Polar fields for AB Doradus

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Accepted 2003 June 30. Received 2003 June 25; in original form 2003 May 12

ABSTRACT

Polar spots are often observed on rapidly-rotating cool stars, but the nature of the magnetic field in these spots is as yet unknown. While Zeeman–Doppler imaging can provide surface magnetic field maps over much of the observed stellar surface, the Zeeman signature is suppressed in the dark polar regions. We have determined the effect on the global coronal structure of three current models for this polar field: that it is composed (a) of unipolar field, (b) of bipolar regions or (c) of nested rings of opposite polarity. We take as an example the young, rapid rotator AB Doradus ($P_{rot} = 0.514$ d). By adding these model polar fields into the surface field maps determined from Zeeman–Doppler imaging, we have compared the resulting coronal structure with the observable properties of the corona – the magnitude and rotational modulation of the X-ray emission measure and the presence of slingshot prominences trapped in the corona around the Keplerian corotation radius. We find that only the presence of a unipolar spot has any significant effect on the overall coronal structure, forcing much of the polar field to be open.

Key words: stars: activity – stars: coronae – stars: imaging – stars: individual: AB Doradus – stars: spots.

1 INTRODUCTION

Since the advent of Doppler imaging it has been possible to map the distributions of star-spots on rapidly-rotating stars. This has revealed that star-spots are typically found not only at the low latitudes where sunspots emerge, but also at very high latitudes, extending all the way to the pole (Strassmeier 1996). At present, there is no consensus on the origins of these high-latitude spots. The only thing that is clear is that rapid rotation seems to play an important role.

Three possible models have been proposed to explain the latitudinal distribution of star-spots. As early as 1992, Schuessler & Solanki (1992) proposed that flux tubes formed deep in the stellar convective zone would be deflected poleward by Coriolis forces as they attempted to rise buoyantly to the surface (Granzer et al. 2000). This would result in a polar cap that was formed of mixed polarity regions of a similar nature to those at lower latitudes. More recently, Schrijver & Title (2001) have presented a model for flux emergence on rapid rotators. A poleward meridional flow carries bipoles towards the poles while at the same time diffusion attempts to disperse them. The inclination of these bipoles to the equator causes the trailing polarities to reach the pole first, leading to a flux distribution which resembles concentric rings of alternating polarity encircling the pole. Finally, Kellett et al. (2002) have suggested on the basis of radio observations that the polar caps are formed of unipolar field, perhaps part of a large-scale dipole.

In all of these scenarios, the polar caps would appear dark in a Doppler image if the polar fields were strong enough to suppress convection. What these Doppler images cannot reveal is whether the polar field is composed of closed-loop structures which may be bright in X-rays, or open field regions which may contribute to the stellar wind. This question becomes of importance when considering the processes of angular momentum loss in a stellar wind, which has traditionally been modelled on the basis of an aligned dipole field where most of the open (wind-bearing) field lines emerge from near the stellar pole. It is also relevant to studies of disc–magnetosphere interaction and channelled accretion flows in young stars.

The purpose of this paper is to determine if there are any observational tests that could distinguish between these three different models for the nature of the polar field. We do this by modelling the effect of these different models on the structure of the coronal magnetic field and the nature of its X-ray emission.

2 AB DORADUS

We take as our example star the young rapid rotator AB Doradus (AB Dor) which has been studied in depth for the last decade or so. Surface brightness maps have been collected annually since 1988 (Collier-Cameron & Unruh 1994; Unruh, Collier Cameron & Cutispoto 1995; Collier Cameron 1995). In the last seven years, Zeeman–Doppler maps of the surface magnetic field have been secured on an annual basis. Long-term studies of the star's X-ray variability have shown a small rotational modulation (5–13 per cent) and a large emission measure of 10^{52-53} cm⁻³ (Vilhu et al. 1993). This implies that AB Dor has either a very extended or very dense corona. AB Dor has an inclination of 60° and therefore much information about the lower hemisphere is lost. In the upper hemisphere however, the pole remains in view constantly and X-ray emission from high latitudes would therefore suffer little rotational modulation. *BeppoSAX* observed a flare (Maggio et al. 2000) that showed no rotational modulation over a period greater than the rotation period of the star. Modelling of the flare decay showed that the flaring loops must be small and hence must be situated at latitudes above 60° in order to remain in view.

Complementary to these observations are spectroscopic studies of the star's X-ray emission from which the thermal structure, abundance stratification, and densities of the corona can be investigated. Recent studies with *XMM* showed coronal densities to be extremely high ranging from 3×10^{10} cm⁻³ (Güdel et al. 2001) to 10^{12} cm⁻³. This high density immediately suggests that the emitting loops would be relatively small and compact. If this is the case, to explain the lack of rotational modulation, these loops would have to be located at latitudes high enough to remain in view as the star rotates. High-latitude magnetic loops are consistent with Doppler images of AB Dor where we can see dark polar spots along with spots at lower latitudes. Zeeman–Doppler images show magnetic flux to be present all over the surface of AB Dor apart from at the poles where the surface brightness is so low that the Zeeman signal is suppressed (Donati & Collier Cameron 1997).

Any model applied for the field at the pole will have to explain the lack of rotational modulation in the X-ray emission as well as being consistent with the observations of large prominences that form preferentially at or just beyond the Keplerian corotation radius, which for AB Dor is at 2.7 stellar radii from the rotation axis (Collier Cameron & Robinson 1989a,b). As many as six prominences may be present at any one time in the observable hemisphere of the star. Because they corotate with the star, they must be held in place by the coronal magnetic field. This suggests that at least some fraction of the coronal field is in the form of closed loops even at these large distances.

The structure of the large-scale coronal magnetic field of AB Dor was investigated by Jardine, Collier Cameron & Donati (2002a). They took the surface magnetic field determined from Zeeman-Doppler imaging and extrapolated it into the corona, assuming it to be potential. They found that the closed field regions of the corona extended over the polar regions. By filling the corona with isothermal plasma in hydrostatic equilibrium, they determined the spatial distribution of the coronal X-ray emission (Jardine et al. 2002b). Much of this emission came from high-latitude regions where it was never rotationally self-eclipsed. This naturally gave a low rotational modulation in X-rays, similar to the observed value. The derived magnitude of the emission measure and the emission-measure weighted mean density were also consistent with observations. Jardine et al. also explored the effect on the X-ray emission of adding in a global dipole and determined that because this would cause the polar regions to be open (and hence dark in X-rays) this could not be reconciled with the BeppoSAX flare observations that suggest the presence of closed loops at high latitudes (Maggio et al. 2000).

In this paper, we consider the impact of some alternative models that may explain the dark polar caps. Rather than a global dipole which extends over the whole surface, we consider a single unipolar spot at the pole which covers a limited surface area. We also consider two possibilities for mixed-polarity regions at the pole: either a single bipole or concentric rings of alternating polarity. These configurations were added to the poles of the 1995–1996 mixed map of AB Dor. In each case, the global field was extrapolated and the positions of stable points which are possible prominence formation sites and the X-ray emission were determined. The effects on these properties were examined for different strengths of polar field ranging from 500 to 2000 G. Below this upper limit, polar fields would escape detection. Although the polar areas on AB Dor are dark and



Figure 1. The graphs above show the longitude for stable points where possible prominences may form and would pass in front of the star so they may be detected. The results here are fairly conclusive showing that all three models have roughly two regions of longitude where prominences could be detected.

3 EXTRAPOLATING THE CORONAL FIELD

The extrapolation of the field is the same as used in Jardine et al. (2002a). Because the method is the same we refer to the previous mentioned paper for a detailed description of the calculations involved. We write the magnetic field **B** in terms of a flux function Ψ such that $\mathbf{B} = -\nabla \Psi$ and the condition that the field is potential ($\nabla \times \mathbf{B} = 0$) is satisfied automatically. The condition that the field is divergence-free then reduces to Laplace's equation $\nabla^2 \Psi = 0$. A solution in terms of spherical harmonics can then be found

$$\Psi = \sum_{l=1}^{N} \sum_{m=-l}^{l} \left[a_{lm} r^{l} + b_{lm} r^{-(l+1)} \right] P_{lm}(\theta) e^{im\phi}, \tag{1}$$

where the associated Legendre functions are denoted by P_{lm} . The coefficients a_{lm} and b_{lm} are determined by imposing the radial field at the surface from the Zeeman–Doppler maps and assuming that at some height R_s above the surface the field becomes radial. Due to the presence of large slingshot prominences observed around the corotation radius which lies at $2.7R_{\star}$ from the rotation axis, we believe that much of the corona is closed out to those heights and so we set the value of R_s to $3.4R_{\star}$. In order to calculate the field we used a code originally developed by van Ballegooijen, Cartledge & Priest (1998).

4 CALCULATING THE POSITION OF PROMINENCES

The numerical method for determining the locations of stable potential minima along field lines is discussed in detail by Pointer et al. (2002) and will only be given a brief review here. For a possible prominence formation site to exist, the component of











Figure 2. Surface maps of the magnetic field for AB Dor for 1995 December shown from a viewpoint looking down on the rotation pole. (a) shows the surface magnetic field as it is observed with no field added to the polar region. (b) has a large unipolar spot, (c) concentric rings of opposite polarity and (d) the bipolar configuration. The strength of the field added to each model is 1 kG.

effective gravity along the magnetic field must be zero, i.e. $\boldsymbol{B} \cdot \boldsymbol{g}_{\text{eff}} = 0$. For this position of equilibrium to be stable, we also require it to be a potential minimum. Thus, the equilibrium must satisfy the condition

$$(\boldsymbol{B} \cdot \nabla)(\boldsymbol{B} \cdot \boldsymbol{g}_{\text{eff}}) < 0. \tag{2}$$

Such stable points may be favoured positions for prominence formation as any gas condensing at this point would neither fall towards the surface nor be centrifugally expelled. The fact that prominences on AB Dor are observed around the corotation radius suggests that such minima in the gravitational-centrifugal potential do have a role to play in determining where prominences form. The existence of such stable points does not, however, guarantee prominence formation. In fact, at distances as far out as the corotation radius, the curvature of the field lines would need to be much smaller in order to overcome the centrifugal acceleration acting on a prominence. Prominences are observed as transient H_{α} absorption features and so can only be seen when they occult the stellar disc. We therefore select out of all possible stable points those that transit in front of the disc. Hence, due to the stellar inclination any points that will transit the disc must satisfy the condition

$$R\cos(\theta + 60) < 1 \tag{3}$$

where *R* is the radial height of the stable point and θ is the latitude. If a star has a purely dipolar field, all such stable points would lie in the equatorial plane and so would be unobservable (Jardine et al. 2001). We anticipate with our unipolar spot model that as the field strength in the polar cap is increased, the polar field will eventually dominate over the low-latitude field and the global topology will resemble that of a dipole. In this case, no stable points in the corona



Figure 3. Closed field emerging only from the polar regions where we have added flux. Strong similarities can be seen between the original image, concentric rings and bipole models. In these cases, the field lines from the polar region connect primarily to the surface at high latitudes. Only in the case of a unipolar spot (b) do the field lines connect to the rest of the stellar surface.

would be observable. For each of our polar field models, we have therefore investigated the number of stable points that could be observed. Fig. 1 shows the longitudes of these stable points.

5 X-RAY EMISSION

The X-ray emission was determined from the closed field regions. First of all, the pressure structure of the corona was calculated assuming it to be isothermal and in hydrostatic equilibrium. Thus, the pressure at any point is

$$p = p_0 \exp\left(\int g_s \,\mathrm{d}s\right) \tag{4}$$

where $g_s = (\mathbf{g} \cdot \mathbf{B})/|\mathbf{B}|$ is the component of gravity along the field and

$$\boldsymbol{g}(r,\theta) = (-GM_{\star}/r^2 + \omega^2 r \sin^2 \theta, \, \omega^2 r \sin \theta \cos \theta), \quad (5)$$

with ω being the stellar rotation rate. The plasma pressure is scaled to the magnetic pressure at the loop footpoints, i.e. $p \propto B_0^2$ where the constant of proportionality is chosen to match the observed emission measure. As we move out to larger heights from the star, the gas pressure is greater than the magnetic pressure and thus forces field lines to open up. We have included this effect in our model by setting the plasma pressure to zero wherever it is greater than the magnetic pressure, i.e. where $\beta > 1$. From the pressure, the corona's density could be calculated assuming it to be an ideal gas. Using a Monte Carlo radiative transfer code, we can then determine the X-ray emission.

6 RESULTS

The magnetic fields added to the star are depicted in Fig. 2 as is the original surface field map. All three additional fields have a strength of 1 kG. This is a reasonable estimate for the field at the pole as it is strong enough to suppress convection yet not so strong as to be detectable in the star's Zeeman–Doppler images.

As can be seen in Fig. 3, where we have shown only those field lines that are anchored at points within the polar region in question, the unipolar spot model has the greatest effect on the global field topology. Closed loops from the polar region are forced down to lower latitudes due to the presence of a strong open field at the pole. This is unlike the other two models with the concentric rings and bipole, which show a strikingly similar appearance to the original data set of having large closed loops crossing directly over the pole. In these models, there is almost no open field emerging from the polar region. The concentric rings and bipole models show greater consistency in the lack of rotational modulation of the flaring X-ray emission seen in the *BeppoSAX* observation.

The difference in the topology of the field that is added at the pole can be seen in Fig. 4 which shows the fraction of the surface flux that is open. In the case of a single unipolar spot added to the pole, this fraction increases as the strength of the polar field is increased, reaching a maximum value of 15 per cent. This is less than the corresponding value of 44 per cent for a dipolar field with the same source surface imposed (Jardine et al. 2002a) but still represents a significant factor. The open field regions extend down to a latitude of 75° with the result that much of the polar regions would be dark in X-rays. For the other two types of polar field, however, most of the polar field lines are closed (see Fig. 3) and so very few of them contribute to the flux of the open field. In this case, the fraction of open field decreases as the polar field strength increases. This is due to the field at the pole being able to connect locally.



Figure 4. The graph shows the change in the amount of open magnetic flux as we increase the field strength at the poles of the various models. Any flux that reaches the source surface is considered open hence we calculate the amount of open flux as a ratio of total flux emerging at the stellar surface: $\sum_{A} |B_{\rm r}(R_{\rm s}, \theta, \phi)| / \sum_{A} |B_{\rm r}(R_{*}, \theta, \phi)|.$ The solid line shows the change for the unipolar spot model, the dotted line represents the concentric rings model and the dashed line the bipolar model. Again, the similarities between the concentric rings and bipole models is easily seen, both slowly decreasing in open flux as we increase the strength of the polar field. The unipolar spot model, on the other hand, shows a reasonable growth in open flux with increasing field strength at the poles. It should be noted that, although we have shown the flux ratios for magnetic fields up to 12 kG, these fields are much too strong to be considered non-detectable and are only shown to display the saturation each of the models has on the open flux.

Positions of possible prominences are less affected by the addition of a polar field. Again, the unipolar spot has the greatest effect forcing the stable points toward the equatorial plane of the star (Fig. 5). Many of these points which lie in or near the equatorial plane cannot be observed crossing the star along our line of sight. Observations of prominences are possible only if the prominences transit our line of sight to the star causing absorption dips in the H α profile. Strangely, however, the number of stable points for the dipole model is not that much less than any of the other models, although there does seem to be some convergence of longitudes as we increase the field strength at the pole for this model. The concentric rings and bipole models reproduce the same pattern of sites as the original image. In all three models we find that the stable points are grouped into two regions where arcades of predominantly east-west field span a range of longitudes. The imposition of the polar field disturbs the summits of these structures, pushing them toward longitude 220° in the unipolar case, and away from longitude 220° in the concentric case.

Clearly, none of these models can fully explain the number of prominences that are observed (up to six in the observable hemisphere at any one time). One possibility is that these stable points are not reliable indicators of prominence formation sites. Alternatively, as suggested by Schrijver & Title (2001) it could be that the prominences are formed in the sheared field produced when differential rotation stretches out the unipolar field of the dark polar cap to produce an azimuthal field. Such fields have been observed on AB Dor for some time (Donati & Collier Cameron 1997). Recently, Hussain et al. (2002) have fitted non-potential magnetic fields to the observed Stokes profiles. They have shown that the currents (which mark the regions where the field departs from its lowest-energy state) are confined to the high-latitude regions at the edge of the dark polar cap. The positions of the stable points in these field extrapolations,



Figure 5. Surfaces with closed field lines show possible locations of prominences. At each of these points the effective gravity along the field line is zero and the point lies at a potential minima. moving from top left to bottom right, polar configurations considered are: nothing at the pole (a), global dipole (b), concentric rings (c), bipole at the pole (d). Each polar cap added has a field strength of 1 kG used.

however, were not significantly different from those determined for a potential field.

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Pointer et al. (2002) performed a potential field extrapolation from a Zeeman–Doppler image of AB Dor with a dipolar field added into the map. They showed that differential rotation acting on such a field would produce a high-latitude ring of azimuthal field similar to that observed (Donati & Collier Cameron 1997). It is possible that the field produced by the flux emergence model of Schrijver & Title (2001) would have a similar effect. Here the differential rotation between the concentric rings of opposite polarity would shear the field crossing this boundary producing an azimuthal field. A third possibility is that, as suggested by Hussain et al. (2002), the closed corona is in fact confined to within $1.6R_{\star}$ and the prominences are confined in the very cusps of helmet streamers, much further out than the rest of the corona. The other observable quantity is the X-ray emission. This was calculated for each model with a polar field of 1 kG. Looking at the X-ray images of the stellar corona (Fig. 6) for each model, it is clear that the original image, the concentric rings and bipole models all show a strong similarity with a predominant X-ray emission from the polar region. The unipolar spot does show some emission from the polar region, although not nearly as much structure as the other models. The average emission measure did not vary significantly between the models, ranging from 1.9×10^{52} cm⁻³ for the concentric rings to 2.73×10^{52} cm⁻³ for the bipole. The unipolar spot model has the highest emission measure with a value of 3×10^{52} cm⁻³ but it has such a large rotational modulation (31.5 per cent) that its average emission lies at 2.61×10^{52} cm⁻³. Fig. 7 shows the rotational modulation for each model in the X-ray emission. The other models all show a level of rotational modulation (9–11 per cent)



(c)

(d)

Figure 6. X-ray images of the stellar corona for each model. Same layout as previous figures. The X-ray emissions are all calculated for a coronal temperature $T = 10^7$ K.

that fits the values predicted by observations of 5-13 per cent (Kuerster et al. 1997). Something else worth noting here is that the models, excluding the unipolar spot, all showed very similar X-ray light curves. This again strongly suggests that the presence of a mixed-polarity field at the pole has little effect on the overall structure of the star.

7 CONCLUSIONS

Using Zeeman–Doppler images of the surface magnetic field of the young, rapidly rotating dwarf AB Dor, we have investigated the effect on the coronal field structure of the three most popular models for the polar fields of young stars. We find that the addition of a mixed-polarity region at the pole results in more small-scale local flux tubes at the pole, but has little effect on the large-scale field structure. Consequently, observations of the magnitude or rotational

modulation of the X-ray emission are not sufficient to discriminate between these types of models. Observations of the 'slingshot prominences' trapped in the coronae of these stars do not provide an observational discriminant either. We have determined possible prominence-bearing structures by calculating the sites of stable mechanical equilibrium. All three models showed no more than two structures that can transit the stellar disc, but the observations show condensations at all longitudes. Due to the nature of alternating magnetic polarity at the surface of the star, it is thought that a helmet streamer model could provide us with more regions of longitude for possible prominence formation sites where each prominence site would lie above and between these regions of opposite polarity (Linker et al. 2001).

The large-scale field structure is affected rather more by the addition of a unipolar region at the pole. This forces more of the polar field lines to be open (and hence dark in X-rays). This gives a larger



Figure 7. Graph showing the X-ray emission measure as it varies with phase for each model. All models here do not differ too much in magnitude and certainly the original data (solid line), concentric rings (dashed line) and bipole (dash-dotted line) show a remarkably similar curve in emission over a whole cycle. This is also reflected in their rotational modulation which shows little variation between these three models and fits into the range of values predicted by observations of 5–13 per cent (Kuerster et al. 1997). The unipolar spot model (dotted line) shows a much higher rotational modulation of 31.52 per cent.

rotational modulation as the closed field regions that are bright in X-rays are now at lower latitudes and so are subject to rotational self-eclipse.

A polar spot extending down to latitude 75° gives a rotational modulation of 31.5 per cent, greater than the observed value of 5–13 per cent (Kuerster et al. 1997). It also forces up to 15 per cent of the flux that emerges through the surface to be open, compared to only 5 per cent when no field is added at the pole. This has potential implications for the angular momentum lost in the stellar wind, not only because it changes the amount of open flux, but also because it affects the distribution in latitudes. The addition of a polar spot introduces many more high-latitude open field lines. The winds from high-latitude regions remove significantly less angular momentum from the star because of the reduced lever arm of the field lines. Schuessler & Solanki (1992) showed that this may explain the apparent slow-down of the angular momentum loss in young rapid rotators.

The change in the global field structure brought about by adding a polar spot may also be relevant to studies of disc-magnetosphere coupling in young stars. The addition of a polar spot means that the largest scale field lines (the ones that would intersect a disc) originate from the poles. In this case, any material accreting from a disc would reach the stellar surface at the poles. In the absence of a polar spot (or in the case where the polar field was of mixed polarity) the accretion process would be more likely to be in the form of discrete accretion funnels, which would intersect the stellar surface in low-latitude 'hotspots'.

While the nature of the polar field – whether single or mixed polarity – clearly makes a difference to the global field structure, the available observations of the X-ray emission measure and the prominence distribution are not sufficient to discriminate between types of polar field. We can, however, rule out the possibility of the unipolar spot model because the results show the modulation amplitude in the X-ray emission to be much too large. Only the degree of modulation of the X-ray emission can be used, but this requires long-term monitoring to eliminate the effects of short-term variability in flares. Phase-resolved observations of line shifts that indicate the presence of a stellar wind would perhaps be a good proof of the field structure, but it may be that it will only be with the advent of Zeeman–Doppler imaging in molecular lines that we will be able to determine the nature of the polar fields.

ACKNOWLEDGMENTS

The authors would like to thank Dr A. van Ballegooijen for allowing us to use his code to calculate the potential magnetic field and Dr D. Mackay for help in implementing it. TMcI would also like to acknowledge studentship support from PPARC.

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