MULTI-MODE KINK INSTABILITY AS A MECHANISM FOR δ-SPOT FORMATION

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ABSTRACT

We investigate the current driven kink instability of twisted magnetic flux tubes in the solar convection zone. The possibility that kinking flux tubes are responsible for the formation of some δ-spot active regions provides the motivation for this work. We simulate the evolution of a twisted flux tube with a highly parallelized three dimensional MHD spectral code run on a 128 cubed grid. We find that highly twisted flux tubes, when perturbed with a single wavenumber mode, develop large kinks which lead to δ-spot tilt angles as large as 60°. We find that when tubes are perturbed with multiple wavenumber modes, the modes can interact to create a localized kink tilted by as much as 80° with respect to the unkinked portion of the tube. We show that this kind of kinked flux tube can create a δ-spot configuration with opposite polarity spots emerging and remaining in close proximity to each other, with shear developing along the neutral line as the region develops, and with the opposite polarity regions rapidly rotating about each other.

INTRODUCTION

δ-spot active regions are a special class of active regions where sunspot umbra of opposite polarity exist within the same penumbra (Zirin 1988, p.337). It is commonly held that active regions are the manifestation in the photosphere of a magnetic flux tube which arches up into the corona from the convection zone. The two opposite polarity spots of a bipolar active region are created by the intersection with the photosphere of the two legs of this arched flux tube. The close proximity of the opposite polarity spots of a δ-spot active region indicate that something forces the legs of the flux tube to remain close together. Other commonly observed properties of δ-spots, namely that the two spots rotate about each other as they evolve and that they develop magnetic shear along the magnetic neutral line between them, indicate that these active regions may be caused by kinked flux tubes, as first suggested by Tanaka (1991).

The current driven kink instability affects twisted magnetic flux tubes, distorting their initially cylindrical configuration into a helical shape. This instability was first proposed by Alfvén (1950) (as a dynamo mechanism), in analogy with the observed kink instability in twisted wires. It has since been widely studied

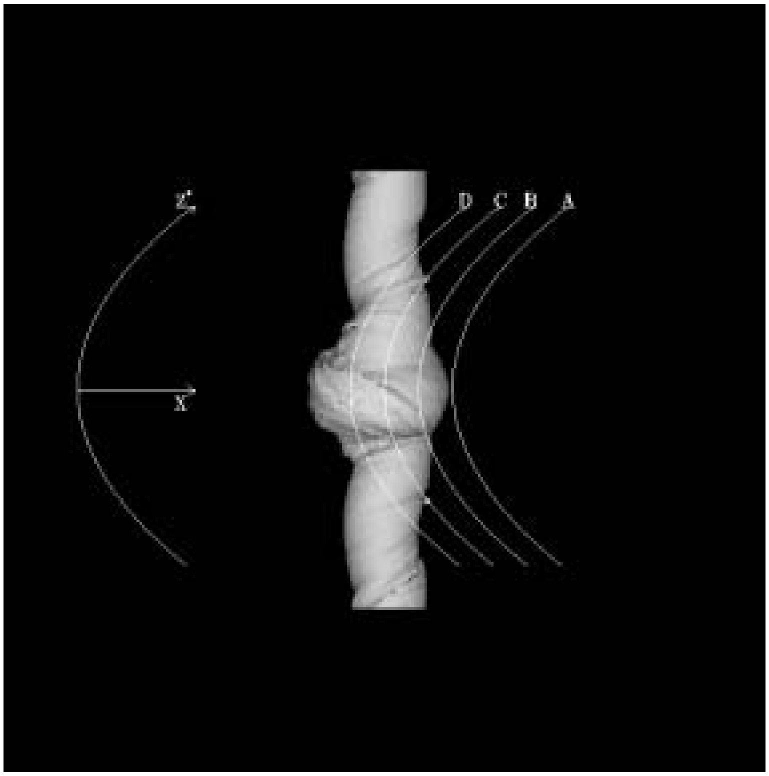

Fig. 1. Isosurface at $|B|^2 = |B_{max}|^2/6$ of the four mode kinked flux tube. Note the highly localized kink at the midplane of the tube.

in both nuclear fusion and solar applications (for linear calculations see review in Priest, 1982 p.259; and Linton *et. at*, 1996; for recent nonlinear simulations see Matsumoto *et al.*, 1998; Fan *et al.*, 1998; Linton *et al.*, 1998; and Galsgaard & Nordlund, 1997). Our goal here is to simulate this instability in a high plasma pressure environment appropriate to the convection zone, and to look for kinks which can create active regions with the aforementioned δ-spot characteristics.

SIMULATIONS AND RESULTS

We performed fully three dimensional magnetohydrodynamic simulations of the kink instability using a visco-resistive, periodic, spectral code on a 128^3 grid. For more details on the code, run on the Naval Research Laboratory's CM500e, see Dahlburg & Norton (1995). We embedded an initially cylindrically symmetrical twisted magnetic flux tube in a gas with β, the ratio of gas to magnetic pressure on axis, of 600. The form of the magnetic field used was

$$\begin{aligned} B_z &= B_0(1 - \frac{r^2}{R^2})^{.25}, \\ B_\theta &= 7.5 r B_z, \end{aligned} \tag{1}$$

for $r \leq R$, and $\mathbf{B} = 0$ for $r > R$. r here is the radial coordinate in cylindrical coordinates, and R is the tube's external radius ($\pi/4$ in units where the simulation box is 2π on a side). This is not a force free configuration: the initial plasma pressure profile is set so that the tube is in pressure equilibrium. At the start of each run, we perturbed this equilibrium profile with a helical velocity profile ($v \sim e^{i(\theta+kz)}$), with a wavenumber k to which, according to linear stability calculations, the tube is kink unstable.

We performed four simulations where the tube was excited with only one wavenumber perturbation: $k = -1$, -2, -3, and -4. All four simulations produced helically symmetric kinks with tilts of about 60°, 60°, 50°,

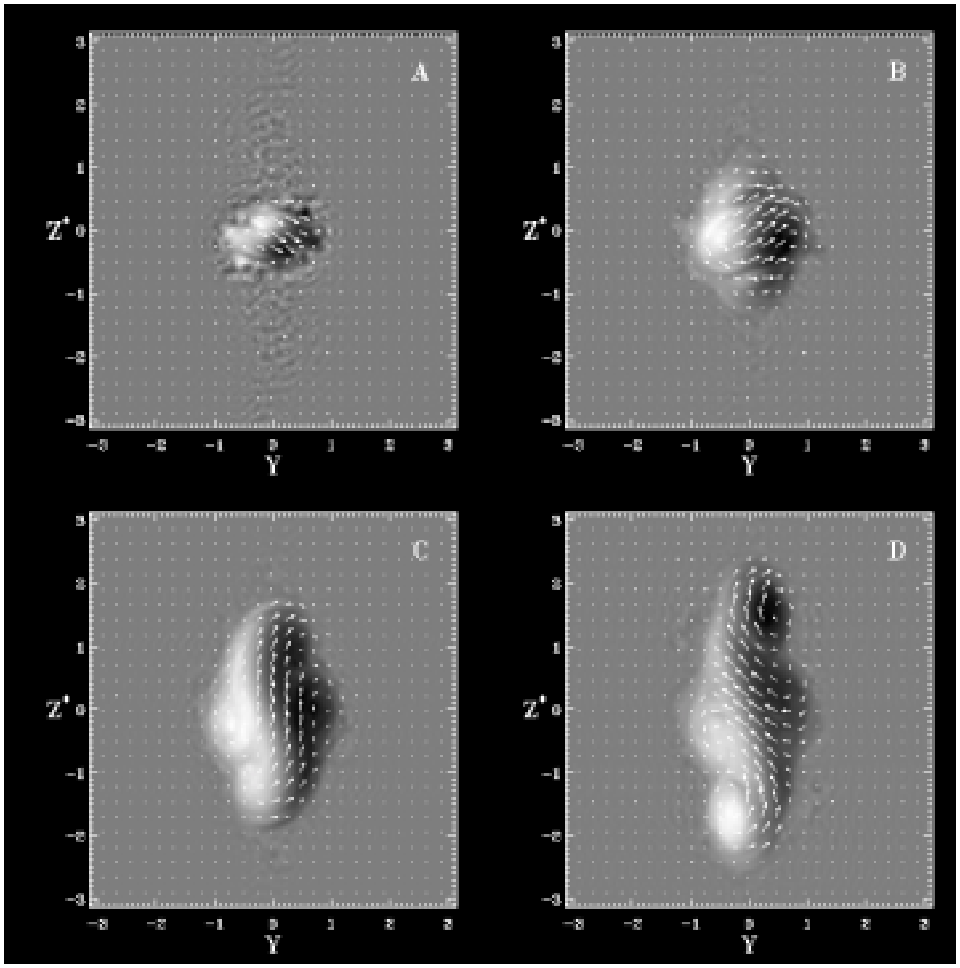

Fig. 2. Magnetogram of δ-spot resulting from the emergence through the photosphere of the kinked flux tube pictured in Figure 1. The letters refer to the planar slices shown in Figure 1, the grayscale shows the magnetic field perpendicular to the plane, the vectors show the magnetic field in the plane.

and 35°, respectively. All therefore could produce large tilts in an active region, with the trend being that lower $|k|$ kinks produce larger tilt angles. We then performed two simulations where different wavenumber instabilities were excited simultaneously: a two mode simulation ($k = -3$ and $k = -4$), and a four mode simulation ($k = -1$, -2, -3, and -4). These simulations produced kinks which were localized at the midpoint of the tube, where the different modes interfered constructively. The resulting tilt angles were larger than any of the tilts the four single mode kinks produced: 70° for the two mode kink, and about 80°, for the four mode kink. Thus the interaction of multiple modes in a kink instability, which is what one would expect to happen if the kink instability were excited by turbulent motions in the convection zone, can produce larger tilt angles than a solitary mode would produce.

The final configuration of the four mode kink is shown in Figure 1, where the surface of constant magnetic field strength $\mathbf{B}^2 = \mathbf{B}^2_{max}/6$ is displayed. One can see that there is a single concentrated kink at the center of the tube which is highly tilted with respect to the rest of tube which remains relatively unkinked. To see what kind of active region this kinked tube would produce as it emerged into the photosphere, we take slices through the tube at various positions to represent the intersection of the tube with the photosphere at various times. Our tube was initially straight (due to the periodicity of our code) but we expect a real convection zone flux tube to be arched. To correct for this geometry, we take slices given by curved surfaces, shown in Figure 1. These curved slices through a straight tube are therefore meant to approximate what one would see from taking straight slices through a curved tube. The magnetic field on these surfaces is plotted in Figure 2. The lettered panels showing successive times snapshots during the tube's emergence correspond to the lettered slices in Figure 1. The grayscale shows the magnetic field perpendicular to the surface, and the vectors show the field lying in the surface. One can see that the opposite polarity spots remain close to each other (in fact in contact) as they evolve, that they rotate about each other, and that they develop strong shear along the neutral line between them.

CONCLUSION

We found that a highly twisted magnetic flux tube in a high β environment can be unstable to a kink instability which produces tilt angles of as much as 60° for single mode kinks, and as much as 80° for multi-mode kinks. We found that the multi mode simulations produced kinks localized at the center of the tube, where the modes were all in phase. These multi-mode, concentrated kinks can reproduce the observed properties of δ-spots in that they produce close, rapidly rotating spots with shear along their neutral line.

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