5. STELLAR ACTIVITY : ROTATION AND MAGNETIC FIELDS

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STELLAR DYNAMO CHARACTERISTICS

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ABSTRACT. Recent discoveries have shown that magnetic activity is typical of cool stars with deep convective zones and magnetic cycles are found in slowly rotating stars like the sun. The current state of hydromagnetic dynamo theory is reviewed, and simplified models are used in an attempt to isolate the dominant nonlinear processes in stellar dynamos.

1. INTRODUCTION

It is just ten years since Olin Wilson's observations of activity cycles in stars were presented at an IAU Symposium in Prague. In that interval a new link between solar and stellar physics has developed. This solar-stellar connection relates magnetic activity in the sun, where detailed spatial structures can be resolved, to that in other late-type stars, where the effects of changing the rotation rate, or the depth of the convection zone, can be discovered. The results of this synthesis are of interest to a wide range of astronomers, as shown by the number of Commissions that have sponsored this Discussion.

The two requirements for dynamo action are rotation and the presence of a deep convective zone. Hence we are concerned with stars of spectral type mid-F or later, which are relatively slow rotators. As we shall see, the most active stars are those that rotate most rapidly; in particular, starspots and flares occur on RS CVn stars (which are close binaries that have evolved off the main sequence) and BY Dra variables (which are rapidly rotating dMe stars). Moreover, we can follow the evolution of main sequence stars as they age, spin down and become magnetically less active. All these properties are reviewed by Baliunas & Vaughan (1985).

In what follows I shall first summarize the observations and then survey the present state of dynamo theory as applied to stars. Finally, I shall indicate how simplified dynamo models can be used to isolate those nonlinear processes that are consistent with the observations. I shall also try to distinguish between what we know, what we don't know and what we can plausibly conjecture.

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2. THE SOLAR-STELLAR CONNECTION

The principal features of the solar cycle are well known. Magnetic activity, as measured, for instance, by a sunspot number, varies aperiodically with a well-defined mean period of about 11 years. At the beginning of each cycle sunspots appear at moderate latitudes and the zones of activity migrate like waves towards the equator, where they disappear as the next cycle begins. The magnetic fields associated with sunspot pairs are predominantly azimuthal, with opposite directions in the two hemispheres, and these directions reverse after each cycle. Hence the magnetic cycle has a period of 22 years. Magnetic activity is also modulated on a longer time scale: for an interval of 70 years in the 17th century sunspots almost disappeared (Spörer 1889; Eddy 1976) and earlier grand minima can be detected from anomalies in ^{14}C dating (Stuiver & Quay 1980). Apparently the amplitude of the activity cycle has been modulated irregularly, for at least the last 7000 years, with successive grand minima several centuries apart.

Stellar magnetic fields can be detected by the Zeeman broadening of spectral lines (Robinson et al. 1980; Marcy 1984; Gray 1984) which implies that kilogauss fields may cover about half the surface of an active star, with flux emerging in many isolated patches (Borra et al. 1984). By analogy with the sun we might expect a similar amount of flux in spots, which scarcely contribute to the average profile of a line. Starspots do, however, lead to variations in luminosity, which can be used to determine the rotation rates of stars. Other indirect evidence for magnetic activity comes from coronal X-ray emission, caused by magnetic heating and correlated with rotation (Vaiana et al. 1981; Pallavicini et al. 1981), and from X-ray and radio observations of flares in active stars.

Most of our information on stellar activity derives from measurements of chromospheric Ca^+ H and K emission (known to be correlated with magnetic fields on the sun) at Mt Wilson . Observations of about 200 stars in the solar neighbourhood show that magnetic activity declines with age and that the sun is relatively feeble (Vaughan & Preston 1980; Soderblom 1985). Ca^+ emission is modulated as the star rotates and the rotation period can therefore be determined (Vaughan et al. 1981; Noyes et al. 1984a). Indeed, there is also evidence of differential rotation (Baliunas et al. 1985). For a star of given mass, magnetic activity increases with increasing angular velocity; moreover, cyclic activity is apparent in a number of relatively slow rotators, like the sun (Wilson 1978; Noyes et al. 1984b; Baliunas & Vaughan 1985).

From all these results it appears that magnetic activity in a main sequence star is controlled by its mass, composition and rotation rate. We can distinguish different types of behaviour in F stars (with shallow convective zones), in G and K stars, in active dMe stars and in fully convective late M stars. Observations of G stars in α Per (Stauffer et al. 1985), the Pleiades (Stauffer et al. 1985) and the Hyades (Lockwood et al. 1984) allow us to describe the rotational and magnetic history of a star of solar mass (Rosner & Weiss 1985). It arrives on the main sequence with a rotation period, P_{rot} , of about

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0.5d and is extremely active; within 30 million years magnetic braking increases P_{rot} to 3d but thereafter the star evolves more gradually, losing angular momentum and becoming less active. For $P_{rot} \gtrsim 20d$ activity is cyclic and the cycle period apparently increases as the star spins down (Noyes et al. 1984b).

3. THE CURRENT STATE OF DYNAMO THEORY

The task for theoreticians is to explain how stellar magnetic fields are generated, to show how magnetic activity depends on the rotation rate and then to describe the evolution of a star as it spins down through magnetic braking. Despite claims that magnetic cycles are caused by Alfvén waves or torsional oscillations, there is no viable alternative to a dynamo (Cowling 1981). In what follows I shall confine myself to dynamo theory, as applied to stars like the sun. The basic concepts are well-known: differential rotation creates toroidal fields from poloidal fields, while cyclonic eddies regenerate poloidal flux from the toroidal field (e.g. Parker 1979; Zel'dovich et al. 1983; Weiss 1983; Schüssler 1983). The latter process can be described by a parameter $\alpha = -1/3\tau_c H$, which depends on the helicity $H = \langle \underset{\sim}{u}.\mathrm{curl}\, \underset{\sim}{u} \rangle$, where $\underset{\sim}{u}$ is the local velocity and τ_c is a characteristic convective turnover time.

The hydrodynamics of the convection zone has been clarified through numerical simulations using the Boussinesq (Gilman 1979) and anelastic (Glatzmaier 1985a) approximations. These computations predict that the angular velocity, Ω, decreases inwards, as indicated by frequency splitting of 5 minute oscillations (Duvall et al. 1984).

The response of the magnetic field, $\underset{\sim}{B}$, to the velocity is governed by the induction equation

$$\frac{\partial \underset{\sim}{B}}{\partial t} = \mathrm{curl}\ (\underset{\sim}{u} \times \underset{\sim}{B}) + \eta \nabla^2 \underset{\sim}{B} \ , \qquad (1)$$

where η is the (turbulent) magnetic diffusivity. Numerical experiments, with convection in a rotating fluid contained between two concentric spheres, have shown that the dynamo process works (Gilman 1983; Glatzmaier 1985a): the field oscillates but dynamo waves progress towards the pole instead of towards the equator. Most dynamo calculations are concerned with mean field (or $\alpha\Omega$) dynamos. In these models the azimuthally averaged field is split into poloidal and toroidal parts:

$$\underset{\sim}{B} = \underset{\sim}{B}_p + \underset{\sim}{B}_T \ , \quad \underset{\sim}{B}_p = \mathrm{curl}\ (A\hat{\underset{\sim}{\phi}}) \ , \quad \underset{\sim}{B}_T = B_\phi \hat{\underset{\sim}{\phi}} \ , \qquad (2)$$

where $\hat{\phi}$ is a unit vector in the azimuthal direction. Then, from (1) and (2),

$$\frac{\partial A}{\partial t} = \alpha B_\phi + \eta \left(\nabla^2 - \frac{1}{r^2 \sin^2\theta}\right) A \ , \qquad (3)$$

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$$\frac{\partial B_\phi}{\partial t} = r\sin\theta\ \underset{\sim}{B}_p.\nabla\Omega + \eta(\nabla^2 - \frac{1}{r^2\sin^2\theta})\ B_\phi\ , \tag{4}$$

referred to spherical polar co-ordinates (r,θ,ϕ). The poloidal field is regenerated owing to the effects of helicity (represented by the parameter α), while toroidal fields are produced by differential rotation. For a given geometry, the system (3) and (4) depends on a single stability parameter, the dynamo number $D = \alpha\Omega' L^4/\eta^2$, where L is a characteristic length scale and Ω' a measure of the angular velocity gradient. The trivial solution $\underset{\sim}{B} = 0$ undergoes an oscillatory (Hopf) bifurcation when $D = D_{crit}$ and is unstable for $D > D_{crit}$. Solutions to the linear (kinematic) problem then give dynamo waves, which propagate towards the equator if $\alpha\Omega' < 0$ in the northern hemisphere. Now helicity results from the expansion of rising gas in a stratified rotating atmosphere, so $\alpha > 0$ in the northern hemisphere, and equatorward propagation then requires that Ω increases inwards. Once again, the process works but the details are wrong.

Where then is the dynamo? A number of arguments point towards the existence of a magnetic layer just below the base of the convective zone (e.g. Spiegel & Weiss 1980; van Ballegooijen 1982) where $\partial\Omega/\partial r$ remains positive but the helicity reverses sign (Glatzmaier 1985b; Rosner & Weiss 1985). Instabilities driven by magnetic buoyancy disrupt this layer and bring stitches of magnetic flux to the surface, where it erupts in active regions (Parker 1979; Schmitt & Rosner 1983; Hughes 1985a,b). A shell dynamo of this type can only operate if the convection zone is neither too shallow nor too deep and it is significant that F stars, with shallow convection zones, and late M stars, which are almost fully convective, seem to show different patterns of behaviour (Giampapa 1983; Giampapa & Rosner 1984).

To go further we must study nonlinear dynamos. We expect that the degree of magnetic activity should depend on the dynamo number D. Now the helicity $H \propto \Omega L/\tau_c$, so that $\alpha \propto \Omega L$, while $\Omega' \sim \Omega/L$ and $\eta \sim L^2/\tau_c$; hence $D \sim \sigma^2$, where the inverse Rossby number $\sigma = \Omega\tau_c$. Noyes et al. (1984a) find that chromospheric activity is apparently a function of σ only, which argues for the presence of a dynamo. Magnetic activity is limited by nonlinear effects, produced by the action of the magnetic field on the motion. There are various possibilities: the Lorentz force may quench the α-effect or suppress differential rotation; or it may generate fluctuations in angular velocity (torsional waves) with twice the frequency of the magnetic cycle, since $\underset{\sim}{j} \times \underset{\sim}{B}$ is quadratic in $\underset{\sim}{B}$. There is some evidence that solar differential rotation varies during the activity cycle (Gilman & Howard 1984; Snodgrass & Howard 1985), and observations of torsional waves are consistent with predictions based on dynamo models (LaBonte & Howard 1982; Schüssler 1981; Yoshimura 1981).

Nonlinear dynamo models fall into three classes. First, there are direct simulations, like those of Gilman (1983) and Glatzmaier (1985a). Next come parametrized models based on mean field electrodynamics, with suitably chosen nonlinear cut-offs (e.g. Ivanova & Ruzmaikin 1977; Yoshimura 1978). Finally, there are highly simplified and truncated models which allow us to explore different qualitative effects and to see whether they are compatible with observations (Zel'dovich et al. 1983; Ruzmaikin 1984).

4. NONLINEAR DYNAMO WAVES

In this section I shall discuss a crude nonlinear dynamo model that reproduces some essential features of stellar magnetic cycles. We suppose that dynamo action is confined to a thin spherical shell, which can be "flattened out" by adopting local cartesian co-ordinates with the z-axis in the radial direction and the x-axis pointing northwards. Then we set $\underset{\sim}{u} = (0,v(z),0)$ and $\underset{\sim}{B} = (0,\tilde{B},\partial\tilde{A}/\partial x)$, where

$$\tilde{A}(x,t) = A(t)\exp(ikx) \ , \quad \tilde{B}(x,t) = B(t)\exp(ikx) \ , \tag{5}$$

so that the poloidal and toroidal fields are described by the complex amplitudes A and B. The linear dynamo equations (3) and (4) can then be reduced to the dimensionless system

$$\dot{A} = 2DB - A \ , \tag{6}$$

$$\dot{B} = iA - B \ , \tag{7}$$

which describes plane dynamo waves whose behaviour depends on the dynamo number $D = \alpha v'/(2\eta^2k^3)$. There is a Hopf bifurcation at $D = 1$ and for $D > 1$ equations (6) and (7) yield exponentially growing dynamo waves, propagating in the direction of decreasing x (Parker 1979).

Nonlinear dynamo waves can be represented by adding terms that describe different physical effects (Weiss et al. 1984; Jones 1984; Weiss 1985). For instance, the α-effect in (6) may be quenched as the magnetic field increases, or the Ω-effect in (7) may be similarly reduced. Enhanced dissipation through magnetic buoyancy can be modelled by including a loss term proportional to $|B|^2B$ in (7) and fluctuations in angular velocity can be described with an augmented system of equations. The modified systems still possess periodic solutions and we can discover how the amplitude and period of the cycles depend on the dynamo number D. Comparison with observations may then guide us towards the physical processes that limit dynamo action in a star.

Consider first the amplitude of the cycle: observations show that magnetic activity increases with increasing σ (Noyes et al. 1984a) so we expect $|B|$ to increase with increasing D. This is the case for most of the mechanisms listed above but if the principal nonlinear effect is a reduction of differential rotation by the Lorentz force the model system has oscillatory solutions with $|B|$ decreasing monotonically for $D > 2$ (Weiss et al. 1984). Physically, nonlinear quenching of differential rotation leads to fields that are predominantly poloidal and unlikely to correspond to activity of the type observed in the sun. Hence this mechanism can be eliminated.

The variation of the cycle period, P_{cyc}, with rotation rate offers

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a better means of discriminating between different processes. Noyes et al. (1984b) considered a sample of 13 slowly rotating stars (including the sun) that showed cyclic activity with periods of 7-13 years. (The sample is limited by the available data and the selection has been criticized by Baliunas & Vaughan (1985).) This sample shows that P_{cyc} depends both on Ω and on the spectral type, and suggests that P_{cyc} decreases with increasing Ω and for later spectral types; for a star of fixed mass the data are consistent with a power law of the form $P_{cyc} \propto P_{rot}^n$ with $n = 1.25 \pm 0.5$. Linear solutions of (6) and (7) have frequencies proportional to $D^{\frac{1}{2}}$, which corresponds to $n = 1$, though this result is sensitive to z-dependent spatial structure (Zel'dovich et al. 1983; Kleeorin et al. 1983). If we suppose that the nonlinear solutions have essentially the same spatial structure as the linear solutions, then nonlinear quenching of the α-effect (or of differential rotation) leads to cycle periods that are independent of D. Such a result seems incompatible with the observations. Thus we should look for limitation owing to losses through magnetic buoyancy or fluctuations in differential rotation (Noyes et al. 1984b).

The truncated models also shed light on the nature of grand minima and the aperiodicity of the solar cycle. Recent advances in the study of dynamical systems have demonstrated that deterministic chaos is common in nonlinear systems and that the behaviour of the solar cycle can be explained without invoking stochastic processes (Weiss et al. 1984; Jones 1984; Weiss 1985). In certain doubly-periodic systems the amplitude of oscillations is regularly modulated; the corresponding trajectories in phase space wind around the surface of a 2-torus shaped like a pinecone with a hole along its axis (Langford 1983). When the torus is destroyed trajectories may become chaotic, and a sixth order truncated model yields solutions that mimic the behaviour of the solar cycle. Moreover, Stuiver (1980) found that the envelope of activity showed a recurrent pattern near grand minima that is consistent with the presence of a vestigial "ghost attractor" resembling the 2-torus described above.

5. SUMMARY

The procedure followed in the previous section illustrates how simple models can be used to isolate the dominant physical processes in stellar dynamos. Clearly there is a need for more reliable and more elaborate calculations but our limited understanding makes it difficult to formulate such problems. First of all, we need more detailed observations of stellar magnetic activity, extended over a longer interval of time, in order to constrain our models. Secondly, we must improve the theory. This requires a phenomenological description of stellar dynamos that is qualitatively correct, followed by computation of more sophisticated models. When we have an adequate theory of cyclic behaviour in stars like the sun, we can go on to study more active, rapidly rotating G and K stars and to explore the effects of shallower or deeper convective zones. Finally, we can combine these results with a quantitative theory of magnetic braking by a stellar

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wind in order to describe the magnetic evolution of lower main sequence stars.

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