Coronal Structure of Pre-Main Sequence Stars

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Abstract. The study of pre-main sequence stellar coronae is undertaken in many different wavelength regimes, with apparently conflicting results. X-ray studies of T Tauri stars suggest the presence of loops with a range of sizes ranging from less than a stellar radius to 10 stellar radii. Some of these stars show a clear rotational modulation in X-rays, but many do not and indeed the nature of this emission and its dependence on stellar mass and rotation rate is still a matter of debate. Some component of it may come from the accretion shock, but the location and extent of the accretion funnels (inferred from optical and UV observations) is as much of a puzzle as the mass accretion rate that they carry. Mass and angular momentum are not only gained by the star in the process of accretion, but also lost in either jets or winds. Linking all these different features is the magnetic field. Recent observations suggest the presence of structure on many scales, with a complex, multipolar field on small scales near the surface co-existing with a much simpler field structure on the larger scales at which the stellar field may be linking onto a surrounding disk. Some recent models suggest that the open field lines which are responsible for carrying gas escaping in winds and jets may also be responsible for much of the infalling accretion flow.

The aim of this splinter session was to bring together the most recent results from these different wavelength regimes to see if a consistent picture emerged which can shed light on the structure of the coronae of these young objects.

1. Introduction

In the time since the last Cool Stars meeting we have made enormous progress in unravelling the complex structure and dynamics of pre-main sequence coronae. Some questions that were addressed at the last Cool Stars meeting are still with us, and new ones have emerged, brought to light by recent observations across a wide range of wavelengths. In this session we attempted to address the issue from three different perspectives, to see if any common themes emerged.

2. The structure of the magnetic field (speakers Jardine, Johns-Krull, Gregory)

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). 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 $\lambda 5876$ 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.

Recent results by Jardine et al. (2006) suggest that the nature of this star-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. 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. This may well explain 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

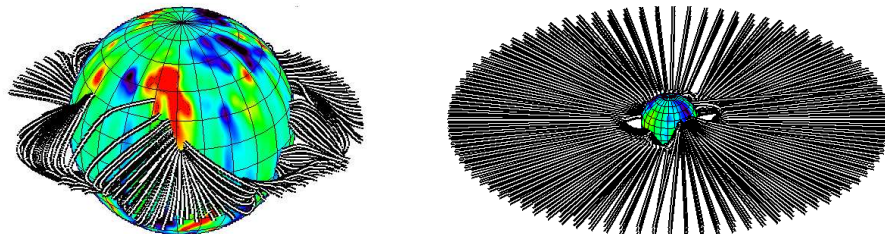emitting field lines of the star but rather with the open, wind-bearing lines (see Fig. 1).

Figure 1.   Calculated coronal structure for a lower-mass (left) and higher mass (right) T Tauri star. 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).

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.

One way to explore this question is to extrapolate the surface magnetic field maps obtained from Zeeman-Doppler imaging (Donati & Collier Cameron 1997; Donati et al. 1999). 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. Therefore, for an isothermal corona, the

pressure along each field line is simply determined by the pressure p_0 at the base of the corona. Jardine et al. (2002a,b) scaled this to the base magnetic pressure $p_0 = K B_0^2$. To determine K they calculated the X-ray emission for the COUP stars and found the value of K that gave the best fit to the observed emission measures. This not only reproduced the observed scaling of emission measure with stellar mass (and its scatter) (see Fig. 2) but a further calculation of the associated accretion rates as a function of stellar mass reproduced the accepted relationship (Gregory et al. 2006b).
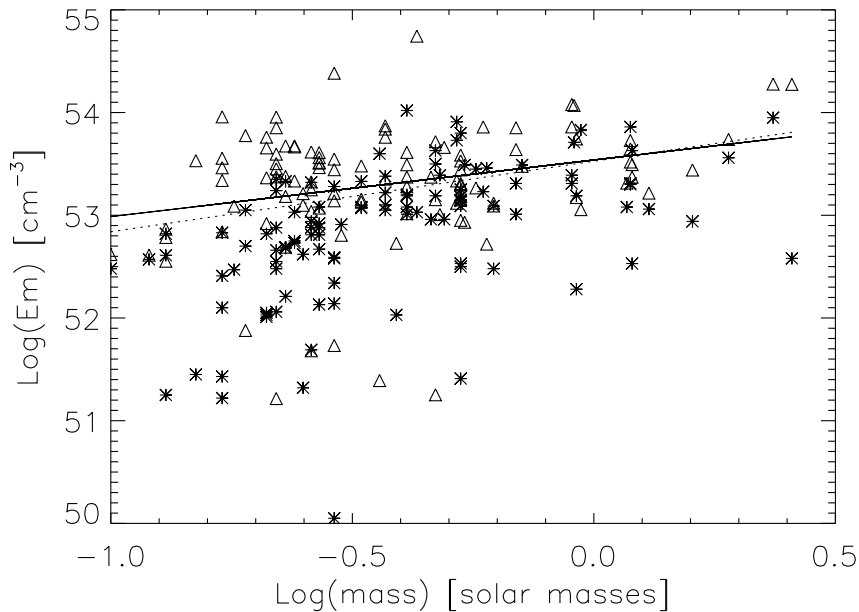

Figure 2. Emission measure as a function of stellar mass for stars in the COUP sample. Crosses show the observed values, which triangles show the calculated values. The solid line is the best fit to the calculated values, while the dotted line is the best fit to the observed values. Taken from Jardine et al (2006).

3. The structure of the inflows and outflows (speakers Pudritz, Dupree, Bouvier, Walter, Forbrich)

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. 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.

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.

An intriguing example of variability in T Tauri systems is provided by S Corona Australis which is a long-period (a >160AU) binary composed of 2 classical T Tauri stars (Walter et al, this proceedings). Both stars are highly variable: changes of as much as 0.3 magnitudes per day in the stellar brightness mirror the accretion luminosity, while inverse P Cygni line changes reflect the instantaneous mass accretion rate (around $2 \times 10^{-7} M_\odot yr^{-1}$) along the line of sight. What is fascinating about this system is the indication of correlated variability on both sources. Given that the light travel time between the stars is more than one day, this may imply a common accretion process onto both stars.

Perhaps one of the most promising approaches to studying the variable accretion processes in T Tauri stars is the use of multi-wavelength campaigns (Forbrich et al, this proceedings). This has been done for the Coronet cluster using simultaneous X-ray, radio, near-infrared and optical monitoring. 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).

4. The structure of the X-ray corona (speakers Flaccommio, Schmitt, Guenter, Maggio)

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 $T = 2 - 4\mathrm{MK}$ 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 (Maggio et al, this proceedings) 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. Of course not all of the infall will occur at the free-fall speed (as is apparent from modelling of accretion infalls (Gregory et al. 2006b) and there may be some absorption by the accretion column itself. Modelling of the X-ray emission from the shock (Günther et al, this proceedings) promises to help untangle the different contributions to the overall X-ray spectrum.

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 timecales 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.

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