IS THE EFFICIENCY OF MAGNETIC BRAKING LIMITED BY POLAR SPOTS?

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ABSTRACT

The presence of high latitude spots on the surface of rapidly rotating cool-stars and the subsequent concentration of magnetic flux near the poles, has lead to the idea that this causes a reduction in the angular momentum carried away by the stellar wind. We apply the analytical MHD wind model of Lima et al. (2001) to determine the influence of the surface flux distribution on the efficiency of magnetic braking.

Our results clearly show that the density, pressure, velocity and toroidal magnetic field are as important as the surface field distribution in determining the angular momentum carried by the wind. In particular, this model predicts that for realistic surface rotation profiles, the angular momentum loss increases as the field concentration increases towards the poles, contrary to what one would naively expect.

Key words: winds; rotation; evolution; X-rays.

1. INTRODUCTION

The angular momentum evolution of cool stars is dictated by the interaction of the stellar magnetic field with the outgoing wind. The observation of ultrafast rotators in young clusters indicates a saturation in the angular momentum loss rate during the pre-main sequence phase (e.g. Barnes & Sofia 1996). Dynamo saturation, that is believed to occur at very high rotation rates, can naturally explain this observation. However, it is not clear whether there are other physical mechanisms that can lead to saturation of the angular momentum loss mechanism at lower rotation rates. An increase in the dead zone with increasing rotation rate can also produce this effect (Mestel & Spruit 1987). Alternatively, as the rotation rate increases, the magnetic field may change from dipole-like to a high order field, leading to a reduced angular momentum loss rate without dynamo saturation (Taam & Spruit 1989). Recently, it has been suggested that the concentration of magnetic flux near the poles of rapidly rotating stars can lead to a saturation in the angular momentum loss rate (Solanki et al. 1997; Buzasi 1997). Here, we investigate whether this mechanism is a valid alternative to dynamo saturation as an explanation for angular momentum loss saturation.

2. THE MODEL

If one assumes the stellar corona to be a low β plasma, then a large concentration of the surface magnetic flux at high latitudes does not produce a coronal field with a similar latitudinal distribution. Indeed, the coronal magnetic field will rapidly expand to regions of low magnetic pressure, creating a relatively smooth latitudinal coronal field distribution (see Aibéo et al. 2005 for detailed calculations). Therefore, in order to have a concentrated coronal field distribution, one must take into account the kinetic and gas pressure, and the azimuthal magnetic field in a self-consistent magnetohydrodynamic wind model. We apply the 2-D steady-state model of Lima et al. (2001) as it is the only available analytical model that allows us to study how the change of the magnetic field distribution at the surface affects the angular momentum loss. This model describes an axisymmetric helicoidal magnetized outflow from a rotating star in which the anisotropy of the various flow quantities is determined by three free parameters, μ, δ, and ϵ. The surface radial magnetic field is given by

$$B_r(\theta) = B_0\sqrt{1+\mu\sin^{2\epsilon}\theta}, \quad (1)$$

where B_0 is the value of the radial component of the surface magnetic field at the pole. The azimuthal component of the velocity varies with co-latitude as

$$V_\phi = V_1\frac{\sin^\epsilon\theta}{\sqrt{1+\delta\sin^{2\epsilon}\theta}}, \quad (2)$$

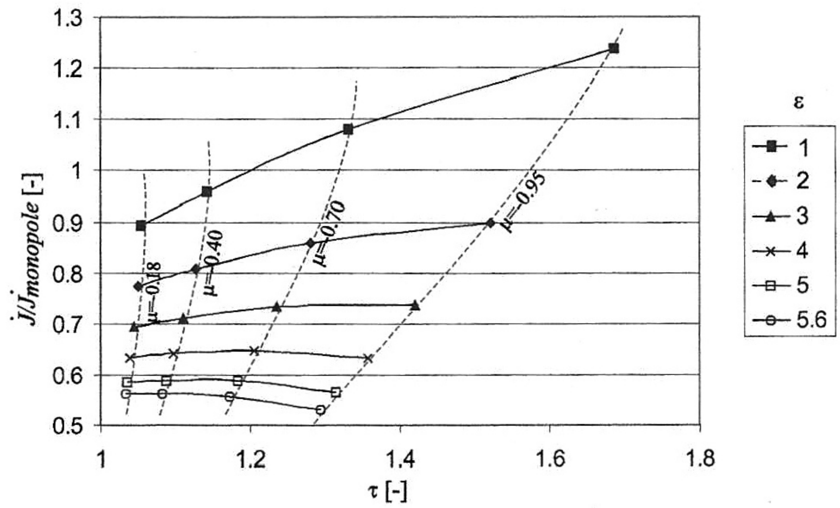

Figure 1. Adimensional angular momentum loss as a function of field concentration towards the pole, τ, for different sets of ϵ and μ.

where V_1 is the value of the azimuthal velocity at the equator. The wind mass efflux is

$$\dot{m}(\theta) = \rho_0 V_0 r_0^2 \sqrt{(1+\mu\sin^{2\epsilon}\theta)(1+\delta\sin^{2\epsilon}\theta)}, \quad (3)$$

with ρ_0, V_0 and r_0 representing the polar surface density, the polar radial surface velocity and the stellar radius respectively. The total angular momentum loss is

$$-\dot{J} = \lambda r_0^3 B_0^2 \int_0^{\pi/2} \sqrt{1+\mu\sin^{2\epsilon}\theta}\,\sin\theta d\theta, \quad (4)$$

where λ is the ratio between the azimuthal surface velocity at the equator and the radial surface velocity at the pole. In order to make sensible comparisons, we need to compare the total angular momentum loss for different field distributions with the same total magnetic flux. This condition determines B_0 in each case.

3. RESULTS

After determining the wind solutions for a particular set of parameters, we use Eq. 4 and determine the angular momentum loss rate. In Fig. 1 we represent the dependence of the angular momentum loss with the field concentration, as measured by the parameter τ, for different parameters' values. We are interested in comparing stars with similar surface rotation, very likely showing near rigid body rotation (Collier Cameron & Donati 2002), but with different surface flux distributions. Therefore, we must constrain the analysis to low values of δ and ϵ and compare solutions with different values of μ for a fixed value of ϵ. For a fixed value of ϵ, as $|\mu|$ increases, the field becomes more concentrated towards the poles and the total angular momentum loss rate increases. Although there is a decrease in the mass loss rate, it is compensated by an increase in the angular momentum loss per unit mass.

4. DISCUSSION

We find that a higher polar magnetic field concentration leads to larger braking rates than a smoother field distribution, contrary to what has been suggested. We interpret this as evidence that there are relevant factors, other than the surface radial field distribution, in determining the angular momentum carried by the wind. Still, further research is needed to determine whether these results are a consequence of the model considered, or can be regarded as a general feature.

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