SOLAR MAGNETIC FIELDS AND DYNAMO PROCESS

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ABSTRACT: We have computed kinematic dynamo models for the Sun making realistic assumptions about the different induction effects. Recent results of helioseismology are used to infer the differential rotation. By changing the value of the angular velocity at the bottom of the convection zone in the models we find more or less agreement with the observations.

1. INTRODUCTION

The spatial distribution of flares on the Sun is presumably closely related to the structure of the *mean* magnetic field (Bai, 1988). Their field geometry can be understood in terms of dynamo theory (Steenbeck and Krause, 1969). During the last 20 years many dynamo models have been investigated and applied to the Sun (see e.g. Roberts and Stix, 1972). The differential rotation, entering into such models as a 'free parameter', has been often treated quite crudely, by assuming certain analytic functions for the rotation profile. More realistic models using results of helioseismology for the internal angular velocity in the Sun have been considered by Makarov *et al.* (1988). They used a WKB method for solving the dynamo equations. Recently Brandenburg and Tuominen (1988) reported on similar results obtained by solving the full eigenvalue problem for the sphere numerically. Detailed agreement with the observations is found. In this poster paper we reconsider these models and extend the investigations also to models with artificially modified rotational profiles.

2. THE SOLAR INTERNAL ANGULAR VELOCITY

The differential rotation $\Omega(r,\theta)$ is important for generating toroidal field from poloidal. The function $\Omega(r,\theta)$ is observed to some extent by means of helioseismology. In Table 1 we have combined data for $\Omega(r,\theta)$ obtained by means of helioseismology which have been published by a number of authors. We have also included angular velocities measured with various tracers such as sunspots and magnetic field patterns.

Table 1 shows that the variation of Ω_e in the radial direction is about 7 %. Furthermore Ω_e is *decreasing* inwards for $0.85R < r < R$ (Hill, 1987) and for $0.65R < r < 0.75R$ (Brown *et al.*, 1988). These results do not seem to fit together at $r = 0.8R$. If the absolute scale measured in both regions is correct, we must conclude that Ω_e is *increasing* inwards somewhere around $r = 0.8R$. This is supported by the fact that youngest sunspots used as tracers rotate with an angular velocity exceeding the surface value by $4 - 5\%$ (Tuominen and Virtanen, 1988). Also long-lived magnetic features rotate $2 - 3\%$ times faster than the surface (Stenflo, 1988). The general interpretation is that young sunspots and magnetic features carry information from somewhere deep in the convection zone. Of course this is not the only possibility. For example the magnetic features observed at the surface and also the active longitudes (e.g. Tuominen, 1962), where sunspots are preferentially born, may be a 'non-axisymmetric dynamo mode', which can propagate around the Sun with an angular velocity slightly larger than the angular velocity at some depth (see e.g. Brandenburg *et al.*, 1988c).

3. A KINEMATIC DYAMO MODEL FOR THE SUN

We have computed dynamo models using for $\Omega_{e/p}$ the data given in the previous section. The profile for the α-effect is derived from a mixing length model using first order smoothing approach (Steenbeck *et al.*, 1966). However, we have scaled the α-profile by a factor 1/200 in order to achieve a marginal solution. This scaling problem is discussed in more detail by Brandenburg *et al.*(1988c). In Figure 1 we have plotted generalized butterfly diagrams for the magnetic field showing contours

Table 1: The internal solar angular velocity at the equator $\Omega_e(r)$ and the poles $\Omega_p(r)$, inferred from results of helioseismology. R is the solar radius. The references are: (a) Brown *et al.*, 1988; (b) Duvall and Harvey, 1984 (their Fig. 1a); (c) Hill, 1987 (his Fig.2); (d) Hill *et al.*, 1988 (their Fig.2). Comparison is made with angular velocities measured with other tracers like sunspots (e, Tuominen and Virtanen, 1988), magnetic patterns (f, Snoddgrass, 1983; g, Stenflo, 1988), and the Mt. Wilson photospheric Doppler velocity (h, Snodgrass, 1983).

method	r/R	$\Omega_e(r)/2\pi$	$\Omega_p(r)/2\pi$
helioseism. (a)	0.65	440	355
helioseism. (a)	0.72	455	350
helioseism. (b)	0.75	460	
helioseism. (b,c)	0.85	425	
helioseism. (d)	0.91	430	
helioseism. (d)	0.96	440	
youngest spots (e)		475	469
oldest spots (e)		462	393
magnetic (f)		462	336
magnetic (g)		466	434
Doppler (h)		455	324

of constant radial magnetic field strength (B_r-component, upper panel) and of constant toroidal field (B_φ component, lower panel).

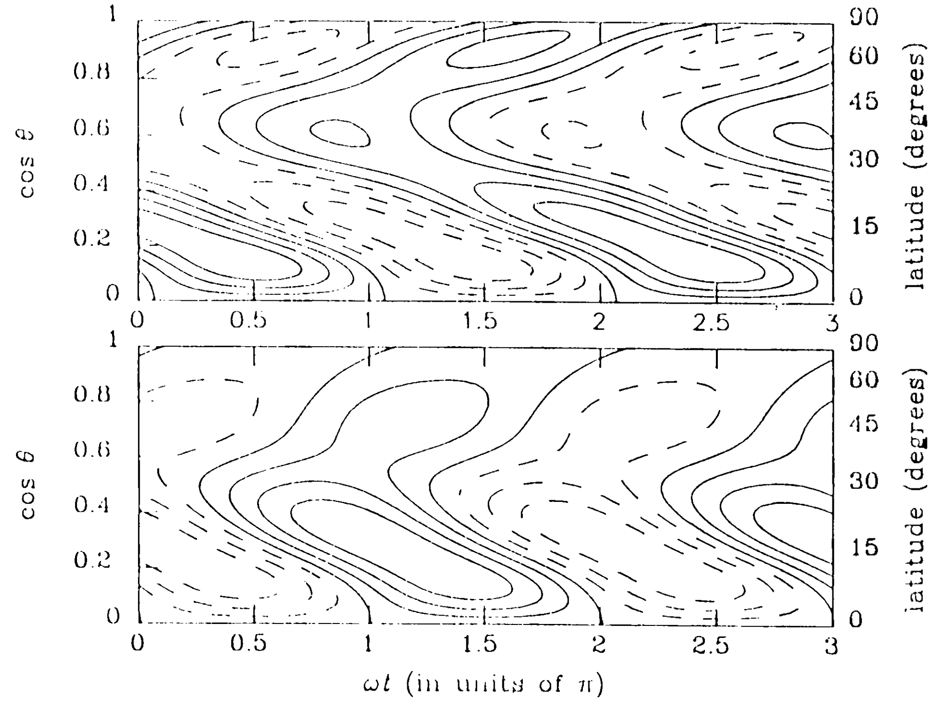

Figure 1 Generalized butterfly diagram for the B_r-component (upper panel) and for the B_φ-component at some reference depth $r = 0.9R$ and $r = 0.85R$, respectively. The horizontal axis is time (π corresponds to the 11 year cycle) and the vertical axis is latitude. In both cases a weighted radial average is displayed using a Gaussian with a width of $0.1R$. The dashed lines refer to negative polarities (taken from Brandenburg and Tuominen, 1988).

Note in particular a poleward migrating branch in the B_r-component. The contour $B_r = 0$ reaches the pole somewhat after the maximum of the toroidal field component ('sunspot maximum'). This is in accordance with the observations (see e.g. Makarov *et al.*, 1983). For a more detailed comparison see Brandenburg and Tuominen (1988).

4. HOW BIG IS Ω_c AT THE BOTTOM OF THE CZ?

The value of Ω_c at the bottom of the convection zone (CZ) is still not well determined. It is possible that the value for Ω_c at $r = 0.75R$ (b, in Table 1) is slightly lower than the real value, although the observations of youngest sunspots indicate that the angular velocity at some deeper layer must still exceed the surface value. The following two pictures show butterfly diagrams obtained from a dynamo model with two different values for Ω_c at the bottom of the CZ.

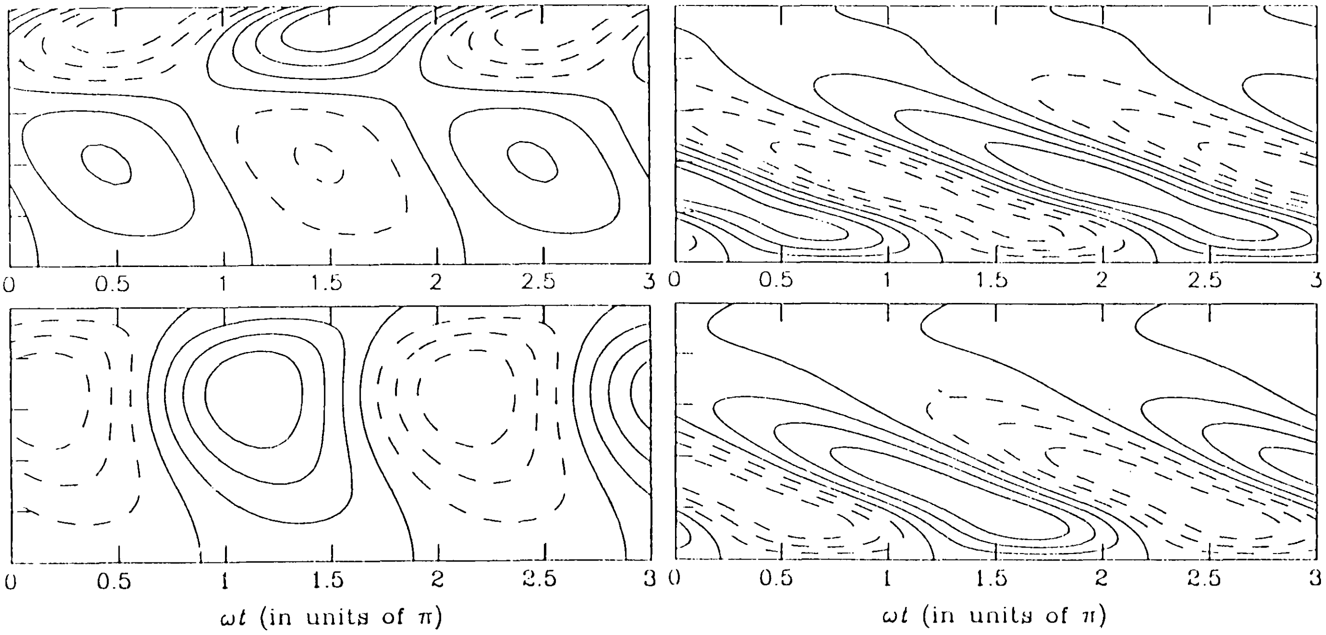

Figure 2: Same as Figure 1, but with different Ω_c at the bottom of the CZ. (a) $\Omega_c \doteq 440$nHz (at r=0.75). The resulting butterfly diagram looks quite unrealistic: the toroidal flux is concentrated at high latitudes and no equatorward migration appears. (b) $\Omega_c = 480$nHz (at r=0.75). An equatorward migration of flux is present, but the slope of the wings is too flat. There is no polar branch. In contrast, the value $\Omega_c \doteq 460$nHz, which has been used for the model in Figure 1, seems to be consistent with observations.

5. CONCLUSIONS

We conclude that, taking the results of helioseismology and mixing length concept fully into account, it is possible to construct more realistic dynamo models which show good agreement with the observed mean solar magnetic field. Models with larger or smaller Ω_c at the bottom of the CZ seem to be incompatible with the observations. For further investigations, it would be of interest to see whether this agreement persists when the nonlinear feed-back is taken into account and when the equation for the mean motion and the induction equation are solved self-consistently. Also the stability of these solutions and the existence of 'mixed parities' (Brandenburg *et al.*, 1988a,b,d) remains to be investigated for solar type models.

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