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INFLUENCE OF THE IAR WITH HALL DISPERSION ON THE FORMATION OF DISCRETE AURORA

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Abstract. Using a three-layer model of the ionosphere we have reanalyzed the physical properties of ionospheric Alfvén resonator (IAR) interaction with magnetospheric convective flow. For a given perpendicular wavelength the position of maximum damping rate shifts to the region with lower ionospheric conductivity. When the convection electric field approaches a certain critical value, the resonator becomes unstable. This results in the IAR feedback instability. A new type of the IAR feedback instability with lowest threshold value of the convection velocity is found which is nearly twice less than the one predicted by the previous analysis provided by Trakhtengertz and Feldstein [1991] and Lysak [1991]. The favorable conditions for the instability onset are realized when the ionospheric conductivity is low, i.e. for the nighttime conditions. The feedback instability of IAR increases the field-aligned currents, which may generate a discrete aurora.

The concept of the IAR has been the subject of great deal of research during the recent years [e.g., Ref.1 and references therein]. The IAR arises due to the strong increase in the Alfvén velocity with altitude which results in wave reflection from velocity gradients and formation of a resonance cavity in the topside ionosphere. The most peculiar features of IAR are observed in the auroral zone, where the structure of currents and electric fields is controlled by interaction and propagation of ULF waves in the topside ionosphere. The basic mechanism of the IAR excitation in the high latitudes is connected with the resonant interaction of the magnetospheric convective flow with the conductive ionosphere. If the convective flow is properly phased with the ionosphere and the magnetosphere, a part of the energy of the convective flow is transferred to the IAR eigenmodes. This effect is known as the fast feedback instability [2, 3]. The role of the Hall divergent currents and the associated with them Hall dispersion of the IAR eigenmodes has been provided recently in Refs. 4, 5. It was shown that the physical mechanisms of the feedback instability has much in common with the Čerenkov radiation in collisionless plasmas. We note that the role of divergent Hall currents in magnetosphere-ionosphere coupling was earler studied by a number of authors [7-9].

It is known that the plasma density in the ionosphere and low altitude magnetosphere varies strongly along the geomagnetic field lines. The typical scale for this variation is of the order of 10^3 km. This parallel plasma inhomogeneity leads to a strong variation in the background Alfvén speed, which in turn results in the appearance of IAR cavity. This cavity modifies the propagation of ULF waves near the ionosphere. Since the IAR is localized at low altitudes (below $1 \div 2R_E$) a straight magnetic field line approximation is used. Let the external magnetic field **B** be directed along the z-axis. For simplicity the plasma is assumed to be homogeneous across the magnetic field lines. The ionosphere-atmosphere interaction in our model is described by the conductive slab with the height-integrated Pedersen conductivity Σ_P and Hall conductivity Σ_H. The shear Alfvén and compressional modes in our model are described by the parallel component of the vector potential **A** and two scalar potentials Φ and Ψ. We choose the reference frame moving with the convection velocity $\mathbf{v}_0$ and let all perturbed quantities to vary as $\exp(-i\omega t)$. If the wavelengths of the considered waves are much larger then the collisionless electron skin-depth then the field-aligned electric field is zero, i.e. $E_z = \partial_z \Phi + i\omega A = 0$. The potentials Φ and Ψ are the solutions of two wave equations

$$\partial_z^2 \Phi + \frac{\omega^2}{\upsilon_A^2(z)} \Phi = 0, \tag{6}$$

and

$$\nabla^2 \Psi + \frac{\omega^2}{\upsilon_A^2(z)} \Psi = 0, \tag{7}$$

where $v_A(z) = B/(\mu_0 \rho)^{1/2}$ is the altitude dependent Alfvén velocity, ρ is the plasma mass density, $\partial_z \equiv \partial / \partial z$ and $\nabla^2 \equiv \partial_z^2 + \nabla_\perp^2$.

These equations should be supplemented by two boundary conditions at the conductive slab ($z = 0$), which may be presented in the following form [4,5]:

$$\left(1 - \frac{\Sigma_\varphi}{\omega + i\nu}\right)\frac{v_{AI}}{\omega}\partial_z\Phi + i\alpha_P\Phi + \omega\alpha_H\left(1 - \frac{\alpha_I\alpha_H^{-1}\Sigma_\varphi}{\omega + i\nu}\right)\Psi = 0, \quad (8)$$

$$\left[\kappa + \frac{i\alpha_P\omega}{k_\perp v_{AI}} + \frac{i\alpha_I\omega\Delta_\varphi}{k_\perp v_{AI}(\omega + i\nu)}\right]\Psi = \frac{\alpha_H}{k_\perp v_{AI}}\Phi + \frac{i\Delta_\varphi}{k_\perp v_{AI}}\frac{v_{AI}}{\omega}\partial_z\Phi, \quad (9)$$

where

$$\Sigma_\varphi = -\frac{k_\perp \upsilon_0 \alpha_C}{\alpha_I}\cos\left[\varphi - \arctan(\alpha_P/\alpha_H)\right],\ \alpha_C = (\alpha_P^2 + \alpha_H^2)^{1/2}, \quad (10)$$

$$\Delta_\varphi = -\frac{k_\perp \upsilon_0 \alpha_C}{\alpha_I}\sin\left[\varphi - \arctan(\alpha_P/\alpha_H)\right], \quad (11)$$

$v_{AI} = v_A(z = 0)$, $\alpha_P = \Sigma_P/\Sigma_w$, $\alpha_H = \Sigma_H/\Sigma_w$, $\Sigma_w = 1/\mu_0 v_{AI}$, and φ is the angle between the wave vector and the direction of the drift velocity. $\alpha_I = (\Delta z/\lambda_{pi})\gamma^{-1}$ is the dimensionless parameter, which controls the electron precipitation, γ represents the number of additional electron-ion pairs created per incident electron, $\lambda_{pi} = c/\omega_{pi}$ is the collisionless ion skin depth, c is the speed of light, $\omega_{pi} = (ne^2/\varepsilon_0 m_i)^{1/2}$ is the ion plasma frequency, and m_i is the ion mass. For the actual ionospheric conditions, γ is nearly a linear function of the incoming electron energy. It is about 100 for 10 keV electrons [10]. According to Ref. 3 $\Delta z \cong \lambda_{pi} \cong 10 - 30$ km. Therefore, α_I is a small parameter of the order of $10^{-1} - 10^{-2}$. A typical recombination frequency for the ionospheric density of 10^{11} m^{-3} and recombination coefficient 10^{-13} m^3/s is $\nu \cong 0.01$ s^{-1}. Usually in the ionosphere α_P and α_H are connected to each other. For example, for sunlight-produced conductivity $\alpha_H \approx 2\alpha_P$ whereas for precipitation produced conductivity $\alpha_H/\alpha_P \approx E^{5/8}$, where E is the energy of precipitating electrons in keV [e.g., Ref. 11]. This ratio is 4.2 for 10 keV electrons and 2.7 for 5 keV. Large values of α_H/α_P of the order of 5 and higher may take place in the auroral zone [e.g., Refs. 6,12]. When deriving eq. 9, we suppose that in the neutral atmosphere ($-d < z < \Delta z$) Ψ varies as [e.g., Ref. 6]

$$\Psi = C\frac{\exp(k_\perp z) - \exp\left[-k_\perp(z + 2d)\right]}{1 - \exp(-2k_\perp d)}, \quad (12)$$

where C is an arbitrary constant. Expression (12) is valid if Ψ vanishes on the surface $z = -d$. Such simplification assumes that the solid Earth is considered to be a perfect conductor. In eq. (20)
$\kappa = 1 + k_\perp\Delta z + \exp(-k_\perp\Delta z)\coth(k_\perp d)$

In order to make our conqsideration as transparent as possible we consider a simplified model of a three-layer ionosphere. This model treats the ionosphere as a height-integrated slab, neglecting Hall and Pedersen conductivities above the ionospheric height. As we shall see in what follows, this simplified model with the sharp jump of Alfvén velocity qualitatively describes all basic features of the problem at hand. The presence of convective flow moving with the velocity $\mathbf{v}_0 = (\mathbf{E}_0 \times \hat{z})/B$, where $\mathbf{E}_0$ is the electric field due to the magnetospheric convection and $\hat{z}$ is a unit vector along **B**, modifies the physical properties of the IAR eigenmodes. In this case equations (8) and (9) have been solved numerically. As an example the change in the dimensionless frequency of the lowest (fundamental) IAR

eigenfrequency for different values of $\sigma = \sigma_{\varphi \max}$ is shown in Figure 1. Here $\sigma_{\varphi \max} \equiv \Sigma_{\varphi \max} L / v_{AI}$ and $\varphi = \varphi_{\max}$ stands for the angle of propagation, calculated numerically, which yields the maximum value of growth/damping rate. It is clearly seen that with the increase in the convection electric field, the major modification of the mode appears basically at $\alpha_P < 1$, that is, when the ionospheric conductivity is low. The modification results in two effects. On one hand, the transition region shifts towards the lower ionospheric conductivity. On the other hand, the fundamental eigenmode frequency increases in value. The extremal value of the frequency is of the order of $2\pi\alpha_C v_0/\alpha_I\lambda_\perp$, while at the large values of α_P it is of the order of $\pi v_{AI}/2L$. Figure 2 shows the change in the damping rate of the fundamental mode. With the increase in the convection electric field the maximum value of the damping rate decreases and the position of a minimum shifts to the lower conductivity. Eventually, the growth rate becomes positive when $\sigma > \pi / 2$. Thus, our analysis shows that most favorable conditions are realized when the ionospheric conductivity is low. We note that this occurs basically during the nighttime conditions. In this case the ionospheric dissipation is small and the electric field of magnetospheric convection can easily penetrate the conductive slab. Thus, the convection flow moves relatively freely through the ionosphere losing its energy due to Čerenkov radiation in the IAR. When ionospheric conductivity is high (day-time) the feedback instability may also arise but the growing oscillations shift to shorter wavelengths.
Recently authors of Ref. 13 presented data from the DMSP satellite showing that the most intense auroral arcs (discrete aurora), which are usually attributed to the small-scale Alfvénic structures [e.g., Ref. 1], appear preferentially in the low conducting ionosphere when a strong electron precipitation is observed. The analysis presented here shows that the preferable conditions for strongest deceleration of the convective flow and subsequent excitation of IAR eigenmodes are probably realized during periods of low ionospheric conductivity during the night-time in accordance with the data [13]. These authors also came to the same conclusions and considered that among other 22 theories of auroral arcs [14] the model with fast feedback instability is the most probable candidate to explain the appearance of discrete auroral arcs.

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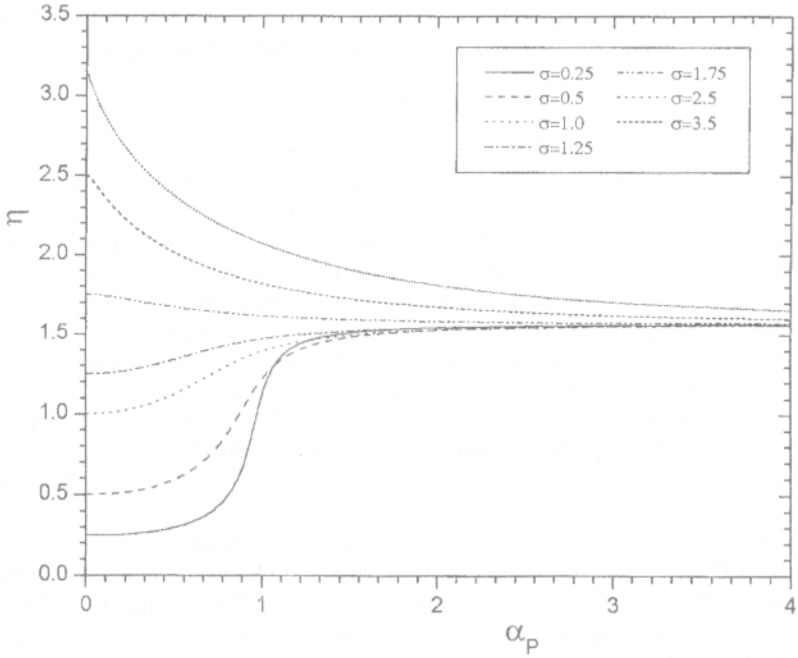

Figure 1. The variation of the IAR fundamental eigenfrequency as the function of α_P for different values of σ . Here $\varepsilon = 0.01$, $\nu = 0.01$, $k_\perp d = 35$, $d = 100$ km, $\Delta z = 15$ km, $L = 700$ km and $\alpha_H / \alpha_P = 1.75$.

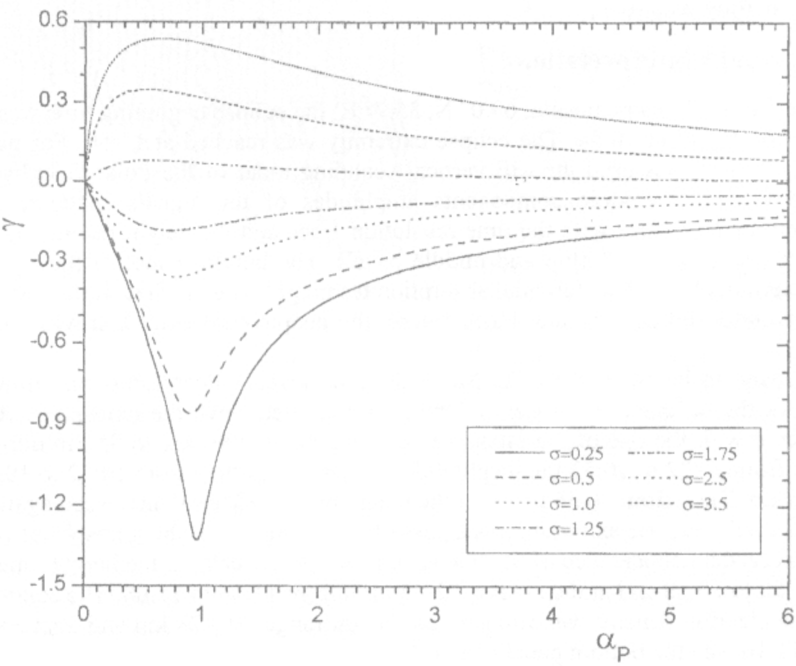

Figure 2. Same as Figure 2 but for the damping/growth rate.