THE EVOLUTION OF LOOP STRUCTURES IN FLUX RINGS
WITHIN THE SOLAR CONVECTION ZONE

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Abstract. Choudhuri and Gilman (1987) considered certain implications of the hypothesis that the magnetic flux within the Sun is generated at the bottom of the convection zone and then rises through it. Taking flux rings symmetric around the rotation axis and using reasonable values of different parameters, they found that the Coriolis force deflects these flux rings into trajectories parallel to the rotation axis so that they emerge at rather high latitudes. This paper looks into the question of whether the action of the Coriolis force is subdued when the initial configuration of the flux ring has non-axisymmetries in the form of loop structures. The results depend dramatically on whether the flux ring with the loops lies completely within the convection zone or whether the lower parts of it are embedded in the stable layers underneath the convection zone. In the first case, the Coriolis force suppresses the non-axisymmetric perturbations so that the flux ring tends to remain symmetric and the trajectories are very similar to those of Choudhuri and Gilman (1987). In the second case, however, the lower parts of the flux ring may remain anchored underneath the bottom of the convection zone, but the upper parts of the loops still tend to move parallel to the rotation axis and emerge at high latitudes. Thus the problem of the magnetic flux not being able to come out at the sunspot latitudes still persists after the non-axisymmetries in the flux rings are taken into account.

1. Introduction

The conventional wisdom about the solar magnetic fields is that they are produced by the dynamo action. Though the solar dynamo theory is at present encountering many serious difficulties, no satisfactory alternative theory has emerged so far (Cowling, 1981; Gilman, 1986). This makes it imperative to look at different aspects of the solar dynamo theory as carefully as possible before passing a verdict on it.

Since the photospheric surface constitutes an opaque screen for the observer, we can observe magnetic activities only at and above the photosphere. As the magnetic fields below the photosphere cannot be observed directly, their properties have to be inferred from other considerations. First, the magnetic fields in the photosphere seem to be of a fibril and intermittent nature. Whether subsurface fields are also intermittent or continuous is a question which is by no means easy to settle. However, theoretical investigations on magnetoconvection (Proctor and Weiss, 1982) seem to suggest that magnetic fields probably exist in an intermittent fashion within the convection zone also. We take this point of view in the present paper and model the magnetic field within the convection zone in the form of flux tubes. Another inference about subsurface fields can be made from Hale’s polarity law of bipolar regions. Though it is quite unclear how the

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field lines of sunspots connect to the global fields underneath the surface (Parker, 1979; Choudhuri, 1986), the polarity law indicates that the global field in the convection zone must be predominantly azimuthal. So it is probably not unreasonable to assume that the magnetic flux within the convection zone basically exists in the form of flux rings going around the rotation axis and forming loop-like structures in places that may give rise to bipolar regions. Lastly, the existence of the 22-year solar cycle compels us to look for a mechanism capable of producing an oscillatory behaviour in the global field.

If the solar cycle is caused by the dynamo action, we have to figure out where this dynamo action takes place. Since the operation of the hydromagnetic dynamo requires convective motions, it used to be tacitly assumed that the convection zone is the site of the dynamo action. However, it has become increasingly clear in recent years that there are several serious difficulties in building a satisfactory model of a convection zone dynamo, one of the main difficulties being the destabilizing effect of magnetic buoyancy (Parker, 1975). This has led several theorists to suggest that the dynamo action takes place in the overshoot region at the bottom of the convection zone. A discussion of this topic with references to the appropriate literature can be found in Section I of Choudhuri and Gilman (1987; hereafter Paper I).

If we assume the dynamo to operate in the overshoot region, we can get around the difficulties confronting a convection zone dynamo model, but we seem to encounter new difficulties which are hardly any less serious. Since the overshoot region is believed to have a thickness of only a few thousand kilometers (van Ballegooijen, 1982), one has to consider whether it is thick enough for the storage of the appropriate amount of magnetic flux. A straightforward arithmetical estimate by Parker (1987) gives the answer that in order to pack the right amount of flux in the overshoot region, it is necessary for the magnetic field there to be at least one order of magnitude larger than the equipartition value. A more serious difficulty is pointed out in Paper I, which studies the influence of the Coriolis force on the dynamo-generated flux as it rises through the convection zone.

When the dynamo was believed to operate within the convection zone, the magnetic flux on the photospheric surface could be regarded as a direct signature of the dynamo action. If the magnetic flux were generated in the convection zone just below the photospheric surface and then emerged to the surface due to magnetic buoyancy, then the latitudes at which the sunspots were appearing could be regarded as indicating the regions where the flux was actually being generated by the dynamo. However, if the dynamo action takes place in the overshoot region, then the magnetic flux at the photospheric surface can no longer be regarded as a direct signature of the dynamo. The whole of the convection zone separates the overshoot region where the magnetic flux is generated and the photospheric surface where the flux ultimately emerges. In order to understand the connection between the dynamo-generated magnetic field and the magnetic fields on the solar surface, one then has to study the intermediate physical processes which cause the dynamo-generated flux to emerge eventually on the photospheric surface after making a transit through the whole of the convection zone.

As far as we know, Paper I was one of the first attempts to look into this problem.