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Magnetic fields in the Sun's interior: What do we know about them ?

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Abstract. The surface observations of the solar magnetic fields put some constraints on the possible magnetic configurations in the Sun's interior. It is currently believed that the solar magnetic fields are generated by a dynamo process at the interface between the convection zone and the radiative core. Detailed calculations on the buoyant rise of the magnetic flux from the dynamo region suggest that the strong toroidal field there should have a magnitude of about 10^5 G. We also discuss a probable configuration of the poloidal field in the convection zone which is consistent with the surface observations.

Key words: The Sun: magnetic fields — MHD

1. Introduction

The solar surface is full of different types of magnetic features. Can we determine the magnetic configurations in the Sun's interior from the surface magnetic data? This is the question we wish to address in this paper. Since there are rather large gaps in our understanding of the dynamo process which creates the solar magnetic fields, this is not a simple inversion problem. In the last few years, however, a cohesive scenario of interior magnetic fields has been emerging that is consistent with most surface observations and appears promising.

Since the fluid kinetic energy of the convective motions is supposed drive the solar dynamo, it used to be assumed that the dynamo operates in the convection zone. But a dynamo operating in the convection zone would be violently unstable to magnetic buoyancy (Parker 1975). It was therefore suggested that the dynamo operates in the overshoot region at the bottom of the convection zone rather the convection zone itself (Spiegel and Weiss 1980; van Ballegooijen 1982). Some detailed models of a dynamo working in a thin layer have been worked out (Choudhuri 1990) It may be noted that the overshoot layer

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dynamo idea was proposed by the theorists before the first helioseismology results on the Sun's internal differential rotation started coming. The helioseismic indication that there is probably a layer of strong differential rotation at the bottom of the convection zone lends strong support to the theoretical conjecture of the solar dynamo operating in the overshoot layer.

The basic idea behind the solar dynamo is that the toroidal and poloidal components of the magnetic field feed each other through fluid motions (see Parker 1979). In the next two sections, we present discussions on what we know about the natures of these two components in the Sun's interior.

2. On the toroidal component

Because of the strong differential rotation at the bottom of the convection zone, the toroidal magnetic field there is supposed to be much stronger than the poloidal magnetic field. We still do not know if the toroidal field in the dynamo layer exists in the form of isolated flux tubes or fills up the whole volume. If we assume that parts of the toroidal field break out of the stable dynamo layer in the form of flux tubes, then we can model the emergence of active regions satisfactorily.

Classical dynamo models suggest that the magnetic energy should be in equipartition with the fluid kinetic energy. Such arguments predict toroidal fields not stronger than about 10^4 G. Choudhuri and Gilman (1987) found that flux rings with such fields starting from the bottom of the convection zone would be deflected by the Coriolis force to move parallel to the Sun's rotation axis and emerge at latitudes higher than where sunspots are seen. Choudhuri (1989) studied the evolution of a non-axisymmetric flux ring of which parts remain anchored in the stable dynamo layer and only parts rise through the convection zone. Even these rising parts were found to move parallel to the rotation axis if the initial magnetic field was taken to be 10^4 G. Only when the initial field was taken to be as strong as 10^5 G, the magnetic buoyancy was sufficiently strong to overpower the Coriolis force and flux tubes starting from low latitudes emerged at low latitudes. Later D'Silva and Choudhuri (1993) found that the observed tilts of the bipolar magnetic regions on the solar surface can be modelled correctly only if we assume the initial magnetic field in the flux tube to be in a narrow range around 10^5 G.

Calculations by others (Fan et al. 1993; Caligari et al. 1995) have confirmed these findings. It may be noted that there are some mechanisms for suppressing the Coriolis force even for 10^4 G flux tubes (Choudhuri and D'Silva 1990; D'Silva and Choudhuri 1991). But these mechanisms can operate only if some very special conditions are satisfied, and it appears more likely that the toroidal magnetic field produced by the solar dynamo has the strength 10^5 G.

3. On the poloidal component

Although sunspots seem to migrate to the lower latitudes with the progress of the solar cycle, the weak diffuse field outside the active regions seems to migrate towards the poles in the opposite direction (see Wang et al. 1989). It is natural to identify the weak diffuse magnetic fields as the poloidal component produced by the dynamo. The dynamo wave in the overshoot layer presumably propagates equatorward in order

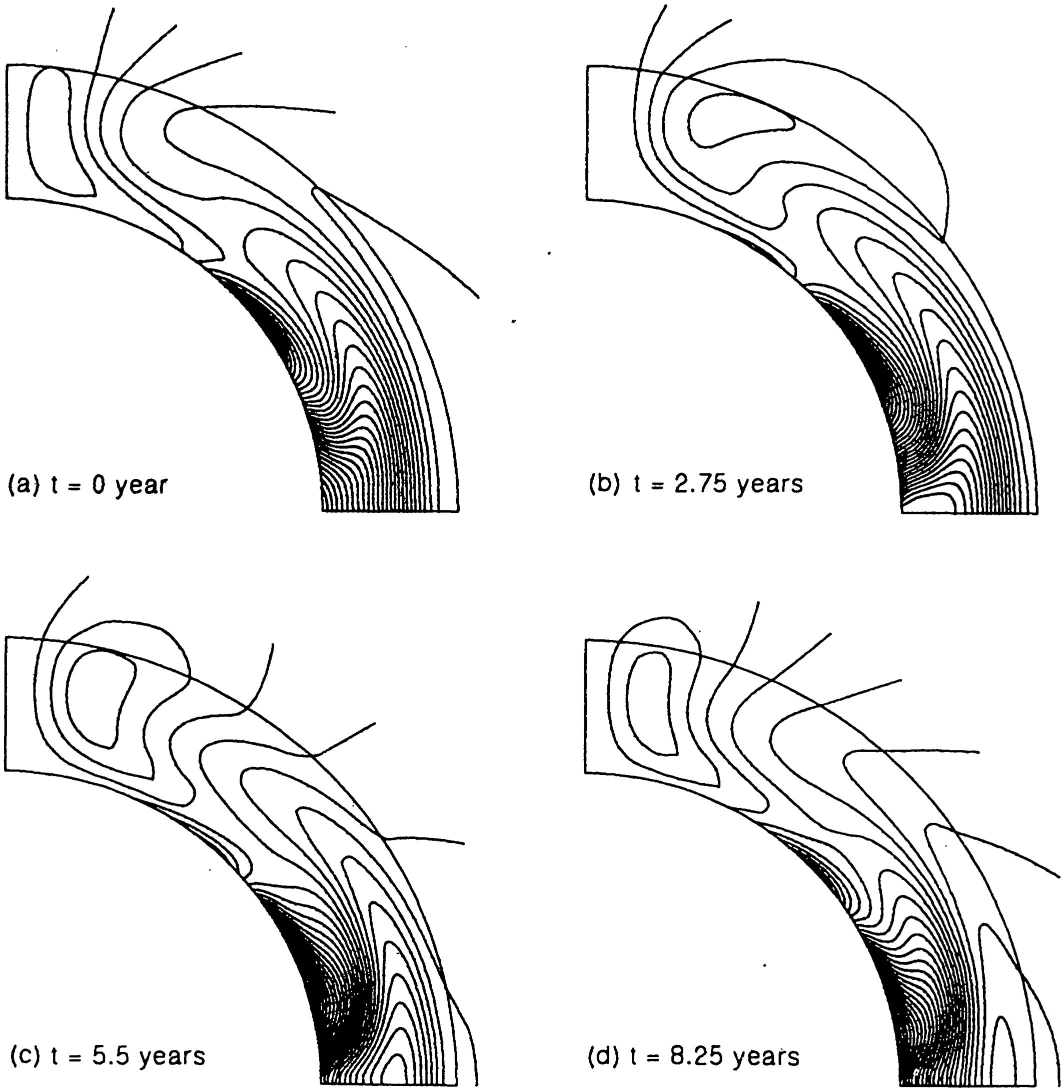

Figure 1. The evolution of the poloidal field lines during a half of the solar cycle (from Dikpati and Choudhuri 1994).

to explain the broad features of the solar cycle. The part of the poloidal field within the dynamo layer should move equatorward with the dynamo. However, if there is a meridional circulation in the solar convection zone which is poleward near the surface and hence must be equatorward at the bottom of the convection zone (see Komm et al. 1993), then the upper parts of the poloidal field may evolve differently.

Dikpati and Choudhuri (1994, 1995) were the first people to study the evolution of the poloidal field in the convection zone subject to turbulent diffusion and meridional circulation, with an equatorward running dynamo wave as the bottom boundary condition. Figure 1 shows the successive configurations of the poloidal field lines during a half-cycle. It is clear that the flux near the surface moves poleward with the meridional circulation, even though the field lines in the bottom part move equatorward with the dynamo.

4. Conclusion

We now summarize the scenario we have arrived at. The toroidal field exists as flux rings of strength 10^5 in the stable dynamo layer at the base of the convection zone. Parts of this field coming out of the stable layer produce the active regions. The poloidal field produced by the dynamo is much weaker and is expected to fill up the convection zone as shown in Figure 1. The central question now is whether the solar dynamo can produce fields as strong as 10^5 G. Recently some radical models of the dynamo are being worked out which may eventually account for these strong fields (Durney 1995; Choudhuri et al. 1995).

It will be particularly helpful if future observations can throw some light on the theoretical scenario sketched here. We hope that the helioseismology data in the coming years will be able to establish whether there is really a toroidal magnetic field of 10^5 G at the bottom of the convection zone.

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