DYNAMO THEORY IN THE SUN AND STARS

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ABSTRACT

Complementarity of solar and stellar observations should increase our knowledge of the basic facts and mechanisms of activity. The great development of stellar activity observations has enhanced theoretical study, most of which is in the framework of dynamo theory.

Even if dynamo theory seems plausible and successful in capturing the essential processes, several uncertainties and intrinsic limits do still exist and are discussed here together with alternative or complementary suggestions.

It is stressed the importance of magnetoconvection and flux tube studies to improve our understanding of both large scale and small scale interaction of rotation, turbulent convection and magnetic field.

Finally, recent models of stellar activity are critically reviewed. It is pointed out that the confront with the new stellar data should extend our comprehension of the dynamo operation modes, which probably depend on stellar structure, rotation and age.

1. THE SOLAR-STELLAR CONNECTION

In the last decade the concept of a unified sight of solar and stellar activity has revealed worthwhile under many aspects gaining the increasing favour of observers and theoreticians. The term solar-stellar connection has recently been introduced to indicate the complementarity of solar and stellar observations (see e.g.Hartmann 1981, Noyes 1981, Worden 1981) to increase our knowledge and understanding of the basic facts and mechanisms of activity. While solar observations offer a detailed study of the activity phenomena in a relatively close astrophysical laboratory and provide a guide to explore stellar activity on the basis of what is learned from the Sun, it is also clear that the complex of solar activity phenomena is to be regarded as " a limiting regime, for a star of solar parameters and its present state of evolution, of features which must be seen in a broader context "

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(Mihalas 1981). Thus, for instance, even if dynamo theory has revealed promising for the Sun and it seems valuable its extension to the more general stellar case, nevertheless possible differences in the dynamo operating modes are expected as a consequence of different stellar properties (structure, angular velocity of rotation ω, depth of the convection zone (c.z.)) and evolutionary age. So that, observation of activity in a large sample of stars may show all the various aspects of stellar activity on a multiplicity of time scales and physical situations leading back to a better understanding of solar activity itself (see, for example, the Maunder minima).

In the most recent years the data collected by IUE and EINSTEIN have widened our knowledge of chromospheric and coronal activity and, in particular, X-ray observations have pointed out the basic relevance of magnetic fields in sustaining stellar coronae (Vaiana 1980, 1981; Rosner 1980; Hartmann 1981; Linsky 1981). Nevertheless, the more classical CaII emission flux observations have still confirmed to be a powerful method of investigation (Wilson 1978; Vaughan and Preston 1980; Vaughan 1980; Vaughan et al 1981; Skumanich and Eddy 1981) and indirect detection of activity regions from photometric variations in RS CVn and BY Dra type stars(+) seems to be more than a promising tool to give further insight on surface phenomena (Hall 1981, Rodonò 1981, 1982). Flares observed in lower main sequence stars, red dwarfs and pre-main sequence objects are of extreme importance to our understanding of the energetics of such violent magnetic field instabilities (Gershberg 1978). Magnetic field measurements are now basically improved with the new Robinson's method that allows to measure field intensities (larger than a kilogauss) and filling factors by comparison of magnetically sensitive and insensitive lines (Robinson 1980). The great development of stellar activity observations has enhanced the theoretical effort to predict, interpret and reproduce the observed features, giving rise to several models, most of which are in the framework of dynamo theory. Dynamo theory must therefore confront with the new observational data, which will surely stimulate improvement of the theoretical background and refinement of the methods of analysis, leading to more general and realistic studies.

In the following we review first the up to date status of dynamo theory together with alternative or complementary suggestions, then we discuss recent stellar activity models.

(+) In the Sun, variations of the solar constant on short and cyclic timescales (Foukal 1980, 1982) should give insight on the convection-magnetic field interaction.

2. CRITICAL REVIEW OF DYNAMO THEORY

Dynamo theory attempts to explain the generation and evolution of cosmic magnetic fields in terms of induction effects in conducting fluid masses and is, in the author's opinion, a plausible and somewhat successful theoretical framework to understand solar and stellar activity even if several uncertainties and intrinsic limits do still exist.

Since the famous anti-dynamo theorem of Cowling (1934) and the pioneristic work of Parker (1955) on the dynamo mechanism in the Sun, many efforts have been done to develop an internally consistent theory of Mean Field Electrodynamics (Steenbeck, Krause, Rädler 1966) in connection with the basic ideas of dynamo action in rotating convective bodies (see for the development of the main concepts and an exhaustive and general formulation: Parker 1979, Moffatt 1978, Krause and Rädler 1980).

Dynamos can be separated into two classes: kinematic (linear) dynamos in which the velocity field is assigned independently, without taking into account the feedback of the magnetic field on the motion; hydromagnetic (non-linear) dynamos in which the back-reaction of the magnetic field through the Lorentz force is considered and the whole system of the magnetohydrodynamic equations is solved simultaneously, assuring the internal consistency. The reliability of the kinematic approximation depends on the (magnetic energy density)/(kinetic energy density) ratio. If this ratio is small compared to the unity the kinematic approximation is reasonable, otherwise the hydrodynamic approach should be dealt with.

2.1. The α-ω Dynamo in the Mean Field Electrodynamics

In its kinematic formulation, dynamo problem reduces to an eigenvalue problem for the magnetic field $\underline{B}$, governed by the induction equation:

$$\partial \underline{B}/\partial t = \mathrm{curl}\ (\underline{u} \times \underline{B}) - \mathrm{curl}\ (\eta\ \mathrm{curl}\ \underline{B}) \qquad (1)$$

where $\underline{u}$ is the velocity field and $\eta = 1/\mu\sigma$, with μ= magnetic permeability and σ= electric conductivity, is the ohmic diffusivity. For a given $\underline{u}$, solutions of the form $B \sim \exp\ (a+ib)t$ are searched to determine the growth rate a and the oscillatory frequency b of the eigenmodes, depending on some physical condition for the dynamo maintenance of the field.

In the framework of the Mean Field Electrodynamics (MFE), the vector fields $\underline{u}$ and $\underline{B}$ are expressed as sums of mean (large scale-slowly varying in time) parts and fluctuating (small scale-rapidly varying in time) parts:

$$\underline{u} = \langle \underline{u} \rangle + \underline{u}'$$

$$\underline{B} = \langle\underline{B}\rangle + \underline{B}'$$

It can easily be shown that this leads to the following equations for the mean and the fluctuating magnetic fields:

$$\partial\langle\underline{B}\rangle/\partial t = \mathrm{curl}\ (\langle\underline{u}\rangle \times \langle\underline{B}\rangle + \langle\underline{E}\rangle) - \mathrm{curl}\ (\eta\ \mathrm{curl}\ \langle\underline{B}\rangle\ ) \qquad (2)$$

$$\partial\underline{B}'/\partial t = \mathrm{curl}\ (\langle\underline{u}\rangle \times \underline{B}' + \underline{u}' \times \langle\underline{B}\rangle + \underline{G}) - \mathrm{curl}\ (\eta\ \mathrm{curl}\ \underline{B}') \qquad (3)$$

where $\langle\underline{E}\rangle = \langle\ \underline{u}' \times \underline{B}'\rangle$ represents an additional mean electromotive force generated by the turbulent interaction between the fluctuating velocity and magnetic fields and $\underline{G} = \underline{u}'\times\underline{B}' - \langle\ \underline{u}'\times\ \underline{B}'\rangle$.

If we consider homogenous turbulence ($\langle\underline{u}\rangle = 0$ in a proper reference system) and introduce the so called first order smoothing approximation (or quasi-linear approximation), which consists in neglecting $\underline{G}$ in (3), we are led to a simplified equation for the fluctuating magnetic field $\underline{B}'$:

$$\partial\underline{B}'/\partial t = \mathrm{curl}\ (\underline{u}' \times \langle\underline{B}\rangle\ ) - \mathrm{curl}\ (\eta\ \mathrm{curl}\ \underline{B}') \qquad (4)$$

This implicitly means to assume $\underline{B}'$ small compared to $\underline{B}$ and is consistent with equation (3) in two cases:

(1) Magnetic Reynolds number $R_m = U\ell/\eta \ll 1$, where U is a typical turbulent velocity and ℓ a typical length scale;

(2) Stroughal number $U\tau/\ell \ll 1$, where τ is the correlation time.

These conditions correspond respectively to the high resistivity case (in which the advection term is balanced by the dissipative one) and to the rapid fluctuation case (in which the advection term is balanced by the variation in time of the fluctuating magnetic field).

Integrating equation (4) over τ, which is a time interval short enough for $\underline{u}'$ and $\langle\underline{B}\rangle$ to be considered time-independent, linearity of $\underline{B}'$ in $\langle B\rangle$ and its space derivatives allows to express $\langle\underline{E}\rangle = \langle\ \underline{u}'\times\ \underline{B}'\rangle$, in the case of isotropic turbulence (+), as:

$$\langle\underline{E}\rangle = \alpha\ \langle\underline{B}\rangle - \beta\ \mathrm{curl}\ \langle\underline{B}\rangle \qquad (5)$$

Substituting (5) into (2) and dropping the brackets, we get the MFE dynamo equation:

$$\partial\underline{B}/\partial t = \mathrm{curl}\ (\underline{u} \times \underline{B} + \alpha\ \underline{B}) - \mathrm{curl}\ \left[(\eta+\beta)\ \mathrm{curl}\ \underline{B}\ \right] \qquad (6)$$

Here $\alpha\underline{B}$ represents an electromotive force, parallel to the mean field $\underline{B}$, generated by turbulence and β is the turbulent magnetic diffusivity.

(+) for anisotropic α-effect dynamos see Busse and Miin (1979)

Turbulent diffusion operates by mixing large scale mean magnetic fields, while it does not destroy the small-scale fields ultimately smoothed out by ohmic diffusion. It can be shown (Krause and Rädler, 1980) that the coefficient α is proportional to the mean helicity $<\underline{u}'.\mathrm{curl}\ \underline{u}'>$ of the turbulent motion $\underline{u}'$ and does not vanish if the turbulence lacks mirror symmetry. In the so called α-ω dynamos the advection term $\underline{u} \times \underline{B}$ generates the toroidal field from the poloidal field by differential rotation ($\ddot{\omega}$-effect), while the $\alpha\underline{B}$ term regenerates the poloidal field from the toroidal field by cyclonic turbulence (Parker 1955, 1979), through the twisting action of the Coriolis force on magnetic field loops in the convective cells (α-effect). The relative strength of the poloidal to the toroidal field is given by $(\alpha/\Delta\omega\ R)^{\frac{1}{2}}$ where $\Delta\omega$ is the differential rotation and R the stellar radius. In the case of the Sun this ratio is of the order of 10^{-2}, depending however on the magnitude of α , whose estimates seem to be in excess.

The dominant time scales involved in the dynamo process are the period of the oscillatory field $(R/\alpha\Delta\omega)^{\frac{1}{2}}$ and the turbulent diffusion time R^2/β. For marginal dynamo instability these two times are expected to be of comparable order of magnitude(+). In the case of the Sun, the probably too large α-value leads to a theoretical period shorter by an order of magnitude. The mean field (dynamo wave) propagates along the surfaces of isorotation (Parker 1955, Yoshimura 1975) in the direction of $\alpha\nabla\omega \times \underline{i}_\phi$ (where $\underline{i}_\phi$ is the azimuthal unit vector). This implies, with a $\gtrless 0$ respectively in the northern and southern emispheres (Stix 1976), $\partial\omega/\partial r < 0$, if the observational constraint of the butterfly diagram (propagation towards the equator) is taken into account. The parity of the mean field with respect to the equator can be even or odd depending on which modes are excited at lower $R_{\alpha c}$. For the Sun the question is open, since no apparent preference is shown for the observed odd parity modes (Belvedere et al 1980b).

2.2. Limits and possible improvements of α-ω dynamo theory

Criticism against α-ω dynamo theory in the mean field electrodynamics concerns essentially two points: the rather crude method of closure- strictly justified only if $\underline{B}'$ is small compared to $<\underline{B}>$ - involved in the first-order smoothing approximation (for the Sun, indeed, $R_m >> 1$ and $U\tau/\ell \simeq 1$) and the role of turbulent diffusion, according to which magnetic field diffusion occurs on time scales considerably smaller than

(+) Marginal dynamo instability arises when the dynamo number $R_\alpha R_\omega$ is slightly larger than a critical value. For fixed $R_\omega = \Delta\omega\ R^2/\beta$, this occurs when $R_\alpha = \alpha R/\beta$ is slightly larger than a critical value $R_{\alpha c}$.

the ohmic ones ($\beta >> \eta$), therefore comparable with the observed solar cycle period. Piddington (see e.g.: 1981, 1982 and earlier references therein) does not agree with the analogy of turbulent diffusion of the magnetic field with turbulent diffusion of a scalar field (see also Knobloch 1977) and claims that eddy diffusivity leads to shear amplification of the field within the eddies. In his opinion no merging of fields can be accomplished by turbulence. Comparison between the merging rate and the amplification rate leads to a non-vanishing field, whose growth is limited only by the equipartition value. He contests both the applicability of the Petschek mechanism within the eddies for rapid reconnection of the field lines (see e.g. Parker 1979, chapter 15) and the accumulation of magnetic field at the cell boundaries shown by numerical experiments of magnetoconvection (see e.g. Galloway and Weiss 1981; Knobloch 1981a and references therein).

This criticism is in part due to some misunderstanding of the role of turbulent diffusivity which applies only to the mean field, not to the fluctuating field. Moreover, even if there are several doubts that the Petschek mechanism can operate at magnetic pressure not comparable with gas pressure as in the deep convection zone (Cowling 1981), Piddington's argument, based on a simple estimate of the rates of accumulation and diffusion of field within the eddies is not very convincing, and seems less founded than the non-linear simulations of the interaction of turbulent convection and magnetic field carried out in magnetoconvection studies. Piddington emphasizes also the fact that convective motions and buoyancy would tend to transport upwards the "newly" generated poloidal field, so that it could not come down to the lower part of the convection zone, where it has to be operated by differential rotation. A possible reply is that also downwards motions are involved in the convective transport and that turbulent diffusion may well do the job (Cowling 1981). Furthermore, the magnetic buoyancy argument suggests the location of both the ω-effect and the α-effect in the same region, which, according to the present view (see e.g. Parker 1975, Rosner 1980 a,d other references quoted later), should be at the lower boundary of the c.z.

The alternative scenario proposed by Piddington consists of a primordial non-reversing dipole - buried in the radiative region to avoid turbulence - whose field lines oscillate in the meridian planes with a period of 22 years and are acted by the ω-effect, generating toroidal fields of opposite signs in two consecutive solar cycles. However, no clear fundament is given to the energy source and the mechanism of this dipole field oscillation. Moreover there are several doubts that a fossil field would have survived the fully-convective Hayashi phase.

Further, Piddington's alternative is not supported by a satisfactory quantitative treatment. This may also apply to Layzer's et al (1979) paper, whose criticism to α-ω dynamo in the MFE formulation is correct in some points concerning the quasi-linear approximation (even if some misunderstandings about the role of turbulent diffusion and the concept of mean field are still present (see Stix 1981)), but which does not offer a real alternative. In the opinion of those autors there are serious observational and theoretical difficulties against dynamo theory, namely the absence of a surface large scale poloidal field, the Maunder minima and some physical and mathematical inconsistencies in the MFE formulation and in particular in the significance of α and β.

For instance β could be negative (Kraichnan 1976, Knobloch 1977), this being in favour of accumulation of field lines in spatially intermittent flux tubes. To this regard, we have to point out with Stix (1981) that the mean field is not to be intended as a smooth diffuse background field between the flux concentrations but as an average field, where the average includes the highly concentrated intermittent fields whose existence in the convection zone is inferred from the surface observations. In this view, we think that observational evidence of intermittent fields is of no obstacle to dynamo theory, although only non-linear calculations can describe the formation of flux concentrations.

The presence in the past (and in the future?)of Maunder minima does not even affect heavily the α-ω theory, which is in principle able to maintain fields at arbitrary low levels (Stix 1981), so that the dynamo mechanism can well operate even if the fields are so weak to give no observational evidence. It remains to be explained how this mode change happens. Following Ruzmaikin (1980) non-linear dynamos can have solutions diverging from a bifurcation point; so that dynamo can operate in a bimodal way, switching from one mode to another in the so called strange attractor behaviour.

Coming back to Layzer et al (1979), the alternative scenario they propose consists of an original field generated by the Biermann mechanism (Biermann 1950), amplified by a sort of dynamo mechanism during the fully convective phase and giving rise ultimately to a large scale tangled field in the uniformly rotating radiative core. Differential rotation acting on the field in the overshooting layer generates a toroidal component which is wound and unwound alternatively. This torsional field oscillation would explain the solar cycle, whose exterior manifestations would be due to fields leaving the toroidal flux region and floating to the surface. Anyway, this alternative model seems too speculative inasmuch as no sufficiently developed physical description and formal treatment of the torsional oscillation are given.

Incidentally, we recall that the 11-years period torsional oscillation discovered by Howard and La Bonte (1980) has been proposed by the same authors (La Bonte and Howard 1982) to sustain the magnetic cycle. However, it is difficult to think that this rather weak oscillation can compete with the much stronger differential rotation or turbulent convection fields. It seems more reasonable that the torsional oscillations is driven by the longitudinal component of the Lorentz force of the dynamo waves which generate the solar-cycle itself (Yoshimura 1981).

The success of the α-ω theory in reproducing the main characteristics of the solar cycle (see e.g.: Köhler 1973; Stix 1976 a,b; Yoshimura 1975, 1978a, 1978b; Parker 1979; Belvedere et al 1980b) seems to confirm the capability of dynamo equations of capturing in a simple way the essential mechanisms that maintain the solar cycle (Weiss 1981). Nevertheless, several questions remain open and should be investigated deeply in a more consistent and detailed non-linear theory:

- The weakness of the first order smoothing approximation still remains, since in the Sun $R_m >> 1$ and $\ell \approx U \tau$. A possibility of overcoming this difficulty is in Cowling's (1981) argument that "$\underline{B}'$ varying rapidly in space is no longer large compared with $<\underline{B}>$, being rapidly smoothed out by ohmic diffusion at small length scales" (see also Cowling's (1981) discussion of the induction equation for $\underline{B}''$, the part of the fluctuating magnetic field correlated with $\underline{u}'$).
- The role of helicity and turbulent diffusion should be clarified on both large and small scales, leading to more plausible intrinsic determinations of α and β in the context of turbulence theory. In particular the present estimates of α seem to be too large. Note, however, that in the case of strong toroidal flux concentrations, a strong α effect should be needed against the no more negligible Lorentz force (Gilman and Miller, 1981).
- The level at which dynamo operates is still matter of discussion: spatial separation of the ω-effect and the α-effect is not plausible and would give rise to problems of upward and downward field transport which are not easily overcome even invoking turbulent diffusion. Therefore, since magnetic buoyancy arguments and stability of flux tube configurations (see later) suggest that the ω-effect operates deeply in the c.z. or in the overshooting layer, also the α-effect is expected to occur mainly at deep levels. This expectation is supported too by the argument that the α-effect on rapidly rising flux tubes should be ineffective (Golub et al 1981).
- The feedback of the magnetic field on the velocity field is not considered in the linear theory, but the Lorentz force is expected to be relevant when strong flux concentrations occur as in the plausible case of toroidal field ropes wound by differential rotation at the bottom of the c.z., or in the observed case of strong filamentary fields at the edges of cellular patterns.
- The magnetic buoyancy force on flux tubes and the problem of their

stability should be studied further in order to get a reasonable estimate of the float-up times, which should be comparable with the amplification time and the diffusion time, both expected of the order of the cycle period.

The two latter points lead to the need of including the Lorentz force, the magnetic buoyancy force and possible stabilizing forces as the hydrodynamical drag and the Coriolis force into the framework describing the interaction of the magnetic and velocity fields. At the present this is done gradually taking into account the different effects separately.

2.3 Non-linear dynamo theory and magnetic flux concentrations

A non-linear analysis of dynamo in the Boussinesq approximation has been done by Cuong and Busse (1981), but seems perhaps too idealized to be applicable to the solar case. Another non-linear compressible dynamo model has been worked out by Schüssler (1979) in cartesian geometry. He finds that the growth of the magnetic field is limited by the Lorentz force and the magnetic buoyancy, but not to such an extent to inhibit dynamo action. No considerable differences from the linear case are found for the magnetic field geometry and the period of the α-ω dynamo. Some characteristics of the observed solar cycle (e.g. equatorwards migration and polarity reversals) are reproduced, but the model suffers from idealized geometry and arbitrary spatial distribution of the induction effects.

Dynamo problem as a problem in magnetohydrodynamic turbulence has been studied by Frisch et al (1975), Pouquet, Frisch and Léorat (1976), Meneguzzi, Frisch, Pouquet (1981), and Léorat et al (1982). One of the most interesting results, obtained by numerical simulation, is that magnetic helicity (scalar product of magnetic field and its vector potential) can give rise to a reverse energy cascade, generating magnetic energy on large scales in competition with what the α-effect does from kinematic helicity.

Dynamo of small scale fields has recently been investigated by Vainshtein (1980), deriving an equation for the dynamics of the magnetic field in the Lagrangian statistical description of turbulence. It is found that for $\eta \ll \nu$ ($\nu \equiv$ kinematic viscosity) a positive growth rate solution for the magnetic field exists. This may explain the origin of fine structure fields.

Non-linear magnetoconvection studies have been carried out to explain the presence of intense intermittent fields ($\sim$1500 Gauss) at the solar surface through mechanisms for formation of isolated flux tubes in the convection zone. Galloway and Weiss (1981) have recently done a further Boussinesq study of convection in the presence of magnetic fields and found that magnetic flux is rapidly concentrated into sheets at the lateral boundaries of the convective cells, while flux expulsion from the cell interior takes a longer time of the order of a few turnover times. Turbulent convection concentrates magnetic flux until the equipartition value B_e ($\ll B_p$, the pressure equilibrium value, unless at the top of the c.z.) is reached. Rapid evacuation of matter from the flux tubes ('collapse') is then expected, to get the pressure equilibrium field B_p. Weaker flux ropes are shredded and dispersed giving rise to smaller size activity features. The observed total flux at the Sun's surface should be compatible, in those authors' opinion, with the toroidal flux contained in a shallow layer located at the bottom of the c.z. This agrees with what is generally speculated on theoretical grounds and with the observational evidence of the coronal hole field corotating nearly uniformly as it were anchored to a deep level in the c.z. (Golub et al 1981).

Non-linear three-dimensional magneto-convection and magnetic field spectrum have been studied by Knobloch (1981 a,b). These works are related to Knobloch and Rosner's (1981) conclusions that the kinematic approach is not sufficient and to Galloway, Proctor and Weiss (1977), who identified different regimes depending on the increasing value of the magnetic field (the kinematic regime, the hydromagnetic regime with fields that can overcome the equipartition value, the overstable regime in which convection is inhibited and no further field concentration occurs).

Knobloch finds that non-linear concentration of magnetic flux by turbulent motions occurs at the cell edges, in agreement with the previous authors (see also Peckover and Weiss 1978), and that different scales of flux tubes arise as a result of different scales of motion. Also a theoretical prediction of size and spatial distribution of the flux tubes is given, as well as the field strength as a function of the tube radius, on the assumption that flux tubes are formed from an initial uniform field in the presence of a given turbulence spectrum. Agreement with the observations is reasonable.

The problem of stability of flux tubes in the c.z. under the action of vigorous turbulent convective motions, magnetic buoyancy, hydrodynamical drag and rotational forces is one of the most debated in the recent years. We refer for a general overview to Parker (1979, chapters 8,10,13)and(Spruit 1981 a,b). This problem is strictly connected with the time scale of the magnetic flux rise to the solar surface to form active regions.

Parker (1975) suggested that toroidal flux generation should occur deeply in the c.z. in order the rise time of the tubes to be comparable with the time scale of the solar cycle. However, some difficulties exist: tubes in thermally equilibrium with the surrounding would float upwards as a result of magnetic buoyancy. But the requirement that they should remain in the c.z. for some years leads to an upper limit of $\sim$200 Gauss to the field, too small in comparison to the equipartition value. On the other hand, if the tubes were neutrally buoyant, their internal temperature should be lower than the surroundings, and it is not clear what mechanism could maintain the temperature difference. The suggestion of the lower part of the c.z. (or even the transition layers) as a site for magnetic flux storage is also founded on stability requirements. Indeed the strict polarity rules of active regions and, in general, the well definite laws which surface manifestations of activity do obey, seem to imply that the sub-surface magnetic field is highly organized and not subjected to strong deformation by convective motions (Van Ballegooijen 1982b).

Van Ballegooijen (1982a) has studied the stability of adiabatic flux tubes in the layers below the convective zone, where the equipartition magnetic field strength should be $\sim 10^4$ Gauss. In his model buoyancy forces are balanced by hydrodynamical drag and emergence of flux loops from the system, driven by instabilities, should take a few days.

Spruit and Van Ballegooijen (1982) have analyzed the conditions of stability of thin adiabatic flux tubes in the equatorial plane of a convective star, without including rotational effects (for the influence of rotation, see Acheson 1979). They point out that toroidal tubes are subjected not only to buoyant rise, but also to buoyant instabilities such small upward displacement or wave-like disturbances - in which fluid can flow from crests to troughs - if the superadiabaticity of the layer is large enough. In addition tubes are not stable against poleward motion (ribbon slip instability).

They conclude that flux tubes in a stellar convective zone seem to be unstable for all field strengths. Therefore they suggest that toroidal field accumulation occurs in the more stable interface layers between the c.z. and the radiative interior. This idea is also in Van Ballegooijen (1982b), who concludes that an additional force is needed to keep the flux tubes in the overshoot layer against the buoyancy force. He suggests that the Coriolis force, acting on a flow along the toroidal tubes, induced by angular momentum conservation during equatorward meridional motion, would do the job.

A flux tube dynamo model of the solar cycle has been proposed by Schüssler (1980), where attention is devoted to the regeneration process operating on flux tubes in a way similar to Leighton's (1969) model . Further he points out that tubes generated by a weaker poloidal field, therefore shredded by violent convective motions and subjected to smaller magnetic buoyancy, take a longer time to reach the surface (older tubes) where they reveal as Ephemeral Active Regions (EAR) and X-Bright Points (XBP); on the contrary stronger tubes take a shorter time (young tubes) and form large active regions. This way, the antiphase of the cyclic variations of the Wolf number and the EAR (and XPB) number is explained. Schussler's somewhat heuristic model is to be considered a reasonable attempt to incorporate flux tube dynamics into global dynamo theory, but it is clear that more efforts are necessary for a more complete description of the basic interaction between convection, rotation and magnetic fields.

An attempt to do this job is in Gilman and Miller (1981), who consider the fully non-linear hydromagnetic problem of dynamos driven by non-axisymmetric convection in a rotating spherical shell (Gilman 1976, 1977, 1978, 1980, 1982 ; Glatzmaier and Gilman 1982). They point out that previous α-ω models owe part of their success to independently choosing the magnitude and profiles of helicity and differential rotation, and suspect incompatibility with the fluid dynamics laws. Unfortunately, their results are not encouraging with regard to the real Sun. Neither equatorward migration is present, nor polarity reversals, nor preferred symmetry. An excessive α-effects is proposed as a cause of the chaotic magnetic field behaviour. The problem of the non-linear global interaction of dynamo magnetic fields and the dynamics of the inducing fluid motions has very recently been reviewed by Gilman (1983), where the dependence of models upon physical parameters as c.z. depth, rotation rate, heating rate, viscous and magnetic diffusivities, compressibility is analyzed, following the results of a large series of numerical experiments . An interesting point is the "regime diagram" which attempts to predict what kind of dynamo action is to be expected, as a function of the electrical conductivity and the influence of rotation on the dynamics of the system. This way, three fundamental regimes are identified: no dynamos, dynamos without cycle, dynamos with cycles, the last corresponding to intermediate influence of rotation. This diagram could be of some relevance in connection with the bimodal dynamo behaviour put in evidence by the Vaughan-Preston gap (see part 3 of the present review). Another interesting point is in the suggestion, coming out from calculations, that "the seat for cyclic dynamo action is in low latitudes outside the tangent cylinder to the inner boundary of the c.z.". However, due to some difficulties and ambiguities in reproducing the observations, Gilman's models are not fully convincing, even if the position of the problem appears to be correct and fruitful.

3 . MODELS OF STELLAR ACTIVITY

It is well known that main sequence stars later than F5 and giant stars later than G0 have outer convective envelopes whose extension increases with decreasing effective temperature. The interaction between rotation and convection, leading in the Sun to the observed differential rotation and (dynamo driven) activity cycle, should in principle do the same job in other stars with convective envelopes, even if with different efficiency and mode characteristics, depending on basic parameters as rotation, luminosity class, spectral type and age. In this framework Durney and Latour (1978) stressed the importance of a dynamo generated magnetic field in sustaining angular momentum loss in late main sequence stars, with an efficiency sharply decreasing at F6,where outer convection is practically absent (+). Belvedere et al (1980 c,d; 1981, 1982) made the first attempt to compute differential rotation and magnetic cycle dynamo models for main sequence and giant stars, in analogy to the Sun (Belvedere and Paternò 1977, Belvedere et al 1980a). The results show that differential rotation, magnetic field strength, latitude extension of the activity belt and cycle period length do increase with the advancing spectral type. It has been pointed out in these papers that the ratio of the global convection turnover timescale to the rotational timescale, namely $\omega d/U \approx \omega d^2/\nu$ (where d is the thickness of the c.z. and ν the kinematic viscosity), which regulates the strength of the interaction of rotation and convection, does increase with the advancing spectral type, leading to increasing differential rotation. This in turn implies a larger R_ω, thus a smaller $R_{\alpha c}$, that means a more favoured dynamo action for later spectral types (see the footnote at p.). The toroidal magnetic field strength, estimated in the assumption of energy equipartition between the magnetic field and the velocity field (Belvedere et al 1981), is expressed by $B \sim (R^2/\beta)^{\frac{1}{2}}(\omega/R_{\alpha c})$,thus being,for a given ω,of the form ω x(an increasing function of the spectral type). The cycle period length essentially reproduces the turbulent diffusion timescale which, in the marginal dynamo instability, should be comparable with the period of the dynamo wave. The theoretical predictions of Belvedere et al. have received indirect support from the EINSTEIN X-ray flux observations in main sequence and giant stars (see e.g. Vaiana 1980, 1981; Pallavicini et al 1981) and agree well with the general observational background suggesting that activity increases towards the later spectral types, and the current conviction that angular velocity and depth of the convection zone are the basic ingredients for interpretation of stellar activity (see e.g. Rosner 1980, Durney and Robinson 1982).

The recent observations of chromospheric Ca II emission in stars (Vaughan and Preston 1980), the direct angular velocity measurements derived from its modulation (Vaughan et al 1981), and the comparison

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(+) A recent study of dynamo in convective zones of declining thickness and efficiency is in Parker (1981).

of activity cycles in old and young stars (Vaughan 1980) have added to our knowledge of stellar activity, in the same line of Wilson (1978 and references therein).

The following scenario has emerged:

-Ca II emission flux *F*(however, measured against the continuum)increases with the advancing spectral type, while for a fixed spectral type, it increases with ω and decreases with the age t. The latter result is consistent with Skumanich's (1972) relation $\omega \sim t^{-\frac{1}{2}}$, the former with Skumanich and Eddy's (1981) result that the total magnetic flux erupted increases with the angular velocity, the Ca II emission flux being a magnetic activity indicator.

- There exists a gap in the F-G region of the log *F* vs.(B-V) diagram, which evidences two well distinct behaviours:

-Stars above the gap (younger and faster rotators ,show a larger emission flux, thus stronger activity, but no definite cycles (chaotic behavior);

-Stars under the gap (older and slower rotators) show a smaller flux, thus weaker activity, but well defined cycles (cyclic behavior);

This bimodal behavior has open new problems to dynamo theory, as the discovery of Maunder minima had previously. Also the bimodal behavior can however be accounted for in the strange attractor framework, which, as we have already seen, allows for different trajectories from a bifurcation point, this being a characteristic of non-linear systems. Thus, multimode dynamos are in principle possible, depending on stellar parameters and age.

A different explanation of the Vaughan-Preston gap is given in Durney, Mihalas and Robinson (1981), who derive a relation among the dynamo number, the colour index and the angular velocity in the range F5-M0 and make an attempt to reproduce the log *F* vs.(B-V) diagram. In their opinion a transition from a single-mode dynamo to a multiple-mode dynamo should occur at some critical dynamo number, leading to chaotic field behavior in rapidly rotating young stars, owing to the superposition of several coexcited and interfering modes. This has some analogy with Parker's (1971) result that large dynamo numbers lead to small scale fields varying rapidly and irregularly in time.

Another alternative is that proposed by Knobloch, Rosner and Weiss (1981) who suggest that, as the reciprocal of Rossby number $\sigma \sim \omega \ell / U$ increases over a critical value σ_c, convection in rolls nearly aligned with the rotational axis is favoured, this decreasing the mean helicity $\underline{u} \cdot \nabla x \underline{u}$. The consequent weakening of the α-effect would lead to a more difficult regeneration of the poloidal field, may be no dynamo at all, if the poloidal field does not reverse. Therefore different dynamo mechanisms would operate in the high and the low angular velocity regimes. Another result of these authors is that the mean strength of the magnetic field should be larger for lower mass stars (later spectral types).

A similar result is found by Durney and Robinson (1982) who have estimated the magnetic field strength in the assumption that the rise time of the flux tubes is of the order of the amplification time.

The main result is that, for fixed ω, both the magnetic field strength and its extension over the stellar surface increase with (B-V). This is in the same line as the results of Belvedere et al (1980d), suggesting that the present models, although subjected to different assumptions, do converge in predicting some basic features of stellar activity. This may indicate that the essential points have been captured. However, a difference between Belvedere's et al (1980d) paper and Durney and Robinson's (1982) is in the cycle period length, increasing with (B-V) in the former, decreasing in the latter. These theoretical estimates are indeed sensitive to the characteristic time scales chosen in different models.

Durney and Robinson's (1982) results are essentially confirmed in a more recent work of the same authors (Robinson and Durney 1982), where a relatively simplified local system of dynamo equations, including the magnetic buoyancy term, is solved in the lower part of the convection zone where the magnetic field generation is assumed to occur. Arguments in favour of the latter point are given by Hathaway (1982) in the framework of an analytical model of turbulence in rotating convective zones. A relevant point in this paper is the derivation of the turbulent stress tensor, to which the (pseudo)-tensorial forms of α and β are related. The resulting stresses, in the presence of rotation, are expected to be larger at the bottom of the convective zones.

We conclude this review hoping that the comparison of dynamo theory with the new stellar activity data will extend our understanding of the dynamo operation modes, which probably depend on stellar structure, rotation and age.

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DISCUSSION

Mullan: (most of question lost)....dynamo?

Belvedere: You mean the work by Durney and Robinson. This point is not very clear in this work. I am not in agreement with what they propose. They offer a parameterization of these effects in terms of depth of the layer where the interaction between rotation and convection occurs. They are more in favour of a location at the base of the convection zone.

Rosner: If I may make a comment, I would like to add that they use dynamo numbers which come from classical α-ω dynamo theory which assume that field production occurs throughout the convection zone.

Serio: The evidence presented at this meeting suggests that the period of the magnetic cycle is independent of the rotation period of a star. Would you comment on this?

Belvedere: There are some such observational results but I believe that is not very clear. Dynamo action must depend on the rate of rotation. But there is no connection in theoretical work between cycle period and rotation rate except in the work by Robinson and Durney, who found such a relation. I think we must wait to see what happens in the next few years.

Weiss: I should like to make a quick comment on Peter Gilman's results. At the meeting in Zurich he presented results more recent than those which have been published. He has got cyclic behaviour with his dynamo model giving dynamo waves. Unfortunately they progress from equator to poles. Nevertheless they are far more like stellar dynamos than anything that model has hitherto produced. Another point about his models is that as the dynamo number is increased differential rotation is suppressed to the extent that an entirely different mode of dynamo action occurs. He believes that this is a good explanation for the change in the pattern of magnetic activity in more rapidly rotating stars. If I may add my own opinion to that, I believe that this is the best explanation of that effect which we have at the moment, despite my attachment to work in which I was involved.

Linsky: I would like to express a note of caution concerning comparison between dynamo calculation and observed X-ray emission. That is that there are a great many steps between the generation of magnetic field by the dynamo and X-ray emission. The magnetic field has to make it to the surface, it has to be thermalized, etc. So whether the magnetic field is in open or in closed structures may make a world of difference in terms of the observed X-ray emission.

Belvedere: Yes, you are right. However, we have to proceed step-by-step with both new theory and new observations. As Dr. Weiss has pointed out Gilman's new results are not a matter of observations. Nevetheless new theoretical directions are suggested by new observational data.

Paternò: Perhaps I can comment on the relationship between ω and rotational period. The linear theory for a marginally critical dynamo provides for having the diffusion time equal to the dynamo wave period. So since the dynamo wave period contains a measure of differential rotation and since the model of differential rotation indicates $\delta\omega$ is proportional to ω, I can suppose that larger rotation rates will produce shorter cycle periods. The dependence should be $\propto \omega^{\frac{1}{2}}$.

Belvedere: This is what I said. The problem is different however. This is an evaluation which results in the particular context of the Parker dynamo wave. We can obtain other relationship also equating amplification times of rise with other things but the length of the cycle as a function of spectral type does depend on the basic assumption you make about the physics of the convection-rotation interaction.

Venugopal: What is your estimate of the thickness of the shell in which the dynamo is working?

Belvedere: This depends on the assumption made. Normally it is a fraction of the scale height of the base of the convection zone. Whereas previously people believed it was of the order of a pressure scale height in this same region.

Rosner: Perhaps I could point out here that the first person to carry out calculations of flux stability at the base of this zone was Acheson.

Belvedere: Yes, I quoted this in the references to my review.

Rosner: It is interesting that the calculations of the Dutch group (van Ballegooijen et al) assume that there are already flux tubes at the base. Acheson, however, assumed the field was initially uniform and posed the question how does one form flux tubes? A number of other people have recently carried out similar calculations viz. Jurgen Schmitt at Harvard and Nigel Weiss and his students.

Belvedere: You mean for the influence of rotation on the stability of flux tube concentration.

Rosner: Yes.