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Equatorial electrojet as a nonlinear ULF antenna for the short-wave heating facility

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Abstract

In this paper, we discuss some questions related to the nature and manifestation of the equatorial electrojet. We study theoretically the equatorial electrojet as a nonlinear antenna for generating ultra-low-frequency electromagnetic signals during periodic heating of the ionosphere by the short-wave heater radiation. It is shown that for periodic heating at the frequency corresponding to the ULF band the generation of electromagnetic signals can be significantly intensified. This effect is especially important for the daytime magnetosphere where there are eigenfrequencies of the plasma magnetospheric maser in the electron radiation belts in the same frequency band. This can lead to a modification of VLF emissions in the subauroral magnetosphere.

Keywords: Heating-facility; Equatorial electrojet; Plasma magnetospheric maser; Magnetosphere

1. Introduction

The interaction of quasi-static electric fields with the equatorial E region, the creation of the equatorial electrojet (EEJ) current, and its observational consequences have been the subject of many experimental and theoretical studies (Rigoti1 et al., 1999; Eliasson and Papadopoulos, 2009; Klimenko et al., 2007). The equatorial electrojet is an important element of the S_q current system of the daytime ionosphere. The equatorial electrojet directed to the east in the midday ionosphere is well investigated experimentally (Onwumechili, 1997). A model of kinematic dynamo is successfully used for its theoretical study. The model of kinematic dynamo is based on the clear assumption that the neutral-wind velocity $\vec{u}_n$ in the atmosphere is known and does not depend on the plasma state. The electric field induced as a result of the ion entrainment with the gas is potential:

$$\boldsymbol{E} = -\nabla\varphi. \tag{1}$$

Under the quasi-stationary conditions (Gershman, 1974; Dimant and Oppenheim, 2011), it can be required that the current-conductivity tensor is fulfilled in the well-known form. According to the generalized Ohm's law, the current density is determined by the following expression:

$$\begin{aligned} \boldsymbol{j} &= \sigma_{\parallel}\boldsymbol{E}'_{\parallel} + \sigma_P\boldsymbol{E}'_{\perp} + \tfrac{\sigma_H}{B}\boldsymbol{B}\times\boldsymbol{E}', \\ \boldsymbol{E}' &= \boldsymbol{E} + \tfrac{1}{c}\boldsymbol{u}_n\times\boldsymbol{B}, \end{aligned} \tag{2}$$

where $\boldsymbol{E}'_{\parallel} = (\boldsymbol{E}'\boldsymbol{B})\boldsymbol{B}/B^2$, $\boldsymbol{E}'_{\perp} = \boldsymbol{E}' - (\boldsymbol{E}'\boldsymbol{B})\boldsymbol{B}/B^2$, σ_P is the Pedersen conductivity, σ_H is the Hall conductivity, $\sigma_{\parallel}$ is the longitudinal conductivity, and c is the light speed. In the conducting atmosphere, the condition that precludes the appearance of a large uncompensated charge should be fulfilled. Therefore

$$\mathrm{div}(\boldsymbol{j}) = 0. \tag{3}$$

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In the so-called model of a thin spherical shell, simplifications are achieved due to the assumption that the vertical current density is small. For such a case, Eqs. (1)–(3) are integrated numerically for several dynamo layer conductivity models. Such calculations were performed to study S_q variation for different distributions of atmospheric winds. As a result of calculations, the authors of several articles (see, e.g., Takeda and Maeda, 1980; Takeda, 1982) determined the typical potential φ distribution at altitudes close to 90 km and the electrical currents in different-altitude ionospheric layers. The results of calculations show that an eastward EEJ is present in the midday ionosphere.

Let us briefly explain the reason for the formation of the midday EEJ. Usually in the dynamo region of the daytime equatorial ionosphere, the neutral wind velocity is directed towards the equator and is of the order of $\boldsymbol{u}_n = 100$ m/s. Therefore, the eastward electric field $\boldsymbol{E} \simeq -(\boldsymbol{u}_n/c) \times \boldsymbol{B}$ is formed in accordance with Eq. (2) with finite currents and a sufficiently high conductivity. Because of the continuity of the tangential component of the electric field, it can be expected that in the entire midday low-latitude ionosphere the approximately uniform zone electric field $E_{zon} \simeq 10^{-3}$V/m is eastward. This field, in accordance with Eq.(2), could create the electric current density in the vertical direction. However, the current is absent in this direction. Therefore, the polarization of the ionospheric layer occurs. A significant vertical electric field appears, which is approximately twenty times larger than the zone electric field. Polarization electric field, in accordance with Eq. (2), creates the eastward current jet. The expression for the eastward current density has the following form:

$$j_y = \frac{\sigma_P(\sigma_C + 4\sigma_\parallel \mathrm{tg}^2\chi)}{\sigma_P + 4\sigma_\parallel \mathrm{tg}^2\chi} E_{zon}, \tag{4a}$$

where χ is the angle of the slope of the magnetic field to the vertical line, $\sigma_C = (\sigma_P^2 + \sigma_H^2)/\sigma_P$ is the Cowling conductivity. Eq. (4a) takes into account both the Ohm's law (2) conductivity expression and the boundary condition for the vertical electric current. The eastward current density reaches the maximum

$$j_{y,\max} = \sigma_C E_{zon}. \tag{4b}$$

Thus, $j_{y,\max} \simeq 5 \cdot 10^{-6}$ A/m^2 at the altitude $h \simeq 105$ km above the magnetic equator, and the current density rapidly falls at the higher altitudes. The total EEJ current is $I \simeq 7 \cdot 10^4$ A , its half-width along the latitude direction is about 400 km, and its magnetic field on the Earth surface $b_x \simeq 70$ nT (Rigotil et al., 1999).

2. Calculation of the variable component of the ionospheric current and its electromagnetic signal

As is well known, pulsed HF heating generates waves in the ULF/ELF range in the midlatitude (Belyaev et al., 1987) and polar (Papadopoulos et al., 2005) ionosphere.

Let the amplitude-modulated radio wave from a high-power HF transmitter affect the EEJ. Assume that the modulation frequency Ω lies in the very low-frequency range or in the geomagnetic-pulsation range (below 10 Hz). In the ionosphere region perturbed by the heating transmitter, the electron temperature T_e as well as the conductivities vary periodically. For definiteness, we confine ourselves to the weak-heating case, where $|\Delta T_e/T_e| < 1$.

Assuming that the undisturbed ionospheric current density j is known. Then it is easy to show that the current density disturbance is equal to

$$\Delta \boldsymbol{j} = \frac{\Delta\sigma_\parallel}{\sigma_\parallel}\boldsymbol{j}_\parallel + \frac{\sigma_P\Delta\sigma_P + \sigma_H\Delta\sigma_H}{\sigma_P^2 + \sigma_H^2}\boldsymbol{j}_\perp + \frac{\sigma_H\Delta\sigma_P - \sigma_P\Delta\sigma_H}{B(\sigma_P^2 + \sigma_H^2)}\boldsymbol{j}_\perp \times \boldsymbol{B}, \tag{5}$$

where $\Delta\sigma_\parallel$ is the perturbation of the conductivity $\sigma_\parallel$. The perturbation notation is similar for all other conductivities.

The relationship between the electron collision frequency ν_{en} and the temperature T_e is determined by the known expressions (Sugiura and Cain, 1966)

$$\begin{aligned} \nu_{eN_2} &= 9.32 \cdot 10^{-12} n_{N_2}(1 - 3.44 \cdot 10^{-8} T_e) T_e, \\ \nu_{eO_2} &= 1.22 \cdot 10^{-10} n_{O_2}(1 + 2.15 \cdot 10^{-2} T_e^{1/2}) T_e^{1/2}, \\ \nu_{eO} &= 5.49 \cdot 10^{-10} n_O T_e^{1/2}, \end{aligned} \tag{6}$$

where the partial collision frequencies are in s^{-1}, the densities are in cm^{-3}, and the electron temperature is in ° K. Then $\Delta\nu_{en}/\nu_{en} \approx \Delta T_e/T_e$ and for the EEJ, according to the simplest current model (4) and (6), we have

$$\begin{aligned} \Delta j_z &= -\tfrac{\Delta T_e \nu_{en}}{T_e \omega_{Be}} j_{y,\max} \sin\chi, \\ \Delta j_x &= \tfrac{\Delta T_e \nu_{en}}{T_e \omega_{Be}} j_{y,\max} \cos\chi, \\ \Delta j_y &= \tfrac{\Delta T_e}{T_e}\left(\tfrac{\alpha n_e}{2\alpha n_e - \Omega} + \tfrac{\nu_{en}\sigma_P}{\omega_{Be}\sigma_H}\right) j_{y,\max}. \end{aligned} \tag{7}$$

Here, α is the dissociative recombination coefficient related to the characteristic time t_e of the electron density variation by the relationship $t_e = (2\alpha n_e)^{-1}$. For the lower ionosphere, 10 s $< t_e < 10^3$ s, i.e., the electron-density perturbation can be neglected for modulation at the frequencies Ω lying in the very low frequency range. These perturbations become significant in the ULF range (Bespalov and Savina, 2012).

In the ULF range for $\Omega/2\pi < 1$ Hz , the electron density modulation gives the main contribution to the density of external current (8). To evaluate the magnetic field of the ULF wave it is possible to use a simple formula for the near-field region. In the near-field region, the disturbances of magnetic field on the Earth's surface are determined by the Biot-Savart law $\boldsymbol{b} = \int \boldsymbol{j} \times \boldsymbol{r}/(cr^3) d^3r$, where $\boldsymbol{j}$ is the current density and "reflected" current density inside the conducting Earth. The disturbing magnetic field under the electrojet with the total disturbing current ΔI at the altitude h