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Some Recent Developments in Solar Dynamo Theory

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Abstract. We discuss the current status of solar dynamo theory and describe the dynamo model developed by our group. The toroidal magnetic field is generated in the tachocline by the strong differential rotation and rises to the solar surface due to magnetic buoyancy to create active regions. The decay of these active regions at the surface gives rise to the poloidal magnetic field by the Babcock–Leighton mechanism. This poloidal field is advected by the meridional circulation first to high latitudes and then down below to the tachocline. Dynamo models based on these ideas match different aspects of observational data reasonably well.

Key words. Sun: magnetic field—sunspots—solar cycle—MHD.

1. Introduction

It appears that major breakthroughs in our understanding of the solar cycle have been taking place approximately at intervals of a half century. The 11-year cycle of sunspots was discovered a little more than 150 years ago (Schwabe 1844); the magnetic nature of this solar cycle became apparent about 100 years ago (Hale 1908); and the hydromagnetic dynamo theory to explain the origin of this cycle was first formulated about 50 years ago (Parker 1955a). On extrapolating this trend, we expect that another major breakthrough in this field should be taking place right now! We indeed believe this to be the case. Some of the earlier breakthroughs were achieved single-handedly by extraordinary individuals like Hale and Parker. We now live in a less heroic age, and the present breakthrough is due to the joint effort of many groups around the world, in which our group in Bangalore also has played a role. This article is something intermediate between a balanced review article and an exclusive report of the research activities of our group. We shall try to present our work in a historical context against the broader developments in this field. For more elementary and detailed introductions to solar dynamo theory, the readers are urged to look at Choudhuri (1998; Chapter 16) and Choudhuri (2003a).

The basic idea of dynamo theory is that the toroidal and poloidal components of the solar magnetic field give rise to each other in a feedback loop. Since the toroidal component gives rise to the sunspots, we can regard sunspots as a kind of proxy for the toroidal component. On the other hand, the weak magnetic field outside active regions is regarded as a manifestation of the poloidal component. In contrast to the sunspots which migrate equatorward with the solar cycle, this weak field migrates poleward (see, for example, Wang *et al.* 1989). This is clearly seen in Fig. 1, which gives

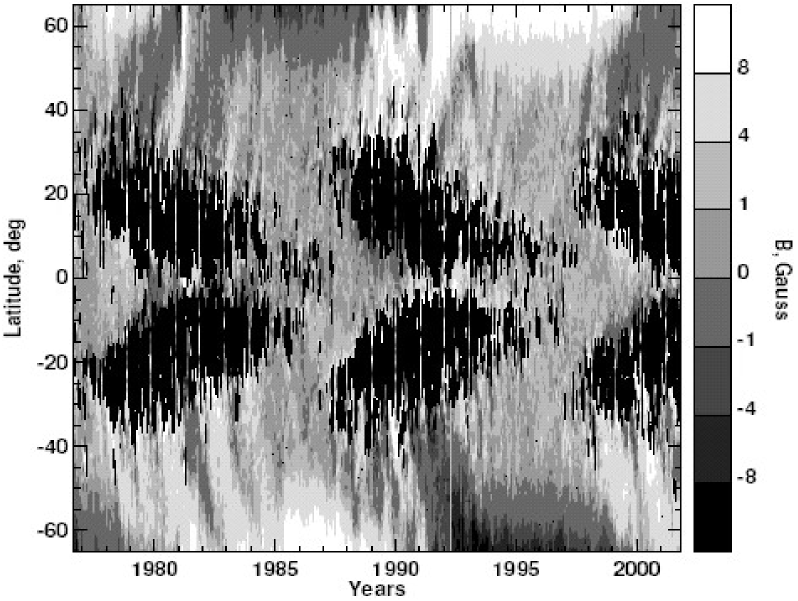

Figure 1. The butterfly diagram of sunspots superposed on a time–latitude plot of the longitude-averaged weak field at the solar surface. Different shades of grey indicate different values of this weak field. Courtesy: A. G. Kosovichev.

time–latitude plot of the longitude-averaged weak field, with the butterfly diagram of sunspots superposed on it. Early work on solar dynamo was mainly confined to explaining the butterfly diagram of sunspots. Now we believe that the behaviour of the weak field also provides some vital clues about the nature of the solar cycle and a full dynamo model should explain this as well.

The generation and the dynamics of the toroidal component is discussed in section 2. Then section 3 discusses the generation of the poloidal component and the role of the meridional circulation. We describe some of the details of our dynamo model (one of the most comprehensive solar dynamo models available at the present time) in section 4. Then our conclusions are summarized in section 5.

2. The generation and dynamics of the toroidal magnetic field

Helioseismology has mapped the angular velocity distribution in the interior of the Sun. A strong radial shear in angular velocity is found at the bottom of the solar convection zone (hereafter SCZ), the region of shear being known as the tachocline. Any magnetic field present in the region of tachocline would be stretched by the differential rotation there to generate a strong component in the toroidal direction. All dynamo theorists agree that the toroidal magnetic field is produced in the tachocline at the base of SCZ. Presumably, interactions with convection keep the magnetic field intermittent, which probably exists in the form of concentrated flux tubes roughly aligned in the toroidal direction (Choudhuri 2003b).

A flux tube in SCZ is subject to magnetic buoyancy (Parker 1955b). However, magnetic buoyancy is significantly suppressed if the flux tube is in a stable region of subadiabatic gradient below the bottom of SCZ (Parker 1979, section 8.8). Consider a flux tube of which the major part lies in the stable region, with a small portion coming inside SCZ. Then this portion should rise due to magnetic buoyancy to reach the solar surface and should eventually produce a bipolar active region. Such a flux rise can be studied through a simulation of the thin flux tube equation. Since Choudhuri & Gilman (1987) showed that the Coriolis force is extremely important in this problem, this force has to be included in such simulations. Results from such simulation have been reported by different groups (Choudhuri 1989; D'Silva & Choudhuri 1993; Fan *et al.* 1993; Caligari *et al.* 1995).

Bipolar active regions on the solar surface typically tend to be inclined with respect to the solar equator. In spite of a large scatter, this tilt is clearly found to increase with latitude – a result known as Joy's law (Hale *et al.* 1919). One requirement of flux rise simulations is that the upper portions of flux tubes reaching the surface should have inclinations in accordance with Joy's law. D'Silva & Choudhuri (1993) discovered that this requirement is met only if the initial value of the magnetic field inside the flux tube is 10^5G at the starting point at the bottom of the SCZ. In addition to providing the first theoretical explanation of Joy's law nearly three-quarters of a century after its discovery, D'Silva & Choudhuri (1993) provided a tight bound on the value of the magnetic field at the base of SCZ – which was confirmed in subsequent simulations and provided a very important constraint on allowable dynamo models.

3. The generation of the poloidal field and the role of meridional circulation

In his classic paper, Parker (1955a) proposed an idea of how the poloidal magnetic field is generated from the toroidal magnetic field. The convective turbulence, which should be of helical nature in a rotating frame of reference, can drag and twist the toroidal field to give a magnetic field component in the poloidal plane. This idea, which was further developed by Steenbeck, Krause & Rädler (1966), is called the α-effect. However, if the toroidal field is as strong as 10^5G at the base of SCZ – a result forced on us by the flux tube simulations (D'Silva & Choudhuri 1993), then the convective turbulence will not be able to twist this magnetic field, and the α-effect should be completely suppressed for such strong fields.

An alternative idea, which is invoked in many present-day dynamo models, was first suggested by Babcock (1961) and Leighton (1969). Since a bipolar active region appears inclined (Joy's law), the two sunspots with opposite magnetic polarities are at slightly different latitudes. When such a bipolar region decays, the two polarities diffuse preferentially at two slightly different latitudes, thereby giving rise to a poloidal field. The Babcock–Leighton process can be phenomenologically modeled by putting a source term of the poloidal field (represented by an α) near the solar surface. When the usual α-effect was found to be inoperative in the solar interior, it was natural to try using the Babcock–Leighton mechanism to complete the dynamo loop. However, the α representing the Babcock–Leighton process has to be positive in the northern hemisphere – which easily follows from the direction of inclination of active regions. Additionally, $\partial\Omega/\partial r$ is positive within the tachocline at low latitudes. The well-known sign rule of the dynamo (see, for example, Choudhuri 1998, section 16.6) suggests that the dynamo wave should propagate poleward in such a situation, in violation of observations.

Choudhuri *et al.* (1995) showed that it is possible to get an equatorward propagation of the dynamo if there is a suitable meridional circulation. Observations suggest a poleward meridional circulation in the upper layers of SCZ (Giles *et al.* 1997). To conserve mass, there must be a return equatorward flow through the bottom layers of SCZ. This flow was found to force an equatorward propagation of the dynamo, provided the advection time scale of the flow was shorter than the diffusion time scale. This new result of Choudhuri *et al.* (1995) allowed a completely new class of dynamo models to be constructed, with the meridional circulation playing a crucial role in them. Since the poleward flow near the surface advects the poloidal field created at the surface towards the pole, such dynamo models have the additional attractive feature of providing a theoretical model of the observed poleward migration of the weak surface field.

4. The full dynamo model

Our aim now should be to use the helioseismically determined differential rotation to construct a dynamo model, in which the poloidal field is produced by the Babcock–Leighton process and the meridional circulation plays an important role. The toroidal field would be produced in the tachocline and then rise to the surface due to magnetic buoyancy. The poloidal field would be produced at the surface, to be advected by meridional circulation first to the pole and then down underneath to the tachocline where it can be stretched. Two-dimensional dynamo models exploring some of these aspects have been constructed by many authors (Choudhuri *et al.* 1995; Durney 1995, 1997; Dikpati & Charbonneau 1999; Küker *et al.* 2001; Nandy & Choudhuri 2001, 2002; Guerrero & Munõz 2004; Chatterjee *et al.* 2004).

Helioseismology has found the strongest differential rotation at high latitudes inside the tachocline. When such a rotation profile is used in a dynamo model, the strongest toroidal field is produced at high latitudes and erupts there, contradicting the observations. Nandy & Choudhuri (2002) proposed a way out of this difficulty. Since the meridional circulation is driven by the stresses in SCZ, it is usually assumed to be confined within the SCZ. However, just as we expect some convective overshooting into the stable layers, we can expect the meridional flow to penetrate a little bit into the stable layers below the bottom of SCZ. In that case, even if the strong toroidal field is produced in the tachocline at high latitudes, it is advected by this penetrative meridional flow to lower latitudes through stable layers where magnetic buoyancy is suppressed. Only at low latitudes, it is brought inside the SCZ and rises due to magnetic buoyancy. Nandy & Choudhuri (2002) obtained butterfly diagrams in good agreement with observations, provided the meridional circulation penetrates slightly below the bottom of SCZ.

The solar magnetic field appears to be of dipolar nature. Many of the dynamo simulations were done in one hemisphere, with the boundary conditions at the equator forcing a dipolar solution. One important question is whether the dipolar mode would be favoured in full-sphere simulations. Dikpati & Gilman (2001) claimed that a Babcock–Leighton dynamo preferentially excites a quadrupolar mode. However, Chatterjee *et al.* (2004) showed that the dipolar mode is preferred if the diffusivity of the poloidal component is sufficiently high to couple it between the two hemispheres.

Figure 2 is a theoretical butterfly diagram from Chatterjee *et al.* (2004), showing also the contours of B_r at the solar surface. This figure has to be compared with

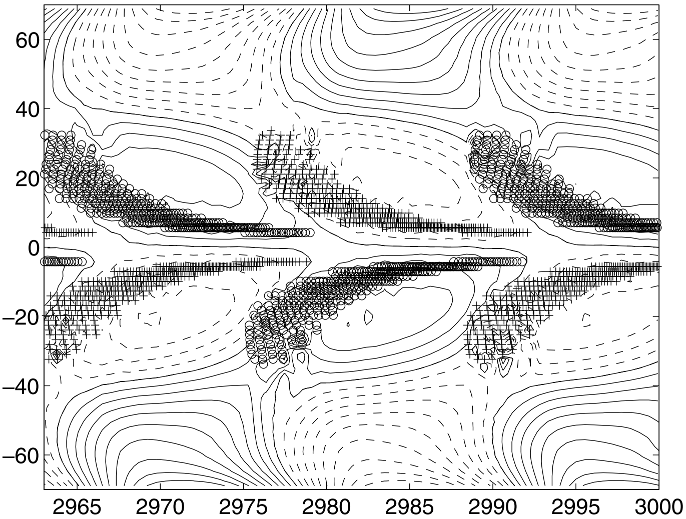

Figure 2. Theoretical butterfly diagram of eruptions from the dynamo model of Chatterjee *et al.* (2004). The background shows contours of the radial field at the solar surface. Eruptions with positive and negative toroidal fields are denoted by '+' and 'o' respectively. The solid contours are for positive B_r and dashed contours for negative B_r.

the observational Fig. 1. It is clear that sunspot eruptions are taking place at correct latitudes. The phase relation between sunspots and the weak field at the surface is also reproduced reasonably well. As we already pointed out, this model favours the dipolar mode.

It may be mentioned that the active regions tend to have negative helicity in the northern hemisphere. One important question is whether this helicity is due to the dynamo and whether our dynamo model can explain it. Based on the qualitative idea of helicity generation proposed by Choudhuri (2003b), it is shown by Choudhuri *et al.* (2004) that their dynamo model also produces the right kind of helicity.

5. Conclusion

In the 1970s and 1980s, many kinematic solar dynamo models were developed by assuming different hypothetical profiles of α and Ω. Now we know that most of these models were based on assumptions which do not correspond to reality. An attractive aspect of the present-day dynamo models is that many of the crucial ingredients of the model are directly based on observations. We know the distribution of Ω from helioseismology. We also observe the decay of tilted bipolar regions on the solar surface and see the Babcock–Leighton mechanism in action. The meridional circulation in the upper layers of SCZ also has been mapped. One of the big remaining uncertainties at the present time is that we do not have any observational results about the nature of the meridional circulation in the lower layers of SCZ. As pointed out by Nandy & Choudhuri (2002), the solutions can be very different depending on whether this circulation penetrates in the stable layers below the bottom of SCZ. This has become an intensely controversial subject at present (Dikpati *et al.* 2005; Choudhuri *et al.* 2005). We hope that future observations and more detailed theoretical modeling will eventually settle this issue. In spite of many remaining gaps in our understanding, the dynamo models developed in the recent years are the first sufficiently-detailed and realistic models of the solar dynamo, of which many aspects will probably stand the test of time. That is why we regard the recent developments as another breakthrough in the historical evolution of solar dynamo theory, as we mentioned at the very beginning of this article.

Although the traditional α-effect would be quenched at the bottom of SCZ with concentrated magnetic fields of order 10^5 G, there can be other physical mechanisms there responsible for giving rise to effects similar to the α-effect. Some studies are being made of such interface dynamos with α at the bottom. We do not discuss these interface dynamo models in this brief article.

Finally, many aspects of the dynamo models we discussed in section 4 are yet to be explored. Since the magnetic field is expected to be intermittent within the SCZ, one important issue is to understand the relation between the dynamo process and the flux tubes. An initial exploratory study of this problem has been presented by Choudhuri (1993b). Another important problem is to understand the irregularities of the solar cycle – at least at a qualitative level. We are now in the process of incorporating stochastic fluctuations in our dynamo model to study this problem.

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