Modeling the corona of AB Doradus

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Abstract. We present coronal models for the active, rapidly rotating K0 dwarf, AB Doradus. The coronal magnetic field is modeled using an advanced version of the high resolution spectroscopic technique, Zeeman Doppler imaging. We evaluate coronal temperatures and densities using an energy balance model. Emission measure distributions derived from this model compare favourably with observations. The observed density ($\approx 10^{13}$ cm$^{-3}$) at the emission measure peak remains difficult to explain.

1. Introduction

AB Dor is a K0 dwarf that has newly arrived on the main sequence. As with other very young stars, it is rapidly rotating ($P_{\text{rot}} = 0.514$ d) and displays strong signs of activity in optical and X-ray wavelengths, $L_X/L_{\text{bol}} \approx 10^{-3}$ (Vilhu & Linsky 1987). Long-term photometry shows a gradual rise and fall in the light level of the star, indicating a 22–23 year solar-type activity cycle (Amado et al. 2001).

The X-ray observations of the star indicate that the coronal activity is both chaotic and complex. As with other young active stars, there are no long-term trends evident in the X-ray light curve of AB Dor. Kürster et al. (1997) analyse ROSAT data of AB Dor spanning 5 years and find evidence for some emission originating in compact structures (rotational modulation is between the 5-13% level). Maggio et al. (2000) model flare decay times using BEPPOSAX data and find evidence for flares originating in compact loops ($H \approx 0.3 R_*$). Density-sensitive Fe lines from EUVE data suggest the presence of very dense plasma ($n_e \approx 10^{13}$ cm$^{-3}$) at temperatures of about $8 \times 10^6$ K (Sanz-Forcada et al. this volume). This temperature also corresponds to a strong peak in the EMD derived using the same dataset (See Fig. 4) and that other active cool star systems, from single young dwarfs to RSCVn systems, have similar characteristics. Observations of a similarly dense, high-temperature region on the contact binary, 4447 Boo, indicate a lack of modulation over a complete rotation cycle (Brickhouse & Dupree 1998). High densities imply very compact features and combined with the lack of modulation of the emission “bump”, it indicates that these region are located near the pole with sizes of about 0.004 $R_*$.
Evidence for extended structures in AB Dor's corona comes from observations of slingshot prominences out to 5 R_\ast. Their presence is inferred from the analysis of fast moving H\alpha absorption transients (Donati et al. 1999, Collier Cameron et al. this volume). The existence of cool material at distances past the Keplerian co-rotation radius (R_K \approx 2.6 R_\ast) is also found in observations of TR lines obtained using both HST and FUSE (Brandt et al. 2001, Young 2001). C IV 1548\AA, Si IV 1393\AA and O VI 1032\AA spectral lines all have extended wings. Assuming that the wings are formed by optically thin plasma, this would indicate plasma at temperatures of about 10^5 K out to 3 R_\ast.

In this paper we set out to explain some of the observations of AB Dor's corona by extrapolating surface magnetic field maps. We present attempts to fit the EMD obtained using the combined results of the EUVE and IUE observations obtained by Sanz-Forcada et al. (this volume). Once EMDs obtained from Chandra and XMM become available (Güdel et al. this volume, Linsky et al. 2001), diagnostics for the plasma at higher temperatures will also be incorporated in our study.

2. Coronal topology of AB Dor

We use an advanced version of Zeeman Doppler imaging (ZDI) to model the magnetic field of AB Dor. ZDI is essentially Doppler imaging applied to circularly polarized spectra (Semel 1989). The circularly polarized spectra of AB Dor used for the imaging analysis were obtained using an instrument setup at the 3.9m Anglo-Australian telescope that included the Semel polarimeter and the UCL Echelle Spectrograph (Donati et al. 1999, Hussain et al. 2000)

As with Doppler imaging, ZDI relies on rotational broadening to separate the signatures from different magnetic field regions in velocity-space. Circularly polarized spectra are sensitive to the line-of-sight component of the magnetic field. Within the weak field regime (under 1kG) the size of the signature scales linearly with the size of the field. By tracking the velocity excursions and intensity variations of the circularly signatures over the course of a rotation cycle we can determine the orientation as well as the size and location of the surface field (Donati & Brown 1997).

In conventional ZDI all field orientations (radial, azimuthal and meridional fields) are assumed to be independent of each other. This means that ZD maps can show physically unrealistic field distributions such as monopoles. We have developed an advanced version of this method that introduces a relationship between all the field vectors. Initially we tried to fit the observed dataset using just a potential field prescription and found that it was not possible to find a solution within a reduced \chi^2 \approx 1.5 for this dataset. We then tried a model in which the curl of the magnetic field, j = \nabla \times B is given by a potential field (j = -\nabla \Psi, with \nabla^2 \Psi = 0). The magnetic field is determined by two free functions, B_\theta(\theta, \phi) and j_\theta(\theta, \phi), at the stellar surface. This provides the additional freedom to obtain a good fit to the polarization profiles and also allows the magnetic field to be extrapolated into the corona in a realistic way.

Figs. 1b & c show the magnetic field distribution on the surface of AB Dor for 1996 December. The contemporaneous brightness map (Fig. 1a) shows that dark starspots cover the pole (extending down to 70° latitude) co-existing
with spots at the equator. The magnetic field analysis assumes that the spectral line depth is uniform over the stellar surface and does not take the presence of these dark starspots into account. Hence it is likely that the actual magnetic field at the stellar surface is considerably stronger in the spotted areas than we can measure using circularly polarized spectra. However, the magnetic field maps (Figs. 1b & c) show equally strong radial and azimuthal field covering the visible part of the stellar surface, even in the bright regions of the star. This pattern is very different to that observed on the Sun where strong azimuthal field tends to be confined to the penumbral regions of starspots. One explanation for this azimuthal field may be that we cannot detect strong radial field in the dark umbrae of starspots and are preferentially reconstructing horizontal field in the brighter penumbrae.

This surface field can be written in terms of spherical harmonic functions, and the assumption that \( \mathbf{j} = -\nabla \Psi \) can be used to determine the radial depen-
dence of the spherical harmonic coefficients. Two coronal field models are plotted in Fig. 2. The source surface, the point beyond which the field is assumed to be open and purely radial, was initially set to \(5 R_\star\) as prominences have been observed out to these distances (see Collier Cameron et al. this volume). However, following our analysis of the thermal stability of these loops in the next section it appears likely that the source surface should be nearer \(1.6 R_\star\). If this is the case it is unclear how prominences can be supported at distances of up to \(5 R_\star\).

![Figure 2. Coronal field topology for AB Dor. The source surface has been set to (a) \(5 R_\star\) and (b) \(1.6 R_\star\).](image)

3. Heating in corona

The properties of the 3D coronal field model were studied using a steady flow model. In our model we take non-thermal heating to be constant in time and seek steady state solutions of the energy balance equations. As the loops are allowed to be asymmetric, there is in general a steady mass flow along the loop. The flow velocity is assumed to be smaller than the sound speed, so the plasma is nearly in hydrostatic equilibrium. We assume that magnetic flux is constant along the loop. Hence, as the magnetic field strength, \(|B|\), drops off with height, the loop cross-sectional area will expand (Schrijver et al. 1989). Energy transport in the lower transition region \((T < 4 \times 10^5 \text{ K})\) is modeled using a parametrisation of ambipolar diffusion. Boundary conditions placed on the footpoints of each loop include setting the footpoint temperature to \(T = 2 \times 10^4 \text{ K}\), and energy fluxes are calculated for each footpoint assuming a simple model of the chromosphere.

3.1. Thermal stability

The heating rate is assumed to depend only on the magnetic field strength:

\[
E_H(s) = \epsilon_0 B(s)^n,
\]  

(1)
where $E_H$ is the heating rate per unit volume as position, $s$, along the loop, and $\epsilon_0$ is a constant.

If the heating rate is proportional to $B$ ($n = 1$), then for high-altitude loops $E_H$ drops off quickly with height and there is insufficient heating at the apex of the loops for a stable solution. We find that for certain distributions of heating the loop is thermally unstable (i.e. there is no steady solution of the energy balance equations). To illustrate this problem we present results for a symmetrical loop ($H=1.8 R_\ast$, $L\approx 2.87 R_\ast$, $n = 1$). Fig. 3 shows the development of a coronal condensation. You can clearly see how the temperature structure changes as a function of position for three steps of the iterative procedure. There is a drop in temperature in the middle of the loop during the third iteration. This instability occurs because the heating near the footpoints is relatively strong, causing evaporation of chromospheric material and this increases the pressure everywhere in the loop. However, the heating rate in the middle of the loop is insufficient to compensate for the local radiative losses, and thermal conduction cannot fully compensate for this deficit. As the temperature at the apex drops, the radiative losses increase further due to the temperature dependence of the radiative loss function. In our iterative procedure the temperature drops immediately to the lowest allowed value ($2 \times 10^4$ K). As we use a fixed grid, the temperature structure of this “coronal condensation” is not properly resolved. In subsequent iterations this condensation disappears and reappears repeatedly, and the temperature, $T(s)$, never converges to a steady state. We believe that this lack of convergence is due to a real thermal instability and is not an artifact of the iterative method.

Figure 3. Temperature versus position along the loop for three iterations of the procedure to solve the energy balance equations. These plots show the development of a coronal condensation.

In the present paper we focus on models with heating independent of field strength, $n = 0$. We assume that the peak of the EMD is due to loops with a maximum temperature, $T_{\text{max}} \approx 8 \times 10^6$ K. Therefore the constant, $\epsilon_0$, is selected to fit $T_{\text{max}}$, so for short loops $\epsilon_0$ must be very large, and for long loops $\epsilon_0$ must be very small. The resulting gas pressure is inversely proportional to loop length, L. We find that for high-altitude loops the gas pressure is larger than the magnetic pressure at the apex of the loop, (i.e. the coronal plasma is no longer magnetically contained). This problem arises for loop heights greater than about $0.6 R_\ast$ which suggests that beyond this height all magnetic fields are open. Therefore, in the following we only present results for the model with the source surface at $1.6 R_\ast$ (see Fig. 2b).
3.2. Expanding cross-sections

To obtain a clear peak in the EMD it is necessary to assume that the cross-section varies with position along the loop. By allowing a loop to expand with height, emission at lower temperatures is suppressed as the legs of the loops at these temperatures have a smaller cross-section. The hotter gas at the loop apex fills a larger volume and produces the type of emission peak that is observed (Schrijver et al. 1989, Ciaravella et al. 1996). Expansion factors (Γ = A\text{max}/A\text{foot}) of between 5-7 are sufficient to explain the enhanced peak observed in Fig. 4.

Observed EMDs obtained with EUVE show emission bumps at temperatures in the range 6 – 10 × 10⁸ K for several active cool stars (Dupree et al. 1993; Brickhouse & Dupree 1998; Sanz-Forcada et al. 2001). In the case of 44i Boo Brickhouse & Dupree (1998) suggest that these bumps arise from compact, high pressure loops located at high latitude on the star. Such low-altitude loops are not expected to have large expansion factors, so it is unclear why they should give rise to a peak in the EMD. In the following we propose a different model in which there is a combination of low altitude (high pressure) and high altitude (low pressure) loops on the star. We show that this model can reproduce the observed EMD and also reproduces the observed density-sensitive line ratios.

3.3. Modeling EMD for AB Dor

First, we investigate the type of compact loops that are thought to be the source of high density measurements at EM peak temperatures (Sanz-Forcada et al., Brickhouse & Dupree 1998). We find that, in order to obtain stable loops with coronal density of about 10¹³ cm⁻³ as observed by EUVE, we have to increase the heating rate such that ε₀ ≈ 4 × 10⁹ erg cm⁻³ s⁻¹ and we have to reduce the loop length to L ≈ 280 km (we assume Γ = 6). The gas pressure in such loops would be about 10⁴ dyne/cm² and the field strength at the feet of such loops must be at least 3000 G, which is larger than the fields observed with ZDI. Assuming there are about 10⁴ such loops at any one time, we can fit both the observed EMD (see Fig. 4a) and the densities at the EM peak. However, their lengths are unrealistic as they are comparable with the height of the photosphere. Furthermore it is unclear why such short loops would have expanding cross-sections, Γ > 5.

Another more realistic model can reproduce the observed EMD but is inadequate when explaining the high densities in the EM peak. As mentioned earlier, expansion factors of 5 < Γ < 7 are needed to reproduce the EM peak in Fig. 4. These factors can be obtained using the model shown in Fig. 2b and assuming loop heights in the range 0.1-0.5 Rₜ. The average length of such a loop is about 0.75 Rₜ and if ε₀ ≈ 10⁻⁵ erg cm⁻³ s⁻¹, it will have a pressure of about 5 dyne/cm², consistent with the TR observations. However, the loops have coronal densities of about 3 × 10⁹ cm⁻³ at T ≈ 8 × 10⁸ K, much less than implied by the EUVE observations. In order to produce higher densities, it is possible to invoke much smaller loops (L ≈ 0.043 Rₜ) with high heating rates and small expansion factors to fit the high temperature tail. The EM resulting from a combination of these two types of loops is plotted in Fig. 4b. These hot loops have densities of nₑ ≈ 10¹³ cm⁻³ at the EM peak temperature, but they contribute only 3% of the EM at the peak, and therefore it is unlikely that this model can reproduce the observed density sensitive lines.
Figure 4. (a) Model 1: very compact expanding loops, $L \approx 0.0004 R_\star$. (b) Model 2: a combination of expanding loops $L \approx 0.75 R_\star$ (dotted line), and more compact dense loops, $L \approx 0.04 R_\star$ loops (dashed line). (c) Observed EMD from 1993-1994 for AB Dor computed from IUE and EUVE data (Sanz-Forcada et al. this volume).

Both models presented here fit the observed EMD well. The model that can reproduce the observed densities as well as fit the EM requires loops that are too short (on the same scale as the height of the photosphere). The second model would appear more reasonable but it cannot reproduce the observed density sensitive lines. Therefore, neither model is fully satisfactory.

4. Discussion

Surface maps of AB Dor indicate the presence of a dark starspot at the pole of the star. This indicates that flux is emerging in this region as also indicated by some coronal observations of the star. By extrapolating these maps we find that the alternating polarities in the radial magnetic field map at the pole allows closed loops to be supported over the pole as expected. Strong azimuthal field recovered near the pole indicates a non-potential component to the surface field distribution. If the radial field is censored in the centre of dark starspots as expected, it is possible that we are preferentially reconstructing horizontal field in the penumbral.

Studies of the thermal properties of the loops in our coronal model indicate that they are unstable beyond about $1.6 R_\star$. At higher heights, loops will develop thermal instabilities due to reduced heating in the middle of the loop compared to the heating at the footpoints. We find that we can, in general, fit observations of the stellar corona using our models. The high densities of about $10^{13} \text{ cm}^{-3}$ observed at temperatures of $8 \times 10^6 \text{ K}$ remain difficult to explain. In order to fit these high densities, it would be necessary to invoke the presence of unrealistically small ($L \approx 0.0004 R_\star$) expanding loops. While the densities at $8 \times 10^6 \text{ K}$ would fit the observations, densities at temperatures of about $3 \times 10^4 \text{ K}$ these would be too high ($n_e > 10^{14} \text{ cm}^{-3}$ compared to observed $n_e \approx 10^{12} \text{ cm}^{-3}$).

A more realistic model that can fit the observed TR densities and EMD involves expanding loops with lengths of $0.75 R_\star$. However, observed densities at the emission peak ($T \approx 8 \times 10^6 \text{ K}$) cannot be fit by these loops alone ($n_e \approx 10^{10} \text{ cm}^{-3}$). If more compact, hotter loops are included in this model then they would have densities of about $10^{13} \text{ cm}^{-3}$ at the EM peak but as they would
contribute only 3% of the emission here, they are unlikely to explain the observed densities at these temperatures. As spectral observations become available from Chandra and XMM, the characteristics and stability of these emitting structures can be studied further.

No steady state solution can be found using our steady flow loop model and we believe that this thermal instability is real and may provide some explanation for the observation of prominences above the Keplerian co-rotation radius.

References

Young, P.R. 2001, private communication
Poster Papers