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The X-ray Corona of AB Dor

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Abstract.
We use surface magnetic maps from Zeeman-Doppler imaging to extrapolate the coronal magnetic field of the young solar-like star AB Dor (P_{rot} = 0.514 days). We assume that the coronal field is potential and find that much of the corona is filled with open magnetic field lines. We calculate the pressure and density within the corona, assuming that the gas is isothermal ($T = 10^7$K) and in hydrostatic equilibrium. Using a Monte Carlo radiative transfer code we determine the X-ray emission measure and rotational modulation. We find that the open field regions can cause the observed rotational modulation of 5%-15% (Kürster et al. 1997) even for an optically thin corona that extends to over $3R_\star$. The corona is highly structured with a low filling factor (0.1% to 1%). By varying the base density, we find that densities in excess of 10^{10}cm^{-3} are needed to explain the observed emission measures of $10^{52} - 10^{53}$cm^{-3} (Vilhu et al. 2001).

1. Introduction

AB Dor is typical of many magnetically active young dwarf stars (e.g. Güdel et al. 1997, 2000) in that it has a high X-ray luminosity (some three orders of magnitude more than the Sun) but shows little rotational modulation in its emission (Kürster et al. 1997). This might suggest that the X-ray emitting corona is sufficiently extended that it does not undergo rotational self eclipse. The observation of large prominences trapped in the corona at some 3 stellar radii from the rotation axis (Collier Cameron & Robinson 1989a,b) support this picture of an extended corona.

Recent observations, however, of AB Dor and similar stars suggest a different picture. Beppo-SAX flare observations give densities of order 10^{12}cm^{-3} (or a volume-averaged density of 10^9cm^{-3}) at temperatures T > 10MK (Maggio et al. 2000). Güdel et al. (2001) report XMM-Newton observations from which they derive densities of $\approx 3 \times 10^{10}$cm^{-3} at temperatures $T \approx 2 - 3$ MK. In both cases, loop lengths smaller than (but comparable to) a stellar radius were derived. In the case of the Beppo-SAX observations, the emission was not rotationally modulated, implying that it originated at high latitudes. These high densities combined with the emission measures of $10^{52} - 10^{53}$cm^{-3} (Vilhu et al.

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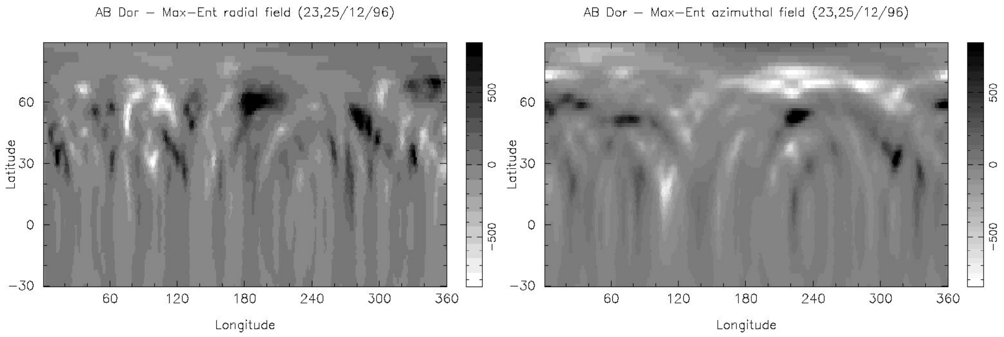

Figure 1. Zeeman-Doppler images of the surface field of AB Dor obtained in 1995. Left panel shows radial field, right panel shows azimuthal field. The scale bar on the right is in Gauss.

2001) imply a very low filling factor for the emitting loops. Indeed, it may only be possible to contain such high-density plasma in very small loops close to the stellar surface. This suggests that AB Dor has a very confined, solar-like corona.

The location of the emitting loops at high latitudes is consistent with Doppler images of AB Dor (and many other stars - see Strassmeier 1996) which show dark spots at or near the pole. These images typically also show however that there are spots at low latitudes. Indeed, Zeeman-Doppler images (see Fig. 1) show flux at all latitudes on AB Dor (Donati & Collier Cameron 1997, Donati et al. 1999). In this paper we use the radial magnetic field map shown in Fig. 1 to extrapolate the coronal field and hence to model the coronal density and X-ray emission. Our aim is to explore whether it is possible to reconcile the apparently conflicting observations of densities, emission measures and rotational modulation.

2. Extrapolating the Field

In order to extrapolate from the surface field into the corona, we have to make some assumption about the nature of the coronal field. Since we believe (Jardine et al. 1999) that a potential approximation is appropriate for *most* of the field, we make this assumption (but see also the paper by Hussain et al. these proceedings). We write the magnetic field $\mathbf{B}$ in terms of a flux function $\mathbf{B} = -\nabla\Psi$ so that 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 $\nabla^2\Psi = 0$ with solution in terms of spherical harmonics:

$$\Psi(r,\theta,\phi) = \sum_{l=0}^{N} \sum_{m=-l}^{l} \left(a_{lm} r^l + b_{lm} r^{-(l+1)}\right) P_{lm} e^{im\phi} \tag{1}$$

where the associated Legendre functions are denoted by P_{lm}. In order to simulate the effect of a stellar wind we use a source-surface model (Altschuler & Newkirk 1969, van Ballegooijen et al. 1998) where we force the field lines to become open at some specified radius (the source surface). Since large stellar prominences are

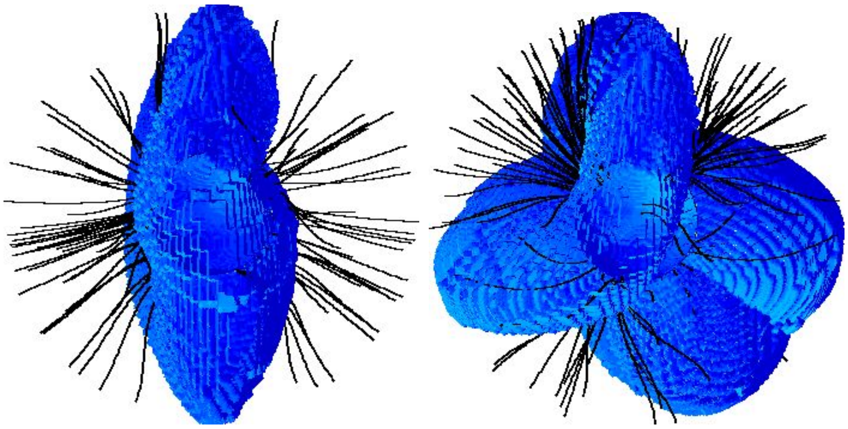

Figure 2. Shown in blue is the boundary of the closed field corona for a combined surface map with the 1995 map in one hemisphere and the 1996 map in the other. Sample open field lines are shown in black. Left: Both hemispheres are symmetric about the equator (positive polarity open region at the same longitude in each hemisphere). Right: Both hemispheres are anti-symmetric about the equator (positive polarity open regions 180 degrees apart in longitude in the two hemispheres).

observed trapped in the corona at around the Keplerian co-rotation radius (some $2.7R_\star$ from the rotation axis) we set the source surface beyond this at $3.4R_\star$. Our boundary conditions are then $B_\phi(3.4R^\star) = 0$ and $B_r(R^\star) =$ observed.

3. Effect of the Unobservable Hemisphere

One of the most surprising aspects of the coronal field is the structure of the open field regions. In all three years for which we have data, these form in two discrete regions of opposite polarity at mid-latitudes approximately 180° apart in longitude. The closed corona (the volume of the corona that could contain X-ray emitting gas) is sandwiched between these two large open field regions. These results are based however on surface magnetic field maps for which there is little information (i.e. field) in the unobservable hemisphere. This makes little difference to the field near the surface which mostly forms connections to nearby flux elements. The global structure of the stellar field (and in particular the large open field regions) may be strongly influenced however. A field line that is open in a model where the unoberved hemisphere has little surface field may connect to the unobserved hemisphere and so become closed if we impose an opposite-polarity region there.

In order to investigate the effect of the unobserved hemisphere we created two test models. In both, we generated a surface map for which the upper hemisphere was the 1995 data set, and the lower was the 1996 data set. We tried two different alignments of these maps. In the *symmetric* case, the positive "open" field regions in the two hemispheres are aligned at the same longitude, while in the *antisymmetric* case, they are 180° out of phase. We anticipated that

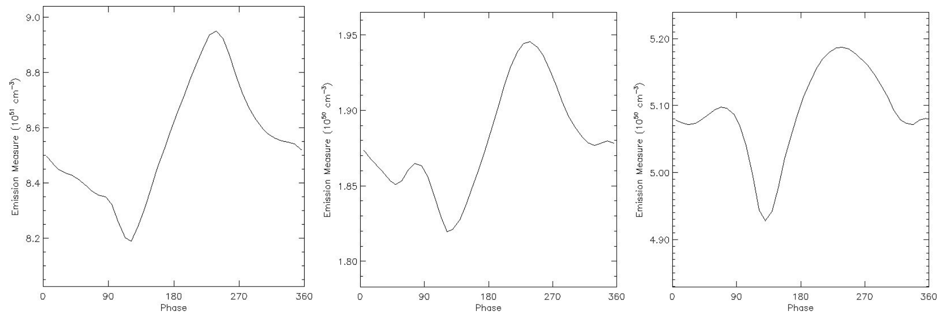

Figure 3. Rotational modulation of emission measure. From left to right the graphs refer to panels 2,3 and 4 respectively of Fig. 4.

in the antisymmetric case, the two "open" field regions at the same longitude would in fact connect to each other forming closed north-south loops. As we show in Fig 2 this is exactly what happens. In the symmetric case, the closed-field region forms a torus that separates the two open field regions. In the anti-symmetric case, the closed field region is a more complex shape that is the sum of two tori, one whose axis is the rotation axis and one whose axis is the line joining the two "open" longitudes.

4. The Structure of the X-ray Corona

In order to relate our model to the observations, we determined the X-ray emission from the closed field regions. As a first step, we calculated the pressure structure of the corona assuming it to be isothermal and in hydrostatic equilibrium. Hence for a stellar rotation rate ω, the pressure at any point is $p = p_0 e^{\int g_{||} ds}$ where $g_{||} = (\mathbf{g}.\mathbf{B})/|\mathbf{B}|$ is the component of gravity (allowing for rotation) along the field and

$$g(r,\theta) = \left(-GM_\star/r^2 + \omega^2 r sin^2(\theta), \omega^2 r sin(\theta) cos(\theta)\right). \quad (2)$$

At the loop footpoints we scaled the plasma pressure p_0 to the magnetic pressure. The plasma pressure within any volume element of the corona was set to zero if the field line through that volume element was open. In order to mimic the effect of a high gas pressure forcing closed field lines to open up, we also investigated the effect of setting the plasma pressure to zero if the plasma pressure is greater than the magnetic pressure i.e. where $\beta > 1$. From the pressure, we calculated the density assuming an ideal gas and used a Monte Carlo radiative transfer code to determine the X-ray emission.

5. Results

Fig. 3 shows the rotational modulation of the emission measure for these models and Fig. 4 shows the computed X-ray images. The top two panels of Fig. 4 show the increase in scale height that results from increasing the temperature from 10^6K to 10^7K. The lower three panels show the effects of our different assumptions about the pressure and density. In panels 2 and 3 we cut off the emission where the gas pressure is greater than the magnetic pressure. It can be seen that lowering the base density can actually increase the extent of the corona (since if the plasma pressure is lower, it only exceeds the magnetic pressure at greater heights). The effect on the emission measure is much more pronounced, however: a factor of ten decrease in the base density leads to a drop of almost two orders of magnitude in the emission measure. The increase in the emitting volume is clearly not enough to offset the decrease in density. The lower two panels both have the same density, but in panel 4 we show the effect of *not* imposing a cutoff in emission where ($\beta > 1$). There is a small increase in the emission measure due to the increase in the emitting volume, but the effect is much less than that of a change in the density. Clearly the regions where $\beta > 1$ do not make a significant contribution to the overall emission.

In summary, by extrapolating the coronal field from surface Zeeman-Doppler maps, we find that large volumes of the corona are filled with open field and are therefore dark in X-rays. These open regions provide the observed $5\% - 15\%$ rotational modulation of the emission, even for an extended optically thin corona. The coronal field (and the emission) is highly structured. If we define a filling factor as the calculated emission measure divided by that from a corona uniformly filled with plasma at the base density, we obtain filling factors in the range $0.1 - 1\%$. The assumed base density is the most significant factor in determining the overall emission measure. We find that densities in excess of $10^{10}\mathrm{cm}^{-3}$ are needed to obtain emission measures of $10^{53}\mathrm{cm}^{-3}$ (Vilhu 2001).

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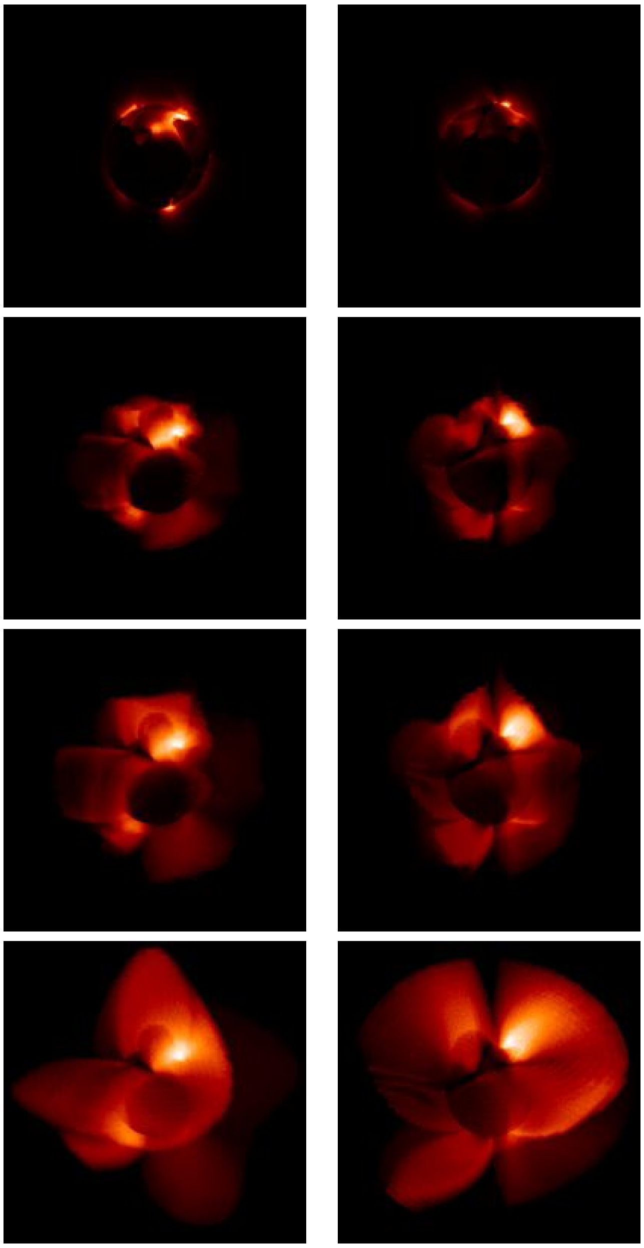

Figure 4. X-ray images of AB Dor. The left and right columns show views from different longitudes. All models have the same magnetic structure as shown on the right hand side of Fig. 2. The rotation rates and temperatures are typical for the Sun (top panel: P_{rot}=26 days, T=10^6K) or AB Dor (lower three panels: P_{rot}=0.5 days and T=10^7K). The base densities are: (top) $n_0 = 6 \times 10^9 \mathrm{cm}^{-3}$; (panel 2) $n_0 = 10^{10} \mathrm{cm}^{-3}$; (panels 3 and 4) $n_0 = 10^9 \mathrm{cm}^{-3}$. The bottom panel is the only one for which there is no cutoff in the emission for $\beta > 1$.