

The Evolution Of The Magnetic Structure of the Solar Corona With The Solar Cycle

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Abstract. The shape of the solar corona changes with the solar cycle, presumably due to the evolution of the large scale coronal magnetic fields. The coronal fields are actually the extensions of the large-scale photospheric fields. The dynamics and evolution of these fields are believed to be governed by the dynamics of the convection zone. Recently a vector model has been built up by Dikpati & Choudhuri (1994) to explain theoretically the observed photospheric features of these evolving diffuse fields by considering the joint effects of a dynamo action at the base of the convection zone, a meridional circulation and a turbulent diffusion inside the convection zone. These weak, large-scale, diffuse fields are extended above the photosphere by assuming a potential field model of the solar corona up to the source-surface at approximately $2.5 R_{\odot}$, where the field lines become radial due to the stretching of the solar wind. Thus the structure of large-scale coronal magnetic fields has been obtained and the evolution of this structure shows the latitude-variation of open field regions, presumably the positions of coronal holes and the source of steady, high-speed streams, with solar cycle.

1. Introduction

Many interplanetary phenomena crucially depend on the magnetic structure in the lower corona. The steady, high-speed solar wind originates from the coronal holes. These high-speed streams rotate with the Sun with the equatorial rotation period and their rotation past the Earth is highly correlated with the recurrence of geomagnetic storms. The coronal magnetic fields are also directly responsible for the coronal mass ejections (CMEs) and the flare-produced accelerated particles. CMEs are believed to be the large-scale eruptions of closed magnetic structures and are associated with interplanetary shocks (Cane et al. 1987) and energetic particle events (Kahler et al. 1984). Hence a study of the

evolution of coronal magnetic fields is the first step towards understanding many interplanetary processes which eventually effect the Earth's magnetosphere in the form of geomagnetic storms.

Since the pioneering work of Altschuler & Newkirk (1969), most models of the coronal fields have been constructed by using photospheric magnetic data as the boundary condition (Wang & Sheeley, 1992). In this approach, no account is taken of the magnetic field underneath the photospheric surface, and no attempt is made to connect the evolution of the coronal magnetic fields with the dynamo process which is responsible for the generation of the magnetic fields. Dikpati & Choudhuri (1994, 1995) had developed a model for the evolution of the dynamo-generated poloidal field in the convection zone. This model enables us to study the coronal fields in conjunction with the fields in the interior of the Sun and thereby opens up the possibility of connecting the coronal evolution with different aspects of the solar cycle including the dynamo process.

2. The Theoretical Model

The solar magnetic field is believed to be generated by the dynamo action at the base of the convection zone, where a dynamo wave propagates equator-ward (Choudhuri 1990, Parker 1993). The sunspots are identified with the dynamo-generated toroidal magnetic field migrating equator-ward with the dynamo wave. The weak, diffuse fields (Hale 1913, Babcock & Babcock 1955) outside the sunspots evolve in an opposite fashion (Makarov & Sivaraman 1989; Wang et al. 1989). These fields can be identified as the poloidal fields generated by dynamo action. There is evidence of meridional circulation inside the solar convection zone and it is equator-ward at the bottom and pole-ward at the top (Komm et al. 1993). In the previous work by Dikpati & Choudhuri (1994, 1995), it has been shown that under the joint actions of equator-ward propagating dynamo wave at the base of the convection zone and the equator-ward subsurface flow, the poloidal fields first move towards the equator where they join with their opposite hemisphere counterparts to form magnetic bubbles. The upwelling flow at the equator pushes these bubbles up. So, after reaching the surface, they are detached from their counterparts and drift towards the pole with the pole-ward surface flow, thus explaining the evolution of weak, diffuse fields.

The evolution of these fields inside the convection zone is governed by the induction equation which, for an axisymmetric poloidal field ($\mathbf{B} = \nabla \times [A(r, \theta, t)\hat{e}_\phi]$), reduces to the following scalar equation:

$$\frac{\partial A}{\partial t} + s^{-1}(\mathbf{v}_p \cdot \nabla)(sA) = \eta(\nabla^2 - s^{-2})A, \quad (1)$$

where $s = r \sin \theta$ and \mathbf{v}_p and η represent the meridional flow and the turbulent diffusivity respectively. The Equation(1) has been solved (Dikpati & Choudhuri 1994, 1995) numerically within the convection zone with a specified meridional circulation \mathbf{v}_p . An equator-ward propagating dynamo wave is taken as the lower boundary condition and acts as the source of these fields. At the equator, the field lines of two hemispheres match smoothly, and at the pole, $A = 0$ to keep the solution nonsingular.

Above the surface, the current free approximation of the solar corona has been used up to $2.5 R_{\odot}$ above which, the solar wind drags the field lines into radial direction along with it. So the field lines satisfy the Laplace's Equation $((\nabla^2 - s^{-2})A = 0)$ up to $R_w (= 2.5R_{\odot}$ here) and the correction due to the stretching of the solar wind has been taken into account (Altschuler & Newkirk 1969) at $r = R_w$. The solution above the surface has been given by,

$$A(R_{\odot} \leq r \leq R_w, \theta, t) = \sum_n \frac{a_n(t)}{r^{n+1}} P_n^1(\cos \theta) \left[c_n + (1 - c_n) \left(\frac{r}{R} \right)^{2n+1} \right], \quad (2)$$

Here $P_n^1(\cos \theta)$ is the associated Legendre's polynomial and the summation is over all the odd values of n . The coefficients c_n 's are found by demanding that

$$B_{\theta} = 0 \quad \text{at} \quad r = R_w,$$

which gives

$$\frac{1}{c_n} = 1 + \frac{n}{n+1} \left(\frac{R}{R_w} \right)^{2n+1}. \quad (3)$$

The upper boundary condition was applied by demanding the smooth matching of the field lines coming from the convection zone satisfying Equation(1) with the field lines above the photosphere satisfying Equation(2).

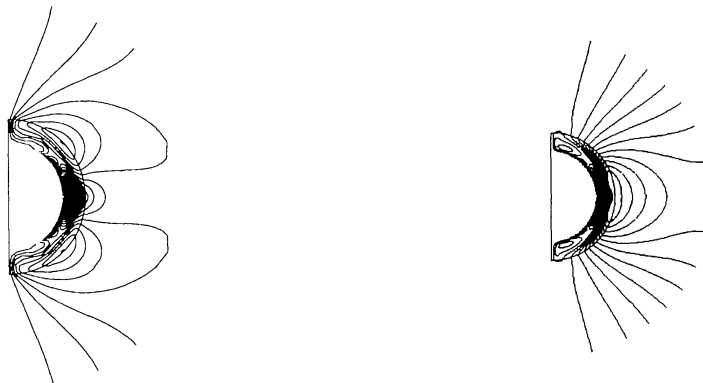


Figure 1. (a) Coronal magnetic fields during solar minimum (left). (b) Coronal magnetic fields during solar maximum (right).

3. Results

The surface features of these weak, diffuse fields were matched (Dikpati & Choudhuri 1995) with observations by adjusting the circulation pattern and turbulent diffusion suitably. Using those parameters, we show in Fig. 1(a) – 1(b) the snapshots of coronal magnetic fields during solar minimum and maximum phase. The constant $Ar \sin \theta$ contours up to $2.5 R_{\odot}$ have been plotted to obtain these magnetic structures of the corona. From these two plots, it is found that the coronal magnetic structure varies quite significantly from a solar minimum phase to a solar maximum phase during a solar cycle. The open field regions may be assumed to form the coronal holes (Pneuman et al. 1978; Levine 1982; Wang & Sheeley 1990). The appearance of these regions near the pole in Fig. 1(a) (i.e. during solar minimum) is in agreement with the observation of polar coronal hole during sunspot minima. On the other hand, near sunspot maximum, the polar hole recedes and an isolated coronal hole appears at lower latitude (Wang & Sheeley 1990). The presence of open field regions at slightly lower latitude in Fig. 1(b) represents this fact. Figs. 2(a) and 2(b) show the iso-gauss contours corresponding to Fig. 1(a) – 1(b) respectively. If the corona is assumed to be magnetically heated mainly, then the uniform iso-gauss contours in Fig. 2(b) predict the more circular corona during the solar maximum than during the solar minimum.

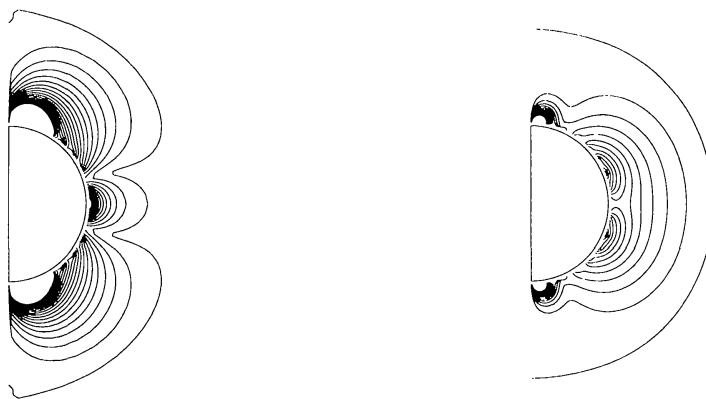


Figure 2. (a) Iso-gauss contours of coronal magnetic fields during solar minimum for Fig. 1a (left). (b) Iso-gauss contours of coronal magnetic fields during solar maximum for Fig. 1b (right).

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Group Discussion

White: Your model could be improved by considering the observational constraint that magnetic flux in active complexes emerge at $\sim 35^\circ$ latitude (L), and moves towards the equator during the cycle. Above $L \sim 35^\circ$, weak fields move towards the poles. Thus there appears to be a break in meridional motion at about $L \sim 35^\circ$ that is a powerful constraint on models describing evolution of magnetic structure in the visible atmosphere.

Dikpati: Yes, we are recently working on that improvement considering the decay of active regions to be another source of these weak, large scale photospheric fields. Then during their evolution there would be two branches, one migrating poleward due to the meridional flow and another equatorward due to the drift of active regions.

Yoshimura: 1. The solar cycle coronal field evolution was studied from the surface field of a theoretical dynamo model. This model predicted evolution of coronal fields as predicted during eclipses.

2. The surface fields, both observed and theoretical, starts in the middle latitudes and one branch propagates towards the poles and other towards the equator. The variation of the coronal fields with the solar cycle reflects this aspect of the surface fields.

Dikpati: 1. We are studying not just the surface fields from the dynamo model. The dynamo operates at the base of the convection zone in our model. The

dynamo generated poloidal components have been studied under the effects of meridional circulation and turbulent diffusion. So, in turn, the evolution of these fields is showing the evolution of large scale coronal fields. This model enables us to study the coronal fields in conjunction with the fields interior of the Sun.

2. We are developing a more realistic model combining the dynamo generated poloidal fields and the decay of active regions to be the source of large scale diffuse photospheric fields. We hope that would produce both the polar and the equatorial branches of coronal fields evolving with the solar cycle.

Bellan: Your model is based on symmetric toroidal currents in the Sun. What generates the toroidal currents? Your model is toroidally symmetric. Dynamos require toroidal asymmetry so I do not see how your toroidal could be generated by a dynamo process.

Dikpati: Yes, antisymmetric magnetic fields cannot be sustained, this is the famous Cowling's theorem. In our model, we first consider that the poloidal fields are already generated by a suitable dynamo action. We have then studied the evolution of these fields inside the convection zone under the propagating dynamo wave, meridional circulation and turbulent diffusion. To explain the evolution we have formulated it mathematically where we have assumed axisymmetry for simplicity and this axisymmetry, for the time being, does not affect their evolution very much. Only the shape of these fields will change slightly. Instead of being like I had depicted in the figures, they will be a backward 'C' type due to the asymmetry (see Wand & Sheely 1992, for details).

Bromage: *Yohkoh* SXT images show a rising and falling of magnetic loops which produces a bubbly effect when speeded-up. What is the time scale of the bubbling in your model? Does this correspond to what is seen in the *Yohkoh* data?

Dikpati: The rising magnetic bubble from the base of the convection zone up to the surface, in our model, depends on the convection zone parameters, such as, the value of the turbulent diffusivity, the up-welling flow speed, concentration of meridional circulation at the equator, etc. The time scale of rising of the bubble, here is approximately few years.