# SENSITIVITY OF THE SPORADIC-$E$ IRREGULARITY SPECTRUM TO THE ION COMPOSITION OF THE LAYER

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Plasma density irregularities in sporadic-$E$ layers below the turbopause level are resulted from the action of turbulence in the neutral atmosphere. A possible dependence of the spectrum of irregularities on the sporadic-$E$ ion composition is considered in this paper. The consideration is based on an analytic expression for the irregularity spectrum. It is shown that the rms level of the relative plasma density fluctuations caused by neutral turbulence and the shape of their spectrum should be sensitive to changes in the metal ion concentration in the layer. The rms fluctuation and the slope of the irregularity spectrum increase with increasing the concentration of metallic ions in the sporadic-$E$. These changes in the spectrum and in the fluctuation level are explained by the reduction in the recombination rate and by the increase in the mean ion mass.

## INTRODUCTION

It is known that the wind-shear mechanism can produce sporadic-$E$ ($E_s$) layers in the auroral and mid-latitude ionosphere [9, 10]. This mechanism provides a redistribution of ionization through the interaction of the plasma imbedded in the neutral wind with the geomagnetic field under the appropriate vertical profile of the horizontal wind velocity. The mechanism is not very effective for the molecular ions which make up the greater part of the total ion content, since these have a lifetime less than the formation time of the layer; rather, the process acts on atomic metal ions (produced as a result of meteoric influx). These are thought to have very long lifetimes in the $E$-region, since the recombination reaction for monatomic ions is very slow compared to the dissociative recombination of molecular ions. The data of observations show that the ion composition of sporadic-$E$ usually differs from that of the normal $E$-region ($NO^+$ and $O_2^+$), and most of the ions at the $E_s$ peak are often metallic such as $Fe^+$ and $Mg^+$ [9, 10]. In addition, if the sporadic-$E$ is not above the turbopause, the neutral air turbulence plays an important role in the $E_s$ formation [2]. Due to turbulent mixing, various values of concentration of metal ions can be expected in the layer. Changes in the concentration of such ions provide changes in values of the effective recombination coefficient, $\alpha_r$, and mean ion mass, $m$, [1, 9]. It is also evident that plasma irregularities are generated by neutral air turbulence in sporadic-$E$. The present report is devoted to the study of the ion composition sensitivity of such plasma irregularities. In particular, here we discuss the irregularity spectra, which can be measured during rocket experiments in sporadic-$E$ layers for three cases of values of the iron ion concentration.

## EFFECT OF IRON ION CONCENTRATION ON SPORADIC-$E$ PLASMA IRREGULARITIES

A starting point of our consideration is an expression for the three-dimensional spectrum, $P(\mathbf{k})$, of plasma density fluctuations produced by neutral turbulence in a weakly ionized gas of the lower ionosphere [4]:

$$P(\mathbf{k}) =(4\pi\Gamma(k))^{-1}(L_N^{-2}k^{-2}(\mathbf{n}\times\mathbf{k})^2 + \frac{\Omega^2}{\nu^2}(\mathbf{b}\times\mathbf{k})^2)\cdot C_1\varepsilon^{2/3}k^{-11/3}, \tag{1}$$

where

$$\Gamma(k) = (2\alpha_r N_0 + (D_a+\mu_n)k^2 + 2\varepsilon^{1/3}k^{2/3})\cdot(2\alpha_r N_0 + D_a k^2 + \varepsilon^{1/3}k^{2/3}). \tag{2}$$

Here $L_N$ is the length scale of the gradient of mean plasma density $N_0$, $\mathbf{n} = L_N\cdot N_0^{-1}\nabla N_0$ is the unit vector along the gradient, $\mathbf{b} = \mathbf{B}/B$ is the unit vector along the geomagnetic field $\mathbf{B}$, $\Omega = eB/mc$ is the ion gyrofrequency, $\nu$ is the ion-neutral collision frequency, $C_1$ is a dimensionless constant of order unity, $\varepsilon$ is the rate of dissipation of turbulent energy per unit mass, $D_a$ is the ambipolar diffusion coefficient, $\mu_n$ is the kinematic viscosity of neutral gas. In our case $D_a\approx\mu_n$.

Expression (1) describes plasma fluctuations with wavenumbers $L_N^{-1} < k < k_d$ ($k_d = (\varepsilon/\mu_n^3)^{1/4}$ is the Kolmogorov dissipation wavenumber) and permits an rms level of the relative plasma density fluctuations, $< \delta N^2/N_0^2 >^{1/2}$, to be estimated:

$$\langle\frac{\delta N^2}{N_0^2}\rangle = \int P(\mathbf{k})\mathrm{d}\mathbf{k} = \int_{k_1}^{k_2} P_1(k)\mathrm{d}k, \tag{3}$$

where

$$P_1(k) = \frac{2}{3\Gamma(k)} \cdot (L_N^{-2} + \frac{\Omega^2}{\nu^2}k^2) \cdot C_1\varepsilon^{2/3}k^{-5/3} \tag{4}$$

($P_1(k)$ is the one-dimensional power spectral density (1D PSD) of fluctuations and may be convenient for explaining possible changes in the spectral form resulted from changes in a relative role of various processes in the creation of irregularities of different scales [5]). Estimates of the rms fluctuation level with use of (3) for three cases of possible $Fe^+$ concentration in the layer are presented in Table 1 ($k_1 = 10^{-3}$ m$^{-1}$, $k_2 \leq k_d \approx 0.2$ m$^{-1}$). An increase in the concentration of heavy metallic ions ($Fe^+$) results in both the reduction in $\alpha_r$ [1] and increase in $m$ [3], hence, the ratio $\Omega/\nu$ decreases ($\Omega/\nu = (m_0/m)\Omega_0/\nu$, $m_0$ is the mean ion mass for the ion composition of the normal $E$-region). Taking into account arguments presented in [6] when diffusion of heavy gas of small concentration in light gas was considered, we may neglect possible changes in $D_a$ and $\nu$ resulted from the increase in $m$. In all these cases the values of $L_N$, $N_0$, $\varepsilon$, $\Omega_0/\nu$, and $D_a$ defined in (2)–(4) are fixed as follows: $L_N = 3 \times 10^3$ m, $N_0 = 10^{11}$ m$^{-3}$, $\varepsilon = 0.1$ m$^2$ s$^{-3}$, $\Omega_0/\nu = 0.01$, $D_a \approx \mu_n = 4$ m$^2$ s$^{-1}$ (the values correspond to the altitude about 95 km).

Table 1: Dependence of values of $m$, $\alpha_r$, and $< \delta N^2/N_0^2 >^{1/2}$ on the $Fe^+$ concentration in the sporadic-$E$

| Case | $Fe^+$, % | $m$, a.m.u. | $\alpha_r$, m$^3$ s$^{-1}$ | $< \delta N^2/N_0^2 >^{1/2}$, % |
|---|---|---|---|---|
| 1 | 0–10 | $\sim 31$ | $\sim 3.8 \times 10^{-13}$ | $\sim 1.7$ |
| 2 | 40 | $\sim 41$ | $\sim 2.5 \times 10^{-13}$ | $\sim 2.3$ |
| 3 | 70 | $\sim 50$ | $\sim 1.5 \times 10^{-13}$ | $\sim 3.4$ |

Figure 1 (dashed lines) shows self-normalized spectra, $P_1(k)/P_1(k_1)$, for all three cases of $Fe^+$ concentration (line numbers = case numbers, a straight line represents the Kolmogorov law $k^{-5/3}$). The use of (4) is quite valid when irregularities are isotropic.

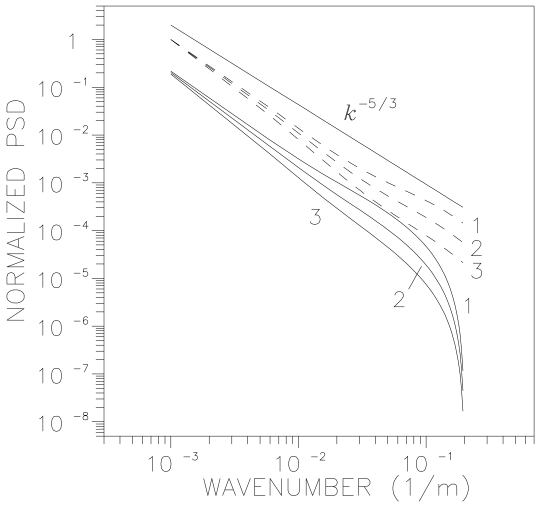


Figure 1: Normalized spectra of plasma density fluctuations under different values of $Fe^+$ concentration in the sporadic-$E$ predicted by (4), $P_1(k)/P_1(k_1)$ (dashed lines), and by (5), $S_1(k_z)/P_1(k_1)$ (solid lines); the straight line represents the slope of the Kolmogorov spectrum

However, because of dependence on $\mathbf{n}$ and $\mathbf{b}$ in (1) the irregularity spectrum is not quite isotropic. Therefore, in order to predict the spectrum expected from an experiment (if the direction of measurement is along the $z$ axis) a 1D spectrum in other form can be derived by use of $P(\mathbf{k})$, (1), namely,

$$S_1(k_z) = \int_0^{\sqrt{k_d^2-k_z^2}} k_\perp \mathrm{d}k_\perp \int_0^{2\pi} P(k_\perp \cos\varphi, k_\perp \sin\varphi, k_z)\mathrm{d}\varphi = \int_0^{\sqrt{k_d^2-k_z^2}} S(k_\perp, k_z) k_\perp \mathrm{d}k_\perp \tag{5}$$

with

$$S(k_\perp, k_z) = (4\Gamma(k))^{-1}(2L_N^{-2}k_\perp^2 + \frac{\Omega^2}{\nu^2}k^2(k_\perp^2 + k_\perp^2\cos^2\theta + 2k_z^2\sin^2\theta)) \cdot C_1\varepsilon^{2/3}k^{-17/3}, \tag{6}$$

if the sounding rocket trajectory is along the gradient of mean plasma density, $\mathbf{n}(0,0,1)$. Here $k^2 = k_\perp^2 + k_z^2$, $\theta = 90° - I$ is an angle between $\mathbf{b}$ and $\mathbf{n}$, $I$ is the magnetic dip angle (say, in the case of the auroral ionosphere, where electron density fluctuations were measured by rockets during the ROSE project [7, 8], $I \approx 77°$). Solid lines in Fig. 1 represent the normalized spectra, $S_1(k_z)/P_1(k_1)$, for all three cases of $Fe^+$ concentration. We see that a rise in the concentration of slowly recombining ions in the sporadic-$E$ increases the slope of the irregularity spectrum and the rms level of plasma density fluctuations. Estimates of the plasma fluctuation level and the shape of the irregularity spectrum obtained here do not contradict to the data gained during the ROSE rocket flights [8].

We can see also that $P_1(k)$, (4), is quite acceptable for an analysis of the irregularity spectrum in the wide range of wavenumbers, $L_N^{-1} < k < k_d$, except the wavenumber region near $k_d$ (see Fig. 1). In particular, (4) allows us to conclude that an increase in the concentration of $Fe^+$ ions leads to broadening the wavenumber range, $L_N^{-1} < k < ((\Omega/\nu)L_N)^{-1}$, in which the plasma irregularities are mainly produced by the turbulent mixing of a background plasma density gradient (since an increase in $m$ decreases the ratio $\Omega/\nu$) [5].

## CONCLUSIONS

Thus, the ion composition of sporadic-$E$ exerts apparent influence on the shape of the spectrum of plasma density fluctuations created by the neutral atmosphere turbulence. The analysis of the irregularity spectrum under different concentrations of $Fe^+$ ions in the layer shows that the presence of slowly recombining ions increases the slope of spectrum and the rms level of the plasma fluctuations. Due to change in the ratio of the ion gyrofrequency to the ion-neutral collision frequency, $\Omega/\nu$, resulted from change in the mean ion mass, some change in fine structure of the irregularity spectrum can be expected too.

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