# THE CORONAL STRUCTURE OF AB DORADUS

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### ABSTRACT

We perform a numerical simulation of the corona of the young, rapidly rotating K0 dwarf AB Doradus using a global magnetohydrodynamic (MHD) model. The model is driven by a surface map of the radial magnetic field constructed using Zeeman–Doppler Imaging. We find that the global structure of the stellar corona is dominated by strong azimuthal tangling of the magnetic field due to the rapid rotation. The MHD solution enables us to calculate realistic Alfvén surfaces, and we can therefore estimate the stellar mass loss rate and angular momentum loss rate without making undue theoretical simplifications. We consider three cases, parameterized by the base density of the corona, that span the range of possible solutions for the system. We find that overall the mass and angular momentum loss rates are higher than in the solar case; the mass loss rates are 10–500 times higher, and the angular momentum loss rate can be up to  $3 \times 10^4$  higher than present-day solar values. Our simulations show that this model can be used to constrain the wide parameter space of stellar systems. It also shows that an MHD approach can provide more information about the physical system over the commonly used potential field extrapolation.

*Key words:* stars: activity – stars: coronae – stars: magnetic field

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# 1. INTRODUCTION

Rapidly rotating young stars are important for the study of stellar activity in two aspects. First, these stars provide an "enhanced" picture of the fundamental stellar magnetic activity also seen in less active stars (such as our Sun) and therefore help to better understand the causes and consequences of stellar activity. Second, these rapidly rotating systems provide an opportunity to observe the repeating rotationally modulated signatures of activity on relatively short timescales.

An example of a well-observed young, active star is AB Doradus (HD 36705, AB Dor hereafter), a K0 dwarf with an age of about 75 Myr (Zuckerman et al. 2004; Luhman et al. 2005; Nielsen et al. 2005; López-Santiago et al. 2006; Janson et al. 2007). AB Dor spins with a rotation period of P = 0.5 days (Pakull 1981), has a mass of about  $M_{\star} = 0.76 M_{\odot}$  (Guirado et al. 1997), and a radius of about  $R_{\star} = 0.86 R_{\odot}$  (Maggio et al. 2000; slightly smaller than the solar radius,  $R_{\odot}$ , and solar mass  $M_{\odot}$ ). AB Dor has been well observed over most of the electromagnetic spectrum (e.g., Lim et al. 1994; Grothues et al. 1997; Schmitt et al. 1997; Vilhu et al. 1998; Cutispoto 1998; Järvinen et al. 2005; Budding et al. 2009) and its activity has been studied in detail in the X-ray band (e.g. Maggio et al. 2000; Güdel et al. 2001; Sanz-Forcada et al. 2003; García-Alvarez et al. 2005; Hussain et al. 2005; Matranga et al. 2005; Hussain et al. 2007). Most importantly for the work in hand, AB Dor has been extensively observed using Zeeman-Doppler Imaging (ZDI; Donati & Semel 1990; Donati et al. 2009). This method enables some inference of the vector magnetic field on the stellar surface based on the polarization of emitted light by the field and the modulation in Zeeman splitting as the star rotates. For rapidly rotating systems such as AB Dor, it is possible to use this method to reconstruct a large-scale map of the stellar surface magnetic topology, analogous to the solar synoptic "magnetograms" (27-day-average surface field distribution), albeit with lower spatial resolution. The ZDI technique has been used to map the

surface magnetic field of AB Dor (Donati & Collier Cameron 1997; Donati et al. 1999; Hussain et al. 2002) as well to study its stellar cyclic activity and surface differential rotation (Donati & Collier Cameron 1997; Collier Cameron & Donati 2002; Pointer et al. 2002; Jeffers et al. 2007). The stellar cycle of AB Dor has also been studied using Doppler Imaging observations by Järvinen et al. (2005).

It is commonly assumed that, like the solar corona, stellar coronae are dominated by their magnetic fields, so that the magnetic pressure,  $P_B = B^2/8\pi$ , is much greater than the thermal pressure,  $P_{\rm th} = nkT$ , and that the plasma  $\beta$  parameter,  $\beta = P_{\rm th}/P_B$ , is much smaller than 1. In this case, the magnetic field can be assumed to be potential (i.e., there are no forces or currents acting on it) and it can be described as a gradient of a scalar potential. Under these assumptions, the three-dimensional distribution of the magnetic field can be obtained by solving Laplace's equation for the scalar potential, where the surface field maps are used as the inner boundary condition, and the outer boundary condition assumes a purely radial field at a certain height above the surface (known as the "source surface"). This technique of extrapolating the coronal magnetic field is known as the "potential field" method (Altschuler & Newkirk 1969; Altschuler et al. 1977). It has been used extensively in solar studies and more recently to extrapolate the coronal magnetic fields of stars such as AB Dor (Donati et al. 1999; Jardine et al. 1999, 2002; Hussain et al. 2002; McIvor et al. 2003). In particular, Hussain et al. (2007) have reconstructed the X-ray corona of AB Dor based on the potential field extrapolation, combined with different X-ray models for coronal loops.

The potential field extrapolation is a useful tool to obtain a first-order approximation of the large-scale structure of a stellar corona based on its surface magnetic map. The approach taken by Hussain et al. (2007) is justified due to the fact that the major part of the coronal X-ray emission is expected to originate from the smaller closed loops near the surface, which

are usually in a near-potential state (in the static case where footpoint motions and other short-term motions are not taken into account). There are, however, good reasons to attempt a more physical approach for describing stellar coronae. First, the potential field approximation (by itself) provides information only about the magnetic field of the system and does not address energy dissipation through driving a wind. Second, the location of the source surface is not well defined, and third, when considering a complete description of the physics involved, including conservation of mass, momentum, and energy, one needs to take into account the effects of coronal heating and stellar wind acceleration, the stretching of the field lines by the highly conductive coronal plasma to a non-potential state as well as the effects of rapid rotation in stars like AB Dor.

Here, we extend the work of Hussain et al. (2007) and present a complete three-dimensional magnetohydrodynamic (MHD) simulation of the corona of AB Dor based on its observed surface magnetic field distribution. For our simulation, we use a global MHD model developed for the solar corona, which provides a self-consistent stellar wind solution driven by surface magnetic field maps. The end result is a steady state, MHD, non-potential solution of the corona and wind of AB Dor, which includes the distribution domain. This more complete solution provides a better understanding of the large-scale coronal structure. We highlight the differences between the coronae of young stars like AB Dor and the solar corona due to rapid rotation of the former. We also provide realistic calculations of the possible mass loss rates for AB Dor, parameterized by the coronal base density.

We present the numerical model and the observational constraints used in the simulation in Section 2. The results are presented in Section 3, and the main findings are discussed in Section 4. We conclude this work in Section 5.

#### 2. NUMERICAL SIMULATION

The simulation of AB Dor is done using the solar corona model by Cohen et al. (2007, 2008), which is a part of the Space Weather Modeling Framework (SWMF; Toth et al. 2005) and is based on the generic MHD BATS-R-US model by Powell et al. (1999). The model is driven by surface magnetic field maps, and the initial condition for the magnetic field, as well as the volumetric energy input for the stellar wind acceleration, is based on the distribution of the potential field. In addition, the boundary condition for the surface plasma density,  $\rho_0$ , is scaled with the magnetic field so that the plasma at closed field regions is more dense than in open field regions, as observed for the solar case (Phillips et al. 1995).

In the solar case, the source surface is usually set to be at  $r = 2.5 R_{\odot}$ . In the case of AB Dor, however, the surface distribution of the magnetic field contains large regions with strong field. Therefore, we expect loops on AB Dor to be much larger than solar loops so we choose to set the source surface at  $r = 10 R_{\star}$ . This should not have any effect on the nonpotential, MHD solution since the potential field only serves at the initial condition. The MHD solution is mostly affected by the distribution of energy deposited into the stellar wind, and this energization is not sensitive to the location of the source surface as long as it is set above the height of the largest closed loops. However, setting the source surface below the actual size of the loops (at  $r = 2.5 R_{\star}$ , for example), forces more field lines to be open and as a result, each plasma cell in the stellar wind is over-energized, resulting in solutions with unrealistically fast stellar winds.

A self-consistent wind acceleration in the code is obtained by assuming an empirical relation between the magnetic flux tube expansion and the terminal stellar wind originating from that flux tube. Wang & Sheeley (1990) and Arge & Pizzo (2000) have derived an empirical formula that relates the final solar wind distribution,  $u_{sw}$ , to the flux tube expansion factor,  $f_s$ . The factor  $f_s$  is the ratio of the magnetic flux of a particular flux tube at  $r = R_{ss}$  and at  $r = R_{\star}$ , where  $R_{ss}$  is the height of the source surface. The empirical method described above predicts the spherical distribution of the solar wind speed at  $r \rightarrow \infty$ . It is reasonable to assume that far from the Sun (or star), the total energy equals the bulk kinetic energy of the plasma, while on the solar surface, the total energy equals the enthalpy of the fluid minus the gravitational potential energy (the kinetic energy is zero). By adopting the conservation of total energy along a streamline (Bernoulli integral), we can relate the final solar wind speed,  $u_{sw}$ , and the surface value of polytropic index,  $\gamma_0$ , assuming that the boundary conditions for the surface temperature,  $T_0$ , are known:

$$\frac{u_{\rm sw}^2}{2} = \frac{\gamma_0}{\gamma_0 - 1} \frac{k_b T_0}{m_p} - \frac{GM_{\star}}{R_{\star}},\tag{1}$$

or

$$\gamma_0 = \frac{\varepsilon}{\varepsilon - 1},\tag{2}$$

with

$$\varepsilon = \frac{m_p}{k_b T_0} \left( \frac{u_{\rm sw}^2}{2} + \frac{GM_{\star}}{R_{\star}} \right). \tag{3}$$

Here,  $k_b$  is the Boltzmann constant,  $m_p$  is the proton mass, and G is the gravitational constant.

Close to the Sun, the value of  $\gamma$  is observed to be about unity (the plasma is highly turbulent), while at 1 AU  $\gamma$  has a value closer to 1.5 (Totten et al. 1995, 1996). This observed modulation in  $\gamma$  can be related to the powering of the solar wind, in the manner that the larger the gradient in  $\gamma$  along a flux tube, the faster the wind flows along that tube. Based on this assumption and on the relation presented in Equation (1), it is possible to construct a volumetric heating function,  $E_{\gamma}(\gamma_0, \mathbf{r})$ , in a way that the observed volumetric acceleration of the solar wind can be recovered. The additional term  $E_{\gamma} \rightarrow 0$  as  $\gamma \rightarrow 3/2$ .

The model described here constructs the particular spatial distribution of  $E_{\gamma}$  based on the input surface magnetic map and its potential field. It then solves the set of conservation laws for mass, momentum, magnetic induction, and energy (the ideal MHD equations):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + pI + \frac{B^2}{2\mu_0}I - \frac{\mathbf{B}\mathbf{B}}{\mu_0}\right) = \rho \mathbf{g},$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0,$$

$$\frac{\partial}{\partial t} \left(\frac{1}{2}\rho u^2 + \frac{1}{\Gamma - 1}p + \frac{B^2}{2\mu_0}\right)$$

$$+ \nabla \cdot \left(\frac{1}{2}\rho u^2 \mathbf{u} + \frac{\Gamma}{\Gamma - 1}p \mathbf{u} + \frac{(\mathbf{B} \cdot \mathbf{B})\mathbf{u} - \mathbf{B}(\mathbf{B} \cdot \mathbf{u})}{\mu_0}\right)$$

$$= \rho(\mathbf{g} \cdot \mathbf{u}) + E_{\mathbf{v}},$$
(4)

with  $\Gamma = 3/2$  until a steady state stellar wind solution is obtained. The stellar input parameters required for the model are



Figure 1. Top-left: original, incomplete ZDI based longitude–latitude map of the surface magnetic field of AB Dor. Top-right: interpolated longitude–latitude map used in the simulation. Bottom: interpolated map displayed over two longitudinal hemispheres. (A color version of this figure is available in the online journal.)

 Table 1

 Adopted Properties of AB Dor

Stellar Parameter	Value	
$\overline{n_0}$	$2 \times 10^8$ , $10^9$ , $10^{10}$ cm <sup>-3</sup>	
$T_0$	5 M K	
R <sub>*</sub>	$0.86R_{\odot}$	
$M_{\star}$	$0.76M_{\odot}$	
P <sub>rot</sub>	0.5 d	

the boundary value for the density,  $\rho_0$ , as well as the stellar radius,  $R_{\star}$ , mass,  $M_{\star}$ , and rotation frequency,  $\Omega_{\star}$ . A summary of the stellar parameters of AB Dor adopted for the simulation, based on the references cited in Section 1, is provided in Table 1.

In the simulations presented here, we assume that the relation between the flux tube expansion and the terminal speed obtained from that flux tube is a universal process that occurs on AB Dor in a similar manner to the Sun. Observations of the corona of AB Dor indicate dominant plasma temperatures peaking in the range 3–30 MK (e.g., Sanz-Forcada et al. 2003; García-Alvarez et al. 2005).  $T_0$  is, in principle, the average temperature of the stellar corona. However, we stress that in our model,  $T_0$ is essentially a free parameter for the boundary condition that controls the energization of the stellar wind. Further description of the adaptation of a solar corona model to stellar coronae can be found in Cohen et al. (2010).

Figure 1 shows the input surface magnetic field map adopted for the simulations. This is based on spectropolarimetric observations obtained in 2007 December and analyzed in a similar manner to the maps described in Hussain et al. (2002, 2005, 2007). The reader is referred to those works for further details. Since AB Dor has an inclination of 60 deg (Kuerster et al. 1994), the part of the stellar surface near the far pole is always hidden from view. Consequently, surface maps for AB Dor are intrinsically incomplete. The initial, incomplete map is shown in the top left panel of Figure 1. To construct a complete map, we enforced hemispherical reflection symmetry on the magnetic field across the equatorial plane. Those parts of the southern hemisphere with magnetic field magnitude of less than 50 G were assigned magnetic field values from the same longitude at the corresponding northern hemisphere latitude, but with the opposite polarity. The complete map used in the simulation is shown as a longitude-latitude contour map (top right panel) and as spherical plots of the two longitudinal hemispheres, colored with contours of the surface magnetic field (lower panels). Figure 2 shows the threedimensional distribution of the potential field calculated based on this input surface map. It can be seen that the loops extend up to the height of the source surface (located at  $r = 10 R_{\star}$ ) and that they have no toroidal component. The field is fully radial above the source surface as required by the analytical solution.



Figure 2. Global structure of the potential field extrapolation for AB Dor (left). The small sphere in the middle represents the stellar surface colored with grayscale contours of the radial field, while yellow lines represent the magnetic field lines. The outer white spherical shade represents the source surface located at  $r = 10 R_{\star}$ . Right panel shows a zoom close to the stellar surface.

(A color version of this figure is available in the online journal.)

We caution that there are a number of sources of systematic uncertainty present in the simulations. First, the ZDI maps are missing part of the stellar surface, and we have extrapolated the field, assuming antisymmetry, to those non-visible areas. Second, the magnetic field maps are of limited resolution (latitudinal resolution of 3 deg) and do not resolve the details of the active regions. Third, large areas in the maps that appear to have strong fields may in fact be dominated by localized active regions that are smeared out due to the lower resolution; such a scenario would lead to a significantly different MHD solution. While the ZDI maps do likely miss low-level structure, the maps should recover the strongest field regions, which are likely to dominate over the large-scale global models such as those considered here. The weaker complex fields would only be interesting much closer to the surface.

Observations of AB Dor reveal that the coronal base density,  $n_0$ , ranges between  $10^{10}$  and  $10^{12}$  cm<sup>-3</sup> (Sanz-Forcada et al. 2003). These measurements, however, were made based on measurements of strong emission lines that are associated with the denser, closed loops. Therefore, the density in the "quiet star" (analogous to the "quiet Sun") where the wind originates should be lower. In order to partially cover this density range, we simulate three test cases with different values for the coronal base density. "Case A" with  $n_0 = 2 \times 10^8 \text{ cm}^{-3}$ , which is the value used for simulations of the solar wind, "Case B" with  $n_0 = 10^9 \text{ cm}^{-3}$ , and "Case C" with  $n_0 = 10^{10} \text{ cm}^{-3}$ . We simulate the wind and corona using a Cartesian box of 30  $R_{\star}$  ×  $30 R_{\star} \times 30 R_{\star}$ , in the frame of reference rotating with the star (to expedite convergence using the local time step algorithm; Cohen et al. 2008). We use a non-uniform grid with a maximum resolution of  $2 \times 10^{-2} R_{\star}$  prescribed near the surface. The grid is dynamically refined during the simulation so that high resolution is applied at the location of magnetic field inversion (current sheets). We performed the simulation using the PLEIADES super computer at the NASA AMES center.

### 3. RESULTS

The steady state MHD solutions for the three test cases are shown in Figure 3. The most notable feature of the solutions for

all cases is the tangling of the field in the azimuthal direction due to the rapid rotation of the star. This feature clearly does not appear in the potential field solution, for which stellar rotation is not a relevant parameter, nor in similar MHD solutions for the Sun (e.g., Cohen et al. 2008).

As might be expected, solutions for the three cases are qualitatively quite similar, though closer inspection does reveal significant differences. It can be seen from the middle panel of Figure 3 that the radial wind speed decreases with an increase of the base density. In addition, the corona is denser in the solution for Case C as compared to Case A. While many of the tangled field lines in Cases A and B are open due to the strong radial stretching by the stellar wind, in Case C, most of the tangled field lines are closed. The closed loops in the low corona are radially stretched in Cases A and B, while the same loops are more potential and less stretched in Case C as seen in the bottom panel of Figure 3.

The interplay between the radial speed and the coronal density structure determines the stellar mass loss rate as well as the stellar angular momentum loss rate to the stellar wind. We follow the method by Cohen et al. (2009) and calculate these loss rates from the MHD solution. This method expands the idealized approach by Weber & Davis (1967) and uses the fact that the MHD solution provides a realistic, non-idealized Alfvén surface, at which the Alfvénic Mach number,  $M_A = u/v_A = 1$ , where  $v_A = B/\sqrt{4\pi\rho}$  is the Alfvén speed. Once the Alfvén surface has been determined, the loss rates can be calculated as

$$\dot{M} = \int \rho \mathbf{u} \cdot \mathbf{d} \mathbf{a}_A, \tag{5}$$

$$\dot{J} = \frac{3}{2} \int \Omega_{\star} \sin \theta \ r_A^2 \ \rho \mathbf{u} \cdot \mathbf{d} \mathbf{a}_A, \tag{6}$$

where  $r_A$  is the local radius of the Alfvén surface,  $da_A$  is a surface element, and the integration is done over the realistic Alfvén surface. It is worth mentioning that the realistic Alfvén surface, at which the magnetic breaking of the stellar wind takes place, is the actual source surface, and it does not have a spherical shape as is assumed to have in the common use of the potential field approximation.



**Figure 3.** Numerical MHD solutions of the coronal magnetic field (top), wind speed (middle), and plasma density (bottom) for AB Dor for Cases A–C (left to right with increasing base density). Top: global structure of the MHD solution with  $P_{\star} = 0.5$  days. The sphere represents the stellar surface colored with contours of the radial magnetic field, the yellow lines represent the three-dimensional magnetic field lines, and the y = 0 and z = 0 planes are shown as transparent white shades. Middle: a side view of the top panel without the field lines. Bottom: a side view of the top panel with color contours of number density and zoomed around the star. The green shade represents an isosurface of  $n = 10^8$  cm<sup>-3</sup>. Cases A–C are shown from left to right. (A color version of this figure is available in the online journal.)

The mass and angular momentum loss rates for the different test cases are shown in the upper part of Table 2. For comparison and verification of these results, we have computed similar wind models for the solar case. The same numerical method described above was employed for a solar magnetogram obtained during the last solar maximum (Carrington Rotation 1958) by the *SOHO* MDI.<sup>4</sup> This solar simulation resulted in a mass loss rate of  $\dot{M}_{\odot} \approx 2 \times 10^{-14} M_{\odot} \text{ yr}^{-1}$  and an angular momentum loss rate of  $\dot{J} \approx 10^{30} \text{ g cm}^2 \text{ s}^{-2}$  with the use of base density of  $2 \times 10^8 \text{ cm}^{-2}$  (same as Case A). These are similar to canonical solar values, as expected.

Instead, the loss rates from AB Dor are significantly higher than solar. The angular momentum loss rate can be two orders of magnitude higher, simply due to the much more rapid rotation of AB Dor. For Case A, the mass loss rate for AB Dor is about a factor of 10 larger than the equivalent solar case. This is perhaps slightly surprising since all parameters other than the rotation rate and, to some extent, the surface field map are fairly similar to those of the active Sun chosen for the comparison. The most

 Table 2

 Mass and Angular Momentum Loss Rates for AB Dor

$P_{\star} = 0.5$ days					
Stellar Parameter	Case A	Case B	Case C		
$\dot{M} (M_{\odot} \text{ yr}^{-1})$	$4.5 \times 10^{-13}$	$2.1 \times 10^{-12}$	$1.1 \times 10^{-11}$		
$\dot{J}$ (g cm <sup>2</sup> s <sup>-2</sup> )	$2.6 \times 10^{33}$	$6.8 \times 10^{33}$	$3.2 \times 10^{34}$		
	$P_{\star} = 25$	days			
Stellar Parameter	Case A	Case B	Case C		
$\dot{M} (M_{\odot} \text{ yr}^{-1})$	$4.3 \times 10^{-14}$	$1.8 \times 10^{-13}$	$1.6 \times 10^{-12}$		
$\dot{J}$ (g cm <sup>2</sup> s <sup>-2</sup> )	$4.4 \times 10^{31}$	$1.0 \times 10^{32}$	$4.4\times10^{32}$		

conspicuous difference is the factor of 50 in rotation rate and it is worth examining the influence of rotation alone in more detail.

We repeated the AB Dor computational runs for Cases A–C for a rotation period of 25 days instead of 0.5 days, with all other aspects of the simulations remaining the same. The solutions for these runs are shown in Figure 4. The azimuthal tangling of the coronal field that characterizes the 0.5 days period results

<sup>&</sup>lt;sup>4</sup> http://sun.stanford.edu/



Figure 4. Same as Figure 3, but for the cases with  $P_{\star} = 25$  days. (A color version of this figure is available in the online journal.)

in Figure 3 is, unsurprisingly, completely absent in this set of solutions, and all field lines are essentially radial. In addition, more field lines are open in these solutions compared to the case with rapid rotation. Mass and angular momentum loss rates are listed in Table 2: mass loss rates are typically a factor of 10 lower than for the 0.5 days period results, and, for the Case A base density, are more similar to the solar value.

## 4. DISCUSSION

The MHD simulations of AB Dor presented here reveal a coronal structure that is manifestly different from the well-studied solar corona. These differences are due to the different magnetic structure, which is mostly composed of high-latitude, large-scale regions of strong magnetic field, and the rapid stellar rotation which induces azimuthal wrapping and tangling of the magnetic field. This tangling cannot be obtained from the static, non-MHD, potential field extrapolation, which is generally useful only for studying the small closed loops near the surface where global effects are less important. We note in passing that for stars with large-scale regions of strong magnetic field, closed loops are probably significantly larger than in the solar case and the choice for the location of source surface location should be at greater radial distance than the common use of  $R_{\rm ss} = 2.5-3.5 R_{\star}$ .

The simulation results show that the mass loss and angular momentum loss rates increase with increasing coronal base density. The explanation for the former is trivial: introducing a greater mass source at the base will necessarily increase the mass flux through a closed surface around this source. The latter effect is more subtle and is due to the fact that  $J \propto \rho u$ . When increasing the base density, the density drop with height decreases and the volume between the stellar surface and the Alfvén surface is filled with more mass and as a result, more torque is being applied on the rotating star, thus increasing the angular momentum loss.

For a given distribution of  $\rho u$ , the angular momentum loss rate is directly proportional to  $\Omega_{\star}$ , so it is not surprising that Jvaries with the rotation rate. We find that the mass loss rate also depends on the stellar rotation rate. This effect is not apparent if the rotation rate is not very high. However, the case of the extremely short rotation period of 0.5 days has a significant effect. The reason for this behavior can be found in the azimuthal tangling of the coronal field. When the rotation is slow, the global topology of the coronal field is radial (as seen in Figure 4). In this case, the coronal density profile essentially drops like  $r^{-2}$ . When strong rotation is present, the azimuthal component of both the magnetic field and the flow becomes important and the radial component of the velocity is reduced. The increase



Figure 5. Alfvén surface for Case A from different view angle (left right) colored with contours of the local value of  $\dot{M}$  with  $P_{\star} = 0.5$  days (top) and with  $P_{\star} = 25$  days (bottom). White shades of the y = 0 and z = 0 plains are also shown. (A color version of this figure is available in the online journal.)

in density in the slow wind case is greater than the decrease in speed, and as a result, the total value of  $\rho u$  increases. Another contributor to the angular momentum loss increase with rotation is the shape of the Alfvén surface for each case.

Figures 5–7 show the shape of the Alfvén surface for each test case with different rotation period. When the rotational period is small, the shape is modified to account for the azimuthal component, and the surface is enlarged. In the case of fast rotation, the shape of the Alfvén surface is modified and signs of the azimuthal component of the coronal field can be seen. It also seems like the size of the Alfvén surface with faster rotation is slightly bigger. The simulations presented here show that the mass loss rate of AB Dor, and presumably also of other rapidly rotating young late-type stars, is substantially higher than the solar mass loss rate, and that it could be as high as  $10^{-12}$  to  $10^{-11} M_{\odot}$  yr<sup>-1</sup>, as suggested by Wood et al. (2004, 2005). These values, however, are strongly dependent on the assumed average coronal base density. Based on measurements of X-ray spectra presumably originating from plasma in closed loops (Section 2), it seems likely that this is generally higher than the solar case, probably by an order of magnitude. For such a case, the predicted mass loss rate for AB Dor is about 100 times the solar rate.

The mass and angular momentum loss rates found from our MHD models here are intriguing for the wider problem of stellar rotational evolution. Models such as we present here could, in principle, be employed to map out theoretical angular momentum loss as a function of stellar activity and rotation rate. While the general picture of stellar spin-down with age as a result of wind-driven angular momentum loss emerged decades ago (e.g., Schatzmann 1962; Weber & Davis 1967; Mestel 1968; Skumanich 1972), the details of the situation have proved somewhat complicated and rotation rate data amassed in the intervening years for late-type stars exhibit a complex dispersion over stellar age and mass.

Faster rotation during stellar youth engenders greater magnetic activity through rotationally powered dynamo action and the correlation of magnetic activity indicators such as chromospheric emission lines and coronal X-ray luminosity with rotation is well established. Observations of Ly $\alpha$  absorption by the interactions of stellar winds with the surrounding interstellar medium—the stellar equivalent of the heliopause—also indicate that stellar wind mass loss rates are larger for younger and more active stars. Wood et al. (2002) estimate a relation  $\dot{M} \propto t^{-2.00\pm0.52}$ , based on combining inferred mass loss rates with X-ray activity and observed X-ray activity versus stellar age. Their relation suggests that at very fast rotation rates, mass loss should approach 1000 times the solar value, though they caution against the reliability of this extrapolation. Here, we find that plausible coronal base densities lead to mass loss rates of 100 times that of the present day Sun.

Observations of rotation rates for stars in open clusters indicate that very young stars with ages of up to 100 Myr or so are not as rapidly spun-down as would be expected based on extrapolation of the Skumanich (1972) spin-down relation, and theoretical spin-down modeling efforts have invoked a magnetic



**Figure 6.** Same as Figure 5, but for Case B. (A color version of this figure is available in the online journal.)

"saturation" that limits the angular momentum loss for very short rotation periods (e.g., Chaboyer et al. 1995; Krishnamurthi et al. 1997; Barnes 2003). While our wind model for a single star, such as AB Dor presented here, cannot itself be used to validate such a saturation approach, the general methodology does in principle allow for a more thorough exploration of the relevant parameter space to provide an MHD wind prediction of angular momentum loss as a function of stellar age. The requisite input parameters here would be the global coronal base density and the magnetic field strength.

The spin-down time of AB Dor can be estimated as (Ud-Doula et al. 2009)

$$\tau = \frac{kM_{\star}\Omega_{\star}R_{\star}^2}{\frac{2}{3}\dot{M}\Omega_{\star}r_A^2} \approx 0.1 \cdot X^{-2}\dot{M}^{-1} \text{ (yr)}, \tag{7}$$

where we used k = 0.1 and write  $r_A = XR_*$ . Based on Equation (7) and the calculated mass loss rates, the spin-down time of AB Dor can range from  $10^9$  to  $10^{12}$  yr depending on the particular case and on the value of X (which ranges from 5 to 10). A value of  $10^9$  yr leads to a rotation of P = 0.5 days  $\cdot e^5 = 71$  days after five billion years. However, Cohen et al. (2009) have shown that the angular momentum loss rate can be 3–4 times higher when the stellar magnetic field is dominated by strong polar spots, as appear to characterize young, fast-rotating stars. We expect the angular momentum loss rate to decrease with time as AB Dor becomes an established main-sequence star with spots at lower latitudes. Therefore, after five billion years a rotation similar to that of the Sun might be expected. In Equation (7),  $\tau$  is independent of  $\Omega_{\star}$ . Therefore, for the same parameters but with different rotation rates, we have  $P_1/P_2 = 25$  days/0.5 days = 50 and  $\dot{J}_2/\dot{J}_1 = 50$  (the inverse of  $\tau_1/\tau_2$ ). The ratios of the angular momentum loss rates for Cases A–C with different rotation rates are 60, 68, and 80, respectively. This is consistent with the expected idealized value.

In principle, we can propose a relation between the wind in our model and the Alfvén radius as follows. Since at the Alfvén radius,  $u_{sw} = v_A$  we have

$$u_{\rm sw}(1/f_s) = v_A(r_A) = \frac{B(r_A)}{\sqrt{4\pi\rho(r_A)}} = \frac{v_{A0}R_{\star}^2}{r_A^2}, \qquad (8)$$

where we assume that  $B(r) = B_0(R_\star/r)^3$  and  $\rho(r) = \rho_0(R_\star/r)^2$ , with  $B_0$ ,  $\rho_0$ , and  $v_{A0}$  being the magnetic field, density, and Alfvén speed at the flux tube base, respectively. From Equation (8) we get

$$\frac{r_A}{R_\star} = \sqrt{\frac{v_{A0}}{u_{\rm sw}(1/f_s)}},\tag{9}$$

which could provide, in principle the location of the Alfvén radius based on a known magnetic field distribution and surface density. The relation, however, is not trivial due to the nonlinear relation between the parameters that define it. In reality, the radial functions of the magnetic field and density used in Equation (8) are not necessarily valid within the Alfvén surface.



**Figure 7.** Same as Figure 5, but for Case C. (A color version of this figure is available in the online journal.)

## 5. SUMMARY AND CONCLUSIONS

We have carried out a three-dimensional global numerical MHD simulation of the corona of AB Dor, driven by a Zeeman-Doppler Image magnetic surface map. We studied three test cases with different base density, and we also compared the solutions with fast and slow stellar rotations. We find that the coronal structure of AB Dor is dominated by the azimuthal tangling of the coronal magnetic field as a result of rapid rotation. Based on the MHD solution, we calculate a realistic Alfvén surface, which enables us to estimate the mass and angular momentum loss rates. Our main finding is that the mass loss rate is dependent on the value of the average coronal base density as well as the coronal field and stellar wind topology which are affected by rapid stellar rotation. The total mass loss rates ranges between 10 and 500 times the solar mass loss rate, while the angular momentum loss rate ranges between 15 and 30,000 times the solar angular momentum loss rate. We demonstrate that the global coronal solution depends, to some extent, on the detailed properties of the coronal plasma.

In addition to the uncertainty in stellar parameters, the surface maps used here to drive the model are not well defined as well. First, we interpolated the field in the "missing" part of the stellar surface, second the resolution of the maps in the regions where data are available is not very high, and third the interpretation of these maps is somehow debatable. In particular, large regions of the map appear with strong magnetic field. One can ask whether these are really large-scale strong field regions, or whether it is more localized active region that is being smeared by the low resolution. The two scenarios should lead to significantly different MHD solutions.

Further modeling effort like the one presented here should focus on constraining stellar parameters such as the stellar wind speed for non-solar-like stars. In addition, a more consistent model to drive the stellar wind can help to generalize the model to stellar systems.

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