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EQUATORIAL ELECTROJET CURRENT DENSITY TURBULENT REDUCTION

Matías de la Vega

Dept. de Fís., Fac. de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria Pabellón I, 1428 Buenos Aires, Argentina.

Abstract

It was shown in a previous paper that turbulence reduces the equatorial electrojet current density at noontime. This problem is further analyzed by computing the turbulence level in the long wavelength region of the spectrum using Kraichnan's direct interaction approximation (DIA). The self-consistent equations for the electrojet current density and turbulence level are solved; the current density thus obtained fits in well with experimental data.

Resumen

En un trabajo previo se mostró que al mediodía la turbulencia reduce la intensidad del electrochorro ecuatorial. En el presente trabajo se profundiza el estudio utilizando la aproximación de interacción directa (DIA) debida a Kraichnan; con esta aproximación se evalua el nivel de turbulencia en la región de longitudes de onda largas del espectro. Del sistema de ecuaciones auto-consistentes para la densidad de corriente y el nivel de turbulencia se obtiene una intensidad que reproduce correctamente la experimental.

1. Introduction

The primary electric field is constant with height in standard equatorial models (see e.g. Richmond 1973). The equatorial current density within a laminar model using the value of the primary electric field measured at F region heights was predicted in a previous work (de la Vega and Duhau 1989). It was found that the value predicted for current density is twice the experimental one; in order to explain this difference, the turbulent nature of the equatorial electrojet has to be taken into account.

Unstable plasma waves arise when the electron velocity exceeds the ion-sound speed and when the vertical electric field is parallel to the electronic density gradient. A bidimensional turbulent regime is established in the unstable region due to the nonlinear interaction of unstable waves and because waves with wave number parallel to the geomagnetic field are promptly damped. The strength of the interactions that generate the instabilities and the mechanisms saturating them defines the turbulence level in the system. The current density is reduced by the turbulence (de la Vega and Duhau 1989) and thus becomes a competitive mechanism coupled with the complex nonlinear interactions which could be involved in the electrojet plasma as wave-induced anomalous diffusion, three-wave cascade processes from unstable modes to dumped ones, two-step mechanism ,etc (see e.g. Kudeki et al 1987) for achieving saturation of the unstable waves and even for fixing the turbulent level. Also this turbulent current density reduction could explain the asymmetric appearance of upward waves as claimed by Kudeki et all. (1985). In this paper the problem of current density reduction is further analyzed by considering the r.m.s. density fluctuations described by means of Krichnan's direct interaction approximation as applied by Sudan (1983) to the electrojet problem.

2. Theoretical Models

2.1. Laminar current density model in the fluid approximation.

We introduce a coordinate system with the x, y, z azis pointing westward, vertically, and northward respectively. The field configuration is:

$$\vec{B}=B\vec{z} \quad ,$$

the dynamo electric field E_x is negative and the vertical electric field E_y is positive. We consider quasi-neutrality with an electron density N, that depends only on y. From the laminar fluid equations of mass and moment conservation and Maxwell equations it is obtained that E_x is constant ant J^L_x, the laminar current density, depends on y through the expression (see e.g. de la Vega and Duhau 1989):

$$J_x^L \cong -E_y^L \sigma_H = -E_x \sigma_H^2 / \sigma_P \cong -eNV_{ex}$$

at the dip equator where neutral wind effects may be disregarded. Here $\sigma_{H,P}$ are the Hall and Pedersen conductivities and depend on height,

$$\vec{V}_e$$

is the electron velocity.

2.2. Plasma instabilities

For wavelengths greater than the ion Larmour radius (in the meter order) a linear stability analysis of the mass and moment conservation equations is performed in the fluid approximation. Considering electrostatic perturbations we obtain the instability condition wich states that the growing rate (γ_k) must be positive for unstable modes (see e.g. Fejer and Kelley 1980) :

$$\gamma_k = \frac{\psi}{\nu_i(1+\psi)}\left(\omega_k^2 - k^2 C_s^2\right) + \omega_k \frac{k_0}{k} - 2\alpha N \qquad (2)$$

where $\vec{k}$ stands for the wave number,

$$\psi = {}^{\nu_i \nu_e}\!/_{\Omega_i \Omega_e}$$

with $V_{i,e}$ and $\Omega_{i,e}$ the collision frequency with neutrals and cyclotron frequency of electrons and ions respectively,

$$k_o = \frac{\nu_i}{\Omega_i}\frac{1}{1+\Psi}|\vec{\nabla} N|/N, C_s,$$

is the ion-acoustic velocity and α the effective recombination ratio. Finally, ω_k , the linear eigenfrequency is given by:

$$\omega_k = \frac{\vec{k}.\vec{V}_c}{1+\psi} \tag{3}$$

2.3. Turbulent current density model in the fluid approximation

According to equation (2) the laminar solution is unstable in the short wavelength region of the spectrum (1m) when Ve exceeds the ion-acoustic velocity (C_S) and in the long wavelength portion of the spectrum (200m) when

$$\vec{E}.\vec{\nabla} N > 0.$$

Due to the non-linear interaction of the unstable waves, the system undergoes a turbulent state. An anomalous contribution to the Pedersen conductivity for the vertical current density due to turbulence modifies equation (1) in the quasi-linear approximation as follows (Rogister 1971):

$$J_x^l \cong -E_y^l \sigma_H = -E_x \sigma_H^2 / (\sigma_P + \sigma_T) \cong -eNV_{ex} \tag{4}$$

where σ_T is the turbulent contribution to the Pedersen conductivity, which is given by:

$$\sigma_T = \frac{1}{2}\frac{eN}{B}\frac{\nu_i}{\Omega_i}\frac{1}{1+\psi}\langle \delta N \delta N \rangle / N^2 \tag{5}$$

where $\langle \delta N \delta N \rangle / N^2$ is the r.m.s. density fluctuation.

2.4. R.M.S. density fluctuation

The Fourier representation of the evolution equation for the density fluctuation normalized to the mean density ($\eta_k \equiv \delta N/N$) is:

$$(\omega - \Omega_k)\eta_k = \int W_{k,k'} \eta_{k'} \eta_{k-k'} d^2k' d\omega' \tag{6}$$

where $\Omega_k = \omega_k + \iota\gamma_k$ and ι the complex unit. The coupling matrix $W_{k,k'}$, is given by:

$$W_{k,k'} = \frac{v_i}{\Omega_i(1+\psi)^2}(\vec{k}-\vec{k}').\vec{V}_e \frac{\vec{k}.([\vec{k}-\vec{k}']\times\hat{z})}{|\vec{k}-\vec{k}'|^2}$$

From equation (6) for η_k, Sudan (1983) obtained a Kolmogorov cascade-type expression for the r.m.s. density fluctuations using Krichnan's direct interaction approximation (DIA) in the homogeneous and isotropic approximation. The complex coupled integral equation which is obtained from the DIA for the power spectrum $I_{\omega,k}$ and the nonlinear growing-dumping rate induced by nonlinear correlations $\Gamma_{\omega,k}$ are solved aproximately by them in the region where $V_e < C_s$ by considering that $I_{\omega,k}$ is given by:

$$I_{\omega,k} = I_k(2\pi\Gamma_k)^{-1/2}\exp\left[\frac{-(\omega-\omega_k)^2}{2\Gamma_k^2}\right] \tag{7}$$

where Γ_k is the angular average of $\Gamma_{\omega,k}$ evaluated at the linear eigenfrequency ω_k. Using this ansatz, Sudan (1983) found that Γ_k and I_k are given by

$$\Gamma_k = \frac{v_i V_{ex}}{\Omega_i(1+\psi)} k^2 I_k^{1/2} \tag{8}$$

$$I_k^{1/2} = \frac{\Omega_i(1+\psi)k^{-4/3}}{v_i V_{ex}}\left[A\left(k_{\min}^{-2/3}-k^{-2/3}\right)+\frac{B}{2}\left(k_{\min}^{4/3}-k^{4/3}\right)\right] \tag{9}$$

where $k_{\min}$ is the long wavelength cutoff for which the power spectrum falls to zero and A, B are:

$$A = \frac{v_i V_{ex}}{2\Omega_i(1+\psi)^2 |\vec{\nabla}N|/N}$$

$$B = \frac{\psi}{v_i(1+\psi)}\left[C_s^2 - \frac{1}{2}\left(\frac{V_{ex}}{1+\psi}\right)^2\right]$$

The expression for the r.m.s. density fluctuations is obtained by integrating the expression thus found for $I_{\omega,k}$:

$$\langle \delta N \delta N / N^2 \rangle = 2\pi \int_{k_{min}}^{k_{max}} k I_{\omega,k} \, dk \, d\omega$$

where k_{max} corresponds to the shortest wavelength excited. Regarding it as being the shorter wavelength for which hidromagnetic theory is valid (2m), as for shorter ones, the kinetic Landau Dumping dumps the spectrum (Schmidt and Gary 1973).

Finally the expression obtained from integration results

$$\langle \delta N \delta N / N^2 \rangle = 2\pi \left[\frac{\gamma_L \Omega_i (1+\psi)}{V_{ex} k_{min} v_i} \right] \left[F\left(\frac{k_{min}}{k_{max}} \right) - F(1) \right] \qquad (10)$$

where $F(\chi)$ is given by:

$$F(\chi) = -\frac{3}{2} \chi^{-2/3} \left(\frac{2s+1}{2s} \right)^2 - \frac{1}{2\chi^2} + \frac{\chi^2}{8s^2} + \frac{\ln \chi}{s} + \frac{3}{2} \left(\chi^{-4/3} + \chi^{2/3} \right) \left(\frac{2s+1}{2s^2} \right) \qquad (11)$$

$$s = \frac{\gamma_L v_i (1+\psi)}{\psi k_{min}^2 \left(C_s^2 - \frac{1}{2} \left[\frac{V_{ex}}{1+\psi} \right]^2 \right)} \qquad \gamma_L = \frac{v_i v_e}{2\Omega_i N} \frac{|\vec{\nabla} N|}{(1+\psi)^2} - 2\alpha N \qquad (12)$$

3. Results and conclusions

The current density in the turbulent regime is obtained from the coupled system of equations (4) and (10) by an iteration scheme. Initial condition of null turbulence level is assumed, then from (4) we determine $V^{(0)}_{ex}$. From the obtained electron velocity and equation (10) the turbulence level

$$\langle \delta N \delta N / N^2 \rangle^{(0)}$$

is calculated; this value permits recalculating $V^{(1)}_{ex}$ from equation (4), etc... Iterative process is continued until stable values are obtained, which demands approximately 10 iterations. The current density in the laminar approximation is obtained directly from equation (1).

The parameters used to make the calculuslus $(E_x, \sigma_{H,P}, N, |\nabla N|, etc)$

are the same as in de la Vega and Duhau (1989) which reproduce the conditions of the density current measurement due to flight 14.176 of Davis et all (1967). The turbulent level obtained is shown in Figure 1.

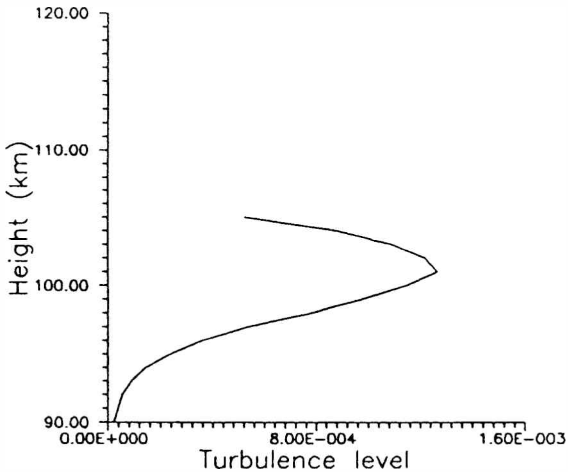

Fig. 1: Height profile of the turbulence level

The order of magnitude of this magnitude (10^{-3}) agrees with the one quoted by Bowles et all (1963). The experimental (flight 14.176 of Davis et all) and theoretically determined (turbulent and laminar) electrojet current density profiles are shown in figure 2. The turbulent calculus is up to 106 km height as the DIA is only valid in the region where long wavelengths are excited.

From Figure (2), it may be noted that the turbulent curve fits experimental data quite well while the laminar curve overestimates the current density in the whole turbulent region (up to 110 km height approximately). We conclude that the inclusion of the turbulence level as given by the DIA in the model of the turbulent electrojet is apropiate for reproducing experimental data.

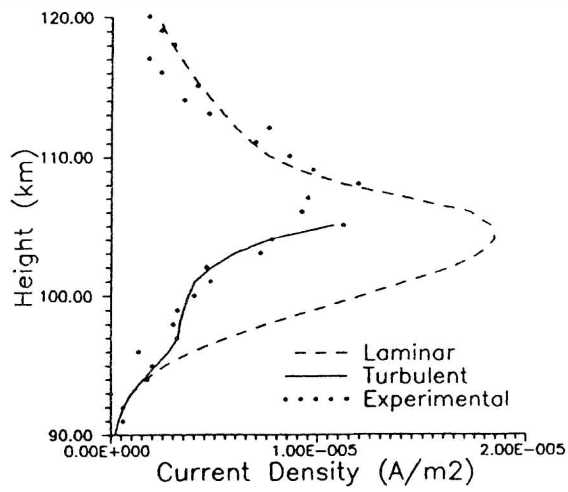

Fig. 2: Height profile of the current density

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