

## LOCATING THE SEAT OF THE SOLAR DYNAMO

Arnab Rai Choudhuri  
Department of Physics  
Indian Institute of Science  
Bangalore 560012. India

**ABSTRACT.** By analyzing the hypothesis that the solar dynamo operates in a thin layer at the bottom of the convection zone, we conclude that this hypothesis can fit observational facts only if there is turbulence with the length scale of a few hundred kilometers in and around the dynamo region.

### 1. INTRODUCTION

The traditional view that the solar magnetic fields are generated by an  $\alpha\omega$ -dynamo operating in the convection zone has been subject to criticisms in recent years because of the following difficulties: (i) magnetic buoyancy would remove any magnetic flux from the convection zone quickly (Parker, 1975), and (ii) self-consistent dynamical models of convection zone dynamos are unable to reproduce the surface rotation pattern and the butterfly diagram simultaneously (Gilman, 1983). In response to these difficulties, it has been suggested that the dynamo operates in a thin layer at the bottom of the convection zone or underneath it rather than operating in the main bulk of the convection zone. The overshoot region underneath the convection zone is supposed to be a suitable location for the operation of the solar dynamo, since the subadiabatic gradient there can suppress the magnetic buoyancy (Spiegel and Weiss, 1980; van Ballegoijen, 1982). Alternative effects such as thermal shadows (Parker, 1987) and the drag due to the meridional flow (van Ballegoijen and Choudhuri, 1988) have also been proposed in order to suppress magnetic buoyancy in a thin layer at the bottom of the convection zone. The differential rotation and the  $\alpha$ -coefficient driving the dynamo action there are also expected to have correct signs, at least in the lower latitudes, so as to make the dynamo waves go in the correct direction (Gilman et al., 1989).

Though the hypothesis that the dynamo operates in a thin layer at the bottom of the convection zone may solve old problems, it raises several new questions. Choudhuri and Gilman (1987) found that even if the flux is initially created at low latitudes at the bottom of the convection zone, the Coriolis force makes the flux rise parallel to the rotation axis and emerge at high latitudes poleward of where sunspots are seen. In § 2 we present recent work on the question whether the flux can be made to emerge at sunspot latitudes. Then § 3 discusses whether the dynamo operating in a thin layer can have the correct period and wavelength. We shall see that completely different arguments in § 2 and § 3 point to the existence of turbulence with the same length scale of few hundred kilometers in the dynamo region.

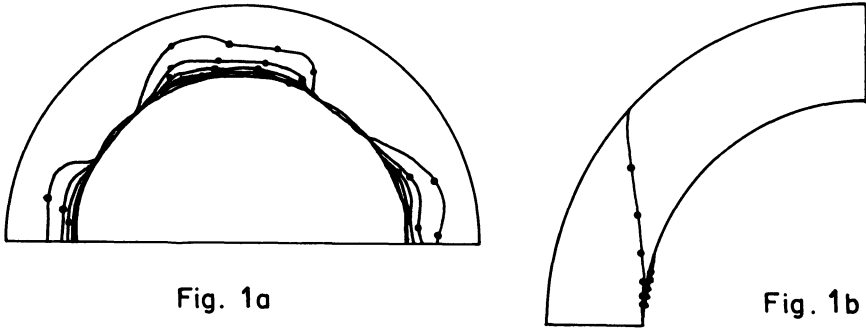


Fig.1. Evolution of a partially anchored flux ring with initial magnetic field  $1.7 \times 10^4$  G. The successive configurations in (1a) or the dots in (1b) are at intervals of 14 days.

## 2. RISE OF FLUX THROUGH THE CONVECTION ZONE

The calculations of Choudhuri and Gilman (1987) were carried out for flux rings symmetric around the rotation axis. In order to investigate whether the Coriolis force could be suppressed by taking account of departures from axisymmetry, Choudhuri (1989) considered initial states in which the flux rings possessed non-symmetric undulations and had parts embedded in the stable layers underneath the convection zone. Though those parts remained anchored there, the upper parts of the flux rings rising in the forms of loops still moved parallel to the rotation axis. Figure 1 shows the evolution of such a non-axisymmetric flux ring starting from  $5^\circ$  latitude with an initial magnetic field of  $1.7 \times 10^4$  G. Figure 1a is a polar plot of the successive configurations in the  $(r, \varphi)$  plane, whereas Figure 1b shows the trajectories in the  $(r, \theta)$  plane of the highest and

lowest points of the flux ring with the growing loops. We clearly see that we are still unable to get the flux out at the typical sunspot latitudes.

More recently, however, Choudhuri and D'Silva (1990) studied the interactions of the rising flux with the turbulence in the surrounding convection zone and found that the flux can be brought out radially if there is turbulent exchange of angular momentum between the flux tube and the surrounding fluid sufficiently rapidly, say in 10 hours or so. Such turbulent exchange is possible only (i) if the flux rises in the form of thin tubes of radius 500 km or so, and (ii) if there is enough turbulence at that length scale of a few hundred kilometers. It is then necessary to satisfy these two conditions if we want the flux created at the low latitudes to emerge at low latitudes on the surface.

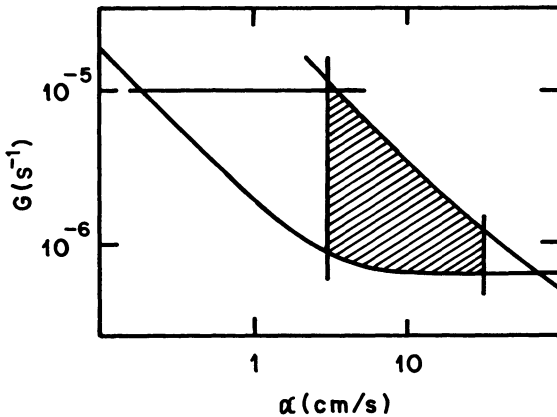


Fig.2. The allowed region (shown by shading) in velocity shear  $G$  vs.  $\alpha$ -coefficient parameter space.

### 3. DYNAMO WITH CORRECT PERIODICITY AND WAVELENGTH

Since the dynamo region at the base of the convection zone is supposed to have a thickness of  $10^4$  km, Choudhuri (1990) has solved the kinematical dynamo equations for a rectangular slab of such thickness. By demanding a period of 22 years and a half-wavelength of  $40^\circ$  in the  $\theta$ -direction, one can put some constraints on the allowed values of various parameters appearing in the kinematical dynamo equations. Figure 2 shows the allowed regions of the parameter space for the  $\alpha$ -coefficient and the velocity shear  $G$ . The allowed values of different parameters suggest that the two source terms in the generation of the toroidal field (i.e. the differential rotation and the  $\alpha$ -effect terms) have to be of the same order of magnitude, making the solar dynamo a truly  $\alpha^2\omega$ -dynamo. Since  $\alpha\omega$ -

dynamos produce very little poloidal field and the poloidal field of the sun is small, it used to be assumed that the solar dynamo is of the  $\alpha\omega$ -type. However, if the dynamo operates at the base of the convection zone, then even if it produces significant poloidal fields, such fields may not leak to the surface. Hence there is no difficulty in invoking an  $\alpha^2\omega$ -type solar dynamo, which may produce substantial poloidal fields in its region of operation.

Choudhuri (1990) also found that the  $\alpha$ -coefficient and the turbulent diffusion  $\eta$  have to be constrained within about one factor of ten, the median values being  $\alpha \sim 10 \text{ cm s}^{-1}$  (see Figure 2) and  $\eta \sim 10^{10} \text{ cm}^2 \text{ s}^{-1}$ . On the basis of mixing length arguments, such values imply reasonable turbulent velocities of about  $30 \text{ m s}^{-1}$ , but rather small turbulent length scales of the order of 300 km.

#### 4. CONCLUSION

We thus see that from two completely different considerations - by demanding that the flux created at low latitudes emerge at low latitudes, and by demanding that the dynamo have correct period and wavelength - we come to the same conclusion that the turbulence in and above the dynamo region should have a length scale of a few hundreds of kilometers. Such a length scale is much smaller than all the scale heights and goes against the current theoretical prejudice that the solar convection should mainly involve giant cells. We merely point out that the hypothesis that the solar dynamo operates in a thin layer at the base of the convection zone can be made consistent with observational facts only if such small-scale turbulence exists.

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## DISCUSSION

**PRIEST:** Taking a field greater than  $10^5\text{G}$  at the base of the convection zone would seem a good solution to your problem of making flux tubes rise through the sunspot zones rather than moving to the north of them. Why should not partial evacuation make the field strength larger than the equipartition value? After all, twenty years ago we did not dream that photospheric field strengths outside sunspots could be as large as  $1\text{kG}$  due to such an effect. Also B Roberts and others feel that helioseismology observations may imply such larger fields at the base of the convection zone.

**CHOUDHURI:** It is true that a field of value  $10^5\text{G}$  would have sufficiently strong magnetic buoyancy to make it come out radially and would solve the problem of making the flux emerge at sunspot latitudes. I, however, personally feel somewhat uncomfortable with the idea of such a large field at the base of the convection zone. Firstly, such a field would completely inhibit convection and the dynamo process. Secondly, bipolar regions are believed to be caused by parts of flux tubes coming through the surface whereas other parts remain anchored deep down. A field of  $10^5\text{G}$  is too strong even to be anchored in the overshoot region (see Choudhuri [1989]). Still I agree that we know too little about the conditions at the base of the convection zone and perhaps we should keep our minds open on this issue.

**GOKHALE:** The emergence of field portions from the base of the convection zone to the surface creates a radial flux across the convection zone. What happens to it as time proceeds?

**CHOUDHURI:** This question has been discussed at length by Parker (1984, *Ap.J.* **281**,839; 1987 *Ap.J.* **312**,868). Though some flux in the neighbouring active regions may be able to escape due to reconnection, Parker believes that the major part of the flux is again pulled below the surface. Hence the repeated emergence of flux in the same active site may involve considerable reprocessing. When Parker considered the question whether a thin layer at the base of convection zone can store enough flux to explain all the flux that we see on the surface, he concluded that a very thin layer would not be sufficient for such storage even if we allow considerable reprocessing. This is another difficulty with the thin-layer dynamo idea which gets more aggravated if the flux is not reprocessed efficiently.