A NEW MODEL FOR FLUX EMERGENCE AND THE EVOLUTION OF SUNSPOTS AND THE LARGE-SCALE FIELDS

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Abstract. Existing models for the evolution of sunspots and sunspot groups, describing the subsurface structure of the magnetic fields and their interactions with the convective motions, are briefly reviewed. It is shown that they are generally unable to account for the most recent data concerning the relationship between the large-scale solar magnetic field structures and the magnetic fields of active regions. In particular, it is shown that the former do not arise directly from the decay of the latter, as required by the Babcock model and all other models based on it. Other observations which are not adequately explained by current models are also cited.

A new model is put forward based on the expulsion of toroidal magnetic flux by the dominant (i.e. giant) cells of the convection zone. The flux expelled above these cells forms the large-scale field and thus the configuration of this field provides a clue to the structure of the giant cell patterns. The flux expelled below the cells becomes twisted into a rope as in the Babcock model but a loop or stitch forms only in the region of upflow of the giant cells. The interaction of this loop with intermediate-sized cells as it rises to the surface determines the configuration and extent of the active region which appears at the surface. The compatibility of the model with other observations is discussed and its implications for theories of the solar cycle are noted.

1. Introduction

All existing models for sunspot structure and evolution are based on Babcock’s (1961) concept of a loop or stitch which forms in a toroidal flux rope near the bottom of the convection zone and drifts upwards under the influence of buoyancy. As the loop breaks the surface, the magnetic flux expands outwards against the weakened gas pressure, leaving two regions of opposite polarity at the surface, within which the leader (L) and follower (F) polarity spots are formed.

As the spots decay, Babcock’s model assumes that the fields associated with them diffuse away from the region and eventually form part of the large-scale background field. Leighton (1969) has proposed a model in which the fields arising from the decay of the F spots execute a random walk, across the supergranules, towards the poles where eventually they produce the polar reversal for each 11-year cycle.

Babcock’s model was intended to explain the properties of the solar cycle and did not attempt to provide a detailed model for the formation and decay of sunspot pairs and groups within the cycle. Thus his time scale was 22 years rather than several months. However, during the past decade, several attempts have been made to provide
more detailed models within this shorter time scale to account for the observed properties of sunspot evolution.

Piddington (1975, and subsequent papers) emphasizes that the rising flux rope should be helically twisted and that the twist plays an essential role in the stability and ultimate decay of the spot. He also stresses that the plasma within the rope remains essentially isolated and does not interact at all with the velocity fields of the convection zone. Zwaan (1978) disagrees with Piddington concerning the importance of helical twist but shares his concept of a compact rising flux rope which is unaffected by the supergranule motions. They both adopt the Babcock model for the origin of the large-scale field.

On the other hand, the models of Ponomarenko (1972), of Meyer et al. (1974) and of Parker (1979) require a more prominent role for the supergranules, assuming that, as the flux rope breaks the surface, it is dispersed into small intense flux tubes which are then concentrated by the supergranule motions. Further, the Meyer et al. model envisages that, as the L spot reaches its maximum development, the direction of the supergranule flow adjacent to the spot reverses, being outwards near the surface, and inwards below, thus stabilizing the spot during the slow decay phase.

Both Parker and Meyer et al. envisage some penetration of smaller-scale eddies into the subsurface flux rope. Parker requires that these give rise to downflow which stabilizes the collection of individual flux tubes below the surface. Both assume that some form of modified convection within the flux rope provides the energy radiated by the umbra.

In a recent review of these models, Wilson (1981) concluded that none provides an adequate account of the modern data concerning sunspot evolution (reviewed by McIntosh, 1981). Here we discuss in some detail the qualitative data which conflict with the current picture of the evolution of sunspot and large-scale fields and put forward an alternative model which is compatible with these data.

We would emphasize that these data cover several different phenomena. Perhaps the most important result is that contained in Section 2 below; i.e., that the large-scale magnetic field patterns do not necessarily arise from the diffusive decay of active region (sunspot) fields. Clearly, quantitative evidence in support of this and other results is necessary before they can be fully accepted. However, we think it is important at this time to draw together these qualitative results and to point out their theoretical consequences in order to encourage the necessary quantitative investigations.

2. Origin of Large-Scale Fields Separate from Sunspots

It has been shown that the large-scale Hα patterns on the solar surface are identical with the large-scale solar magnetic fields measured with solar magnetographs (McIntosh et al., 1976; Duvall et al., 1977; McIntosh, 1979). Hα synoptic charts are preferred over the synoptic magnetograms in studies of the structure and evolution of large-scale magnetic field because of (a) their superior spatial resolution in defining the boundaries of large-scale features, (b) their better clarity in showing the organization of these fields into long-lived and coherent features (McIntosh, 1980, 1981), and (c) the homogeneity of the data back to, at least, the beginning of solar cycle 20 (1964). Thus the systematic