ON THE ORIGIN OF CURRENT HELICITY IN ACTIVE REGIONS

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ABSTRACT

Observations indicate that solar active region magnetic fields have a predominantly negative (positive) helicity in the northern (southern) hemisphere. This helicity is likely to have a subsurface origin. One possible explanation for the helicity is that the rising toroidal flux tube causing the active region collects flux from the general poloidal magnetic field of the Sun. This flux first wraps around the rising tube, then slowly penetrates it by turbulent diffusion. Here we present recent results concerning how this nonlinear diffusion proceeds. The models show that with a plausible choice of assumptions a mean twist comparable to the observations results.

Key words: Sun; MHD; magnetohydrodynamics.

1. INTRODUCTION

Magnetic fields in solar active regions are known to possess helicity. Observational determinations of the current helicity density $h_{c} = \mathbf{B} \cdot (\nabla \times \mathbf{B})$ have established a higher occurrence of negative (positive) helicity in the northern (southern) hemisphere. The observations show that the typical average value of the current helicity parameter $\alpha_{p} = h_{c}/B^{2}$ in an active region is on the order of $10^{-8}$ m$^{-1}$ (van Driel-Gesztelyi et al. 2003). All current methods yield a single mean value of $\alpha_{p}$ over the whole active region. This is because the low $S/N$ ratio of vector magnetograph measurements inhibits a reliable study of current helicity distribution along the plage. For the same reason, usually only pixels with relatively high field strength ($B > 100$ G or so) are used in the determination. It is to be hoped that future improvements in magnetograph sensibility will remedy this situation.

The basic question regarding the origin of the observed magnetic helicities is whether they are generated after the emergence of the flux loop or the flux emerges already in a helical form. In an important paper Pevtsov et al. (2003) studied the time development of the helicity in young, emerging active regions and found a good correlation between emergence rate and helicity increase. In particular, further increase of helicity ceases once the emergence of the loop, as measured by the increase in footpoint separation and area growth, comes to a halt. This observation seems to settle the issue in favor of a subsurface origin of the observed twist.

Proposed mechanisms which may naturally introduce twist in the structure of emerging flux loops include helicity generation by the solar dynamo (Miesch et al. 2003) and buffeting of the rising flux tubes by helical turbulent motions (Longcope et al. 1998). A further possibility is the effect of Coriolis force on flows in rising flux loops (Fan and Don 2000). This latter process is responsible for the generation of positive writhe in active region flux tubes in the northern hemisphere, and thereby for the observed tilt of active regions. As magnetic helicity is conserved in ideal MHD (Berger 1999), the same process should then also give rise to a twist of opposite sense, so that the net helicity remains constant. The amount of helicity generated by this process, however, is too low to explain the observed values of $\alpha_{p}$. On the other hand, a strongly twisted flux tube can develop a writhe by means of the kink instability. This mechanism should lead to a positive correlation of twist and writhe, in contrast to the helicity preservation argument above. Indeed, recent observations by López Fuentes et al. (2003) and Holder et al. (2004) indicate that this mechanism may be important in the case of at least some active regions with unusually high tilt.

A further possible theoretical explanation of the observed helicity was proposed by Choudhuri (2003), who suggested that the poloidal flux in the solar convection zone (SCZ) gets wrapped around a rising flux tube, as sketched in Fig. 1. Choudhuri et al. (2004) later showed that this mechanism gives rise to helicity of the same order as what is observed. Choudhuri et al. (2004) also used their dynamo model to calculate the variation of helicity with latitude over a solar cycle and found that the latitudinal distribution of helicity from their theoretical model is in broad agreement with observational data.

In order to produce a twist in the flux tube, the poloidal field needs to diffuse from the sheath into the tube by turbulent diffusion. However, turbulent diffusion is strongly
Figure 1. During the rise of a toroidal flux tube (here shown in cross section, hatched) through the convective zone, field lines of the weak external poloidal field may get wrapped around it. After Choudhuri (2003).

suppressed by the magnetic field in the tube. In order to study to what extent the wrapped up poloidal field can penetrate the flux tube, we modelled this nonlinear diffusion process and we studied the evolution of the magnetic field in the rising flux tube, as it keeps collecting more poloidal flux during its rise and as turbulent diffusion keeps acting on it.

2. MODEL

The nonlinear diffusion of magnetic field in a strong flux tube of finite thickness was studied in an untwisted flux tube by Petrovay and Moreno-Insertis (1997). The model was subsequently successfully applied for sunspot decay (Petrovay and van Driel-Gesztelyi 1997). In the work presented here we extended this model by including the poloidal component of the magnetic field (i.e. the field which gets wrapped around the flux tube) and we studied the evolution of the magnetic field in the rising flux tube, as it keeps collecting more poloidal flux during its rise and as turbulent diffusion keeps acting on it. Further details can be found in Chatterjee et al. (2006)

Consider a straight, cylindrical, horizontal magnetic flux tube rising through the solar convective zone. As all variables in this model depend only on the radial distance \( r \) from the tube axis and on time, we study the wrapping of the large-scale poloidal field around the flux tube by considering a radially symmetric accretion of azimuthal field by the flux tube. A further complication is the expansion of the flux tube during its rise, due to the decrease of the external pressure. This expansion is assumed to be self-similar, so that the Lagrangian radial coordinate \( \xi \) is related to the Eulerian radius \( r \) by \( \xi = F(t)r \), where the expansion factor \( F(t) \) was taken from thin flux tube emergence models. In the Lagrangian frame, flux density is rescaled as \( B'_\xi = B_\xi/F^2 \) and \( B'_\phi = B_\phi/F \). With these notations and assumptions, the induction equation takes the form

\[
\frac{\partial B'_\xi}{\partial t} = F^2 \frac{1}{\xi} \frac{\partial}{\partial \xi} \left( \eta \frac{\partial B'_\xi}{\partial \xi} \right)
\]

(1)

\[
\frac{\partial B'_\phi}{\partial t} = F^2 \frac{\partial}{\partial \xi} \left[ \frac{1}{\xi} \frac{\partial}{\partial \xi} (\xi B'_\phi) \right] - F \frac{\partial}{\partial \xi} (v B'_\phi).
\]

(2)

(Note that the advection term with the rise speed \( v \) appears in the \( \phi \) component only, as it does not represent a truly radially symmetric inflow; instead, it is just designed to mimic the effect of the wrapping of poloidal field lines around the rising tube.) The magnetic diffusivity \( \eta \) is specified in the form

\[
\eta = \frac{\eta_0}{1 + \left( B/B_{eq} \right)^2}
\]

(3)

All our calculations are performed for a flux tube of flux \( 10^{22} \) Mx and initial field strength \( 10^5 \) G.

Numerical solutions of the equations are presented in the figures. The conclusions drawn from our model hinge on some assumptions, especially concerning the subsurface magnetic field structure in the last phases of the rise of the tube. The field strength in the rising tube, as calculated from thin flux tube emergence models, decreases well below the turbulent equipartition value \( B_{eq} \) near the surface \( (B_{eq}/\mu_0)^2 = \nu v^2 \), \( \nu \) being the r.m.s. turbulent velocity. The presence of 3000 G magnetic fields in sunspots is a compelling proof that magnetic fields may never fall to such low values; in fact, at least in photospheric layers, they are at about 3\( B_{eq} \). This is presumably the result of flux concentration processes such as turbulent pumping and convective collapse. Thus, it may be more realistic not to allow the magnetic field to fall below 3\( B_{eq} \). Figs. 2–4 present results without and with such a constraint, respectively.
Figure 3. Same as Fig. 2, but the field inside the flux tube is not allowed to decrease below $B_{eq}$ at any height (case B1). The values of $(B/B_{eq})$ at the centres of these flux tubes at these positions are 10, 1.72, 1.0, 1.0, 1.0, respectively.

Inspecting the lower panels of the figures one finds that the typical value of $\alpha_p$ in the internal parts of the flux tube is of order $\sim 10^{-3}$ m$^{-1}$ at a depth of $0.85R_\odot$ in both cases. However, as the flux reaches the solar surface, in case A the $B_p$ component spreads out due to diffusion and its gradient becomes smaller, reducing $\alpha_p$ by about one order of magnitude. Only if the magnetic field inside the flux tube remains stronger than the equipartition field (the case B2) is the $B_p$ component unable to diffuse inside so that its gradient remains strong and $\alpha_p$ is of order $\sim 10^{-8}$ m$^{-1}$ even near the surface. This value is close to what is observed, suggesting that our case B may be closer to reality, i.e. during the rise of the flux tube from $0.9R_\odot$ to $0.98R_\odot$ effective flux concentration processes are at work, keeping the field strength at a value somewhat above the equipartition level.

3. CONCLUSION

It is likely that the accretion of poloidal fields during the rise of a flux tube is just one contribution to the development of twist. Its importance may also be reduced by 3D effects: considering the rise of a finite flux loop instead of an infinite horizontal tube, the possibility exists for the poloidal field to “open up”, giving way to the rising loop with less flux being wrapped around it. It is left for later multidimensional analyses of this problem to determine the importance of any such reduction. In any case, the results presented above indicate that the contribution of poloidal field accretion to the development of twist can be quite significant, and under favourable circumstances it can potentially account for most of the current helicity observed in active regions.

Note that in the calculations presented here the poloidal field was assumed to be 1 G, independent of depth. For alternative assumptions, significantly different current helicities may result, so the above conclusion should be treated with proper reservation. Details of the radial dependence of the poloidal field strength may strongly depend on the dynamo model.

Nevertheless, a robust feature of the current helicity distributions, present in all the lower panels of our plots, is the presence of a ring around the tube with a current helicity of the opposite sense. This is clearly the consequence of the fact that on the outer side of the accreted sheath the radial gradient of the azimuthal field, and thus the axial current, is negative. This is an inevitable corollary of the present mechanism of producing twist in active regions. A rather strong prediction of this model is, therefore, that a ring of reverse current helicity should be observed on the periphery of active regions, somewhere near the edge of the plage.

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