What are Traveling Convection Vortices?

M. Tavares and M. A. M. Santiago
Universidade Federal Fluminense
Instituto de Física, Av. Litorânea, s/n,
Boa Viagem, CEP 24210-340, Niterói, RJ, Brasil

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Traveling convection vortices (TCV) are studied using a theoretical ideal MHD model for the equilibrium and perturbed plasma. In this first approach, we do not consider the viscosity and the flow of the plasma column in the equilibrium . The linearized equations are solved using normal mode analysis. The solutions show an $m = 1$ kink instability which is in good agreement with the experimental data. It is calculated numerically a growth rate of 28 minutes to be compared with experimental data, indicating a quite good result with our model. Clearly, the results indicate the behaviour of the TCV as a kind of kink instability as supported by the agreement between theoretical and experimental values for the growth rate. Also the filamentation currents calculated through the theoretical model agree quite well with the experimental observations by satellites.

I Introduction

Conspicuous ionospheric features in the dayside at auroral latitudes are the traveling convection vortices (TCV),proposed by some authors, [1],[2],[3],[4],[5],[6], to be possible ionospheric signatures of the solar wind magnetosphere coupling processes. They identified traveling ionospheric current systems which are associated with a series of field-aligned filament currents 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 the order of $1000 - 3000$ km. These vortices are typically observed during 15-20 minutes and they move anti sunward with velocities of aproximatelly $5km/s$. Friis-Christensen and others,[1],[5],[7], modeled the field distribution assuming that the field aligned current densities are around $3 \times 10^{-6} A/m^2$. Friis-Christensen and Glassmeier,[1],[6], presented the first reports about the phenomenon; both employed dense arrays of ground-based magnetometers to monitor the ionospheric currents. They report on pairs of oppositely rotating cells of current vortices showing up preferably in the prenoon hours around 9:00 magnetic local time (MLT). These vortices were found to move rapidly westward at speeds of several kilometers per second approximately along lines of constant L-shells around 72^0 invariant latitude.Vogelsang,[8], reported a field-aligned current density of 1.0 $\mu A m^{-2}$and $0.4 \mu A.m^{-2}$ for the downward and upward currents, respectively, at ionospheric heights. Beside the current density they also could make predictions on the shape of the current filaments. The east/west extent of the two current tubes can be estimated from the duration of the field gradients around 06:13 and 06:16 UT and from the relative velocity. In addition equivalent currents deduced from ground-based magnetic observations fit nicely together and provide strong evidence that the field-aligned current filaments are part of the TCV identified on the ground. Also McHenry proposed that the vortices could be due to Kelvin -Helmholtz instability in the low latitude boundary layer,[9]. 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 details of the pattern of the magnetic field and currents. The present model proposes that traveling convection vortices are created by kink instabilities in the magnetosphere due to an azimuthal field B_θ (due to the parallel current) growing relating 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 $m = 0$ mode. 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,[10],[11]. For the kink instability ($m = 1$) the distortion grows because the magnetic pressure on the concave side increases (the B_θ lines are closed together), while on the convex side, it decreases (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:

$$q = \frac{krB_z(r)}{B_\theta(r)} \tag{1}$$

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 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 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 partially with the hypothesis presented by Glassmeier, 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 (II) the model and the formulation of kink instabilities in the magnetosphere is described, in section (III) is shown the results and conclusions.

II Theoretical Model

This is a simple model for the auroral region of the magnetosphere regarded as a circular cylinder with radius r_0 and length L, and with boundary conditions, corresponding to perfectly conductor walls, using the MHD equations and cylindrical coordinates,[11]. This kind of modeling of the magnetosphere has been done by Goertz, [12]. In order to better clarify the model we are including a picture with the described situation in the region of the magnetosphere, where traveling convection vortices and also parallel currents are observed, see Fig. 1. The parallel current is J and the tubes are constructed around of these currents. We model the magnetosphere by taking a long cylinder aligned with the 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 of the magnetic azimuthal field, B_θ. This magnetic field initiates the instability and the present study of this instability is based using the MHD equations. The standard MHD equations describe the equilibrium and they have been applied to plasmas with scalar pressure p steady state without flow and without body forces. The instabilities are analysed by applying a perturbation on the equations. If the equations describe the equilibrium this corresponds to the order zero of the equations and the quantities are unperturbed. The ideal magnetohydrodynamics equations (MHD) governing a compressible viscous hydromagnetic fluid are given by Santiago, [13], [14]. These equations correspond to the equation of continuity and the adiabatic equation. The meaning of the symbols $\rho, \vec{v}, p, \vec{J}, \vec{B}$, and μ are density,velocity, pressure, current, magnetic field and viscosity respectively , the constant $\gamma = 5/3$ as usually for gases.

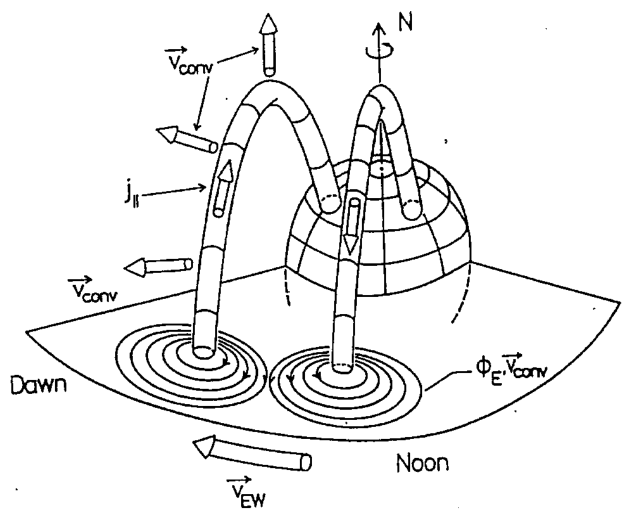

Figure 1. The auroral region and the theoretical cylinder around of the parallel current in our model.

The linearized equations which we solve are obtained after some calculations in Santiago [14],

$$\rho(\partial^2\vec{\xi}/\partial t^2) + 2\rho\vec{v}.\nabla(\partial\vec{\xi}/\partial t) - \hat{F}(\vec{\xi}) = \mu[\nabla^2(\vec{v}.\nabla)\vec{\xi} + \nabla^2\partial\vec{\xi}/\partial t] + \mu/3[\nabla\nabla.(\vec{v}.\nabla)\vec{\xi} + \nabla\nabla.\partial\vec{\xi}/\partial t] \tag{2}$$

where $\hat{F}$ is a operator defined by:

$$\hat{F}(\vec{\xi}) = \nabla(\gamma p \nabla.\vec{\xi} + \vec{\xi}.\nabla p - \vec{B}.\vec{Q}) + \vec{B}.\nabla\vec{Q} + \vec{Q}.\nabla\vec{B} + \nabla[\rho\vec{\xi}(\vec{v}.\nabla)\vec{v} - \rho\vec{v}\vec{v}.\nabla\vec{\xi}] \quad (3)$$

and

$$\vec{Q} = \nabla \times [\vec{\xi} \times \vec{B}] \quad (4)$$

Here $\vec{\xi}$ is a small displacement of a fluid element from its equilibrium position given by

$$\vec{r} = \vec{r}_0 + \vec{\xi}(r_0, t) \quad (5)$$

where $\vec{r}_0$ represents the trajectory of the element in equilibrium. In this preliminary case we do not consider the flow thus $v_\theta = 0$, $v_z = 0$ and , $\mu = 0$, what means there is no viscosity considered. We assume for $\vec{\xi}$ a normal mode analysis (Fourier eigenmodes) of the form

$$\vec{\xi} = \vec{\xi}(r) exp^{i(m\theta + kz + \omega t)} \quad (6)$$

III Numerical Results

A typical event is shown in Fig. 2. Clearly, the picture shows the formation of two vortices, meaning parallel currents with opposite directions. Fig. 3 shows another event in september of the same year.

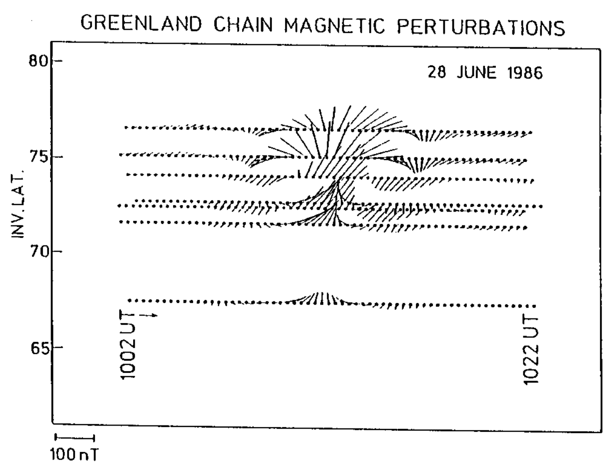

Figure 2. Total horizontal magnetic perturbation vectors measured by the Greenland magnetometer chain on June 28, 1986 have been rotated by 90^0 counterclockwise and plotted every 20 seconds during the interval from 10 : 02 : 00 to 10 : 22 : 00 UT. For each time the position of the vectors have been off-set to the right by a distance corresponding to $80km$ to account for an assumed $4km/s$ westward motion (to the left) of the pattern.

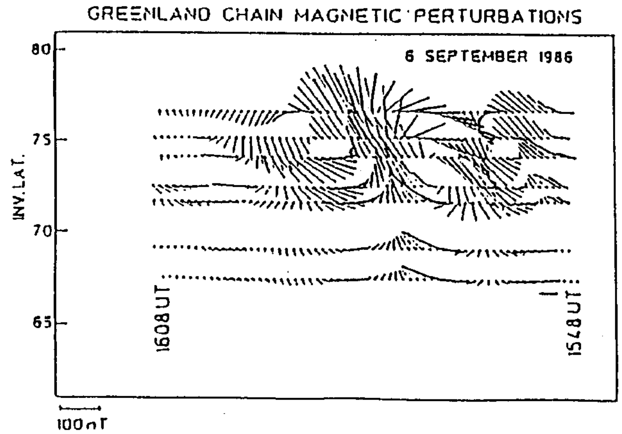

Figure 3. Total horizontal magnetic perturbation vectors measured by the Greenland magnetometer chain on September 06, 1986 have been rotated by 90^0 counterclockwise and plotted every 20 seconds during the interval from 15:48:00 to 16:08:00 UT. For each time the position of the vectors have been off-set to the left by a distance corresponding to 80 km to account for an assumed 4 km/s eastward motion (to the right of the pattern).

Our numerical solution of equation (2) with $\vec{v}_0 = 0$ and $\mu = 0$, give the eigenvalues and eigenfunctions for the $m = 1$ mode, known as kink mode, that generates two filamentary and parallel currents in opposite directions.The theoretical model and the experimental approach fitt very well. As our model is linear, soon the non linear saturation should occur. The boundary conditions for this simple model are that perturbation is null on the central axis (r=0) and at the wall. The wall is supposed far enough to take the cylinder as a perfect conductor. More calculations for other modes should be interesting because in this case we could affirm that the kink mode is predominant or not. The perturbed equation (2) is solved numerically, taking into account the boundary conditions, using the software "Mathematica",[13],[14], and we obtain a set of discrete eigenvalues and its corresponding eigenfunctions. The profiles for the magnetic field B_z and B_θ before the perturbation are shown in Fig. 4. These profiles show the behaviour of these variables in two dimensions. The eigenfunctions (real and imaginary parts) of the fundamental $m = 1$ mode are shown in Fig. 5. The growth rate for that eigenmode is calculated on basis of some experimental values,[1], [2],[3],[4],[15].

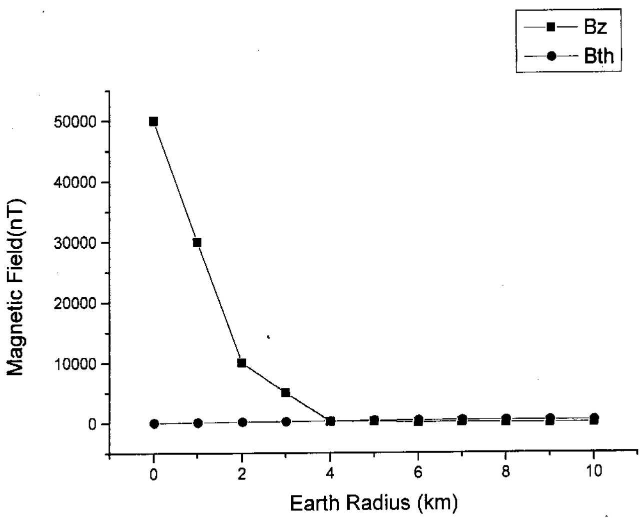

Figure 4. Plot of the equilibrium magnific fields B_z and B_θ in the model considered.

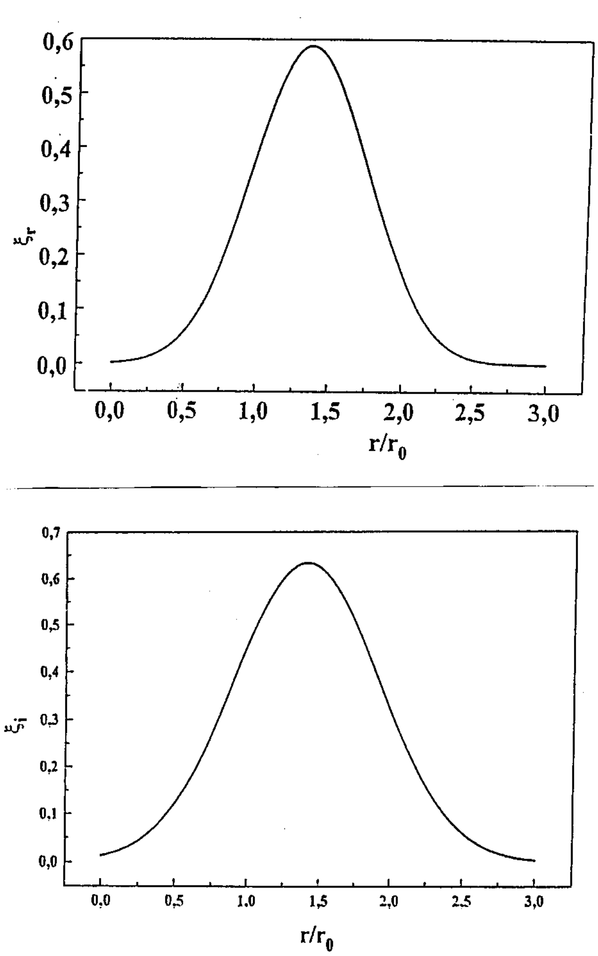

Figure 5. Plot of the eigenfunctions as are calculated in the model.

At four radius from Earth, the magnetic field ($B_z \approx B_\theta$) is around 250 nT, and the density is around $400m^{-3}$. The Alfven hydromagnetic transit time associated τ_A is of the order of $6.6 \times 10^3 s$ and the dimensional eigenfrequency corresponding to the eigenvalue obtained for the m = 1 kink mode is $\omega_i = 5.8 \times 10^{-4} s^{-1}$, indicating that the value for the growth rate of the mode is 28 minutes, while the experimental data show typical values around 20 minutes. The calculations reveal gross MHD instabilities that fit well with several results obtained experimentally for TCV's, [5],[9]. In a former work,Tavares,[16], the results are 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. It means that in the region we mention above the magnetic field B_z is decreasing and the B_θ from the parallel current is nearly the same in the region we consider. 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 convection 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, we 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. Actually Potemra et al,[7], had observed very intense fluxes of low-energy (near $100eV$) electrons and ions (peaks near $500eV$) 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 ion flux coincide with the intense electron flux, and Birkeland currents, and it is observed that the region at dayside magnetopause is where often irregular magnetic pulsations often occur,[1],[2], and they also proposed that the traveling convection vortices events could be associated with the observed irregular pulsations.

IV Conclusions

The conclusions of this preliminary analysis 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. Our simple model agrees quite well with the data. Further calculations could show more details since we have used a linear theory and therefore the saturation of the mode was not taken into account. This theoretical result agrees roughly with the experimental values found by [5], [1],[8] . The region where this kind of events occur is probably located around $4R_e$; this fits with the orbit of the Viking satellite.Some analysis about data and precipitation of particles have been done recently,[17]. 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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