Solar magnetic activity is observed on a wide range of scales, from the intriguingly regular and well-ordered large-scale field, to much more complex small-scale structures. In this article we shall primarily be concerned with the large-scale features, and the associated large-scale dynamo that is responsible for their occurrence. The small-scale magnetic field at the photosphere may also owe its existence to a dynamo mechanism; however, dynamo action of this form is highly localized and is very different in character from the large-scale dynamo, and so the two issues are largely addressed separately. More details about small-scale dynamo action can be found in the review by Cattaneo and Hughes (2001), while further information about photospheric magnetic features and sunspots can be found elsewhere in this issue (Tobias and Weiss 4.28, Proctor 4.14).

Sunspots are the most obvious large-scale magnetic features at the photosphere; their intense magnetic field means that they appear as dark regions on the solar surface (see figure 1 of Tobias and Weiss, page 4.28, this issue). Sunspots have been studied for centuries and the regular pattern of their occurrence has fascinated observers. Figure 1 shows a butterfly diagram, which plots the latitudinal position at which sunspots appear, as a function of time. Sunspots are confined to low latitudes and regions of sunspot emergence, which start each cycle at latitudes of around 30°, appear to migrate towards the equator over a period of approximately 11 years – this is known as the Schwabe cycle. Sunspots often appear in pairs and are probably the result of a deep-seated band of azimuthal magnetic field becoming buoyantly unstable and piercing the solar surface, generating two regions of opposite polarity where it emerges. The line segment joining the centres of these two regions tends to be slightly tilted with respect to the east–west direction, and the spots follow Hale’s law, which states that leading spots of pairs in the northern hemisphere tend to have the same polarity, with the reverse polarity for leading spots in the southern hemisphere. After about 11 years the sunspot field reverses, so that the opposite pattern of polarities is observed in each hemisphere. The sunspot field is one part of the overall large-scale solar field; the other is the polar field, which also reverses every 11 years,
The sunspot number (a measure of magnetic activity) over the past four centuries. Clearly marked is the absence of sunspots during the late 17th century—a period known as the Maunder Minimum. Even though there was little surface activity, it is believed that cyclic dynamo action persisted during this period, but the field strength fluctuated below the amplitude required for the production of active regions. Evidence for this idea comes from analyses of $^{10}$Be and $^{14}$C—terrestrial isotopes produced in the atmosphere by interactions with the solar wind—which abundances are anti-correlated with solar magnetic activity. The cycles in $^{10}$Be abundance persisted throughout the Maunder Minimum (shaded area in figure 3a), while the $^{14}$C data indicate that such periods of low activity are a characteristic feature of solar magnetic activity, with a grand minimum occurring (on average) about every 200 years.

The search for the solar dynamo

The large-scale solar magnetic activity is most likely to arise from the operation of a dynamo. The idea of a hydromagnetic dynamo is based upon the concept that the motion of an electrically conducting fluid across a magnetic field will induce a current, which (in turn) will generate more magnetic field. This regeneration process works against the continual drain of magnetic energy owing to the resistance of the fluid; the total magnetic energy will be amplified—i.e. dynamo action will take place—if the inductive process is more efficient than magnetic diffusion. Because the complex physical processes within the solar dynamo can be described by a set of nonlinear partial differential equations, it is possible to attempt to investigate aspects of the global dynamo process through large-scale numerical simulations. However, although this has been successfully carried out for the Earth’s dynamo (see, for example, Glatzmaier and Roberts 1995 and references therein concerning early attempts in the solar case), the vast range of scales and extreme parameter regimes required in the solar context mean that it will be a long time before we can model the whole solar dynamo computationally. Even if computational resources allowed us to do this, the results from such simulations may be difficult to interpret without a good prior understanding of the key physical processes. As such, the majority of the work on the solar dynamo has been geared towards understanding the crucial physical processes involved by investigating simpler, more idealized models.

The dynamo problem is often simplified by neglecting the nonlinear feedback of the magnetic field upon the flow, via the Lorentz force. It is then “simply” a case of finding a prescribed velocity field that is capable of amplifying a seed magnetic field. This is known as the kinematic problem. However, it soon became apparent that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward. In 1934 Cowling established that even the kinematic problem is far from straightforward.
Mean-field electrodynamics

Building upon the pioneering ideas of Parker (1955), Steenbeck, Krause and Rädler (Steenbeck et al. 1966) formulated a mathematical theory to describe the way in which small-scale effects play a crucial role in the generation of large-scale magnetic fields (see also Moffatt 1978). The starting point is the induction equation

$$\frac{\partial B}{\partial t} = \nabla \times (U \times B) + \eta \nabla^2 B$$

(1)

that governs the evolution of a magnetic field $B$ within an electrically conducting plasma of magnetic diffusivity $\eta$, moving with a velocity $U$. Progress is made by assuming that we can decompose the magnetic and velocity fields into a mean part ($B_0$, $U_0$, say) varying on a length-scale $L_0$, and a randomly fluctuating part ($b$, $u$, say) varying on a much smaller length-scale, $\ll L_0$. Defining averages, denoted by $\langle \cdot \rangle$, over an intermediate length-scale, we have

$$B = B_0 + b, \quad U = U_0 + u$$

(2)

where $\langle b \rangle = 0$. Substituting this decomposition into the induction equation (1) and averaging, we obtain an equation for the mean field

$$\frac{\partial B_0}{\partial t} = \nabla \times (U_0 \times B_0) + \nabla \times \epsilon \nabla^2 B_0$$

(3)

where $\epsilon = \langle u \times b \rangle$ is the all-important new quantity, and is known as the mean electromotive force.

In order to proceed we must be able to express $\epsilon$ in terms of the mean quantities alone. With this in mind we note that the equation for the fluctuating field, $b$, may be obtained by subtracting (3) from (1), yielding a linear relationship between $B_0$ and $b$. Hence it is reasonable to assume an expression for $\epsilon$ of the form

$$\epsilon = \alpha \epsilon_0 B_0 + \beta_\alpha \frac{\partial B_0}{\partial x_\alpha}$$

(4)

where the tensors $\alpha_\epsilon$ and $\beta_\alpha$ depend upon the fluctuating velocity and the diffusivity, and all higher order derivatives in (4) are negligible under the assumption that $L$ is sufficiently large. In order to understand the effects of the electromotive term we consider the simplest case of homogeneous isotropic turbulence, so that $\alpha_\epsilon$ and $\beta_\alpha$ are isotropic tensors and can be written as

$$\alpha_\epsilon = \alpha_0 \delta_\epsilon, \quad \beta_\alpha = \beta_0 \delta_\alpha$$

(5)

In this case, equation (3) becomes

$$\frac{\partial B_0}{\partial t} = \nabla \times (U_0 \times B_0) + \nabla \times (\alpha_0 B_0) + \eta \nabla^2 B_0$$

(6)

Thus we see that $\beta$ represents a turbulent enhancement of the magnetic diffusivity, while $\alpha$ represents the ability of the underlying turbulence to act as a source for the mean field. In order for the $\alpha$-effect to be non-zero, it follows that the turbulent velocity field must lack reflectional symmetry - a notion that is often associated with fluid motion within rotating bodies.

The idea of the kinematic dynamo problem is to solve equation (6) for $B_0$, given a prescribed velocity $U_0$ and a chosen diffusivity and $\alpha$-effect. Any solutions of this linear problem are either exponentially growing or exponentially decaying. In the (more complicated) dynamic problem, in which we would solve equation (6) together with an equation for the fluid flow, the feedback effects of the magnetic field on the fluid would limit the amplitude of the generated field. An attempt at including such effects into the kinematic model has been made by making the dynamo coefficients dependent on the magnetic field strength. Algebraic, parameterized expressions are often used as an ad hoc representation of the tendency of strong magnetic fields to resist the $\alpha$-effect:

$$\alpha = \frac{\alpha_0}{1 + \xi B_0^2}$$

(7)

where $\alpha_0$ is the value in the absence of a magnetic field, and $\xi$ is a parameter that determines the strength of the quenching (see the discussion in the main text). Similar expressions are often used to represent the quenching of $\beta$ by strong magnetic fields.

long time it was feared that there was no hope of making the dynamo work.

A better understanding of the kinematic dynamo problem comes from describing the magnetic field in terms of its poloidal and toroidal components. For an axisymmetric magnetic field, the poloidal component of the magnetic field lies in the meridional plane, while the toroidal component is purely azimuthal. Kinematic dynamo action is then possible if we can find a velocity field that is capable of regenerating both the toroidal and the poloidal components of the magnetic field. Historically, the first key ingredient of such a velocity field to be identified was the observed differential rotation at the solar surface. Assuming that the plasma is highly conducting, this is known to stretch out an initially poloidal field to provide a toroidal component (figure 4a). This process became known as the $\omega$-effect. Having found this mechanism, the next step was to identify a physical process that can complete the cycle by regenerating the poloidal field.

The second part of the cycle is much more complex. In a ground-breaking paper in 1955, Parker suggested that small-scale helical motions (resulting from convection in a rotating body) could twist segments of a toroidal field into loops of field in the meridional plane (figure 4b). The net effect of many of these (non-axisymmetric) small-scale events would then give rise to a large-scale meridional field, thereby completing the dynamo cycle. A decade later a mathematical formulation of this argument, known as mean-field electrodynamics (see box “Mean-field electrodynamics”), was developed by Steenbeck, Krause and Rädler (1966). This theory more formally describes the way in which small-scale magnetic and velocity fluctuations combine in order to generate a large-scale poloidal magnetic field. This mechanism has subsequently become known as the $\alpha$-effect.

Having established the physical processes that enable the regeneration of magnetic field, we now need to relate these ideas to the Sun, and determine where the dynamo process is actually taking place. Given that Parker’s $\alpha$-effect results from convective motions, and that the Sun is rotating differentially at the surface, the solar convection zone would appear to be a viable location for the dynamo. Many early theoretical models, where dynamo action was distributed throughout the convection zone, were successful in reproducing several of the main qualitative features of the large-scale solar magnetic field (see, for example, Stix 1976). This type of dynamo model is, however, not without its problems. In particular, it is difficult for a dynamo that operates solely within the convection zone to produce the strong magnetic fields that are found within active regions. Regions of concentrated magnetic flux tend to be less dense than their surroundings, and will therefore rise buoyantly up to the photosphere on a time-scale that is short when compared to the solar cycle period (Parker 1979). It is therefore doubtful that magnetic flux could be held within the convection zone long enough to be amplified to the required field strength.

Turbulent motions will also tend to expel magnetic flux from the convection zone. Like magnetic buoyancy, this will inhibit the operation of any dynamo that is acting solely within this region. However, as a result of these convective motions, magnetic flux will be concentrated into a thin layer in the convectively stable region just below the base of the convection zone (Spiegel and Weiss 1980). This suggests an alternative idea for the solar dynamo, namely that the dynamo may be located in the region around the base of the solar convection zone (Galloway and Weiss 1981). Magnetic flux within this stably stratified region will not be as susceptible to magnetic buoyancy instabilities; therefore, if this is where the bulk of the flux is stored, stronger
fields may be able to develop before they become buoyantly unstable. It should also be stressed that a further problem associated with strong magnetic fields is that they are likely to resist deformation by convective upwellings, which will reduce the efficiency of the $\alpha$-effect and hamper the generation of magnetic field. However, this (so-called) $\alpha$-quenching problem is reduced if the bulk of the magnetic flux is stored beneath the convection zone, away from where the $\alpha$-effect is presumably operating.

The interface dynamo

The idea that the solar dynamo may be operating around the base of the convection zone has been further reinforced by helioseismological findings regarding the distribution of differential rotation within the Sun (for further details see the article in this issue by Thompson 4.21; figure 4 of that article shows the inferred differential rotation profile). Many of these helioseismological findings were surprising and hold great significance for solar dynamo theory. In particular, helioseismology resolved the conflict between early theories of differential rotation, that predicted constant angular velocity along cylindrical surfaces aligned with the rotation axis and decreasing with depth, and early dynamo models that required the angular velocity to increase with depth. In fact, contours of constant angular velocity lie roughly on lines of constant latitude throughout the convection zone. The layer of pronounced radial shear around the base of the convection zone, commonly referred to as the tachocline (Spiegel and Zahn 1992), is also of particular interest to dynamo theorists. The tachocline acts as a transition region between the (relatively weakly) differentially rotating convection zone and the almost rigidly rotating region below, and appears to be the site of the strongest differential rotation within the Sun.

Following this discovery, and with the aim of circumventing some of the problems associated with the implied presence of a strong magnetic field at the base of the convection zone, Parker (1993) formulated a new model known as the interface dynamo. In this model, the two generation effects are spatially separated: the $\alpha$-effect operates in the turbulent convective layer and the $\omega$-effect in the shear layer below.

An essential part of the dynamo’s success is the diffusive transport of flux between the two regions. Since turbulence enhances the effects of diffusion, the diffusion within the tachocline region is assumed to be significantly smaller than that within the convection zone proper. Parker’s simple model is not only effective in generating magnetic fields, but also addresses the $\alpha$-quenching issue by allowing strong toroidal fields to be generated in the tachocline, away from the region where the $\alpha$-effect is operating (see also Charbonneau and MacGregor 1996).

The interface dynamo model has since grown in popularity, and evolved in a manner that not only makes use of a deeper understanding of the main physical mechanisms ($\alpha$, $\omega$ and diffusion), but also incorporates additional important effects. In particular, it has long been known that the magnetic buoyancy instability is responsible for the transport of toroidal field from the tachocline to the convection zone, and it is now believed that magnetic pumping (the downwards expulsion of flux by turbulent convection) is an effective mechanism for returning poloidal field to the tachocline. Recent numerical simulations of turbulent, penetrative, compressible convection by Tobias et al. (2001), in which an unstable region (the convection zone) overlies a stable overshoot region, have examined the fate of an initially horizontal layer of magnetic field inserted into the unstable region. As shown in figure 5, the strong vortical down-
flows are efficient at wrapping up the magnetic field and dragging it downwards with them as they penetrate the stable layer. Furthermore, the pounding of the overshooting convection tends to confine the flux there, offsetting the effects of magnetic buoyancy. The effects of incorporating the pumping mechanism into a model of the interface dynamo have also recently been investigated, revealing that there can exist a preferred magnitude of pumping for which the dynamo is most efficient (Mason et al. 2004, in preparation).

Our increased understanding of the processes operating in the solar dynamo has led us to the scenario illustrated in figure 6. Building upon Parker’s original model, it is believed that the toroidal field is generated via the shearing of the poloidal field in the tachocline. The newly generated toroidal field is then susceptible to the magnetic buoyancy instability and rises into the convection zone, where the poloidal field is regenerated via the α-effect. The convection zone acts as a filter, allowing only the strongest field to continue to rise to the surface and appear as active regions. The weaker field is churned up by the convection, and is recycled, being transported back to the tachocline by the turbulent pumping, where the cycle repeats. In current solar dynamo research, each individual process that occurs in the dynamo, and the interaction of these processes, is actively being investigated, generating many unresolved issues and areas of debate (see Osendarp in 2003 for a thorough review).

**Current areas of debate**

The site of strongest differential rotation, and hence the location of the ω-effect, is now well established. Dynamo theorists have moved away from the surface as the site for the generation of the toroidal field and, on the basis of the recent helioseismology results, have now pinned down the ω-effect to the tachocline at the base of the convection zone. In many recent dynamo models, differential rotation within the Sun has been represented by choosing, as an imposed velocity field, an analytic fit to the solar differential rotation profile. An example of such an analytic fit, similar to that used by (for example) Dikpati et al. (2004), is shown in figure 7. While the details of the ω-effect are now relatively well known, many aspects of the α-effect remain subject to debate.

As discussed above, Parker’s suggestion was that the poloidal field is regenerated by the twisting action of cyclonic convection upon an initially toroidal field. It is generally accepted that this mechanism will be suppressed as the magnetic field increases in strength; however, the threshold strength of the field at which this quenching prevents regeneration is less clear. Recent numerical simulations (Cattaneo and Hughes 1996) suggest that the quenching may be severe even for weak fields, with ω in equation (7) – being “Mean-field electrodynamics” box – being comparable to $R_{\alpha}$ (a dimensionless measure of the efficiency of advective effects relative to diffusion, which is very large in the convection zone). Thus, with such extreme quenching, it is difficult to generate fields of the observed strength, and this problem has led to the search for different physical mechanisms that could regenerate poloidal field.

A model that has recently regained popularity is the Babcock–Leighton dynamo (Babcock 1961, Leighton 1969). In these models it is the decay of tilted bipolar active regions that produces poloidal flux, so that the “α-effect” only operates at the solar surface. At the time when only the surface differential rotation was known, these models were very attractive. With the discovery of the tachocline, the models evolved into so-called *flux transport dynamos*, in which the α-effect operates in the tachocline and a meridional circulation is invoked in order to couple the two generation regions. A polewards flow is observed at the solar surface (Hathaway 1996), although it should be noted that the details of any subsurface meridional motions are uncertain. In fact, the effects of compressibility will mean that any equatorwards flow in the vicinity of the tachocline will be relatively weak, which will reduce the efficiency of flux transport in this region. Having said that, because a strong field is required in order for the surface α-effect to operate, the quenching issue described above is not such a problem here. However, this also means that the dynamo cannot operate in times of grand minima and we need another mechanism to account for the persistence of the solar cycle throughout these periods. Additionally, because of the large separation of the two generation regions, the models are much less effective than those in which both the α and ω-effects operate within the same region, or near to one another (Mason et al. 2002). Many of these questions have been addressed in a recent paper by Dikpati et al. (2004), which incorporates an additional deep-seated α-effect that is calculated from the kinetic helicity profile of a global instability caused by the latitudinal differential rotation within the tachocline (see also Dikpati and Gilman 2001). This model is able to reproduce many of the qualitative features of the solar cycle, including the reversals of the polar field. Several other aspects of this model, including the feedback of the magnetic field upon the meridional flow are currently being investigated by Dikpati and Rempel, and their collaborators.

An alternative idea is that the α-effect is confined solely to the region around the tachocline. This would imply that the dynamo can operate efficiently around the base of the convection zone, without a meridional flow (although a surface flow may still be needed in order to produce polar reversals). Various physical mechanisms, besides the helical instability considered by Dikpati and Gilman (2001), could give rise to a tachocline-based α-effect, and one of the most plausible of these centres around the magnetic buoyancy instability. The effect from magnetic buoyancy is easiest to visualize if the large-scale magnetic field in the neighbourhood of the tachocline is assumed to be a collection of many individual flux tubes. Unbundar buoyancy instabilities of these flux tubes will create loops of magnetic field that will tend to twist under the influence of the Coriolis force. This macrodynamic process is (in some sense) analogous to the microdynamic convectively driven α-effect and is therefore assumed to be capable of producing a similar effect (Ferriz-Mas et al. 1994). An alternative (and probably more likely) picture is that the large-scale magnetic field at the base of the convection zone is in the form of a continuous layer. In this case the magnetic buoyancy instability in the presence of rotation can result in unstable waves that can also give rise to an α-like effect (see, for example, Moffatt 1978, Thelen 2000).

This buoyantly driven α-effect differs in several important ways from an α-effect that is driven by turbulent convection. In particular the magnetic buoyancy instability actually requires relatively strong fields in order to operate, so an α-effect that is driven by this mechanism is not subject to the same quenching problems as
the turbulent $\alpha$-effect. Having said that, there is probably still some quenching for very strong fields, where the magnetic buoyancy instability may be so efficient that flux escapes from the tachocline region before it can contribute to the dynamo process. In most mean-field simulations, $\alpha$-quenching is usually represented in a simple parameterized way. The relative importance of different nonlinear quenching mechanisms remains an open question, so parameterized quenching mechanisms are probably best viewed as a convenient way of forcing the dynamo to saturate in the nonlinear regime.

In order to apply the idea of a buoyantly driven $\alpha$-effect to a mean-field solar dynamo model, we need to determine its region of operation within the Sun. This process is not yet well understood and so we have to rely primarily upon physical intuition. The $\alpha$-effect must be concentrated around the base of the convection zone, where the bulk of the magnetic flux is located, but its latitudinal variation is much harder to predict – although it should be antisymmetric about the equator in order to reflect the equatorial antisymmetry of the Coriolis twisting effect. An approach that is commonly used when modelling the solar dynamo is to fix the radial distribution of the $\alpha$-effect and then vary the latitudinal dependence until results are obtained that are consistent with observations. In this way, observational details are used to constrain the $\alpha$-effect.

The natural assumption to make is that the $\alpha$-effect is strongest at high latitudes (due to its dependence upon the Coriolis force). However, when coupled with the strong negative radial shear there within the tachocline, this tends to lead to oscillatory dynamo action only at high latitudes, where active regions are never observed on the Sun. One way to resolve this problem is by somehow suppressing the $\alpha$-effect in this region. Very recently it has emerged that a strong radial shear may inhibit non-axisymmetric instabilities in a magnetic layer (Tobias and Hughes 2004). If the $\alpha$-effect is driven by magnetic buoyancy, this then provides possible justification for prescribing an $\alpha$-effect, in a mean-field model, that is confined to lower latitudes (where the radial shear is weaker).

By restricting the $\alpha$-effect to low latitudes in mean-field dynamo simulations, it is possible to produce results that are in greater agreement with observations. Figure 8 shows contours of the azimuthal component of the dynamo-generated field at the base of the convection zone for a model of this form, in which the nonlinearity is due to a parameterized $\alpha$-quenching mechanism. For this solution, dynamo activity is restricted to low latitudes. Since the radial shear at low latitudes is positive, the equatorwards propagation of magnetic activity is a consequence of the fact that $\alpha$ has been chosen to be negative in the northern hemisphere (Parker 1955). This solution qualitatively matches the pattern of sunspot activity shown in figure 1, although it should be noted that the magnetic cycles overlap more in this simulated solution than the cycles observed on the Sun. Like the sunspot magnetic field, the azimuthal field shown in figure 8 is antisymmetric about the equator. Given that the meridional field is symmetric about the equator, this is consistent with the dynamo having dipolar symmetry, which is actually what is observed on the Sun. It is therefore possible to match closely many of the main qualitative features of the solar magnetic cycle with a mean-field model, provided that the $\alpha$-effect is confined to low latitudes at the base of the convection zone.

Periods like the Maunder Minimum and other time-dependent features suggest that there is more to the solar dynamo than the basic solar cycle. If this modulation is deterministic, then it should be possible to adapt mean-field models so as to produce time-dependent behaviour that resembles the long-term solar magnetic activity. One way to do this is by considering a mean-field model that includes the back-reaction of the azimuthal component of the Lorentz force upon the differential rotation profile (Malkus and Proctor 1975). This involves solving an evolution equation for the velocity perturbation; however, this dynamical nonlinearity is probably more physical than an arbitrarily parameterized $\alpha$-quenching mechanism. By introducing a separation in scales between the magnetic diffusion time and the viscous dissipation time for the fluid, it is possible to produce time-dependent behaviour in such models (Tobias 1997, Moss and Brooke 2000). Figure 9 shows a dynamo solution from a simplified Cartesian model, which exhibits strong amplitude modulation with pronounced “Grand Minimum” phases.

The induced angular velocity perturbation is an interesting aspect of these models. Dynamical variations in the solar differential rotation profile were first detected as a surface pattern of alternating bands of faster and slower than average local rotation, which migrate from mid to low latitudes with an 11-year periodicity (Howard and LaBonte 1980). This 11-year cycle is strikingly similar to the sunspot cycle and is consistent with the idea that these (so-called) torsional oscillations may be magnetically driven. Figure 10 illustrates the oscillatory part of the total velocity perturbation, taken from a mean-field model that incorporates the nonlinear feedback of the magnetic field upon the flow. This oscillatory pattern bears a clear resemblance to the observed torsional oscillations, at least at low latitudes, on the surface of the Sun (the equatorwards migration of the low-latitude branch of the torsional oscillations can be seen in Thompson this issue 4.21 figure 5).

Torsional oscillations raise several other interesting questions regarding the solar dynamo. In the models described above, all the dynamo action and torsional oscillations are primarily confined to low latitudes around the base of the convection zone. Recent observations not only suggest that the strongest oscillations occur at the surface, but also that there may be an additional band of torsional oscillations at high latitudes (Vorontsov 2002, Thompson this issue 4.21). A possible explanation for one of these discrepancies lies in the fact that the solar convection zone is highly stratified (Covas et al. 2004). The very low fluid density at the photosphere will mean that even a relatively small perturbation to the local angular momentum at the surface would be able to produce a large angular velocity perturbation. The existence of a high-latitude branch to the torsional oscillations presents a more interesting problem, since it is difficult to see how such torsional oscillations could be magnetically driven without the presence of strong magnetic fields at high latitudes, where active regions are never observed. If, however, there is weak dynamo action at high latitudes, it is possible to produce a high-latitude branch to the torsional oscillations that is consistent with observations (Bushby 2004, in preparation). This is an interesting open question.
The future

Direct numerical simulations of the solar dynamo are currently not feasible, so much of the recent progress in the subject has relied upon mean-field dynamo theory. Using the mean-field approach, it is possible to reproduce many of the observed features of the solar dynamo in relatively simple numerical models. By imposing a solar-like rotation law, and then choosing an appropriate spatial dependence for the $\alpha$-effect, it is possible to find model solutions that are dipolar, confined to low latitudes and migrate equatorwards during each cycle. Mean-field theory is therefore capable of reproducing observations provided that the parameters of the model are chosen accordingly.

Another successful aspect of mean-field modelling is that it has highlighted key areas for future research. The tachocline is obviously of great importance to the solar dynamo, but is of interest in its own right, with several issues concerning its formation and stability still not fully understood. There are also issues that still need to be resolved concerning the $\alpha$-effect. In particular, there is a need to determine the relative importance of the various physical mechanisms that may be responsible for generating poloidal magnetic field. It seems likely that an $\alpha$-effect that is driven by convection may be quenched by relatively weak magnetic fields. Unless we can overcome this issue, a tachocline-based $\alpha$-effect, driven, for example, by the magnetic buoyancy instability (which is not subject to the same quenching problems), seems to be the most plausible alternative mechanism. Having said that, when applying this idea in a mean-field model, a (buoyancy-driven) tachocline-based $\alpha$-effect must be confined to low latitudes in order to reproduce solar-like behaviour. At present, there is some justification for the suppression at high latitudes, but further work is needed in order to fully assess the interaction of the magnetic buoyancy instability with the strong differential rotation that is found in the tachocline. Finally, it is still unclear which of the various possible nonlinear quenching mechanisms is of primary importance to the solar dynamo. Most basic models rely upon simple parameterized mechanisms, which give an instantaneous quenching effect. The existence of toroidal oscillations is evidence of the fact that dynamical nonlinearities are likely to be very important.

Mean-field theory has enabled significant progress to be made in the theoretical understanding of the solar dynamo, although it is only possible to use this theory to produce a qualitative picture of the dynamo process. However, attempts are being made to predict solar magnetic behaviour using a flux-transport dynamo (see Dikpati et al. 2004). The ability of this model to reproduce many features of the solar cycle has led to the suggestion that by using available observational data for the meridional flow, certain aspects of future solar cycle behaviour might be predicted. It could be argued that attempting to make predictions from any such simplified model is quite ambitious, particularly given the lack of certainty around the sub-surface meridional flow structure. Until solar dynamo theory has evolved beyond the stage where many physical aspects of the problem are only understood in a qualitative sense, it is certainly going to be difficult to make any more quantitative predictions based upon a mean-field model.

Highly illustrative models can be used to describe very simple physical problems or even very complicated aspects of dynamical behaviour. Simplified models of this kind have already enhanced our understanding of the solar dynamo, and there is every reason to suppose that this approach will continue to be a useful one. Although it is not yet possible to investigate the large-scale solar dynamo through direct numerical simulation, it is possible to simulate directly more localized processes, which can then be pieced together to form a more global picture. An example of this is the simulation of small-scale dynamo action by turbulent convection in the solar photosphere (see, for example, Cattaneo and Hughes 2001 and references therein). This is an interesting problem, many aspects of which have yet to be explored.

Finally, it is worth considering to what extent it is possible to extend these ideas to other stars. It may seem likely that dynamos in other solar-type stars can be described in a very similar way; however, it should be stressed that much of this theory has become very specific to the Sun. Dynamos in fully convective stars or very rapidly rotating late-type stars will probably be very different in character from the solar dynamo. Although plausible assumptions can be made in order to construct dynamo models for such stars (see, for example, Bushby 2003), such models are inevitably somewhat speculative. It should be possible to make significant advances in solar dynamo theory over the next few years. Through increased computational power, higher resolution observations, and progress in our theoretical understanding of the dynamo mechanisms, we are likely to move nearer to our goal of understanding how magnetic fields behave in the turbulent Sun.

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References