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DISTRIBUTION OF MAGNETIC FLUX ON THE SURFACE OF RAPIDLY ROTATING STARS

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ABSTRACT We have performed MHD simulations of the eruption of unstable magnetic flux tubes from the overshoot layer below the outer convection zone of a cool star. We find that, due to the action of the Coriolis force, stars with rapid rotation and a sufficiently deep convection zone show magnetic flux emergence at high latitudes.

Doppler images of rapidly rotating stars show a brightness pattern (associated with magnetic fields, see Donati et al. 1992), which is strikingly different from that exhibited by the Sun. Large spots are found at high latitudes and are often seen to straddle the stellar poles (e.g. Vogt & Hatzes 1991, Strassmeier et al. 1991, Kürster et al. 1992). To explain the high latitudes of the observed spots, Schüssler & Solanki (1992) proposed that, for sufficiently rapid rotation, the Coriolis effect forces rising magnetic loops to follow a trajectory running roughly parallel to the rotation axis of the star (cf. Choudhuri & Gilman 1987). Thus on such stars magnetic fields should indeed emerge near the poles. Here we present numerical results which support this conjecture. We have simulated the eruption of magnetic loops in a stellar convection zone for various rates of rotation. The initial configuration is a toroidal flux tube (a flux ring) in mechanical equilibrium which is stored within a (stably stratified) overshoot layer below the convection zone. In the framework of the thin flux tube approximation this equilibrium is determined by a balance of rotational and magnetic forces (Moreno-Insertis et al. 1992), viz.

$$R_0^2(\Omega_i^2 - \Omega_e^2) = v_A^2 ,$$

(Ω_i: angular velocity of the matter in the tube, Ω_e: angular velocity in the environment of the tube, R_0: radius of the flux ring, v_A: Alfvén velocity in the tube). The flux tubes have to be non-buoyant since (with the exception of the equatorial plane) the component of the buoyancy force parallel to the axis of rotation cannot be balanced by the other forces.

When the field strength of the toroidal flux ring exceeds a critical threshold, non-axisymmetric (undular) instability sets in and flux loops erupt towards the stellar surface while the parts between them sink deeper down into the overshoot region and become firmly anchored there. The general linear stability criteria for this process have been determined by Ferriz-Mas & Schüssler (1993, 1994). It

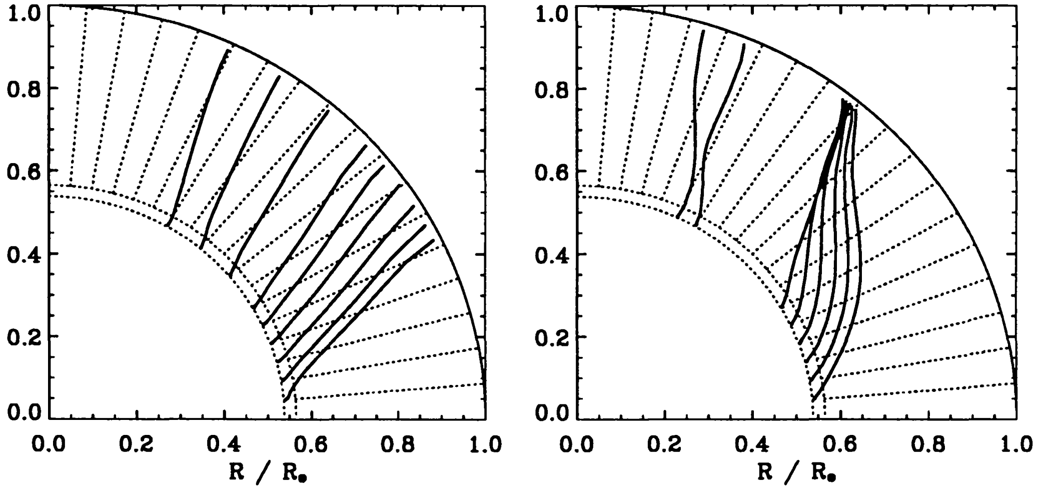

FIGURE I Erupting flux loops in the 'young' Sun. Trajectories of the peaks of erupting flux loops, projected onto a meridional plane of the star, are given for a set of unstable flux tubes with different initial latitudes. **left:** solar rotation rate $\Omega_\odot = 2.7 \cdot 10^{-6}$ s^{-1}, **right:** rotation rate $\Omega = 10 \cdot \Omega_\odot$.

turns out that the stability properties are mainly determined by the stratification of the star (sub- or superadiabatic), its rate of rotation, and by the field strength of the flux tube. The critical field strength for instability increases with the rotation rate and with the degree of subadiabaticity of the storing overshoot region.

For these first simulations of the dynamics of erupting flux tubes in a rapidly rotating, cool star, we have used a model of the 'young' Sun, just after leaving the Hayashi track. In the stellar evolution code used (cf. Ahrens et al. 1992), the convective regions are treated with aid of a non-local mixing-length formulation, so that an overshoot layer below the outer convection zone is consistently included (Skaley & Stix 1991). The linear stability criteria are then used to determine (for given rotation rate and given location of the tube in the overshoot layer) the field strength for which a flux tube becomes unstable with a linear growth time of a few hundred days. Such flux tubes are then taken as the initial configuration for the nonlinear simulation of the eruption process.

The simulation code is based on the thin flux tube approximation and describes the flux tube by a string of mass elements which form a closed curve in 3D space. The time evolution of the tube is then followed within a spherical shell. We have performed series of calculations for flux tubes with a magnetic flux of 10^{22} mx starting at latitudes between 5° and 60°. Fig. I shows trajectories of the peaks of erupting flux loops, projected onto a meridional plane of the star, for two values of the stellar (rigid) rotation rate, namely the solar equatorial value, $\Omega_\odot = 2.7 \cdot 10^{-6}\mathrm{s}^{-1}$ (left-hand side), and $\Omega = 10 \cdot \Omega_\odot$ (right-hand side). Dashed lines indicate the boundaries of the overshoot region and the (spherically) radial directions. Even for solar rotation a poleward deflection (up to 20° in latitude) due to the action of the Coriolis force is clearly visible. For a model of the *present* Sun with the same rate of rotation, this effect is much less pronounced

(Schüssler et al. 1994), mainly because of its shallower convection zone. In the fast rotating case on the right-hand side, all tubes move nearly parallel to the axis of rotation and erupt at high latitudes.

We conclude that our MHD simulations confirm the conjecture of Schüssler and Solanki (1992), namely that stars with rapid rotation rate and sufficiently deep convection zones do show magnetic flux emergence at high latitudes. A pre-main sequence star of one solar mass exhibits a distinct concentration of the surface field at high latitudes for rotation rates as low as 10 times the solar value, while the present Sun (which has a less deep convection zone) has to be spun up by a factor of about 100 to show the same effect.

We are presently extending the calculations to stars with other masses and at later evolutionary stages (subgiants and giants). We expect that the very deep convection zones of giants should lead to the formation of truly polar spots.

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