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III. THE SOLAR DYNAMO

(M. Stix)

Traditionally the theory of the solar dynamo has been divided into two parts. The first, more difficult part, is the derivation of equations governing the mean magnetic field; the second, easier, is the solution of this equation, and the interpretation of the result in terms of observed solar magnetism. This report follows the traditional division.

1. Mean Field Equations

Mean field equations contain the effects of turbulence in form of transport coefficients, notably the turbulent diffusivity β, and the regeneration coefficient, α, for the mean poloidal field. These coefficients have often been calculated in the "approximation of second order correlations" (= "first order smoothing"). A formally complete solution has been given by Hoyng (1985). For the case of isotropic turbulence Nicklaus (1987), using an ensemble of polarized waves (Drummond et al., 1984) and the formalism of ordered cumulants, calculated corrections arising from fourth order correlations. These are proportional to $S^2 = (u\tau/l)^2$, which unfortunately is of order 1 in the solar convection zone. Moreover, not only the α-coefficient, but also the correction to the β-coefficient depends on the helicity of the turbulent flow.

In a different approach, Drummond and Horgan (1986) used the same set of polarized waves and calculated the exact Lagrangian solution of the induction equation. For the purpose of averaging they computed the paths of a large number ($\simeq 10^5$) of fluid particles. In the examples treated they obtained α and β coefficients which were surprisingly close to the results of the second order correlation approximation. The Lagrangian approach was also employed by Molchanov et al. (1984) and by Vainshtein and Kichatinov (1986) in more general investigations of a magnetic field in a turbulent medium of high conductivity.

A different derivation of an α-coefficient was given by Schmitt (1984, 1985) on the basis of dynamically unstable magnetostrophic waves (propagating in a magnetic layer at the base of the convection zone, see below).

The role of magnetic field fluctuations (on the Sun, these are large compared to the mean field!) in dynamo theory was emphasized by Hoyng (1987a,b). He derives a new equation for the tensor $\langle \mathbf{BB} \rangle$ and shows that, in addition to α and β, a third important transport coefficient, related to the mean vorticity, occurs.

2. Solar Dynamo Models

Solutions of the mean field equation in a spherical geometry have been systematically studied by Rädler (1986a), Bräuer and Rädler (1987), and Yoshimura (1984a,b,c). These studies bear on the question of mode selection, e.g. whether a mean field of odd or of even parity will be excited first, or whether the field is oscillatory or steady. Hoyng (1987b) suggests that a number of dynamo modes could be simultaneously present at any one time due to stochastic excitation, and that these modes should be compared to the modes analysed by Stenflo and Vogel (1986). The dominant mode found by these authors is a combination of odd zonal harmonics, all with the same period of 22 years, and corresponds to the leading mode predicted by most $\alpha\omega$-dynamos. Non-axisymmetric modes are strongly opposed in $\alpha\omega$-dynamos by the differential rotation (Rädler, 1986b).

Parker (1984) points out that the traditional boundary condition of vanishing toroidal field, B = 0, should be replaced by the condition $\partial B/\partial r = 0$ because of the difficulty the field has to escape into the highly conducting corona. The new condition somewhat lowers the critical dynamo number and increases the period of the oscillatory dynamo solution (Choudhuri, 1984).

Much attention was paid to dynamos operating in an overshoot layer at the base of the Sun's convection zone. Such a dynamo would not suffer from rapid loss of magnetic flux due to instabilities. Thanks to a sign reversal of α in the lower part of the convection zone it would perhaps also avoid the poleward migration of the field which is found in dynamos based on hydrodynamic and hydromagnetic calculations (Glatzmaier, 1984, 1985a; Gilman and Miller, 1986; for the sign of α s.a. Krivodubskii, 1984b).

Inversion of p mode frequencies (Christensen-Dalsgaard et al., 1985) suggests that the base of the convection zone lies at a depth of ≈ 200000 km. An overshoot layer at this depth, obtained through a non-local version of the mixing-length theory, is ≈ 15000 km thick and quite capable of storing enough magnetic flux to account for the observed activity (e.g. Pidatella and Stix, 1986; for a more general approach, with "plumes", see Schmitt et al., 1984).

Unfortunately there is no indication of a concentrated shear layer at a depth of ≈ 200000 km. Rotational splitting of p mode frequencies (Duvall and Harvey, 1984) yields a gradual inwards decrease of the angular velocity, i.e. $\partial\omega/\partial r > 0$, at low latitude (Duvall et al., 1984); dynamic considerations extend this functional behaviour of ω to the cylindrical isorotation surfaces known from the work of Gilman, Glatzmaier, and others (s.a. Rosner and Weiss, 1985). To concentrate magnetic flux generated in a broader shear region (and to counteract the effects of instability) one must possibly rely on mechanisms which transport flux downward into the overshoot layer. An example is the diamagnetic effect, as recently again suggested by Krivodubskii (1984a).

Independent evidence for a magnetic layer at the base of the convection zone could also come from p mode frequencies: Woodard and Noyes (1985) and Fossat et al. (1987) found a mean decrease of ≈ 0.4 μHz between 1980 and 1984 for frequencies of degree 0 to 3, and attribute the change to the solar cycle. The change has been disputed by Pallé et al. (1986). Moreover, a change of 0.4 μHz would require a field strength of order 10^6 G, which is much larger than theoretically expected (Roberts and Campbell, 1986)! So the question is open. In any case it is interesting to note that a narrow magnetic layer would cause a more subtle effect: in addition to a mean term, we would expect a frequency shift which (for any given degree) is periodic in the frequency itself (Vorontsov, 1987), and perhaps detectable by this signature.

A kinematic $\alpha\omega$-dynamo model for the overshoot layer has been constructed by DeLuca (1986; s.a. DeLuca and Gilman, 1986). It employs a shear with $\partial\omega/\partial r > 0$, and $\alpha < 0$ (in the northern hemisphere; $\alpha > 0$ in the south), so that the mean field migration is equatorwards as desired. These ingredients to the kinematic model are confirmed in the full dynamic calculation of Glatzmaier (1985b). The model of Schmitt (1987) is a similar $\alpha\omega$-dynamo, he employs the α-effect arising from the magnetostrophic waves. Unfortunately all these models seem to predict the wrong phase relationship between the mean poloidal and toroidal field components (Stix, 1987).

Aperiodic behaviour, such as the Maunder minimum in the 17th century, has been attributed to the dynamic properties of the mean field equation. Non-linear interaction terms allow for the desired chaotic solutions (Weiss et al., 1984) although a different explanation, based on a stationary field in the core, has been offered by Pudovkin and Benevolenska (1985).

Reviews on the solar dynamo include those by Belvedere (1985), Gilman (1986), Moss (1986), Stix (1984, 1987), and Weiss (1986, 1987).

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IV. SMALL SCALE MAGNETIC FIELDS

(S.K. Solanki)

Considerable progress has been made during the last four years in the theoretical and empirical investigation of the small scale solar magnetic field and associated phenomena. Although the basic outlines established in the 1970s of the structure of the field, namely small fluxtubes or magnetic elements with kilogauss fields embedded in a relatively field free medium have survived, many of the details have changed and some of the large gaps in our knowlegde of these captivating structures have been filled. In the following we briefly outline some of the highlights.

One direction in the thrust for a better understanding of magnetic elements has been towards the construction of comprehensive theoretical models, e.g. by Deinzer et al. (1984a,b) in 2-D slab geometry and by Nordlund (1986) in 3-D. Although these models still lack some essential features (too small spatial resolution in the 3-D models, no proper treatment of the radiative transfer in the 2-D models; the latter shortcoming is being remedied at the moment by a number of groups), they do illustrate the physics and give rise to the hope that within a decade models of magnetic elements of equal detail and generality as the granulation models of Nordlund will be available. However, considerable hurdles must be surmounted first, since magnetic elements are considerably more difficult to model than granulation. Waves, for example, cannot be neglected, since wave heating (perhaps involving dissipation via shocks, cf. Herbold et al., 1984) is probably quite important even in the photospheric layers and is certainly so in the chromosphere. The work of Ayres et al. (1986) actually supports the conclusion that the hot chromosphere only exists within fluxtubes. Another complexity facing 3-D fluxtube modellers is the possible presence of a boundary current sheet, which requires very fine grids for a proper treatment. Two dimensional models, like the ones of Deinzer et al. or of Steiner et al. (1986), have the advantage that they can take such boundary layers into account in detail.

A breakthrough in the radiative transfer of polarized light was achieved by Van Ballegooijen (1985). He presented a method for obtaining the formal solution of the radiative transfer equations for polarized light in the presence of a magnetic field. Besides providing deep insight into the process of solution, his method also allows contribution functions to be defined and calculated. Thus the determination of the heights of formation of the Stokes profiles has been placed on a secure theoretical footing. This advance will play an important role, not only for the proper diagnostics of observations, but also for interpreting the spectra produced by the emerging breed of comprehensive fluxtube models. The one remaining problem with his definition is that it mixes the contribution to the lines with that to the continuum. However, a remedy is already in sight.

Given the present state of theory, observational and empirical work is still indispensible. The main observational advance has come from the extension of the Fourier transform spectrometer (FTS) at the NSO McMath telescope into a spectral polarimeter, which is currently capable of registering Stokes I, V, and Q in thousands of spectral lines simultaneously at very high spectral resolution. Data from this instrument, built by J.W. Brault and converted into a polarimeter by J.W. Harvey and J.O. Stenflo, have led to a considerable fraction of the observational advances concerning small scale magnetic fields in the last three to four years. Although such data do not have high spatial or temporal resolution,