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POLICE WHISTLE TYPE EXCITATION OF THE IONOSPHERIC ALFVEN RESONATOR AT MIDDLE LATITUDES

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Abstract. A new model for the generation of the ionospheric Alfven resonator (IAR) at middle latitudes is developed. It is shown that the mechanism of the IAR excitation in this region is similar to the operation of the ordinary police whistle. The Earth's ionosphere wind system in this case is capable of sustaining the generation of electromagnetic oscillations that can be detected by ground magnetometers. The general IAR dispersion relation describing the linear coupling of the shear Alfven and fast magnetosonic/compressional modes is obtained recently by Surkov et al. (2004). The dependence of the IAR eigenfrequencies and damping rates on the perpendicular wave number and on the ground conductivity during the day- and nighttime conditions is analyzed both analytically and numerically. In order to demonstrate the IAR excitation by neutral winds the power spectra of the geomagnetic perturbation on the ground surface are calculated. Furthermore, it is found that Kolmogorov spectra of the ionospheric turbulent neutral winds and the IAR eigenfrequencies lie in the same frequency range that makes it possible to enhance the IAR excitation. The relevance of the developed theoretical model to the ground based observations is emphasized.

1. Introduction

The low-frequency electromagnetic (EM) perturbations in the frequency range of $10^{-3}-10$ Hz are of special interest in geophysical studies [e.g., *Kangas et al.*, 1998]. Nearly all magnetospheric and ionospheric resonances fall into this class. The MHD resonances of the magnetosphere as a whole, the field-line and Shumann resonances of the Earth-ionosphere cavity are among them. This frequency range is associated with operation of the so-called Alfven masers generating the ion-cyclotron waves in the Earth's magnetosphere [*Andronov and Trakhtengertz*, 1964; *Bespalov and Trakhtengertz*, 1986] which defines the characteristic life-time of the trapped radiation (*Kennel and Petschek,* 1966). A special credit has been paid in the past to the study of the ionospheric Alfven resonator (IAR) that arises due to a strong increase in the Alfven wave refractive index in the ionosphere [*Polyakov*, 1976; *Polyakov and Rapoport*, 1981]. The resonator lower boundary coincides with the E-layer where nearly all plasma parameters undergo a strong jump. The upper boundary is located a few thousands kilometers from the Earth's surface due to the reflection of the IAR eigenmodes caused by nearly exponential decrease in plasma density above the maximum of the F-layer. The latter results in the violation of WKB approximation and partial wave reflections that form a resonance cavity in the topside ionosphere. The same cavity serves as the waveguide for the fast/compressional mode. The existence of the IAR was well documented by ground-based observations both in middle [*Polyakov and Rapoport*, 1981; *Belyaev et al.,* 1987, 1990; *Hickey et al.,* 1996; *Bosinger et al*., 2002] and in high latitudes [*Belyaev et al.,* 1999; *Demekhov et al.,* 2000]. The resonator was also identified in the Freja and FAST data [e.g., *Grzesiak,* 2000; *Chaston et al.,* 1999, 2002, 2003]. The basic mechanism of the IAR excitation at high latitudes usually refers to the development of the fast feedback instability induced by the large-scale ionospheric shear flows [*Lysak,* 1991; *Trakhtengertz and Feldstein*, 1991; *Pokhotelov et al.,* 2000, 2001]. The energies of this instability were reviewed by *Lysak and Song* [2002]. The nonlinear theory of the IAR was recently developed by *Pokhotelov et al.* [2003, 2004] and *Onishchenko et al.* [2004]. It should be noted that the feedback instability can serve as the basic mechanism of the IAR excitation at high latitudes, where the convection electric fields can reach quite strong values. On the contrary, at middle latitudes other sources of free energy can join. For example, generation of the IAR can be associated with the thunderstorm activity [e.g., *Polyakov and Rapoport*, 1981; *Belyaev et al.,* 1987, 1990]. In some cases the IAR manifests itself as the anomalous ULF transients and can be observed in the upper ionosphere on board the low-orbiting satellites above strong atmospheric weather systems [*Fraser-Smith*, 1993]. In due time *Sukhorukov and Stubbe* [1997] considered the nonlinear conversion of the lightning discharges energy into the IAR eigenmodes. We note that at middle latitudes there is a natural source of free energy stored in the ionospheric neutral wind motions which can excite the IAR similar to operation of a police whistle. The consideration of this new mechanism is the subject of the present study.

2. Basic model

It is of common knowledge that traditional mechanisms of the IAR excitation such as feedback instability becomes less important in the mid- and low-latitudes. In these regions of the ionosphere the electric fields are basically generated by neutral winds [*Kelley*, 1989]. In part, this mechanism is similar to acoustic autovibration in such a system as "a police whistle". Indeed, let us imagine a cylindrical case blocked at one end and open at the other. It is known that an aerial flux externally tangent to the open end of the shell results in excitation of the aerial column eigenmodes. In such a case the energy flux coming from the external source is governed solely by the aerial column. The fluctuations of the tangent aerial flux, which frequencies are close to the aerial column eigenfrequencies in the shell can give rise to enhancement of the eigenmode magnitudes. A detailed mathematical analysis presented by *Surkov et al.* [2004] shows that a similar scenario may operate in the ionospheric resonance cavity. In this case the neutral wind in the lower ionosphere can serve as an energy source for the cavity excitation. The part of the gas kinetic energy is transferred into the energy of the electric current in the conductive ionospheric slab, which is then converted into the energy of the shear and fast modes. Some of this energy is lost/dissipated due to the ionospheric Joule heating and wave energy leakage into the magnetosphere. The fluctuations of the neutral wind can result in the enhancement of the energy flux flowing from the wind into the resonance cavity if the fluctuation frequency range is close to the IAR eigenfrequencies. Such fluctuations, which arise from the gas turbulence, are usually observed in the vicinity of turbopause and they can occur in the E-layer. In order to find the frequency range that is typical for the turbulent pulsations one needs a rough estimation of the neutral wind parameters. The gas flow pattern is characterized by the Reynolds number $\mathrm{Re} = \Delta v \lambda \rho / \xi$, where ρ is the neutral gas mass density, Δv denotes the variation of the mean gas velocity and λ is the characteristic scale of the variations. The gas viscosity ξ due to molecular collisions can roughly be estimated as $\xi \approx (k_B T m)^{1/2} / \sigma_c$, where k_B is Boltzmann constant, T is the gas temperature, m denotes the average ion mass and σ_c is the collisional cross-section of the neutral particles. At the altitudes of the E-layer (100-130 km) the average ion mass $m \approx 27 - 28$ units of proton mass that approximately corresponds to nitrogen molecular with $\sigma_c \approx 0.8 \times 10^{-18}\ m^2$. Using these parameters one can find the rough estimation $\xi \approx 1.6 \times 10^{-18}$ Pa•s. We note that due to the interaction between eddies in the flow located below turbopause, the effective viscosity can be much larger than the molecular viscosity calculated above [*Kelley,* 1989]. Our estimation is rather relevant to the E-layer where the turbulent mixing gradually decreases. The neutral particle number density N decreases drastically with the altitude so that $N \sim (10^{19} - 7 \times 10^{17})\ m^{-3}$ within the height interval under consideration. Choosing $N = 2 \times 10^{18}\ \ m^3$ as an average value one obtains $\rho = Nm \approx 9 \times 10^{-8}$ kg/m³. The wind speed is the subject to diurnal and seasonal variations. For example, the diurnal wind variations increase with the altitude from 10-30 m/s at 95 km up to 100-150 m/s at 200 km. So, the value $\Delta v \approx (10 - 100)\ \mathrm{m/s}$ seems to be a relevant estimation for the wind velocity fluctuations at the altitudes of 100-130 km. Taking λ= (1-10) km as a characteristic spatial scale of such fluctuations, one finally obtains $\mathrm{Re} \approx 6 \times (10^1 - 10^3)$.

With this estimation in mind, one can assume that such a great value of the Reynolds number exceeds the critical value that is necessary for transition from the laminar to turbulent regime. The latter can give rise to the turbulence of the gas flow. The Kolmogorov theory [cf. *Landau and Lifshits*, 1986] assumes that if a neutral flow is stirred at some wavelength λ, the certain structures will be formed in a so-called "inertial subrange" in k space, where the energy will cascade to larger and larger values of k, i.e. from the large- to the small scales. The cascade is bounded from below by the value λ^{-1} and from above by the so-called Kolmogorov dissipative scale $k_m = \lambda^{-1}\,\mathrm{Re}^{3/4}$, where the influence of the molecular viscosity becomes significant and the energy dissipation occurs. So within the interval $\lambda^{-1} << k << \lambda^{-1}\,\mathrm{Re}^{3/4}$ the energy is transferred from eddy to eddy with no net energy gain or loss. In an isotropic homogeneous medium the omnidirectional spectral density of the mechanical energy of the turbulent flow, has a power law spectrum $\propto k^{-5/3}$. The typical frequencies of turbulent pulsations are evaluated as ω∝kv, where v is the smoothed mean velocity that slowly varies along the flow. Hence we find that Kolmogorov spectrum is localized in the frequency range given by $v/\lambda << \omega << (v/\lambda)\mathrm{Re}^{3/4}$, where the lower margin corresponds to large-scale pulsations whereas the upper one stands for the dissipative turbulence scale, i.e. for the smallest pulsations in the turbulent flux. For instance, taking the parameters v=100 m/s, $\Delta v = 50$ m/s and λ=10 km one obtains 0.01<<ω<<4 Hz. These estimations show that the typical frequency band of the gas flow turbulence can be close to the eigenfrequencies of the ionospheric resonance cavity that results in the most effective transition of the gas kinetic energy into the hydromagnetic wave energy. The detailed numerical calculations show [*Surkov et al.,* 2004] that the magnitude of the power spectrum can be detectable at ground level in spite of the energy dissipation due to Joule heating and wave leakage into the magnetosphere. In fact this analysis shows that the IAR dispersion relation comprises of two modes. The first one corresponds to the ordinary shear Alfven wave propagating along the geomagnetic field. Its spectrum practically does not depend of the perpendicular wave number k. However, corresponding damping rate increases with the increase in k. The second mode corresponds to the fast mode and it's eigenfrequency and damping rate strongly depend on k. The latter is one or two order of magnitude smaller than that for the shear Alfven wave. For the actual plasma conditions both modes are linearly coupled through the E-layer Hall conductivity.

3. Conclusions

Summarizing, we note that:

1. The IAR excitation at the mid-latitudes can be associated with the turbulent motions of the neutral winds. The estimations show that this mechanism is capable of producing observable geomagnetic perturbations on the ground.
2. The IAR dispersion relation comprises two coupled modes, the shear Alfven wave and the fast mode. The eigenfrequencies of the first mode practically do not depend on the perpendicular wave number k, whereas for the fast mode they approximately follow the linear dependence on k. The fast mode damping rate decreases with the increase in k, while the shear mode exhibits an opposite dependence.
3. The IAR power spectra contain the peaks both due to the shear and fast modes. The day- and nighttime power spectra have essentially different shapes and magnitudes and thus strongly depend on the wind parameters and ground/ionosphere conductivities. The nighttime IAR excitation should be expected to be more intensive because the peaks of the nighttime spectra are found to be greater than those for the daytime conditions. For detailed discussion of all these features see *Surkov et al.* [2004].

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