Turbulent Boundary Layer in the Polar Ionosphere

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The interaction between ionosphere and neutral atmosphere at heights of the dynamo-region leads to the development of Alfvén mode instability when the convection velocity exceeds the threshold value $V_{\Pi} \approx 0.1$ km/s. The ionospheric Alfvén resonator (IAR) plays an important role as an accumulator of turbulent energy. As a result, a turbulent boundary layer is formed consisting of anisotropic Alfvén vortices captured in the IAR. Their anomalous dissipation contributes greatly to the substorm energy budget.

1. Introduction

In the auroral region at the ionospheric *E*-layer heights there is a strong interaction of the magnetospheric convection with the neutral atmosphere, which leads to the excitation of oblique Alfvén waves (Alfvén vortices) with $l_{\perp} \ll l_{\parallel}$ ($l_{\perp}$ and $l_{\parallel}$ are wavelengths along and across $\mathbf{B}_0$, respectively). Waves with $l_{\perp} \approx 10^2$ km propagate throughout the magnetospheric convection region (ATKINSON, 1980; SATO and HOLZER, 1973; TRAKHTENGERTS and FELDSTEIN, 1984; WATANABE and SATO, 1988), and perturbations with $l_{\perp} \approx 1$ km are trapped into an ionospheric Alfvén resonator (IAR), bounded by the ionospheric *E*-layer from below and by the region of a sharp increase of the Alfvén velocity at heights up to the Earth's radius from above (TRAKHTENGERTS and FELDSTEIN, 1984). IAR eigenmodes are developed much quicker than the large-scale ones. The instability arises in the region where the ionospheric electric field E_0 is at maximum; and the optimal ionospheric parameters providing for good electrodynamic matching of *F* and *E*-layers are realized. It's likely to be one of the quiet auroral arcs at the night-side auroral oval region. The saturation of an Alfvén vortex amplitude is due to vortex current instability development and anomalous resistivity layer formation near the upper wall of the IAR (TRAKHTENGERTS and FELDSTEIN, 1984, 1987). As a result, a turbulent Alfvén boundary layer (TABL) is formed at heights 10^2 to 10^4 km. Anomalous dissipation of Alfvén vortices leads to turbulent plasma heating and formation of a powerful source of high-energy electrons ($W_e \approx 10$ keV) at heights $h < 10^4$ km with energy flux density of several tens of $\text{erg} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$, which can contribute appreciably to the substorm energy budget.

2. The Quantitative Consideration

1) Some important features of the TABL formation can be found using the linear theory of laminar convection stability (TRAKHTENGERTS and FELDSTEIN, 1982, 1984, 1987). According to TRAKHTENGERTS and FELDSTEIN (1987) the growth rate γ characterizing the exponential increase of an Alfvén vortex amplitude in the IAR is of the form

$$\gamma = \frac{V_{A0}}{L} \cdot \frac{\delta}{1 + \delta^2} \cdot \left(1 - \frac{V_{\Pi}}{V} \right), \quad \delta = \Sigma_P / 3\Sigma_w, \quad (1)$$

where Σ_P is height-integrated Pedersen conductivity, the wave conductivity $\Sigma_w = C^2 / 4\pi V_{A0}$ contains the Alfvén velocity V_{A0} in the F -layer maximum; L is the characteristic scale of concentration decrease above F -max; V_{Π} and V stand for the threshold velocity and the laminar convection velocity, respectively. The expression (1) characterizes the growth rate of the fundamental IAR eigenmode having eigenfrequency

$$\omega_0 \approx 4V_{A0} / L. \quad (2)$$

The optimal wavelength transverse to $\mathbf{B}_0$, $l_{\perp} = 2\pi / \alpha_{\perp}$, can be obtained from the double-resonance condition:

$$\bar{\alpha}_{\perp} \bar{V} = k_{z0} V_{A0} = \omega_0, \quad l_{\perp} \approx \frac{\pi V}{2V_{A0}} \cdot L \ll l_{\parallel} \approx \frac{2\pi}{k_{z0}}. \quad (3)$$

The ratio δ is small ($\delta \approx 0.1$) under the night-side magnetically-quiet conditions but approaches and even exceeds unity during magnetic disturbances. Assuming, in particular, $L \approx 10^3$ km, $V_{A0} \approx 3 \cdot 10^2$ km/s, $\delta \approx 0.2$ and $V \approx 0.5$ km/s it follows that $\omega_0 \approx 1.2 \text{ sec}^{-1}$, $l_{\perp} \approx 2.5$ km, $l_{\parallel} \approx 250$ km, and $\gamma \approx 0.06 \text{ sec}^{-1}$. According to TRAKHTENGERTS and FELDSTEIN (1987) the threshold velocity is equal to $V_{\Pi} \approx 0.1$ – 0.2 km/s.

2) The key problem is that of the rate of energy supply to the Alfvén vortices (the TABL power) from the regular magnetospheric convection, as well as the problem of the mechanisms for dissipation of this energy. The TABL power $\mathcal{P}$ is defined by the following expression:

$$\mathcal{P} = \sum_{n=0}^{n_m} \gamma_n \int W_n dz, \quad n = 0, 1, \dots, n_m, \quad (4)$$

where the summation is over the excited modes of the IAR; γ_n is the growth rate of the n -th mode, $W_n = b_n^2 / 8\pi = l_{\perp}^2 \cdot j_n^2 / 2\pi c^2$ is its energy density, b_n is the magnetic field amplitude in the Alfvén wave which is related with the field-aligned current j_n in the Alfvén vortex as $b_n = 2j_n l_{\perp} / c$. The integration in (4) is over the IAR volume with a unit transverse cross-section. Taking into account (1)–(3), it follows that

$$\mathcal{P} \approx \frac{0.5\bar{n}}{c^2} \cdot \frac{V^2}{V_{A0}} \cdot j_0^2, \quad (5)$$

where $\bar{n}$ is the number of excited modes, j_0 is the fundamental mode current amplitude. For $\bar{n} \approx 3$, $V_{A0} \approx 3 \cdot 10^2$ km/s, $V \approx 0.5$ km/s and $j_0 \approx 10^{-4}$ A/m² we obtain $\mathcal{P} \approx 2 \text{ erg} \cdot \text{cm}^{-2} \text{sec}^{-1}$. In intense auroral phenomena V and j_0 can reach rather large values that, according to (5), give a certain supply in the estimates of $\mathcal{P}$.

3) The next important problem is that of particular ways in which the Alfvén vortex energy can be transformed into the kinetic energy of auroral plasma. One of possible efficient mechanisms of Alfvén wave dissipation in the TABL may arise from the development of anomalous resistivity and turbulent plasma heating (TRAKHTENGERTS

and FELDSTEIN, 1984; LYSAK and DUM, 1983). The fact is that the field-aligned current in the Alfvén vortices forming the TABL can readily exceed the critical value corresponding to the ion-acoustic instability threshold. The most favorable conditions for the anomalous resistivity occur near the upper wall of the IAR (see Fig. 1). A rise of anomalous collision frequency results in a pronounced enhancement of longitudinal electric field in an Alfvén vortex and, essentially, in formation of an unsteady electromagnetic double layer at altitudes of 10^3 – 10^4 km. According to the estimations of TRAKHTENGERTS and FELDSTEIN (1987) the characteristic parameters of such a double layer are

$$\omega \approx 1 \text{ s}^{-1}, \quad z_a \approx 300 \text{ km}, \quad E_{\parallel} \approx 10 \text{ mV/m}, \quad \nu_a/\omega_p \approx 10^{-3}, \quad (6)$$

where ν_a and ω_p are the anomalous collision frequency and the plasma frequency, respectively. Inside the double layer the acceleration of the so-called runaway electrons up to the energy

$$W_e \approx \frac{2j_B l_{\perp}}{n_{AB}\omega_{pB}} \left(\frac{\nu_{aB}}{\omega} \right)^{1/2} = \frac{\pi V j_B L}{2c\omega_{pB}} \left(\frac{\nu_{aB}}{\omega} \right)^{1/2} \left(\frac{\mathcal{N}_{\max}}{\mathcal{N}} \right)^{1/2} \quad (7)$$

takes place; the index "B" denotes values near the upper wall of the IAR, $\mathcal{N}_{\max}$ is the electron number density at the F -layer maximum. For example, the accelerated electron energy is $W_e \approx 3$ keV if $j_B \approx 5 \cdot 10^{-5}$ A/m² ($\mathcal{N}_B \approx 3 \cdot 10^2$ cm⁻³, $V \approx 0.5$ km/s, $\nu_a/\omega_{pB} \approx 10^{-3}$,

Fig. 1. The small-scale (in transverse direction) anisotropic Alfvén vortices trapped into the ionospheric Alfvén resonator. The zone of electron (e) acceleration near the wall of the resonator and the motion direction of accelerated particles are indicated. Shown to the left are the altitude profiles of ionization distribution N_e (the solid line) and of ion drift velocity V_i (dashed line). $J_{\perp}$ is the transverse current in the ionosphere, j is field-aligned current in the Alfvén vortices, B is the Earth's magnetic field.

$\omega_0 \approx 1 \text{ s}^{-1}$). As the estimations show (TRAKHTENGERTS and FELDSTEIN, 1987), the greater inertia of ions results in their acceleration to significantly lower energies.

4) Above the Alfvén vortex amplitude was suggested to be assigned. Now we'll consider the self-consistent approach taking into account the turbulent plasma heating and the electron acceleration as the current saturation mechanism. The electron acceleration plays the crucial role in this problem. The matter is that the precipitating energetic particle flux affects the Pedersen conductivity in such a way that electrodynamical matching of the ionospheric E and F -layers becomes better, thereby giving rise to the higher rate of energy transfer from the convection to Alfvén vortices trapped in the IAR. It's readily seen from the expression (1) for γ . The energy balance equation may be written in this case as the energy conservation law:

$$\frac{d \int W dz}{dt} = \mathcal{P} - Q_1 - Q_2, \quad (8)$$

where W is the Alfvén wave energy density, $\mathcal{P}$ is determined by (5), the terms Q_1 and Q_2 describing the turbulent heating and the electron acceleration, respectively, may be presented as

$$Q_1 = a_1 j^3, \quad Q_2 = a_2 j^{3+p}, \quad p > 0, \quad (9)$$

a_1 and a_2 are some constants.

Let's consider the stationary state when $(d/dt)(\int W \cdot dz) = 0$; taking into account the additional ionization in the E -layer it follows that

$$\Sigma_P = \Sigma_{P0}(1 + Q_2/Q_b)^{1/2}, \quad (10)$$

where Σ_{P0} corresponds to the background source Q_b (the diffusive precipitation). Using (1)–(4) we can obtain the following equation for the stationary amplitude j as a function of V :

$$\frac{\left(\frac{V}{V_n} - 1 \right) (1 + a j^p)^{1/2}}{1 + \delta_0^2 (1 + a j^p)} = q j^{p-2}. \quad (11)$$

Here $\delta_0 = \Sigma_{P0}/3\Sigma_w$, a and q are constants. Under the conditions typical for the night-time ionosphere, when $\delta_0^2 \ll 1$, the dependence $j(V)$ in accordance with (11) is of hysteresis characters. Figure 2 shows such a dependence. As V increases, the TABL at the point $V = V_*$ jumps to the upper steady branch. The calculations have shown (TRAKHTENGERTS and FELDSTEIN, 1987) that the above-discussed TABL energy status (values of $\mathcal{P}_m$ and W_c) is realized under such a transition. The value of V_* is approximately few hundreds of $\text{m} \cdot \text{s}^{-1}$ under typical conditions. The characteristic time of the TABL development is of the order of the inverse maximum growth rate

$$\tau_0 \approx \gamma_m^{-1} \approx \frac{2L}{V_{A0}} \approx 7 \text{ sec.}$$

Fig. 2. The amplitude of field-aligned current j versus convection velocity V under TABL development V_n is the lowest threshold convection velocity necessary for an instability to develop, V_* is the convection velocity corresponding to the jump-like increase of j amplitude (the transition from the state 1 to the state 2). The arrows indicate the motion directions along the hysteresis curve as the value of V increases or decreases.

3. Summary

Summarizing the above results we can say that, macroscopically, the TABL demonstrates itself as the efficient energy source which may be characterized by the energy flux density

$$Q = Q_* \left(\frac{V}{V_*} \right)^2 \theta(V - V_*) = Q_* \left(\frac{E}{E_*} \right)^2 \theta(E - E_*), \quad \theta(x) = \begin{cases} 1, & x > 0, \\ 0, & x < 0, \end{cases} \quad (12)$$

where $V_* \approx 0.5$ km/s, $E_* \approx 30$ mV/m, $Q_* \approx 5$ erg·cm⁻²sec⁻¹. As the convection velocity increases the greatest part of the TABL energy is transformed into the accelerated electrons with energy $W_e > 1$ keV. It has been shown by TRAKHTENGERTS and FELDSTEIN (1989) that at the base of the TABL concept it is possible to quantitatively explain numerous substorm displays in the polar ionosphere.

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