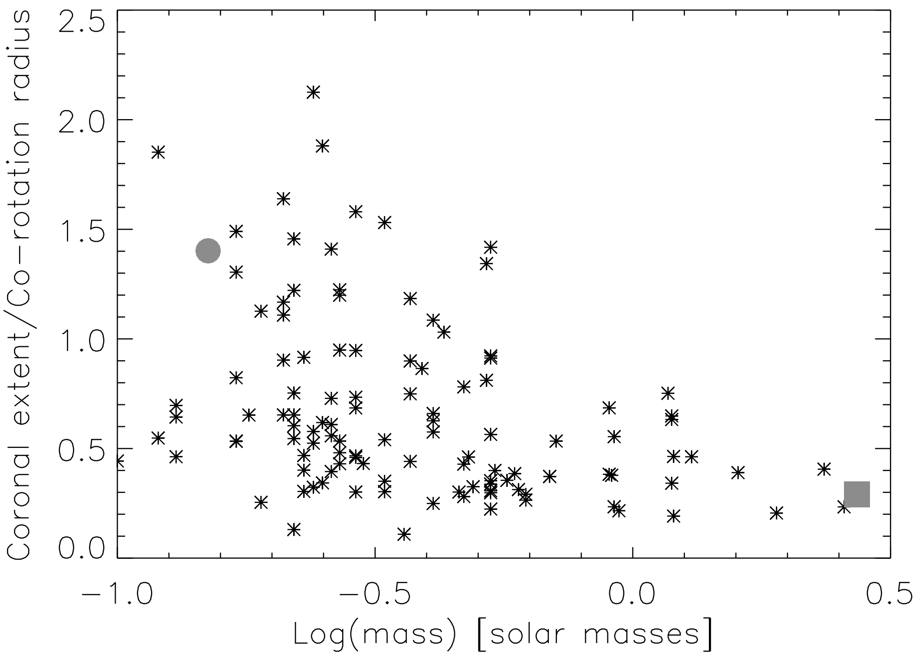

Fig. 2. Calculated coronal extent (in units of the Keplerian co-rotation radius) as a function of stellar mass for stars in the COUP sample. Two stars (marked with a circle and square) have been selected as examples. Their coronal structure is shown more fully in Fig. 3. Taken from Jardine et al (2006).

envelope. Stars that are of low enough mass to be fully convective are not able to support an interface dynamo (since they have no interface between a convective and radiative zone) and their magnetic field generation may be different again. These difference are apparent in field structures derived from Zeeman-Doppler maps (Donati et al. 2006b; Donati et al. 1999; Donati et al. 2006a). As shown in Fig. 1 this can be done using the *Potential Field Source Surface* method developed many years ago for modelling the solar corona (Altschuler & Newkirk Jr. 1969). This assumes that at some height above the stellar surface (known as the source surface) the outward pressure of the hot coronal gas forces the magnetic loops open and allows the gas to escape to form the stellar wind. Inside the source surface, the field is potential and so along each field line the gas settles into hydrostatic balance (Jardine et al. 2002a,b).

As shown in Fig. 1, the young high-mass star Tau Sco has a complex field which may be a fossil remnant, while the solar-mass star AB Dor has a field that is complex on small scales, but resembles a tilted dipole on large scales. By contrast, the fully-convective star V374 Peg has an almost purely dipolar field. These results suggest that the growth of the radiative core in T Tauri stars may be associated with the onset of a different type of dynamo activity and hence a different coronal field structure. Some indication of this may be apparent in the COUP sample of stars. Those that are expected to have a radiative core appear to have a lower X-ray luminosity than their fully-convective counterparts (Rebull et al. 2006).

The nature of the interaction between a T Tauri star and its disk also depends on the coronal field structure. Recent results by Jardine et al. (2006) suggest that the nature of the star-

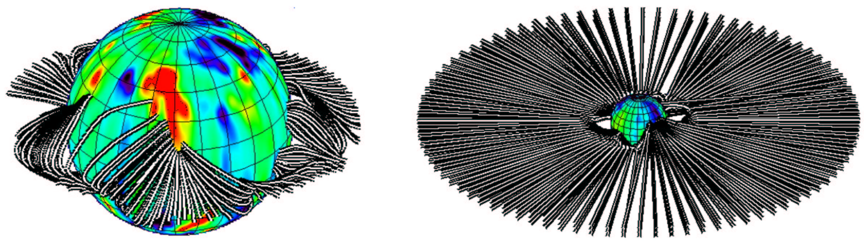

Fig. 3. Calculated coronal structure for the lower-mass (left) and the higher mass (right) T Tauri star shown in Fig. 2. For the lower mass star, the natural extent of the corona is greater than the co-rotation radius, and so the disk strips off the outer parts of the corona, reducing the available X-ray emitting volume. For the higher mass star, the corona is well within the co-rotation radius and so the field lines that interact with the disk are the open ones. Taken from Jardine et al (2006).

disk interaction may be fundamentally different in high and low mass stars. If we consider pre-main sequence stars of progressively lower mass, their pressure scale heights Λ will *increase* (since for a polytrope $R \propto M^{-1/3}$ and so $\Lambda \propto M_*^{-5/3}$) while their co-rotation radii will *decrease*. Thus the lower the stellar mass, the more likely it is that the co-rotation radius will be within the corona (see Figs. 2 and 3). If a disk is present, this may mean that the disk strips off the outer edge of the corona, but even in the absence of a disk, centrifugal effects may do the same job. As Fig. 4 shows, this not only explains the drop in X-ray emission measures towards lower masses seen in the COUP dataset (Getman et al. 2005), but it also suggests that for the higher-mass stars, whose coronae may not extend as far as the co-rotation radius, any disk that exists at the co-rotation radius may interact not with the closed X-ray emitting field lines of the star but rather with the open, wind-bearing lines (see Fig. 3). A further calculation of the associated accretion rates as a function of stellar mass also reproduced the accepted relationship (Gregory et al. 2006b).

3. Angular momentum loss

The importance of the open field lines (i.e. those with one footpoint on the star and the other either attached to the disk, or to the interstellar field) has become apparent from several independent lines of research. It has also emerged out of MHD modelling of accretion onto a stellar magnetic field which additionally suggests that the open field lines may themselves carry much of the accretion torque (von Rekowski & Brandenburg 2004; Long et al. 2006). So how much of the stellar field is in the form of open field? One clue to this may come from the detection of rotational modulation of X-ray emission from the COUP stars (Flaccomio et al. 2005). This suggests that the X-ray coronae are compact, with discrete bright and dark regions. Gregory et al. (2006a) have modelled the structure of T Tauri coronae and found significant rotational modulation, with X-ray periods that are typically equal to the optical period (or one half of it). The dark regions are sites of open field where the stellar wind escapes. Some preliminary measurements of such wind properties are now being made.

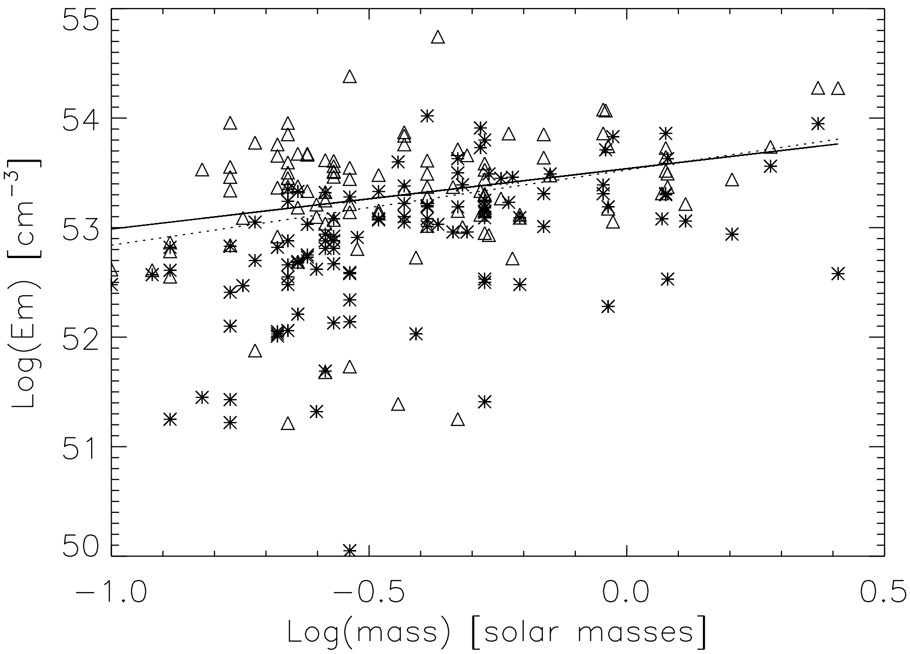

Fig. 4. Emission measure as a function of stellar mass for stars in the COUP sample. Crosses show the observed values, which triangles show the calculated values. The solid line is the best fit to the calculated values, while the dotted line is the best fit to the observed values. Taken from Jardine et al (2006).

At the same time as observations of stellar magnetic fields have suggested a complex structure, modelling of accretion inflows and wind outflows have also raised questions about the applicability of "disk locking" models. In the original theory of disk locking a dipolar magnetic field connects to the disk at the truncation radius (Ghosh & Lamb 1978; Königl 1991). Strong fields are however needed in order to ensure that the truncation radius is close to the co-rotation radius, thus ensuring that the star is close to torque balance. This raises problems for the model since field strengths derived from circular polarisation measurements are of order 100G, not the 1000G values needed by disk-locking theory. In addition, the field lines that connect beyond the co-rotation radius and provide the spin down torque will be opened up by the shearing effect of the Keplerian velocity of the disk, and so will be unable to exert a torque on the star. The X-wind model solves the angular momentum problem by launching a wind from the region of the disk truncation radius (close to the co-rotation radius). Observations of T Tauri jets however suggest they carry much more angular momentum than is present at this radius. Such a large amount of angular momentum must come from further out in the disk in the form of a disk wind.

An accretion powered stellar wind on the other hand carries away the angular momentum imparted to the star by the accretion process. Its effectiveness (relative to a disk wind) lies in the large lever arm that is associated with its large Alfvén radius. This wind is powered by the energy of the accretion flow itself. Indeed, a significant fraction of this energy is needed to drive the wind and a consistent model for this energy transfer process remains the greatest challenge for this theory. Nonetheless, recent 2D MHD models extending the work of Matt & Pudritz (2005) suggest that even with relatively weak stellar fields (of only 300-400G) the wind torque dominates over a "disk-locking" torque by a significant amount and the star can achieve low spin rates.

Observational signatures of such hot winds are now becoming accessible (Dupree et al. 2005, 2006). A very promising technique for examining the nature of such winds is the use of co-ordinated observations, using both FUSE data and Zeeman-Doppler imaging to determine the magnetic field structure. This has been done for AB Dor, a star in the post T Tauri phase which no longer has a disk, but whose field structure has been well studied. Field extrapolation from Zeeman-Doppler images shows two dominant regions of open field in the upper hemisphere that are separated by about 180 degrees in longitude. UV spectra obtained with FUSE show variations with rotational phase that are consistent with this magnetic structure. Longitudes with open field regions show narrower, weaker OVI profiles whose asymmetry suggests outflows, while longitudes with mainly closed field regions show higher flux and the presence of compact active regions at mid-latitudes and of height 1.3-1.4 stellar radii.

4. Variability

While this is a promising technique for studying the structure of both the wind regions and the X-ray bright regions of T Tauri coronae, it provides only an instantaneous view of the system. This is a limitation shared by many T Tauri observations. A complementary approach is the type of long-term study that has been undertaken of AA Tau, which accretes at a moderate rate of only $10^{-9} M_{\odot} \mathrm{yr}^{-1}$. Over the last 10 years there have been four campaigns monitoring the photometric and spectral diagnostics of magnetospheric accretion on timescales of days to years (for a review see Bouvier et al. (2006)). The system is seen at a high inclination of about 75 degrees and the photometric brightness variations are consistent with a warp of the inner disk that is situated at 8.8 $R_{\star}$ (approximately at the co-rotation radius). This warp may be caused by a large-scale magnetic field inclined to the stellar rotation axis (Romanova et al. 2003; Long et al. 2006), and is consistent with He I observations (Valenti & Johns-Krull 2004b). For AA Tau, Hβ line profiles also show redshifted absorptions that appear near the middle of photometric eclipse, suggesting a spatial relationship between the disk warp and the funnel flows. The general characteristics of this variability are reproduced by non-symmetric radiative transfer models (Symington et al. 2005) although the predicted degree of variability is too high. On a timescale of weeks the change in the redshifted absorption component of Hα can be interpreted as due to field inflation (Lynden-Bell & Boily 1994; Goodson et al. 1997) as field lines that link to the disk are sheared by the Keplerian flow until they expand and ultimately reconnect. On longer timescales, however, AA Tau's V-band eclipses change shape over several years, perhaps suggesting that the inner disk warp changes on that timescale. This may be pointing towards a magnetic cycle, or longer timescale variation in the accretion.

Perhaps one of the most promising approaches to studying the variable accretion processes in T Tauri stars is the use of multi-wavelength campaigns. This has been done for the Coronet cluster using simultaneous X-ray, radio, near-infrared and optical monitoring (Forbrich et al. 2007). This is the first attempt to examine the correlation between radio and X-ray variability in class 0 and class 1 protostars. Preliminary results suggest that the variability at radio and X-ray is uncorrelated, but that a relationship does exist between the luminosity at X-ray and radio wavelengths (Benz & Guedel 1994).

In addition to the ubiquitous flaring-like variability seen in the X-ray emission of the COUP stars, there is also a clear rotational modulation in a small but significant number of these stars. Such modulation has previously been difficult to detect because it requires continuous observation over several rotation periods (Güdel et al. 1995; Marino et al. 2003; Hussain et al. 2005). This rotational modulation shows clearly that although these stars appear to lie in the "saturated" part of the rotation-activity relation, they have coronae in which the dominant X-ray emission structures must be compact and cannot be distributed homogenously in longitude. Both in the COUP study and also more recently in the DROXO (Deep Rho Ophiuchi XMM-Newton Observation) study, there are flares for which modelling suggests the loops responsible must be large - perhaps reaching out into the accretion disk (Favata et al. 2005). If this represents a single flaring loop (rather than many loops) it suggests that the magnetic interaction between the star and the disk may be a violent one. Most flares from T Tauri stars are at much lower energies however and show a distribution in energy that is broadly compatible with what is observed on the Sun, which is consistent with energy release from a corona dominated by nanoflares.

The question still remains however of the contribution to the X-ray emission that may be made by the accretion process itself. Material falling onto a T Tauri star at the free-fall speed v_{ff} will be shocked to a temperature $T \propto v_{ff}^2 \propto M_\star/R_\star$. For typical values, this gives $T = 2 - 4$ MK which would contribute to the soft X-ray spectrum. A few well studied stars such as TW Hya (Stelzer & Schmitt 2004; Kastner et al. 2002) and more recently MP Muscae do indeed show the high densities and soft excess that would be expected from accretion, although this is not true of all T Tauri stars (Argiroffi et al. 2007). Of course not all of the infall will occur at the free-fall speed (as is apparent from modelling of accretion infalls; see Gregory et al. 2006b) and there may be some absorption by the accretion column itself. Modelling of the X-ray emission from the shock promises to help untangle the different contributions to the overall X-ray spectrum (Günther et al. 2007).

5. Conclusions

Our understanding of the processes by which T Tauri stars accrete material from their disks while remaining at moderate rotation rates has advanced enormously over the past few years. The old models of stars with strong dipolar fields that lock the star to its disk have been replaced by (or perhaps only challenged by) new and more dynamic models. In these pictures, the star and the disk are not in torque balance. The accretion flows, which form into discrete funnels, transport angular momentum onto the star. Through some as yet unknown mechanism this process of accretion allows the star to drive a powerfull wind that carries away enough angular momentum to keep the star rotating slowly.

The picture is more complicated than we might have thought some years ago, but observations of both the X-ray structure of T Tauri coronae and also of the magnetic field structure point to a degree of complexity inconsistent with a dipolar field. This complexity is also seen in the variability of the accretion process which appears to change on timescales from hours to years. Multiwavelength studies promise to be enormously valuable in studying the relationship between the closed-field, X-ray bright regions of the stellar corona, the accreting regions and the open-field wind-bearing regions. It appears that only by understanding the relationship between these different components of the coronal structure can we hope to understand the rotational evolution of T Tauri stars.

Acknowledgements. I would like to thank Maria Massi and Thomas Preibisch for organising such a stimulating and fruitful meeting which brought together such a diverse range of topics.

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