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ELECTRON FLUX SCATTERING IN STRONGLY TURBULENT IONOSPHERIC PLASMA REGIONS

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ABSTRACT

The results of analysis of low energy electron flux decreases recorded by a high time-resolution counter system on the satellite *Cosmos-1809* crossing strongly turbulent plasma regions are discussed. The near-satellite plasma turbulization is induced by the HF radiation pulses of the powerful onboard sounder transmitter. The energy spectrum dip near the energy ~120 eV is the electron flux perturbation interpreted in terms of the charged particles scattering/deceleration.

INTRODUCTION

The experimental investigations of electron scattering/deceleration in strongly unstable plasmas have been carried out previously in laboratory conditions only. Studying such processes on a spacecraft is a rather difficult problem especially in the simultaneous presence of accelerated and decelerated ambient electrons. However, under some conditions it can be done using the topside sounder on the *Cosmos-1809* satellite.

SCIENTIFIC INSTRUMENTS

The swift-sweep counter system with high time resolution (HTR) spectrometer SF-3M was used for the perturbed electron flux recording. The electron concentration n_0 and temperature T_e were measured by two plasma probes. The electron plasma and cyclotron frequencies, ω_{pe} and ω_{ce} , were determined quite reliably. The orientation of the satellite in respect to the Earth's magnetic field $\mathbf{H}_0$ and its velocity vector $\mathbf{v}_s$ were determined by an onboard magnetometer and a solar sensor.

EXPERIMENTAL DATA

So far the experimental study of the electron flux perturbations due to an electromagnetic pumping wave has been confined to the recording of fluxes accelerated either by resonance with electron cyclotron frequency harmonics, or by plasma wave absorption by electrons (Galperin et al., 1981; Shuiskaya et al., 1991), including modulation instability mechanism. In Figure 1 the electron flux dependence on radiation frequency is shown, measured by the HTR counter system under somewhat different conditions ($q = \omega^2_{pe}/\omega^2_{ce} \approx 0.17$, the accumulation time for each of the four counters τ = 3 ms). The most important difference is the substantially higher unperturbed level of auroral soft electron flux, which made it possible to investigate the intensity reduction of hot electron. In Figure 2 the electron spectrum is shown as recorded by 1-3 HTR counters for the frequency range *b* (see Figure 1). For time τ = 3-6 ms a strong

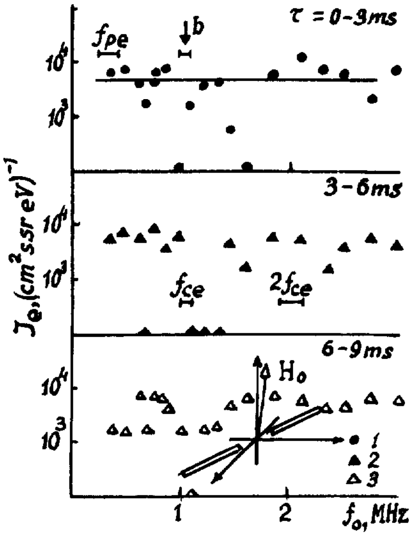

Fig. 1. The electron fluxes with energy ε_e = 140eV for a typical case (negative bursts) $T_e \approx$ 8800K, $n_0 \approx$ 2500cm^{-3}, $\alpha_p \approx$ 105 - 135°, $f_{pe} \approx$ 0.44MHz, $f_{ce} \approx$ 1.05MHz ($q \approx$ 0.17). The solid line is the level of unperturbed fluxes; 1,2,3 mark the electron fluxes recorded by HTR counters 1,2,3. Mode τ = 3 ms, the invariant latitude $\Lambda_o \approx$ 55 - 68°, 08:49 - 08:53 UT, orbit 265 of *Cosmos-1809*.

fall of the electron flux J_e is observed in the narrow energy range $\varepsilon_e \sim$ 80-350 eV with pitch-angles $\alpha_p \approx$ 105-135°. The electron flux intensity reduction is observed in the frequency range $\omega^2_{ce} \leq \omega^2_0 \leq \omega^2_{ce} + \omega^2_{pe}$. No effects were seen on the HTR counter 4 (not shown). It is natural to assume that the sharp electron flux decrease may be due to scattering by plasma oscillations. When the pumping wave amplitude exceeds a certain threshold level $E^2_0 \geq E^2_{th}$, parametric instabilities develop in a plasma and, as a result, Langmuir and ion-sound oscillations grow with an increment γ_p (Galeev et al., 1977). The turbulent plasma fluctuations may contribute substantially to the effective collision frequency ν_{ef}. Quite similar results have been obtained during rocket experiments with electron beam and neutral gas injection. For example, the injected electron intensity in the experiment *Polar-5* was considerably reduced at altitudes of 150-180 km, where beam-plasma discharge processes produced a sharp electron-ion collision frequency growth (Maehlum et al., 1980). By contrast, the principal feature of the observed phenomenon on the *Cosmos-1809* satellite is the kinetic collissionless stage of the interaction of the auroral electrons with the turbulent plasma excited by HF radiation from the dipole antenna.

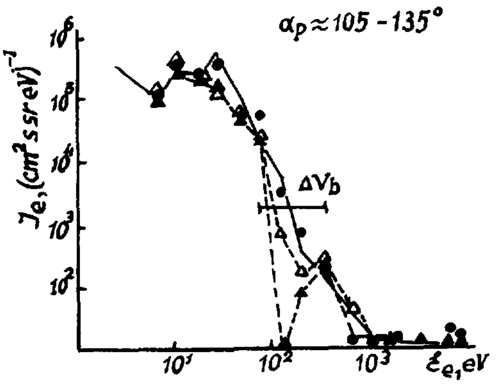

Fig.2. The perturbed electron spectrum relaxation for the frequency range b (Fig.1), the solid curve is the unperturbed electron spectrum.

THE INTERACTION OF ELECTRON BEAMS WITH A TURBULENT PLASMA

In Figure 3 a qualitative picture of the electron beam interaction with a turbulent plasma is shown. The path of a satellite after an HF pulse through hot auroral electron beams is shown by the thick dashed line. This model experiment represents a continuation of well-known active experiments in space to investigate various problems of wave-particle interactions in space (Oraevsky et al., 1994). To consider an instability of an electron beam with density n_b, bulk velocity $\mathbf{v}_b$ and thermal velocity range $\Delta\mathbf{v}_b$, it is necessary to estimate the effective collision frequency ν_{ef}. We use the results by Pustovalov and Silin (1970), Mishin et al. (1993) to determine the turbulent Langmuir and ion-sound fluctuation energy density levels W_L and W_S. One can estimate W_L from a condition of energy dissipation of the pumping wave into Langmuir turbulence and the short-wave repumping $\nu'_{ef} \cdot E^2_0/8\pi = \gamma_0 \cdot W_L$, where γ_0 is the modulation instability increment and $\nu'_{ef} \approx \alpha\omega_{pe}W_L/n_0T_e$, i.e., $W_L/n_0T_e = \alpha^2 M/m \cdot (E^2_0/8\pi n_0T_e)^2$ ($\alpha \approx 0.7$, M/m is ion-to-electron mass ratio). Near the parametric instability threshold, the ion-sound fluctuation level is $W_S/n_0T_e = [E^2_0/E^2_{th} - 1] \cdot 9.2 \cdot 10^{-3}\ (T_e/T_i) \cdot (\gamma^2/k^2\mathbf{v}_{Te})$, where γ is the high-frequency plasma wave damping decrement, and $\mathbf{v}_{Te}$ is the electron plasma thermal velocity. The energy threshold of instability is evaluated from $E_{th}/4\pi n_0T_e \approx 16(\gamma_s/\omega_s)\ (\gamma/\omega_{pe})\ [1+(\omega^2_0 - \omega^2_{pe})/(\omega^2_0 - \omega^2_{ce})]$, here the ratio of the ion-sound oscillation damping decrement to the ion-sound oscillation frequency is $\gamma_s/\omega_s \approx 0.014$ and $\gamma/\omega_{pe} \approx 10^{-3}$. Then the effective collision frequency is

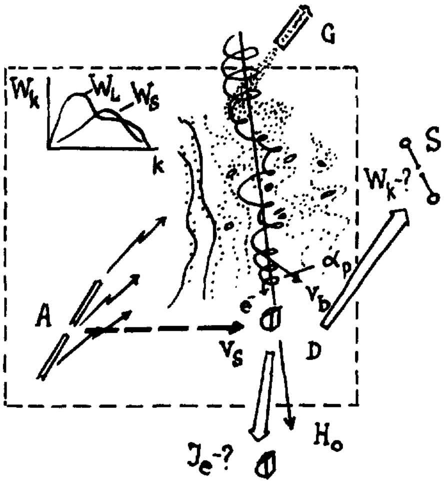

Fig.3. A qualitative picture of the electron beams interaction with the turbulent plasma, induced by impulse from HF dipole antenna A; G is electron gun, D is electron probe, S is the electric field sensor.

$$\nu_{ef} \approx \omega_{pe}\left[\left(\frac{W_L}{n_0T_e}\right)^{1/2} + \frac{W_S}{n_0T_e}\cdot\frac{\omega_{pe}}{\gamma(k)}\right]\cdot\left(\frac{T_e}{\varepsilon_b}\right)^{3/2}. \qquad (1)$$

The contribution by Langmuir and ion-sound turbulence to the frequency ν_{ef} will depend on the time delay and satellite location in space. Since the plasma fluctuation growth occurs mainly along a resonance angle θ_r, the value of ν_{ef} for the parametric instability increment is maximal when $\theta = \theta_r$, and $\Delta\omega_0 = \omega_0 - \omega_{UH} = \omega_s$ (Oraevsky and Sagdeev, 1962). It is obvious that in real conditions the distribution of the electric fields excited by the HF radiation is extremely complicated and only qualitative evaluations are possible so far.

The dispersion equation for the complex frequencies of almost longitudinal oscillations in a system consisting of a "cold plasma and hot beam" is as follows

$$1-\frac{\omega_{pe}^2}{\omega^2}\cos^2\theta-\frac{\omega_{pe}^2}{\omega^2-\omega_{ce}^2}\sin^2\theta+i\frac{\omega_{pe}^2}{\omega^3}\nu_{ef}\left[\cos^2\theta+\sin^2\theta\frac{\omega^2\left(\omega^2+\omega_{ce}^2\right)}{\left(\omega^2-\omega_{ce}^2\right)^2}\right]+\frac{\omega_{be}^2}{k^2v_{be}^2}\left[1+i\sqrt{\pi}z_0\sum_{n=-\infty}^{\infty}A_n\left(X_{be}\right)W\left(z_n\right)\right]=0,$$

$$z_n=\frac{\omega-n|\omega_{ce}|-k_zv_b}{\sqrt{2}k_zv_{bc}^2},X_{be}=\left(\frac{k_\perp v_{be}}{\omega_{ce}}\right)^2. \qquad (2)$$

Here v_{be} is thermal velocity of the beam electrons, $\omega_{be} = 4\pi e^2 n_b/m$ and k_z, $k_\perp$ are the wave vector parallel and perpendicular components with respect to the magnetic field, respectively, $A_n(X_{be}) = (X_{be})^{|n|}/2^{|n|}|n|!$, $W(z_n)$ is the probability integral. Stepanov and Kitsenko (1961), accepting that $\omega = \omega_{UH} + \delta\omega + i\gamma_b$, have obtained the solution for γ_b in the case when $v_b >> v_{bc}$ ($v_{bc} \sim \Delta v_b$), and $E_0 = 0$ ($\nu_{ef} \approx 0$). The electron current $I_b \approx \pi\rho^2_b n_b e v_b$ (ρ_b is Larmor radius) is a fraction of a milliampere for auroral beams with density $n_b = 0.3\text{-}0.5$ cm^{-3}, temperature $T_{be} \sim 200\text{-}300$ eV and average energy $\varepsilon_b \sim 400$ eV. In our case $\omega_0 > \omega_{ce}$ the increment value $\gamma_b/\omega_{pe} \approx 10^{-5}$ is quite negligible, and the relaxation length $L_r \approx v_b/\gamma_b$ is tens of kilometers.

In the paper by Baranets et al. (1995), for the case $\nu_{ef} \neq 0$ and under conditions $\omega_{UH} \approx k_z v_b$ (n=0) and $|z_0| < 1$, the solution of Eq. (2) was considered for the case $\omega = \omega_{UH} + \varepsilon$ ($\varepsilon = \delta\omega + i\gamma'_b$; $\varepsilon << \omega_{UH}$). The solution of (2) for the increment $\gamma'_b << (\omega_{UH} - \omega_{ce})/2\omega_{UH}$ and $\theta = \theta_r$ is defined by expression

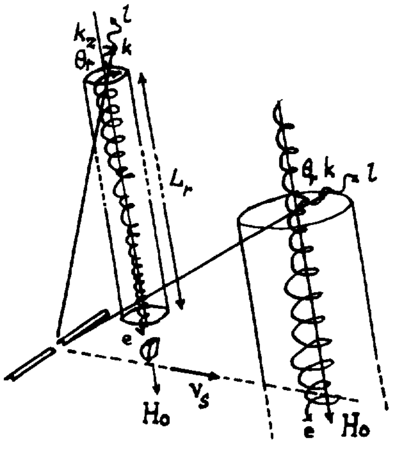

Fig.4. Displacement and widening of the interaction regions at the relaxation length L_r of electron beams under their interaction with turbulence. It is shown that the resonance angle θ_r is increased for the plasma oscillation l, when detuning $\omega_0 - \omega_{ce}$ is increased.

$$\gamma'_b/\omega_{UH}\approx\frac{A}{4B^2}\left[\alpha_\nu-\sqrt{\frac{\pi}{2}}\cdot\frac{\omega_{be}^2\,\omega_{UH}}{k^3v_{be}^3\cos\theta_r}\left(z_0^2+1\right)\exp\left(-z_0^2\right)\right]-\frac{1}{2B}\left[\beta_\nu+\frac{\omega_{be}^2}{k^2v_{be}^2}z_0\exp\left(-z_0^2\right)\right], \qquad (3)$$

where

$$A=-1+\frac{\omega_{pe}^2\cos^2\theta_r}{\omega_{UH}^2}+\frac{\omega_{pe}^2\sin^2\theta_r}{\omega_{UH}^2-\omega_{ce}^2}, \qquad B=\frac{\omega_{pe}^2\cos^2\theta_r}{\omega_{UH}^2}+\frac{\omega_{pe}^2\omega_{UH}^2\sin^2\theta_r}{\left(\omega_{UH}^2-\omega_{ce}^2\right)^2},$$

and α_ν, β_ν are functions of ν_{ef}, ω_{pe} and ω_{ce}. For $\omega_0 \to \omega^{(1)}$, the resonance angle $\theta_r \to \pi/2$, and the main interaction region displaces (Figure 4). In Figure 5 the increment γ'_b dependence on detuning $\delta = (\omega_0 - \omega_{ce})/\omega_{ce}$ is shown, as well as values of the resonance frequency $\omega_{UH}(\theta)$ and cut-off frequency $\omega^{(1)}$ when $q \to 1$. The sign of γ'_b is negative for the real parameter values of auroral ionosphere $\omega^2_{be}/k^2v^2_{be} \sim 10^{-5}$, i.e., the dissipative instability is developed in this case ($\nu_{ef} >> \gamma_b$).

The damping by particle effective collisions implies plasma heating. In Figure 6 results of numerical calculations ($v > \omega_{UH}/k_z$) for arbitrary beam currents I_b with electron energy ε_b are given. The problem is reduced to determination of the pumping wave amplitude E_0 when the beam instability stabilization occurs ($\gamma'_b \approx 0$). In this case the transport of the beam energy will be possible to a large distance L_r. The bulk of strong turbulence energy is concentrated in the long-wave region of the source. Thus to produce the beam instability development at $\omega_{UH} \approx k_z v_b$, the energy repumping in the spectrum is necessary to the absorption region. Under the competition of different ionospheric plasma processes the modulation instability development must have a pulse character. Thus it becomes possible for the electron beam to produce phase bunching, or the beam density modulation.

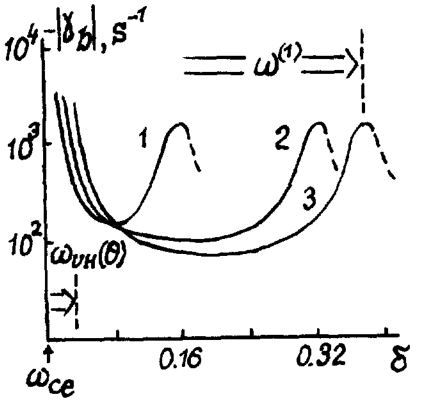

Fig.5. Dependence of the longitudinal oscillations increment γ'_b for different values of parameter q. In this case $T_e \approx 6500$ K, $\theta \approx 17°$: 1 - $n_0 \approx 2500$ cm^{-3}, $f_{pe} \approx 0.44$ MHz, $f_{ce} \approx 1.10$ MHz, $q \approx 0.16$; 2 - $n_0 \approx 2500$ cm^{-3}, $f_{pe} \approx 0.44$ MHz, $f_{ce} \approx 0.71$ MHz, $q \approx 0.38$; 3 - $n_0 \approx 5500$cm^{-3}, $f_{pe} \approx 0.66$MHz, $f_{ce} \approx 1.10$MHz, $q \approx 0.86$.

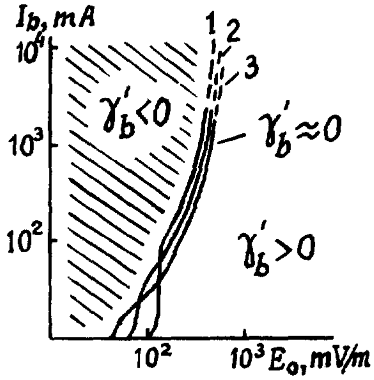

Fig.6. Relation of electron beam current I_b with the pumping wave amplitude E_0 in the case $\gamma'_b \approx 0$. The shaded region ($\gamma'_b < 0$) corresponds the collision dissipative region. The parameters are the same as on the Figure 5.

CONCLUSIONS

The main results of our analysis of the electron flux deceleration/scattering effects in the turbulent ionospheric plasma at short time scales for the case $\omega_0 > \omega_{ce}$ are as follows.

1) Electron flux reductions have been recorded in the frequency range $\omega^2_{ce} \leq \omega^2_0 \leq \omega^2_{ce} + \omega^2_{pe}$ in the energy range $\varepsilon_e \approx 80$-350 eV after powerful HF pulses.

2) The duration of the reduced electron fluxes was up to ~ 9 ms, the maximum decrease was observed for recording delay time ~ 3-6 ms after an HF pulse.

3) The principal mechanism of electron damping in the turbulent region is the elastic scattering/deceleration by plasma oscillations with effective frequency ν_{ef} of order of ~10^4 s^{-1}.

4) As the resonance detuning $\omega_0 - \omega_{ce}$ is increased, the active region of the auroral electron flux interaction with the turbulent plasma widens and displaces to the radiation source direction.

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