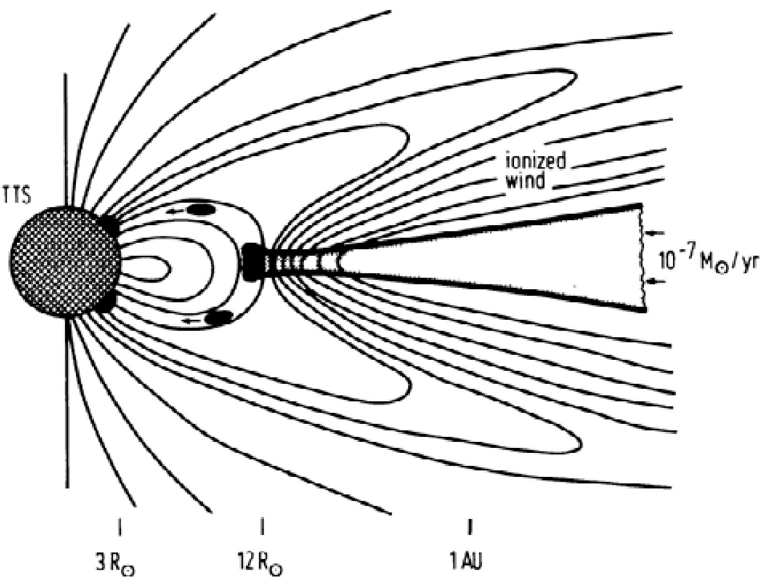
Session 9

Stellar ejections



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Winds and Ejecta from Cool Stars

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Abstract. As young stars evolve from the time of their formation onto the main sequence, they lose mass in a variety of ways. At the very earliest stages, mass loss may be in the form of jets associated with accretion from a surrounding disk. These cool jets carve out the surrounding gas and their changes over time may indicate changes in the star-formation process. At later stages, mass loss is predominantly in the form of a hot, magnetically channelled wind that carries mass, but more importantly angular momentum, away from the star. This wind determines the rotational evolution of cool stars and is intimately connected to the process of field generation deep inside the star. Mass loss also occurs in a sporadic way in the form of the ejection of cool clouds of coronal gas. The coronal distribution and evolution of these clouds (or prominences) gives us vital clues about the structure and short-timescale evolution of stellar coronae. In this review I will discuss recent advances in our understanding of the coronae, winds and accretion processes in cool stars and show how these processes may be related at different stages of evolution.

Keywords. stars: magnetic fields, stars: coronae, stars: imaging.

1. Introduction

In this review I would like to take a step back from the detailed studies of the solar corona that we have been hearing about to consider the types of mass loss that occur on other, solar-like stars. Mass loss also occurs on stars much more massive than the Sun, and on more evolved stars, but I will focus only on those stars that are of mass similar to (or less than) one solar mass. In this review I will concentrate on the so-called "main sequence" stars - those that have ignited Hydrogen in their cores - and the next review will focus on the earlier phase of evolution, when stars are still contracting out of their parent molecular clouds.

There are two ways in which mass loss can occur: in a continuous form through winds or jets, and in an intermittent form, as ejected prominences. In contrast to solar studies, however, we are not so interested in the amount of mass or energy that is removed in these mass ejections, but more in the amount of angular momentum that is removed. We can see the effect of this loss of angular momentum if we look at distributions of stellar rotation speeds in clusters of different ages. If we compare these distributions for α Persei (aged 50 Myr), the Pleiades (aged 70 Myr), and the Hyades (aged 600 Myr) we find that as we go towards the older clusters, the number of rapid rotators diminishes, until all the stars are rotating slowly (Soderblom *et al.* 1993). It appears that some mechanism causes stars to spin down as they age. This is only part of the story however. When stars are very young - when they are still surrounded by a dusty disk - the presence of the disk appears to act as a "governor", preventing the spin up that would naturally occur as the star continues to contract. Once the disk has dissipated however, the star

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is free to spin up. This increase in rotation rate is accompanied by enhanced dynamo activity and hence - since these stars possess a magnetically-controlled wind - by enhanced angular momentum loss. Once the loss of angular momentum in the wind is sufficient to counteract the spin-up due to the star's own contraction, the star will begin the slow spin-down that continues until well beyond the age of the Sun. This theory of stellar spin down is well established and reproduces the observed scaling of rotation rate as a function of time ($\Omega \propto t^{-1/2}$) (Weber & Davies 1967; Skumanich 1972). In order for the theory to reproduce the cluster rotation distributions, however, it was necessary to force the angular momentum loss of the most rapid rotators to be inhibited. This was achieved by assuming that at the highest rotation rates, the dynamo saturates so that the field strength no longer increases with increasing rotation rate (Endal & Sofia 1981; Charbonneau & MacGregor 1993; Collier Cameron & Li 1994).

The need for this assumption has been questioned recently however. Solanki *et al.* (1997) showed that angular momentum loss can be reduced if the star's magnetic flux is concentrated at the rotation pole, rather than being distributed uniformly over the stellar surface as had previously been assumed. A wind emerging from close to the rotation pole has a much smaller lever arm than one that emerges from the equator. The net result is that this can mimic the effect of dynamo saturation on the stellar spin down.

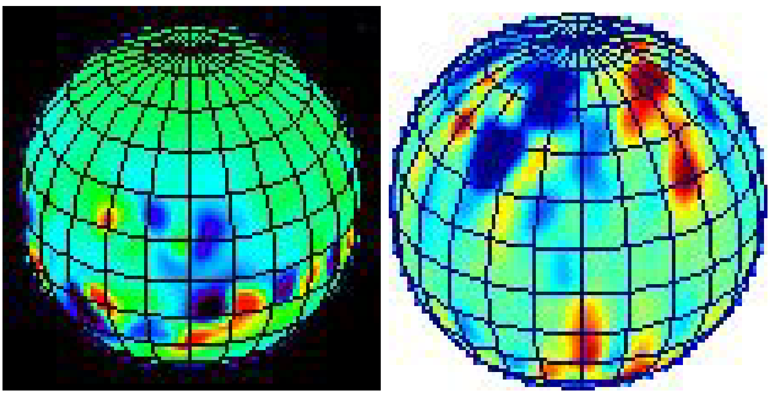

Figure 1. Shown (left) is a solar magnetogram taken at around cycle maximum. Red denotes positive polarity, blue denotes negative polarity. The appearance of bipoles at low to mid latitudes is clearly seen. Shown (right) is a magnetogram produced by Zeeman-Doppler imaging of AB Dor, a young, solar type star which rotates 50 times faster than the Sun (P=0.514 days). Mixed polarity flux is present all all latitudes.

2. Where does flux appear on stellar surfaces?

There are good reasons for expecting that on rapid rotators flux should emerge through the surface at high latitudes. Schuessler & Solanki (1992) showed that flux tubes formed at the base of the convective region in rapid rotators do not have time to exchange angular momentum with their surroundings as they rise buoyantly towards the surface and so they are forced to rise parallel to the rotation axis to emerge at high latitudes.

In addition to these theoretical reasons for expecting high-latitude spots, Doppler images of these stars do indeed typically show dark polar caps, although they also tend to show spots at low latitudes too (Strassmeier 1996). One of the best-studied examples is AB Dor, a marginally pre-main sequence, rapidly-rotating K0 dwarf (period 0.514 days) aged 20-30 million years (Cameron & Foing 1997; Innis *et al.* 1988). The surface

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of this star shows spots at all latitudes and in particular all the way up to the pole. The inclination of its rotation axis at about 60° does however mean that little information can be gleaned about the hemisphere that is tilted away from the observer.

Curiously, although AB Dor is such a rapid rotator, its latitudinal differential rotation is close to that of the Sun. It takes 120 days for its equator to pull ahead of the polar regions by one complete rotation, compared to 110 days for the Sun (Donati & Collier Cameron 1997). Similar results have now been found for other such stars, and indeed it appears that the differential rotation is a function of stellar mass, falling to zero towards the low-mass end of the main sequence (Barnes *et al.* 2004).

Brightness images only tell part of the story however. If we are to understand the structure of the coronal magnetic fields of these stars properly, we need information about the polarity of the magnetic elements. This is now possible with Zeeman-Doppler imaging (Donati & Collier Cameron 1997; Donati *et al.* 1999). As shown in Fig. 1 the pattern of surface flux on AB Dor is quite different to that of the Sun, with mixed-polarity regions extending up to the rotation pole. There are also indications that AB Dor (and indeed the Sun) possess so-called active longitudes (Jetsu *et al.* 1993; Korhonen *et al.* 1999; Berdyugina *et al.* 2002; Berdyugina & Usoskin 2003; Benevolenskaya 2002; Bigazzi & Ruzmaikin 2004). These are longitudes of enhanced flux, which in the case of the Sun can only be detected by studying a very long time series of data.

In common with other rapid rotators, AB Dor has a high X-ray emission measure (10^{53} cm^{-3}), but this shows very little rotational modulation (Kürster *et al.* 1997). This suggests that the emitting gas is rarely eclipsed by the star - something that can be achieved by having a very extended corona, or a fairly compact one, but one where the emitting gas is confined at high latitudes where it is always in view.

The question of the extent of stellar coronae has been raised also by the recent results from the X-ray satellites XMM-Newton and Chandra, as well as from FUSE. Densities derived for stellar coronae can be very large, as high as 10^{13} cm^{-3} (Dupree *et al.* 1993; Schrijver *et al.* 1995; Brickhouse & Dupree 1998) and for AB Dor values range from $10^9 - 10^{12}$ cm^{-3} (Maggio *et al.* 2000; Güdel *et al.* 2001; Sanz-Forcada *et al.* 2003). Differential emission measures also show that much of the emission comes from temperatures as high as 10^7K, something only seen on the Sun during flares. These very high densities in particular suggest that the coronae of these stars must be compact, since large loops could not be stable at such high densities. Additional support for the suggestion that these coronae are compact comes from Beppo-SAX observations of two flares on AB Dor (Maggio *et al.* 2000). The flare decay phase lasted for more than one complete stellar rotation, but showed no rotational self-eclipse. Modelling of the flare decay phase suggested that the loops were small (0.3 $R_\star$) and so the only solution is to have the flaring loop(s) at high latitude where they are never self-eclipsed.

3. Modelling stellar coronae

Clearly, trying to learn about the structure of stellar coronae from the X-ray data alone is an extremely challenging problem, and one that is unlikely to have a unique solution. A more useful approach is to tackle the forward problem: to specify the form of the magnetic field and then to predict the observable signatures and compare them with the real observations. This was originally done for the Sun over 30 years ago by taking surface magnetograms and extrapolating a potential coronal field assuming that at some radius (the "source surface") the field is forced open by the effects of the stellar wind to become purely radial (Altschuler & Newkirk, Jr. 1969). Fig. 2 shows a field extrapolation for AB Dor based on data acquired in December 2002 (Donati *et al.* 2003). Since one half

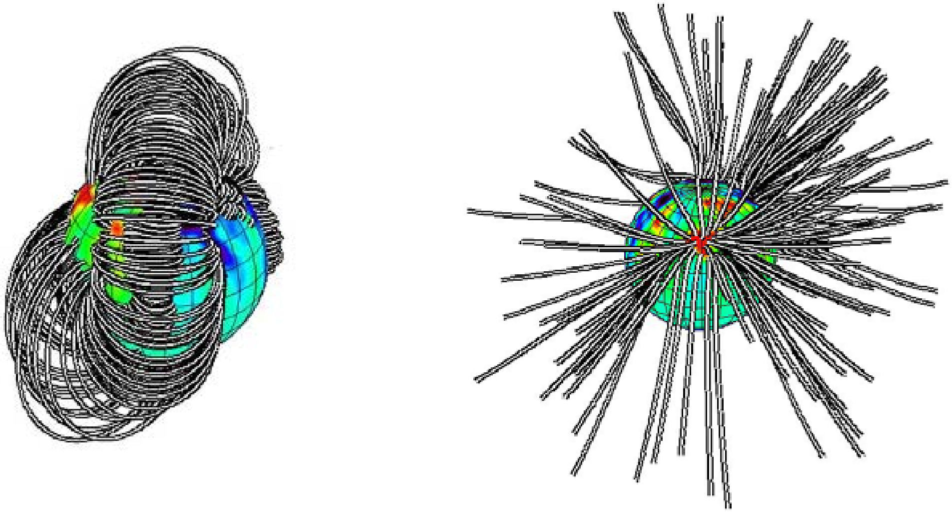

Figure 2. Shown is a potential field extrapolation for a surface magnetogram of AB Dor from December 2002. The source surface has been set to 3.4 $R_\star$. Shown (left) are the closed and (right) open field lines.

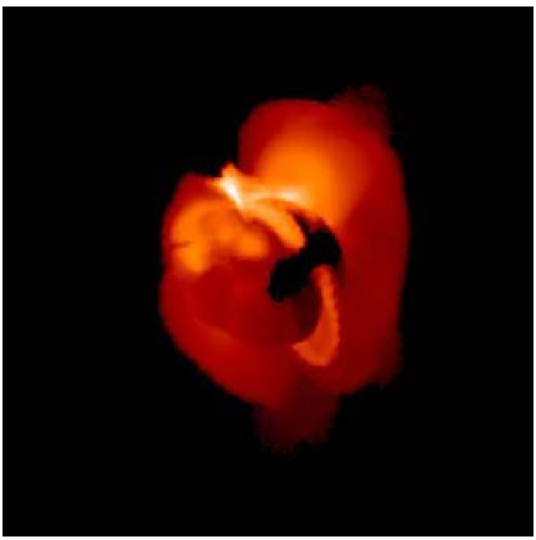

Figure 3. Shown is an X-ray image at a temperature of 10^7 K for the field extrapolations shown in Fig. 2.

of the star is of predominantly positive polarity and the other half is of predominantly negative polarity, on the largest scales the field lines simply connect these polarities to produce large East-West loops than form an arcade that runs from the equator up over the pole (Jardine *et al.* 2002a). Of course, on smaller scales the field is much more complex with many low-lying loop structures. Indeed, we find loops on all scales in the corona. While this figure shows a potential field extrapolation, it is worth commenting that it is possible to do this for non-potential fields. Hussain *et al.* (2002) have developed a method for fitting non-potential fields directly to the Stokes profiles. On the large scales, however, the global field structure is very similar to that for a potential field.

The behaviour of the open field is of course the most interesting from the point of view of stellar winds. As Fig. 2 shows, the open field regions for this magnetogram lie in two discrete mid-latitude regions separated by 180° of longitude. This suggests that much of the coronal volume is filled with open field, and that the stellar wind may indeed leave not from the polar regions, but from mid-latidues. This has important consequences for angular momentum loss in stellar winds (Solanki *et al.* 1997; Holzwarth 2004).

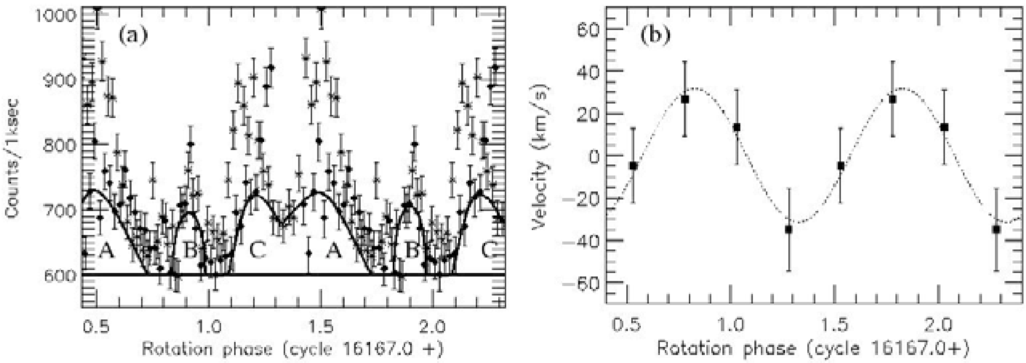

Figure 4. (a) Chandra/LETG lightcurve folded with AB Dor's rotation period. Asterisks and diamonds represent consecutive rotation cycles. The horizontal solid line represents the flat, unmodulated emission level while the curves trace the quiescent modulated emission from the star. (b) The phase-folded mean velocity shifts in the line centroids of the OVIII 18.97 Angstrom profile (+ is red-shifted while - is blue-shifted). The dotted line is the best-fit sine-curve. Figure taken from Hussain *et al.* (2004).

If we are to test these field extrapolations, however, we need to calculate the predicted observable signatures and compare them with what is observed. We can do this by calculating the X-ray emission from the field structure (Jardine *et al.* 2002b).We do this by assuming that the coronal plasma is isothermal and in hydrostatic balance along each field line. We can therefore determine the pressure everywhere with only one free parameter, which is the plasma pressure at the base of the corona. We set this proportional to the magnetic pressure so that $p_0 = RB_0^2$. In addition, we set the plasma pressure to zero if a field line is open, or if anywhere along a field line the plasma pressure exceeds the local magnetic pressure and so should have opened up that field line. As the constant of proportionality R is increased, so is the coronal density and hence the emissivity which is proportional to n_e^2. We increase R until the emission measure matches the observed value for AB Dor which is around 10^{53} cm^{-3} Maggio *et al.* (2000). This then naturally produces an emission measure-weighted density that is in the observed range of about 10^{11} cm^{-3} and a low rotational modulation of the X-ray emission, since most of the emitting regions are at high latitude and so never pass behind the star (see Fig. 3).

We can then compare the variation of the X-ray emission as the star rotates with what was observed by Chandra at the time when the ground-based optical observations were being undertaken (Hussain *et al.* 2004). Fig. 4 shows the Chandra counts phased on the rotation period for AB Dor. Almost 2 successive stellar rotations were observed, allowing a determination of the degree of rotational modulation in the X-ray emission. This Figure shows a) a base level of emission that is always present, b) rotational modulation that is outlined by the thick line and c) transient emission superimposed on this. The feature marked "B" appears only very briefly as the star rotates and so is likely to have been located close to the pole of the star that points away from the observer. Features "A" and "C" are reproduced by the forward modelling procedure. Shown on the right panel is the velocity shift of the centroid of the OVIII line due to the rotation of the star. The value of 30 kms^{-1} is also consistent with the forward modelling.

While a coordinated observing campaign that combines ground-based observations (to provide surface brightness and magnetic maps) with space-based observations (to determine the X-ray coronal spectrum) is capable of determining the structure of a stellar corona, it can only provide a snapshot. Stellar coronae, just like that of the Sun, are not static and can show significant variations from year to year. An example is shown in Fig. 5 which shows the open field lines for LQ Hya which has a rotation period of 1.6 days. In December 2000, the open field structure was similar to that of AB Dor, with much of the open field emerging from two mid-latitude regions, 180° apart in longitude. One year later however, the open field emerged mainly from the pole (Donati *et al.* 2003; McIvor *et al.* 2004).

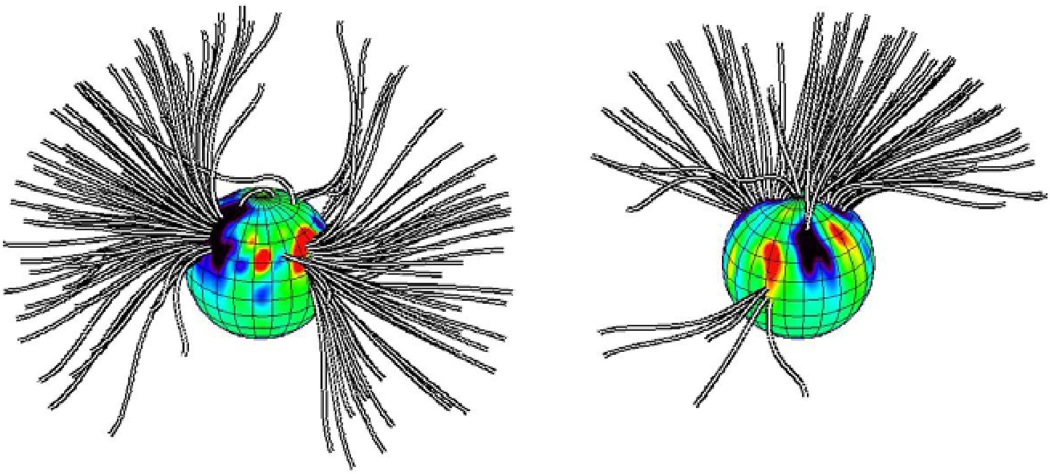

Figure 5. Shown are the open field lines from a potential field extrapolation for surface magnetograms of LQ Hya from December 2000 (left) and December 2001 (right) (Donati *et al.* 2003). The source surface has been set to $3.4R_{\star}$.

To what extent do the details of the field structure really affect the behaviour of the stellar wind over time? Solanki *et al.* (1997) showed the effect of a poleward concentration of flux, but what about other field structures, such as we see in these field extrapolations? To answer this question, we can consider the evolution of a solar mass star from the point where it is released from its disk (Holzwarth & Jardine 2004). We assume that the star has one of four types of flux distribution, shown in Fig. 6. Based on these, we calculate the angular momentum loss at each timestep as the star evolves and so follow the star's rotational history. We can then compare the stellar rotation rate as a function of time with what would have been predicted if the star had possessed a field that was uniform at the surface (as assumed by the classic model of Weber & Davies (1967)). Fig. 7 shows the deviation from the Weber-Davis prediction as a function of time for the different types of flux distribution. Shown are stars that were released from their disks with three different rotation rates. It is clear from this that the detailed structure of the stellar field can be as important as the original rotation rate in determining the rotational evolution.

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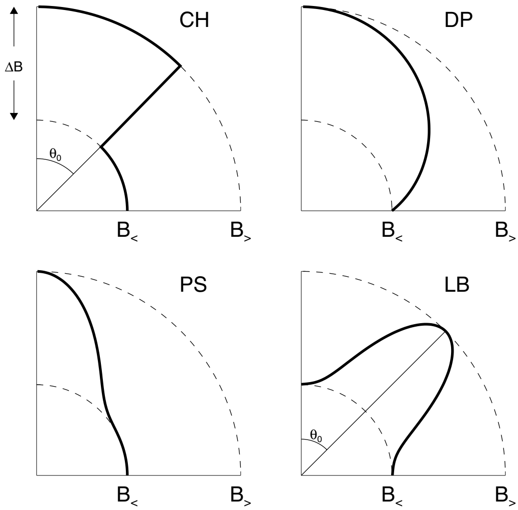

Figure 6. Field distributions close to the stellar surface: coronal hole (CH); dipolar field (DP); polar spot (PS) and latitudinal belt (LB). Dashed lines indicate the upper and lower field strengths. Figure taken from Holzwarth & Jardine (2004).

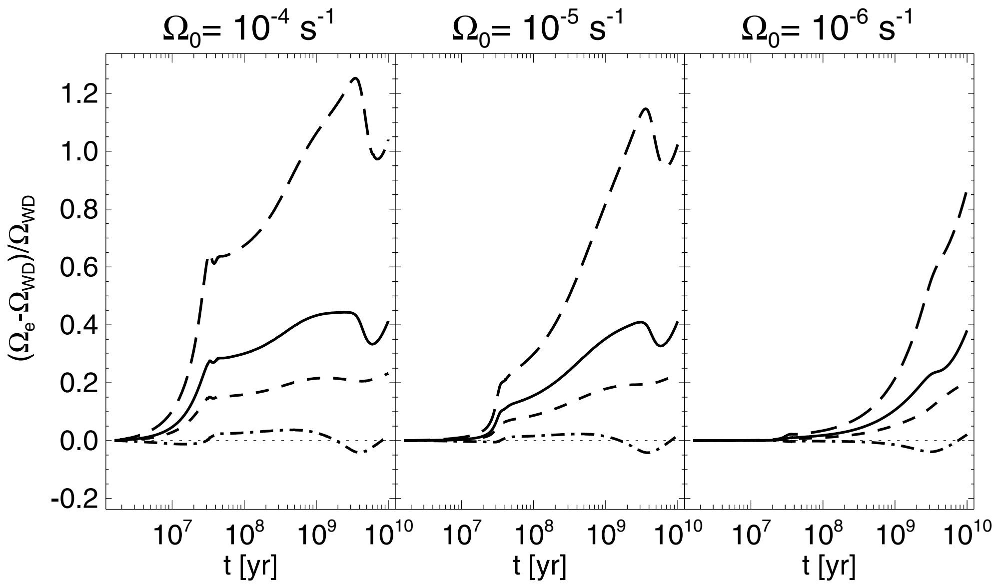

Figure 7. Deviations of the stellar rotation rate from the value obtained using the Weber-Davis formalism. Shown are curves for the four different field geometries of Fig. 6: coronal hole (solid); dipolar field (short dashed); polar spot (long dashed) and latitudinal belt (dashed dotted). Curves are shown for stars with three different initial rotation rates. Figure taken from Holzwarth & Jardine (2004).

4. Stellar prominences

The other way in which these stars lose mass is by the intermittent ejection of stellar prominences. These are observed as transient absorption features that move through the Hα line as the prominence passes between the star and the observer. They form on a

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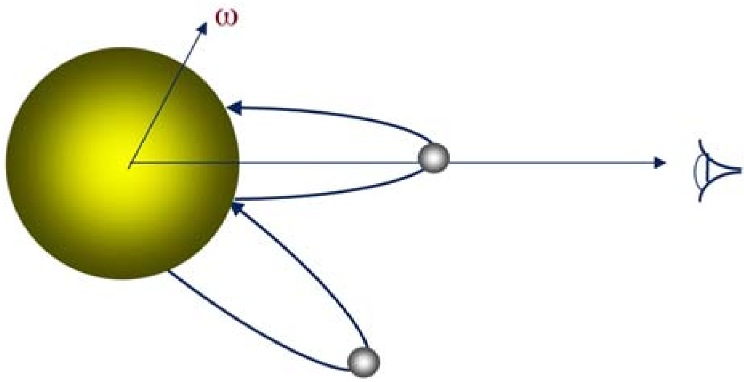

Figure 8. Schematic illustration of the effect of the stellar inclination on the visibility of prominences. Both prominences are at the same distance from the rotation axis, but only the high-latitude one occults the disk as seen by the observer.

timescale of about one day, and typically live for one or two days. At any one time, there are typically some 5 or 6 present in the observable part of the corona of AB Dor. Their masses have been estimated to be about 10^{17}g, about 100 times that of a large quiescent solar prominence (Collier Cameron & Robinson 1989a,b). These prominences typically form at or just beyond the Keplerian co-rotation radius, which is the point at which the outward pull of centrifugal forces just balances the inward pull of gravity. For the Sun, this point is at some 40 solar radii and has little impact on the physics of the corona, but for these rapidly rotating stars, the point of centrifugal balance is inside the corona. These prominences are detected both in binary stars and in single stars, and have been found in 90% of young (pre-) main sequence stars with rotation periods less than one day.

In addition to AB Dor and four G dwarfs in the α Per cluster (Collier Cameron & Woods 1992), other stars for which prominences have been detected include HD197890 (Jeffries 1993); HK Aqr (Byrne *et al.* 1996); RE J1816+541 (Eibe 1998); PZ Tel (Barnes *et al.* 2000) and RXJ1508.6-4423 (Donati *et al.* 2000). This last star is particularly interesting as the prominences were seen in emission (and hence by solar terminology are indeed correctly called prominences, not filaments). This star is viewed at a very low inclination and so the Hα-emitting clouds are never eclipsed by the star.

The ejection of these prominences does not remove significant amounts of angular momentum or mass; indeed the mass loss rate in prominences is probably only comparable to that in the solar wind, and hence is several orders of magnitude less than in a stellar wind (Wood *et al.* 2004). The reason for such interest in these prominences is more to do with what they can tell us about the structure and dynamics of stellar coronae. If providing enough mass to fuel a solar prominence is a challenge for the theorists, the same problem for stellar prominences with their greater mass and greater heights is much more acute. The very number of prominences also gives us a great deal of information about the structure of the corona. Fig. 8 shows two prominences both located at the same distance from the stellar rotation axis. The prominence in the equatorial plane would, however, be unobservable, since it would never cross in front of the observer. Similarly, any prominences in the lower hemisphere would also never be observed. The observed number of prominences is therefore a lower limit to the number that may be present in the stellar corona. Their presence shows that the coronae of these stars still retain a high degree of complexity even out to 3-5 $R_\star$ where the prominences are held in co-rotation.

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If these stars had simple dipole fields after all, the prominences would by symmetry all lie in the equatorial plane and would never be observed.

Some progress has been made in modelling the mechanical and thermal equilibria of these prominences (Collier Cameron 1988; van den Oord 1988; Jardine & Collier Cameron 1991; Ferreira & Jardine 1995; Ferreira & Mendoza-Briceño 1997; Ferreira 2000; Jardine *et al.* 2001). Progress so far has however been limited to simple field configurations and static equilibria. Studies of the dynamics of prominence formation and ejection could yield important insights into the fundamental timescales governing the evolution of stellar coronae, which may in turn shed some light onto the problem of coronal mass ejection on the Sun.

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Discussion

Gopalswamy: What is the origin of mass in the prominences? Is prominence material observed between the surface and the critical height where usually prominences reside?

Jardine: The mass must come from the surface, but we never see it "in transit" (i.e. between the surface and the co-rotation radius). This means that the material must flow from the surface out to $\sim 3R_*$ in less than 12 hours (the rotation period of AB Dor).

Yousef: 1) What is the size of a starspot?
2) Have you detected star flares?

Jardine: 1) The smallest starspots we can detect are about the same size as the largest sunspot.
2) Yes, these stars flare often - so often that you can not directly associate any particular flare with any particular prominence.

Schmieder: 1) Have you a Doppler signal in your Hα observation? 2) Do you observe magnetic field lines (Zeeman effect) at the same time than your Hα lines? Do you cross correlate the result? 3) With same Hα modeling, you could distinguish if the prominence is on the surface or a cloud.

Jardine: 1) No, in the time when the prominence system is visible, there is no significant evidence of radial velocity.
2) Yes, Hα is observed at the same time as the photospheric lines used for Zeeman-Doppler imaging, but I'm not aware that they have been cross-correlated (perhaps because there are so many magnetic signatures).
3) Yes, the time taken for the features to cross the line profile show that they are not a surface feature.

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