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Theoretical Model of Traveling Convection Vortices

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RESUMEN

Se ha construido un modelo teórico para explicar la formación de vórtices convectivos migratorios. El modelo propone que los vórtices viajeros corresponden a inestabilidades tipo "Kink" generadas en las regiones magnetosféricas, donde la corriente es suficientemente fuerte para crear un campo acimutal B_θ del mismo tamaño que la componente del campo alineada B_2 en el plano ecuatorial. Se supone que en estas regiones (alrededor de 4_e) esta corriente produce un campo magnético acimutal que origina una clase de inestabilidad conocida como tipo "Kink". Los resultados de los cálculos hechos en el modelo, basados en valores típicos observados a bordo de naves espaciales, se han comparado con los patrones de los vórtices convectivos migratorios deducidos a partir de magnetómetros en tierra.

Los filamentos múltiples de corriente que son observados frecuentemente en estos patrones se propone que tienen su explicación en la incidencia de inestabilidades tipo "Kink" en la megatosfera.

ABSTRACT

A theoretical model has been constructed to explain the formation of traveling convection vortices. This model proposes that traveling convection vortices correspond to kink instabilities generated in magnetospheric regions where the current is strong enough to create an azimuthal field B_θ of the same size as the field aligned component B_z in the equatorial plane. It is assumed that in these regions (around $4R_e$), this current produces an azimuthal magnetic field which creates a kind of instability, known as the kink instability. The results of model calculations based on typical values observed on spacecraft have been compared with the patterns of traveling convection vortices derived from ground based magnetometers.

The multiple current filaments which are often observed in these patterns are proposed to be explained by the occurrence of kink instabilities in the magnetosphere.

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1. Introduction

Conspicuous ionospheric features in the dayside at auroral latitudes are the traveling convection vortices proposed by Friis-Christensen *et al.* (1988), Glassmeier *et al.* (1989), Glassmeier and Heppner (1992), to be possible ionospheric signatures of solar wind magnetosphere coupling processes. They identified traveling small-scale ionospheric current systems which are associated with series of field-aligned currents filaments moving rapidly along the cleft. The field aligned currents filaments normally occur in pairs, creating a basic twin vortex convection pattern in the ionosphere, with a size of order 1000-3000 km. These vortices are tipically observed during 15 minutes and they move anti sunward with velocities of aproximatelly 5km/s. Friis-Christensen *et al.* (1988), Potemra *et al.* (1992), Glassmeier and Heppner (1992) modeled the field distribution assuming that the field aligned currents densities are around 3×10^{-6} A/m^2. McHenry *et al.* (1990b) proposed that the vortices could be due to Kelvin-Helmholtz instability in the low latitude boundary layer. However, the hypothesis was not satisfactory in describing all the aspects of the data like for example the growth rate of the instability or the datails of the pattern of the magnetic field and currents. The present model proposes that traveling convection vortices are created by kink instabil-ities in the magnetosphere due to an azimuthal field B_θ growing relative to B_z, the magnetic field along the field lines. To have an idea about the model, let us to imagine that we have $B_z = 0$ meaning no longitudinal magnetic field, and B_θ, produced by a longitudinal current density J_z within the plasma. We suppose a poloidal symmetric radial perturbation which constricts the plasma column in one place and makes it bulge out in other places. Since the same total current flows through the constricted area, the B_θ field at the plasma surface is increasing, and the enhancement of the magnetic pressure makes the constriction contract further. This instability is called sausage instability or the $m = 0$. It is inhibited if a longitudinal B_z field is present, because the perturbation is forced to compress this field. To stabilize the instability it is necessary to add a small longitudinal field but this provocates a new instability called the kink instability (Bateman *et al.*, 1974). For the kink instability ($m = 1$) the distortion grows because the magnetic pressure on the concave side, it is increased (the B_θ lines are closed together), while on the convex side, it is decreased (the B_θ lines are further apart). The parameter describing the probability of this instability is called Kruskal- Shafranov stability criterion and is normally described by the letter q. This parameter shows whether the plasma is unstable or not, and also whether the m=1 instability takes place. It is given by:

$$q = \frac{krBz\left(r\right)}{B\theta\left(r\right)} \tag{1}$$

here $k = 2\pi/L$, where L is the length and r is the radius of the cylinder. For $q < 1$ the m = 1 kink mode is unstable, whereas it is stable for $q > 1$. Let us imagine that the region where the phenomena occurs is a large cylinder with radius "a" and length $L=8 \times a$; for this case the main requeriment for $q < 1$ is that B_θ is of the order of B_z. An instability is a process in a which free energy in the plasma is exponentially converted into fluctuating electromagnetic field energy. As the field energy grows, a nonlinearity of the plasma may cause a change in some quantities which may or may not be directly involved with the instability, they may cause the instability to saturate. Two types of effects result: effects on the plasma particles and effects on the waves. This agrees partly with the hypothesis presented by Glassmeier (1989), implying that large currents in the magnetosphere may eventually become unstable and potentially lead to particle acceleration supported by the observations of dayside auroral activity associated with such twin-vortex systems. In fact, the currents create a new magnetic field and this magnetic field could be responsible for this instability. This paper is organized as follows; in section (1) the model and the formulation of kink instabilities in the magnetosphere is described, in section (2) is shown the results and conclusions.

2. Theoretical Model

In this simple model the auroral region of the magnetosphere is regarded as a circular cylinder with radius a and length L, and with boundary conditions, corresponding to perfectly conductor walls, using the MHD equations and cylindrical coordinates (Bateman, *et al.*, 1974). This kind of modeling of the magnetosphere has been done by for example Goertz *et al.* (1985). We model the magnetosphere by taking a long cylinder with magnetic field of the Earth. Inside of this cylinder a current created by several sources coming from the Low Latitude Boundary Layer is responsible for a rise in the magnetic azimuthal field, B_θ. This magnetic field initiates the instability and the present study of this instability is based on using the MHD equations. The standard MHD equations are in equilibrium and they have been applied to plasmas with scalar pressure in the steady state without flow, and without body forces. The instabilities are analysed by applying a perturbation to the equations. When the equations are considered in equilibrium this corresponds to the order zero of the equations and the quantities are unperturbed. The objective of this paper is to study the evolution of these values after the perturbation in the magnetosphere. The sources of this perturbation is the continuous enhancement of the azimuthal magnetic field relative to the magnetic field of the Earth. When the quantities are perturbed some of the terms in the equations will be of first order, some will be of the second order. In the perturbation analysis performed here only first order terms will be considered. The expression of the perturbed field is written in the form Bateman (1978),

$$\xi(r,t) = \xi(r)\exp(\gamma t + im\theta - kz) \tag{2}$$

This perturbation is substituted in the MHD equations. We also need some algebraic reduction. The first one is the definition of the total perturbed pressure, taking the thermodynamic pressure plus magnetic pressure as the total pressure. And

$$\nabla\xi = -\frac{\rho \times \gamma^2 (p* -(2/\mu r)(B_\theta)^2)\xi r}{(\rho \times \gamma^2 + F^2 / mu)\Gamma p^o} \tag{3}$$

where the total pressure is , $P* = \dfrac{p^1 + B^o . B^1}{\mu}$. To simplify these calculations, we set $\nabla\xi = 0$ which implies,

$$P* = \frac{2(B\theta)^2 \xi_r}{\mu} \tag{4}$$

where F stands for the scalar product of the wave vector and the equilibrium magnetic field,

$$F = \vec{K} \times \vec{B} = \frac{m}{rB_\theta - kB_z} \tag{5}$$

All the other perturbed variables are expressed in terms of $r\xi_r$ and p^*. After some algebraic calculations we finally get:

$$i\xi_\theta = (m/r)P^* - 2 \times B_\theta / \mu)F\xi_r\rho\gamma^2 + F^2/\mu \tag{6}$$

$$i\xi_z = -kp^*\rho\gamma^2 + F^2/\mu \tag{7}$$

and for the components of the magnetic field we get:

$$iB_r^1 = F\xi_r, \tag{8}$$

$$B_\theta = Fi\xi_\theta - r\xi \frac{\partial(B_\theta / r)}{\partial r}, \tag{9}$$

$$B_z = Fi\xi_z - \xi_r \frac{\partial B_z}{\partial r} \tag{10}$$

The solution to ξ_r is assumed consist of a Bessel functions because this agrees with the searched experimental solution. The value of the current is found by deriving the $\nabla \times B$. In simulation based on these equations valid for the magnetosphere we used the following parameters, $B_z = 830\text{nT}$ far from the Earth and the parallel current $J_Z = 10^{-6} A/m^2$. The reason for using this value of the magnetic field of the Earth comes from the necessity of this field to be weak enough for the kink instability to occur, obeying the basic criteria, $q < 1$. If we consider a current flowing along the field line from the auroral region to the ground, the cross section of the current as well as the unperturbed flux density B_z changes along the current path. However, because $B_\theta = \mu J / 2\pi a$ and $\pi a^2 B_z = const.$, we can see that the instability condition does not depend on position along the current path, and hence can be evaluated at any point. If we take as typical values near the ground, $B_z \sim 5 \times 10^4\gamma$, $L \sim 1.5 \times 5\ R_e = 4.7 \times 10^4$ km and $B_\theta \sim 200\gamma$, the circumferential length of the current cross section $2\pi a$ becomes smaller than 4.7×10^2 km. That is, if the current flows down into the ionosphere with a cross sectional radius of approximately 100 km, the instability occurs, and the current path is bent. The plots have been produced for the magnetic field and the total current has been compared with the results in several papers by Friis-Christensen *et al.* (1988), and Glassmeier and Heppner (1992). The plots shows the instability and the filamentary currents created, clearly we observe the two parallel currents appearing in opposite directions. The plots also show a similar behaviour for the magnetic field B_z. Several observations support such calculations of the kink instability, for example the one observed by Vogelsang *et al.* (1993). The observations of traveling convection vortices in one typical event is shown in Figure 1 by Glassmeier and Heppner (1992).

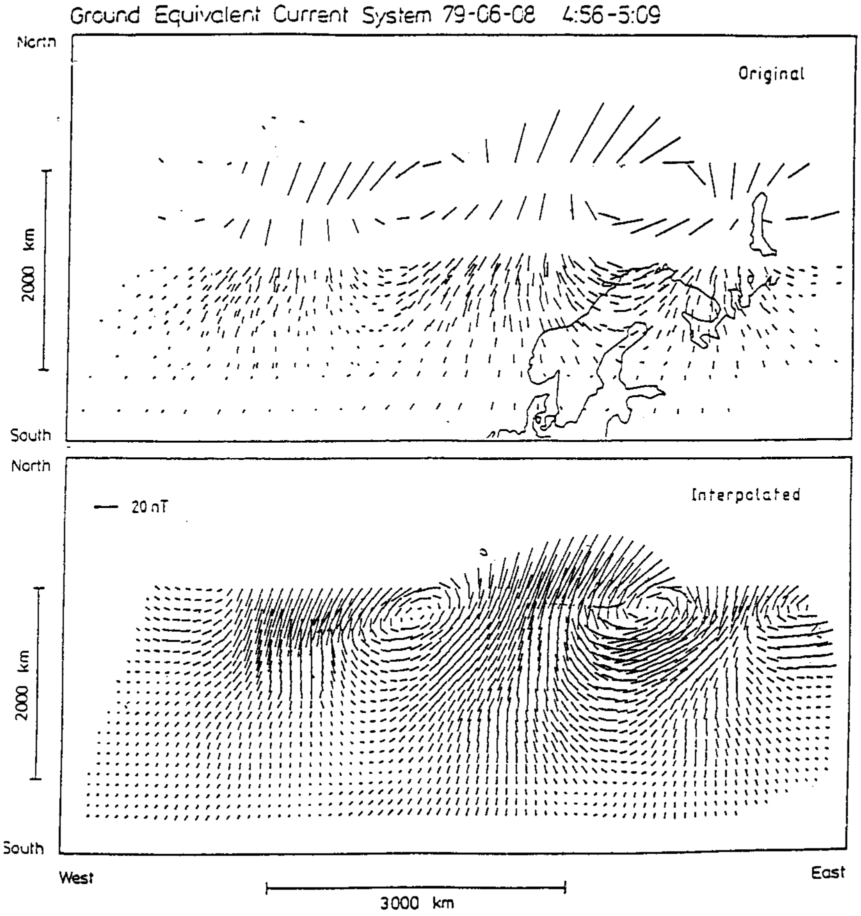

Fig. 1. Distribution of ground equivalent current vectors of the 8 june 1979 event as constructed from instant-aneous current distributions applying a merging technique. The upper part, shows the original current distribution while the bottom part displays an interpolated one, using a Thiessen triangulation technique and linear interpolation. The coastline of northern Scandinavia is shown in the upper part for 5:06 *UT*, from Glassmeier and Heppner (1992).

3. Numerical Results

The plots of the magnetic field B_T and current for the instability mode m = 1 are shown in Figures 2 and 3 for cross-sections at $z = 0$ and at $z = L/2$.

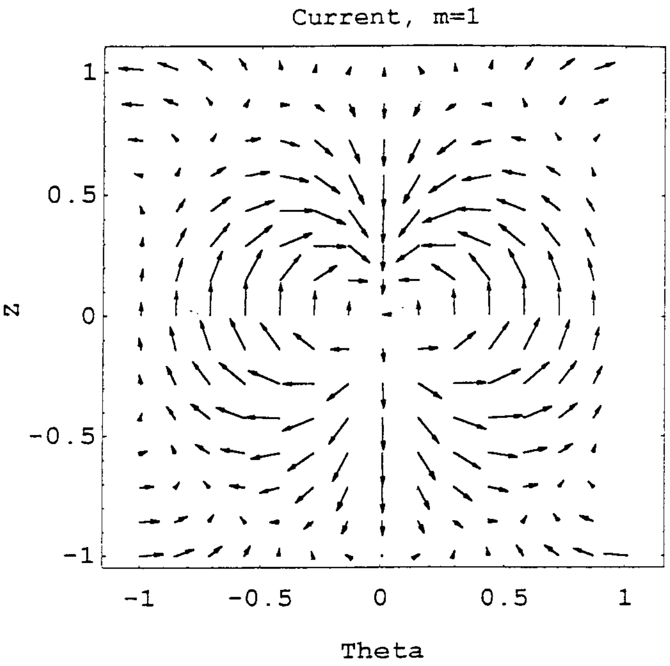

Fig. 2. Simulation showing the configuration of the currents when m=1 and the to azimutal field is 0.8 of the z- magnetic field.

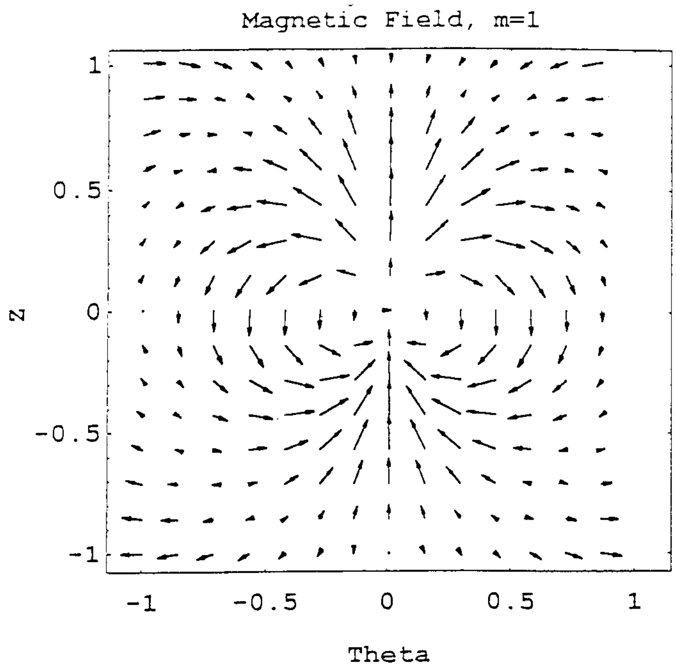

Fig. 3. Simulation to the magnetic field 2D dimension B_z and B_θ to the instability m=1 or the kink instability. Azimuthal field is 0.8 of the z- magnetic field.

For this mode the instability is a flow pattern whose cross section looks like two vortices rolling of each other as shown in Figure 1 considering the middle of the cilinder or in z = 0. The graphs were constructed varying the position of z and the values of q (The Kruskal-Shafranov criterium).

The growth rate of the instability has been calculated for m = 1. Supposing a free boundary the formula of the growth rate Bateman *et al.* (1974) is given by:

$$\frac{\gamma^2 = B_\theta^2 \mu\rho(a^2)\lambda \times [1 - q - (1 - q)^2]}{1 - a^2 / rw^2} \tag{11}$$

The value of the left hand side is the growth rate. On the right hand side all the values were taken from the data typical for the magnetosphere in the auroral region. This means that the magnetic field is around $10^{-}5nT$, the density is around 400 particles per m^{-3} Phan and Paschmann (1996) on the right hand side only the last term $(1 - q)^2$ is important Bateman (1978). The value found from simulation it was 14 minutes, compared to the experimental data that show typical values around 10 minutes. The calculations revealed gross MHD instabilities that fit well with several results obtained experimentally for TCV's, Glassmeier and Heppner (1992), McHenry *et al.* (1990). In this numerical calculation we find the following: (1) Vortex patterns are apparent in the velocity field of each instability, (2) the total current is divided into two, creating two filamentary parallel currents. As a consequence of these instabilities in plasmas, we should expect an enhancement of waves and several non linear phenomena which modify the plasma states. The conclusion, is that for the generation of traveling convection vortices, the locations where B_θ is slightly larger than the value of B_z should easily occur. In the ionosphere, assuming that the value of the current is the same, and the value of B_z is decreasing with the distance of the surface of the Earth, it is possible to affirm the existence of traveling convection vortices. The enhancement of the B_θ field, in comparison with the B_z field makes the generation of the traveling convections vortices possible in regions far from the ionosphere. The two currents appear because the kink instability creates filamentary and secondary currents relative to the first stronger one. When "kink" instability occurs the plasma is totally distorted and the particles run away in such way that one should observe an enhancement of the number of particles after the phenomena. Finally an enhancement of the waves in the magnetosphere or precipitation of particles into the ionosphere, may occur, Potemra *et al.* (1992) had observed a very intense fluxes of low-energy (near 100 eV) electrons and ions (peaks near 500 eV) in association with a traveling convection vortice phenomena. These ions do not show the distinctive decrease energy dispersion of the ions observed earlier by the same authors. The intense ions fluxes coincide with the intense electrons fluxes, and Birkeland currents. Friis-Christensen (1985), Friis-Christenen *et al.* (1988) observed that the region at dayside magnetopause is where often irregular magnetic pulsations often occur. They also proposed that the traveling convection vortices events could be associated with the observed irregular pulsations.

4. Conclusions

The conclusions of this preliminary analyses are the following; field aligned currents create an azimuthal magnetic field. In the magnetosphere where the Earth's magnetic field is sufficiently weak, kink instabilities may occur. This theoretical result agrees roughly with the experimental values found by Glassmeier 1992), Friis-Christensen *et al.* (1988), Vogelsang *et al.* (1993). The region where this kind of events occur is probably located around $4R_e$; this fits with the orbit of the Viking satellite. Some analyses about data and precipitation of particles have been done recently, by Yahnin and Moretto (1996). The numerical growth rate is close to experimental results for TCV's. The occurrence of this kink instability creates more field aligned filamentary currents, of a temporary character associated with particle precipitation due to the transmission of energy to waves and particles. The disappearance of this instability is due to the destruction of the plasma in such regions.

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