Magnetic Modulation of Stellar Angular Momentum Loss

Cecilia Garraffo[1], **Jeremy J. Drake**[1], **Ofer Cohen**[1]

[1] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St. Cambridge, MA 02138*

Abstract.
Angular Momentum Loss is important for understanding astrophysical phenomena such as stellar rotation, magnetic activity, close binaries, and cataclysmic variables. Magnetic breaking is the dominant mechanism in the spin down of young late-type stars. We have studied angular momentum loss as a function of stellar magnetic activity. We argue that the complexity of the field and its latitudinal distribution are crucial for angular momentum loss rates. In this work we discuss how angular momentum is modulated by magnetic cycles, and how stellar spin down is not just a simple function of large scale magnetic field strength.

1. INTRODUCTION

Stars spin-down through their magnetized winds that carry away mass and angular momentum (magnetic breaking). These winds corotate with them up to a certain distance, called the Alfvén radius (R_A), where the speed of the wind reaches the Alfvénic speed ($u_A = B/\sqrt{4\pi\rho}$, being B the magnetic field strength and ρ the density of the plasma). The strength of the wind is expected to scale up with field strength and, therefore, stellar spin-down is a function of magnetic activity. Weber & Davis (1967) provided the first analytical expression for magnetic breaking, $\dot{J} = \frac{2}{3}\Omega\dot{M}R_A^2$, where $\dot{J}$ is the angular momentum loss rate, Ω the angular velocity, $\dot{M}$ the mass loss rate, and where spherical symmetry has been assumed (a split magnetic monopole was used and R_A is constant).

Recently, improved observational techniques like Zeeman Doppler Imaging (Donati & Brown 1997) have provided us with new information about the magnetic topology of almost a hundred stars (see Donati & Landstreet 2009; Morin et al. 2010, and references therein). The fact that most of them show much more complex structure than that of a dipole has drawn a great amount of attention towards the role of magnetic topology in angular momentum loss.

Since then, some authors have discussed the importance of topology for the winds structure and efficiency of magnetic braking (Cohen et al. 2009; Garraffo et al. 2013; Lang et al. 2014; Cranmer & Saar 2011). Both analytical and numerical models have been built aiming, with increasing success, to realistically study the interplay between spin-down rates and magnetic structure at the surface of stars (Mestel & Spruit 1987; Kawaler 1988; Chaboyer et al. 1995; Parker 1958; Matt et al. 2012; Cranmer & Saar 2011; Cohen et al. 2009; Cohen & Drake 2014).

In this work we study the relevance of magnetic active regions and their latitudinal locations on stellar spin-down rates. Using a three dimensional magnetohydrodynamic (MHD) code we perform simulations to explore the effect of stellar spots on mass and angular momentum loss rates.

2. NUMERICAL SIMULATION

We use the generic *BATS-R-US* code (Powell et al. 1999; Tóth et al. 2012) that solves the set of MHD equations for the conservation of mass, momentum, magnetic induction, and energy on a spherical, logarithmic in the $\hat{r}$ coordinate grid. We take advantage of the code's Adaptive Mesh Refinement capabilities to refine the grid around regions where the magnetic field changes its sign. This way we better resolve current sheets that form during the simulation.

We carry out simulations for a set of magnetic maps, starting with two pure dipoles (with field strengths of 10 and 20 Gauss at the poles) and superimposing the magnetic active regions observed for the sun near solar maximum (Carrington Rotation 1958). We place these two rings of spots at three different latitudes, using the same shift in latitude for both hemispheres, and with three different scalings for the spots strength.

From the resulting solutions we compute the mass and angular momentum loss rates and study the spatial distribution of the contributing quantities (density and wind speed) at the Alfvén and stellar surfaces, as well as the shape and size of the Alfvén Surface itself.

3. RESULTS AND DISCUSSION

The general behaviour is ruled by the latitude of the magnetic active regions and is well described by two limiting cases: magnetograms with low-latitude and high-latitude spots (see figure .1). We group our results in these two categories that represent the general trend of the whole sample.

In order to illustrate the qualitative effect of the magnetic active regions in each of these two regimes, in Fig .2 we compare the mass (both at the Alfvén and at the stellar surfaces) and angular momentum losses as a function of latitude for a magnetogram with low-latitude spots and the same with the spots shifted towards high-latitudes. The transition latitude from one regime to the other is determined by the limiting latitude between open and closed field lines regions on the stellar surface of the pure dipolar solution.

We find that, for all cases, there is a significant reduction of mass and angular momentum loss when magnetic active regions are located at high-latitudes compared to both the pure dipolar solution and the one with low-latitude spots.

In general, the introduction of magnetic active regions within the "dead-zone" from which wind does not escape for the dipolar case (low-latitudes) does not change systematically the mass or angular momentum loss rates. However, any reallistic distribution of active regions will produce a small residual dipolar component as a result of the spatial separation of the spots. For rings of spots at low-latitudes, this competing dipole will be almost perpendicular to the rotation axis and original dipole, and will result in a tilt of the Alfvén surface. Consequently, the low-latitude active regions lead to a change in orientation of the Alfvén surface. In contrast, the introduction of active regions at high-latitudes leads to a significant reduction in both mass and angular momentum loss rates. The reason for this is that spots located in the open field lines regions of a star can efficiently couple to them and close them, therefore reducing the amount of wind carrying plasma away (see Fig .3 for a qualitative plot).

It is also worth noticing from Fig .2 that most of the mass being lost is coming from mid-latitudes at the stellar surface and it funnels towards the equator when approaching the Alfvén surface. This makes sense because closed field lines cannot contribute to the mass loss mechanism. As a result, most of the torque experienced by the star will be located in a narrow band at mid latitudes, fundamentally at the transition latitude where the open field lines begin to appear and that that divides the low and high-latitude regimes.

In summary, we find a bi-modal regime regulated by the latitude of spots by which magnetic active regions efficiently reduce mass and angular momentum loss rates *only* when located outside of the dead zone (the closed field line region on the stellar surface). The mechanism behind it is the closing of otherwise open field that leads to a reduction in the plasma being carried away (see Fig .3). As a result, magnetic cycles of stars whose spots cross the limiting latitude of the dead-zone, and therefore turn on and off this mechanism, will experience a large modulation of mass and angular momentum loss, by a typical factor of the order of a few (see Fig .2).

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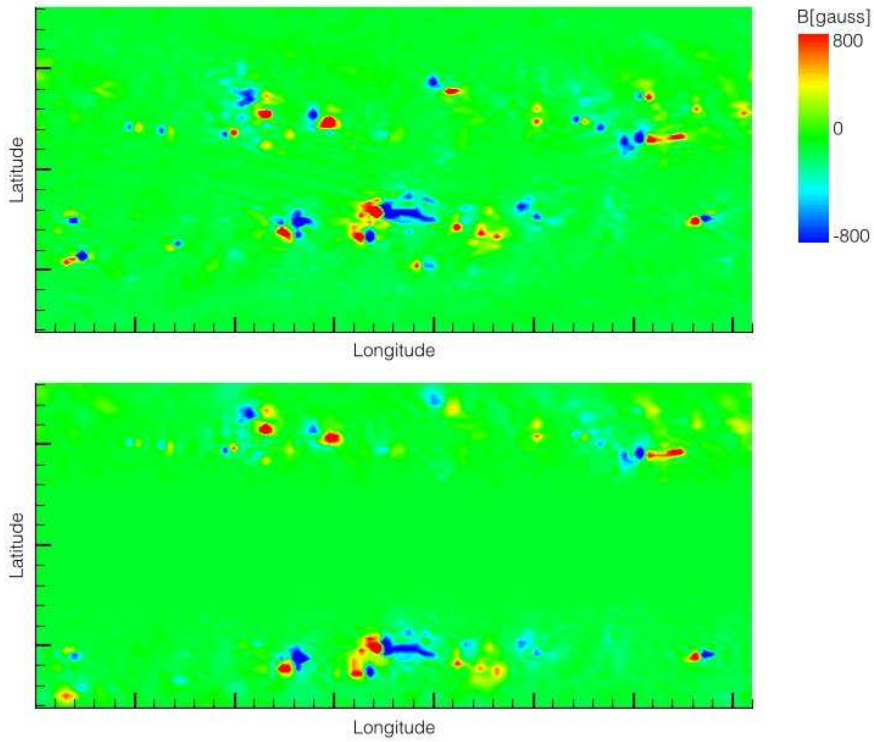

Figure .1: Typical stellar magnetograms used in our simulations for magnetic active regions at low (top) and high (bottom) latitudes

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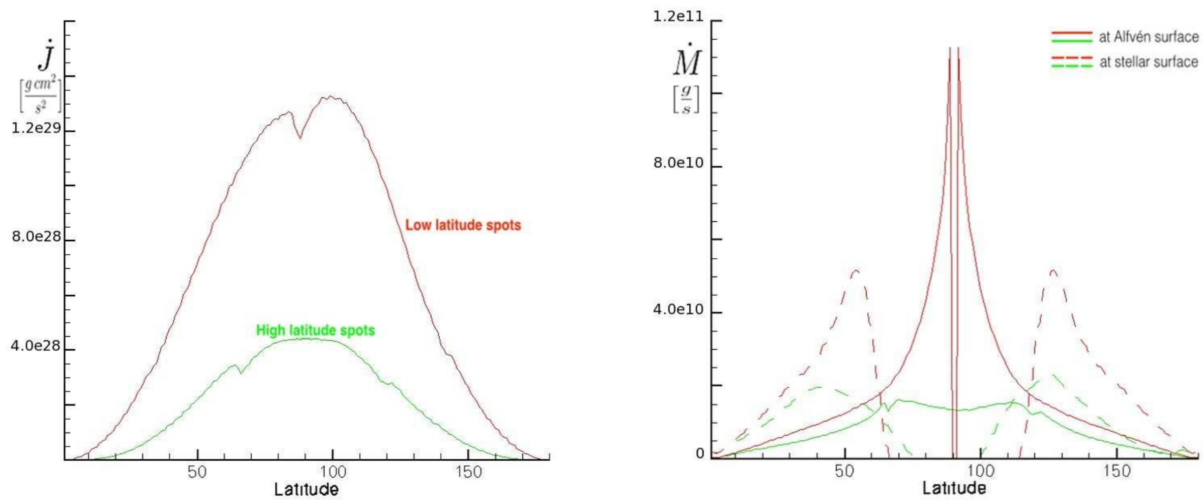

Figure .2: Mass loss and angular momentum loss as a function of latitude for low-latitude (red) and high-latitude (green) magnetic active regions at the Alfvén Surface (solid line) and at the stellar surface (dashed line).

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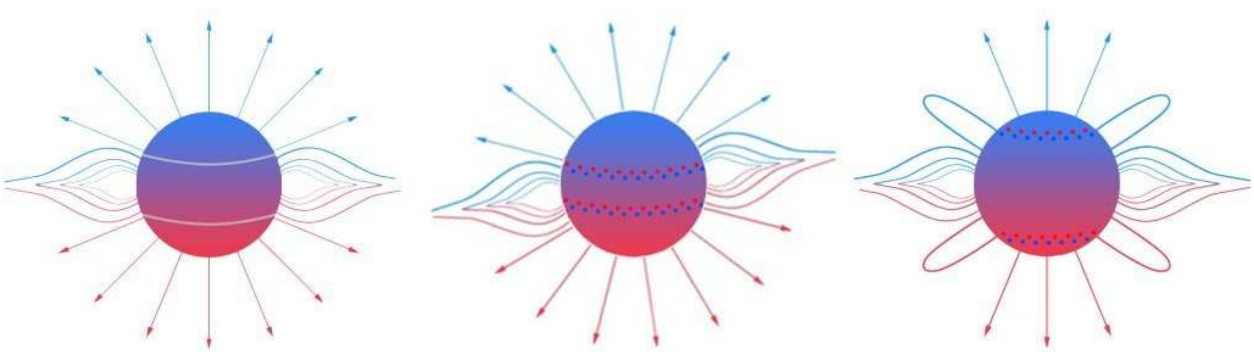

Figure .3: Qualitative plot of the wind structure for a dipole (left), with the limiting latitude between open and closed field line regions shown in white. The wind structure for the same dipole with low-latitude (center) and high-latitude (right) magnetic active regions. The addition of spots at fairly low latitudes—within the "dead zone" where field is already closed—makes little difference to the wind morphology or mass and angular momentum loss rates, and only results in a tilt of the magnetic axis. Adding spots at higher latitudes closes field lines and quenches mass and angular momentum loss.