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STELLAR DYNAMOS: THE ROSSBY NUMBER DEPENDENCE

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ABSTRACT Using novel parametrizations of stellar turbulence we construct time-dependent, two-dimensional solar dynamo models for different rotation rates. For dynamos operating in the overshoot layer the poloidal field saturates at rotation periods faster than 10 days. For slower rotation, the cycle period increases with the rotation rate.

INTRODUCTION

In standard mean field dynamos it is assumed that both the α-effect and the differential rotation, Ω', increase linearly with the rotation rate Ω. The dynamo number, $\mathcal{D} = \alpha\Omega' R^4/\eta_T^2$, is then proportional to Ω^2. (R radius, η_T turbulent magnetic diffusivity.) In a variety of cases with quadratic nonlinearities (magnetic buoyancy, α-quenching, feedback from large scale motions), the magnetic field strength continues to increase with increasing Ω, without ever saturating (see, e.g., Fig. I in Keppens et al., this volume). One reason for this unphysical behavior is that standard expressions for α and η_T are only valid for small values of Ω. According to recent theories of Rüdiger & Kitchatinov (1993), α saturates for large values of Ω, but η_T begins to decrease. In the following we investigate consequences of this qualitatively new behavior. We consider two different locations of the dynamo: (i) the overshoot layer between the convection zone and the radiative interior, and (ii) the convection zone proper (distributed dynamo).

OVERSHOOT LAYER DYNAMO

There are a number of reasons favoring the overshoot layer as the site of the solar dynamo. However, those reasons are also compatible with the idea that dynamo action occurs in the entire convection zone, and that turbulent pumping leads to the accumulation of magnetic fields in the overshoot layer, from which strong flux ropes can emerge to form sunspots.

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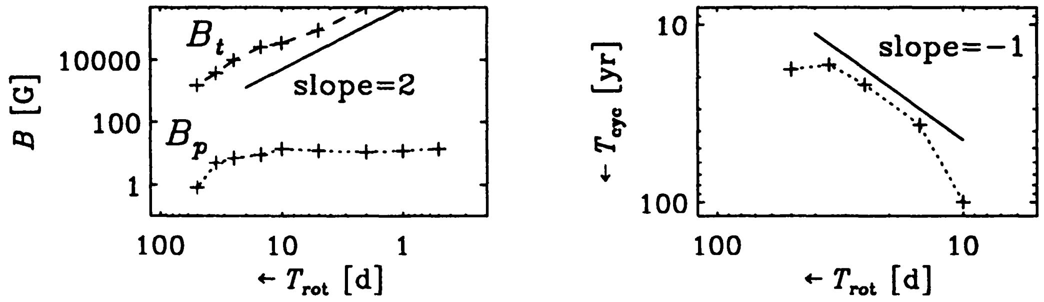

FIGURE I The dependence of the poloidal (B_p) and toroidal (B_t) magnetic field components, and of the cycle period $T_{\rm cyc}$, on the rotation rate for a dynamo operating in the overshoot layer.

Using new expressions for α and η_T, Rüdiger & Brandenburg (1993) constructed a solar dynamo model where α was concentrated in the overshoot layer. This was formally achieved by assuming that the stratification of the turbulent intensity alone is responsible for the α-effect. This model produced a field geometry compatible with that of the sun, and the cycle period was close to the solar value due to the rotationally reduced value of η_T. The dependence of the magnetic field strength and the cycle period on the rotation period is shown in Fig. I, where differential rotation is now generated by Reynolds stresses (Küker et al., this volume), and not taken from helioseismology.

Note that the poloidal field saturates for rotation periods faster than 10 days, while the toroidal field increases. Unfortunately, current expressions for the α-tensor are only valid either for strong fields *or* for rapid rotation, but not for both. For the sun the effects of rapid rotation are more important, and therefore our models become progressively uncertain for strong magnetic fields.

The most dramatic feature of the present model is the decrease of the cycle frequency, $\omega_{\rm cyc} = 2\pi/T_{\rm cyc}$, with increasing rotation rate, $\Omega = 2\pi/T_{\rm rot}$. This is mainly due to the fact that the magnetic diffusion time, R^2/η_T, increases with Ω. This reasoning is however not compulsory, because nonlinear dynamos can have cycle frequencies that are progressively larger than the inverse diffusion time as Ω increases.

SCALING ARGUMENTS AND DISTRIBUTED DYNAMOS

In the limit of rapid rotation, $\alpha \rightarrow$ const and $\eta_T \rightarrow \Omega^{-1}$ (cf. Rüdiger & Brandenburg 1993). Assuming now $\Omega'/\Omega \sim \Omega^\kappa$, the dynamo number scales like

$$\mathcal{D} \sim \Omega^{3+\kappa}. \tag{1}$$

For nonlinear dynamos, the cycle period depends on $\mathcal{D}$ like

$$\omega_{\rm cyc} \sim (\eta_T/R^2)\mathcal{D}^{\hat{n}} \sim \Omega^{\hat{n}(3+\kappa)-1} \equiv \Omega^n. \tag{2}$$

The observed value of n is around 1.25 (Noyes et al. 1984), and for standard (distributed) dynamos, $\hat{n}$ is between 1/3 (Noyes et al. 1984) and 1/2 (Moss et

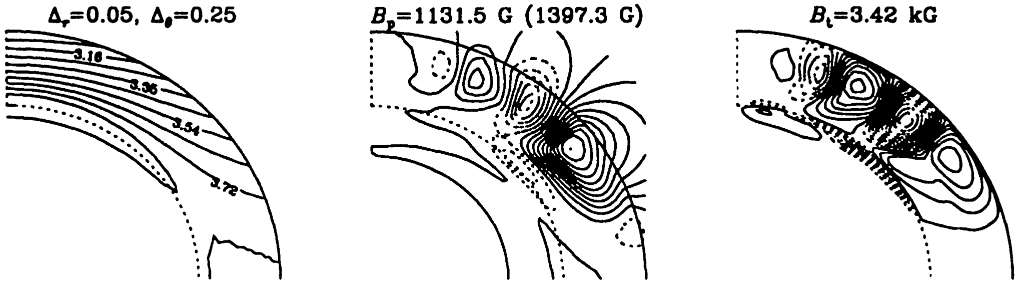

FIGURE II Contours of the angular velocity, poloidal field lines, and contours of the toroidal field (dashed contours refer to negative values) for a distributed dynamo. $T_{\rm rot} = 20\,$d.

al. 1990). If we now consider κ as unknown, we can reproduce the observed value of n if $\kappa = (n+1)/\hat{n} - 3$ is between 3.75 and 1.5, respectively.

In order to understand the period dependence for the overshoot dynamo we computed the scaling exponent $\hat{n}$ and found a value around 1/6. This would imply $\kappa = 10.5$, which is an unrealistically large value. Thus, it seems rather difficult for the overshoot dynamo to explain the observed period relation. The same is true for the scaling of the magnetic field strength: with $B \sim (\eta_T/R)\mathcal{D}^{\hat{m}} \sim \Omega^{\hat{m}(3+\kappa)-1} \equiv \Omega^m$ and $\hat{m} = 0.5$, this large value of κ would imply $m \approx 6$ which, again, is rather large.

Given the rather weak dependence of the cycle period on the dynamo number for dynamos operating in the overshoot layer, we need to reconsider the possibility of dynamo action in the convection zone proper. To this end we now restore the effects of the density stratification on the α-effect (cf. Rüdiger & Kitchatinov 1993), using a solar mixing length model; see Fig. II.

Our model of a distributed dynamo resolves at least partly the problem with the scaling of the cycle frequency: we find $\hat{n} \simeq 0.5$ which would imply $\kappa \simeq 1.5$. At the same time we face a number of well-known problems regarding the shape of the butterfly diagram and the cycle period. Also, the magnitude of the α-effect relative to the Ω-effect is now much larger than in the overshoot dynamo. Consequently, $\omega_{\rm cyc}$ and B do not depend on $\mathcal{D}$ alone. Moreover, the poloidal magnetic field at the surface is now rather strong.

In conclusion, the overshoot dynamo seems to work well for the sun, but when it is to be applied to stars with different rotation rates a problem arises in that the observed period dependence cannot be explained.

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