SOLAR DYNAMO MODELS WITH REALISTIC INTERNAL ROTATION

Arnab Rai Choudhuri\textsuperscript{1,2} and Dibyendu Nandy\textsuperscript{1,3}

\textsuperscript{1}Department of Physics, Indian Institute of Science, Bangalore - 560012, India
\textsuperscript{2}Max-Planck-Institut für Aeronomie, 37191 Katlenburg-Lindau, Germany
\textsuperscript{3}Department of Physics, Montana State University, Bozeman, MT 59717, U.S.A.

ABSTRACT

Solar dynamo models based on differential rotation inferred from helioseismology tend to produce rather strong magnetic activity at high solar latitudes, in contrast to the observed fact that sunspots appear at low latitudes. We show that a meridional circulation penetrating below the tachocline can solve this problem.

Key words: Solar dynamo; solar rotation; meridional circulation.

1. INTRODUCTION

Solar magnetic fields are believed to be generated by the nonlinear interactions between the solar plasma and the magnetic fields underneath the Sun’s surface (Parker, 1979; Choudhuri, 1998). The aim of solar dynamo theory is to study these interactions in detail and then come up with theoretical explanations for different aspects of the solar cycle.

To build a detailed model of the solar dynamo, we need various bits of information about the solar interior. Even about two decades ago, very little of such information was available and making a model of the solar dynamo was like intuitive (and occasionally inspired) guesswork. One important development in the last few years is that helioseismology has mapped out the distribution of angular velocity in the solar interior. This is shown in Fig. 1. The challenge before a dynamo theorist now is to construct a satisfactory model of the solar dynamo with helioseismically determined rotation profile.

The next section discusses the basic characteristics which a modern solar dynamo model is expected to have. Then in §3 we describe efforts of building solar dynamo models with helioseismically determined rotation, point out the difficulties which such models are facing and finally discuss our recent proposal (Nandy & Choudhuri, 2002) to solve these difficulties. Our conclusions are summarized in the final section.

2. BASIC CHARACTERISTICS OF MODERN SOLAR DYNAMO MODELS

If we assume axisymmetry, then the magnetic field in spherical geometry can be written as

\[ \mathbf{B} = B_\phi \mathbf{e}_\phi + \nabla \times (A \mathbf{e}_\phi). \] (1)

In the jargon of dynamo theory, the first term is referred to as the toroidal component and the second term as the poloidal component. The sunspots on the surface are believed to be produced from the magnetic buoyancy of the strong toroidal component and therefore provide a proxy for the toroidal component underneath. On the other hand, the weak diffuse magnetic field outside the active regions is usually associated with the poloidal component. With

\[ \text{Proc. 'SOLMAG: Magnetic Coupling of the Solar Atmosphere Euroconference and IAU Colloquium 188'
Santorini, Greece, 11-15 June 2002 (ESA SP-505, October 2002)} \]

© European Space Agency • Provided by the NASA Astrophysics Data System
the progress of the solar cycle, belts of sunspot activity migrate equatorward, whereas belts of weak field migrate poleward. A successful model of the solar dynamo should explain both of these features.

The basic idea of dynamo theory is that the toroidal and poloidal components sustain each other, while drawing their energies ultimately from the reservoir of kinetic energy of convective motion in the interior of the Sun. The toroidal field must arise from the poloidal field as a result of stretching due to the internal rotation of the Sun as shown in Fig. 1. On the other hand, the poloidal field is produced by the twisting of toroidal field lines. More comments will be made on this twisting afterwards.

It is clear from Fig. 1 that rotational shear is concentrated in a layer at the base of the convection zone—often called the tachocline. The toroidal field must be produced there and then rise through the convection zone to give rise to sunspots. Numerical simulations of this buoyant rise process indicated that various observed features of the solar surface (latitudinal distribution of sunspots, tilts of bipolar regions) can be explained only if the initial toroidal field at the base of the convection zone is as strong as $10^5$ G, which is much larger than the equipartition value (Choudhuri & Gilman, 1987; Choudhuri, 1989; D'Silva & Choudhuri, 1993; Fan et al. 1993).

We now need a mechanism that can twist the strong $10^5$ G toroidal field to produce the poloidal field. An important ingredient of traditional dynamo models is the α-effect—originally due to Parker (1955) and Steenbeck et al. (1966). This effect involves the twisting of field lines by convective turbulence which moves helically in a rotating system. However, if the magnetic field is as strong as $10^5$ G, then this effect will be completely impossible. We, therefore, invoke another idea for the generation of the poloidal field that goes back to Babcock (1961) and Leighton (1969). The magnetic buoyancy of the toroidal field gives rise to bipolar regions which emerge with tilts due to the Coriolis force. When a tilted bipolar region decays and the magnetic flux spreads around, we get a net poloidal field. Thus the decay of tilted bipolar regions acts as the intermediate step in generating the poloidal field from the toroidal field.

The poloidal field generated at the solar surface is advected poleward by the meridional circulation which has been observed in the upper layers of the convection zone (Giles et al., 1997; Braun & Fan, 1999). Nothing much is known about the nature of the meridional circulation at the bottom of the convection zone, except that it must be equatorward there to conserve mass. Fig. 2 shows a pattern of meridional flow which is often used in theoretical solar dynamo models. When the meridional flow sinks near the pole, it carries the poloidal field with it to the tachocline, where the poloidal field can be stretched to produce the toroidal field. This toroidal field would then rise to the surface to produce bipolar sunspots, which finally decay to produce the poloidal field again by the Babcock-Leighton mechanism. This is how the solar dynamo is believed to work. There have been several efforts in the recent years to build solar dynamo models along these lines (Wang et al., 1991; Choudhuri et al., 1995; Durney, 1995, 1997; Dikpati & Charbonneau, 1999; Küker et al., 2001; Nandy & Choudhuri, 2001, 2002a).

3. DIFFICULTIES WITH REALISTIC SOLAR ROTATION AND A POSSIBLE SOLUTION

A careful look at Fig. 1 would make it clear that the shear $d\Omega/dr$ within the tachocline, which is negative at high latitudes and positive at low latitudes, is much stronger at high latitudes compared to low latitudes. This invariably produces a much stronger toroidal field at high latitudes compared to low lati-
Figure 4. A pattern of meridional circulation that penetrates below the tachocline (the grey region).

Figure 5. Theoretical butterfly diagram produced with the internal rotation as shown in Fig. 1 and meridional circulation as shown in Fig. 4.

pects this circulation to remain confined within the convection zone. As our theoretical understanding of meridional circulation is still extremely poor, Nandy & Choudhuri (2002a) suggested a scenario in which the meridional circulation penetrates somewhat deeper—below the tachocline, as shown in Fig. 4. The crucial point to note here is that a magnetic field always tends to be buoyant within the convection zone, but its buoyancy is suppressed when the magnetic field is put below the convection zone (Parker, 1979). Even if the strong toroidal field is produced within the tachocline at high latitudes, the meridional circulation shown in Fig. 4 would push it into the stable layers below where magnetic buoyancy is suppressed and will not allow it to erupt at high latitudes. The meridional circulation would then carry this toroidal field to lower latitudes through the stable layers. The toroidal field would eventually come within the convection zone with the rising meridional flow at the low latitudes. Then the toroidal field would become buoyant and rise to the surface to produce sunspots. In this scenario, the toroidal field is mainly produced at high latitudes, but comes up to the solar surface only at low latitudes. The resulting theoretical butterfly is shown in Fig. 5, which clearly looks very solar-like. The details of our model will be presented in a forthcoming paper (Nandy & Choudhuri, 2002b).

4. CONCLUSION

We conclude that a meridional flow penetrating below the tachocline can solve the problem of strong magnetic activity at high latitudes, which at first appears like an inevitable consequence of dynamo models using the helioseismically determined rotation profile. Since our understanding of the physical processes at the base of the convection zone is so incomplete, we propose that a deeply penetrating meridional flow should be regarded as a realistic possibility. Further developments in helioseismology and in numerical simulations of convection should throw more light on the meridional circulation in the next few years.

We are fully aware that a meridional circulation going below the tachocline is a drastic suggestion. Any flow carries the angular momentum with it, and understanding the angular momentum transfer in the present scenario is a tricky problem. However, a penetrating meridional flow would help in solving some problems connected with abundance anomalies. The surface layers of the Sun have Li (but not Be) depleted with respect to the interstellar neighborhood. The type of meridional circulation we are suggesting would take the material of solar surface to depths where Li (but not Be) is burnt.

ACKNOWLEDGMENTS

ARC would like to thank the Alexander von Humboldt Foundation for supporting his stay at the Max-
Planck-Institut für Aeronomie, where this paper was prepared. ARC is also grateful for an IAU grant which made it possible for him to attend the IAU Colloquium 188.

REFERENCES

Nandy D., Choudhuri A. R., 2002a, Science 296, 1671
Nandy D., Choudhuri A. R., 2002b, in preparation
Parker E. N., 1979, Cosmical Magnetic Fields, Clarendon Press