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Superthermal Electron Flux Generation and Optical Airglow Enhancement in Midlatitude Ionosphere F-Layer

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1. Introduction

The results of surface observations and satellite measurements show [1] that in midlatitude ionosphere F-region (at an altitude 250-300 km) in winter months the intensity of visible (optical) part of airglow spectrum 6300 Angsgtrom (A) (red line of atomic oxygen) begins to enhance 2-3 hours before the start of local astronomical twilight and during one hour increases more than two times. It is shown experimentally in the paper [2] that more than on 65 % 6300 A airglow intensity is explained by direct collisions of oxygen atoms with photoelectrons which came from magneto-conjugate ionosphere. At the same time airglow intensity is proportional to the section of nonelastic collision, maximum of which comes on the photoelectron energy region of several tens of eV [3]. In order to provide the observed intensity of red line 6300 A (in average 150-200 Rayleigh (R) [1]) when electron energy is $20 \div 50\ eV$, $10^7 - 10^8\ sm^{-2}sec^{-1}$ integrated electron flux is required [4]. On the other hand rocket measurements, performed at an altitude 200-350 km [2,5], show that in ionosphere sunlit region (conjugate ionosphere) at an altitude ~300 km integrated flux of superthermal electrons with energy $20 \div 50\ eV$ reaches the value $10^8\ sm^{-2}sec^{-1}$.

In connection with this the following question arises - is it possible the direct transport of conjugate superthermal photoelectron flux in local (which is in shade) ionosphere without energy loss? We will show that direct transport of superthermal photoelectrons between conjugate ionospheres is difficult due to inevitable loss of energy by electron beam on excitation of wave perturbation different modes. New mechanism of the transport of conjugate superthermal photoelectron energy in local ionosphere based on the event of strong Langmuir turbulence is suggested.

2. Langmuir wave excitation by superthermal photoelectron beam in conjugate ionosphere

Inculcation of conjugate superthermal photoelecton flux in ionosphere plasma (above 200 km ionosphere is considered to be totally ionized) is an analogue of well studied problem of interaction of electron beam blurred in energy with low temperature magnetoactive plasma. Such quite blurred beam on linear stage kinetically excites Langmuir wave with the frequency $\omega = \omega_p \left[1 + 3k_z^2 r_D^2/2 + \omega_c^2 k_\perp^2 / \left(2\omega_p^2 k_z^2\right)\right]$ at Cherenkov resonance $\omega/k \simeq V_b$. Here $\omega/k \equiv V_p$ is wave phase velocity, V_b - beam particle initial velocity; ω and k - frequency and wave vector of excited perturbation; $\omega_p^2 = (4\pi ne^2/m)^{1/2} > \omega_c = eB_0/mc$; $r_D = V_T/\omega_p$, $V_T = (2T_e/m)^{1/2}$; $\vec{B}_0$ - Earth geomagnetic field induction directed along the axis z; k_z and $k_\perp$ - wave vector components of perturbations along and across the magnetic field respectively - $k = (k_\perp^2 + k_z^2)^{1/2}$, $k_z > k_\perp = \left(k_x^2 + k_y^2\right)^{1/2}$; n_e - density, m - mass, T_e - temperature, e - electric charge of background electrons respectively. Increment of beam-plasma instability $\gamma_0 = \pi \left(n_b/n_e\right) \left(V_b/\triangle V\right)^2 \omega$ (where $n_b \ll n_e$ is photoelectron beam density and $\triangle V$ - thermal dispersion of photoelectron beam particle velocities).

The main effect causing the saturation of oscillation growth is quasilinear relaxation of beam particle distribution to the "plateau" condition in longitudinal velocities. Time t_0 in which beam quasilinear relaxation in the velocity interval $\triangle V \sim V_b$ takes place can be estimated using the equation of transport of excited perturbation energy density and is equal: $t_0 \sim ln\Lambda/\gamma_0 \sim (n_b/n_e)\,\omega^{-1} ln\Lambda \ll \nu_{ei}^{-1}$ (where $ln\Lambda$ is Coulomb logarithm, ν_{ei} - frequency of electron collisions with ions). So, after the photoparticle birth in conjugate ionosphere long-wavelength Langmuir perturbation excitation takes place for the first time.

3. Generation of descending flux of superthermal electrons at an altitude ~300 km in local ionosphere as a result of Langmuir collapse

As a result of beam-plasma instability photoelectron energy is pumped in Langmuir oscillations. On the stage of quasilinear saturation wave energy density can be estimated as $W \equiv E^2/8\pi n_e T_e \sim n_b m V_b^2$ (where E is Langmuir oscillation electric field amplitude). Thus at typical parameters of superthermal photoelectron flux and ionosphere plasma the criterion of instability of spatially homogeneous Langmuir oscillation background with respect to self-modulation - $W > k^2 r_D^2$ is fulfilled with reserve.

According to the paper [6], modulational instability via collapse causes the appearance of energy flux in the direction of short-wavelength modes with their forthcoming absorption because of Landau damping on local thermal electrons.

Problem of Langmuir wave collapse in magnetoactive plasma has been solved in the paper [7]. As a result of modulational instability the density holes (caverns) appear in plasma, longitudinal size of which $\ell_{\|}$ does not depend on magnetic field strength

$$\ell_{\|} \sim k_z^{-1} \sim r_D \left(\frac{n_e}{|\delta n|} \right)^{\frac{1}{2}}, \tag{1}$$

while transversal size is proportional to the field strength

$$\ell_{\perp} \sim k_{\perp}^{-1} \sim \ell_{\|} \frac{\omega_c}{\omega_p} \left(\frac{n_e}{|\delta n|} \right)^{\frac{1}{2}}. \tag{2}$$

Here δn is the plasma density perturbation under the influence of plasma pressure. It is evident that caverns are flattened in the direction of magnetic field $\left(\ell_{\|} < \ell_{\perp}\right)$. From (2) it follows that during collapse and $|\delta n|$ growth, as soon as density variation amplitude reaches the value $|\delta n|/n_e \sim \omega_c^2/\omega_p^2$, cavern becomes isotropic and magnetic field does not act on further process of collapse.

Stationarity of turbulent state in considered problem is achieved as a result of the following: energy dissipating in large scales because of beam-plasma instability (source region), is pumped during collapse to small scales (inertial interval), after which it is absorbed by resonant particles (absorption region) and finally goes on the acceleration of the particles of particle distribution function tail.

According (1) and (2) in long-wavelength source region plasmon spectrum is significantly anisotropic $k_{z0} \simeq r_D^{-1} (W/n_e T_e)^{1/2}$, $k_{\perp 0} \simeq k_{z0} (\omega_p/\omega_c)(W/n_e T_e)$.

In inertial interval Langmuir oscillation energy spectral density W_k^{in} is proportional to the number of caverns N in given scale of turbulence. This allows on the basis of continuity equation for plasmon quasistationary density in wavenumber space $N(k_{\perp}, k_z)$ to define Langmuir spectrum in inertial interval:

$$W_k^{in} dk_{\perp} dk_z \simeq N(k_{\perp}, k_z)\, dk_{\perp} dk_z = \frac{C}{k_{\perp}^3 k_z^3} dk_{\perp} dk_z, \tag{3}$$

where the particular form of constant $C = const$ is defined from the condition of sewing of solution (3) with corresponding solution in source region.

In absorption region spectrum of quasistationary turbulence becomes isotropic. So, the resonant electron distribution function $f(V)$ (non-Maxwellian tail) and plasma spectra W_k^{ab} in this region have the form [8]:

$$f(V)\frac{A}{V^{7/2}}, \qquad W_k^{ab} = \frac{B}{k^{7/2}}, \qquad V_{min}(t) < V < V_{max}(t), \qquad k > k_* = \omega_p/V_{max}, \qquad (4)$$

where V_{min} is the minimum velocity of the particles on which energy is absorbed and equals to several thermal velocities of electrons, V_{max} - upper limit of resonant particle velocity spectrum tail. At the same time constant volume flux of particles in spectrum $J(V)$ is determined by the integral [6]

$$J(V) = \frac{8\pi e^2\omega_p^2}{m^2 V}\int\limits_{\omega_p/V}^{\infty}\frac{dk}{k^3}\cdot W_k^{ab}\cdot\frac{\partial f}{\partial V}. \qquad (5)$$

In order to find the constant B in the formula for the plasmon spectral density (4) we use the normalization condition $(2\pi^{-3})\int\left(W_k^{in}d\vec{k}/k^2\right) = W$ and the condition of spectrum continuity on the boundary of inertial interval with absorption region $k = k_*$:

$$B = 64\pi^2 k_{\perp 0}\left(k_{\perp 0}{}^2 + k_{z0}{}^2\right)k_{z0}{}^2 k_*^{-5/2}W. \qquad (6)$$

Volume flux of energy transferred to particles can be presented in the form $mV_{max}^2 J/2$. Using (4) and (5) and equating this flux to the plasma turbulence energy flux $\gamma_m W$ ($\gamma_m \simeq \omega_p mW/mn_eT_e$ - is the increment of modulational instability) we will obtain relation connecting constant A with long-wavelength plasmon energy:

$$A = \frac{11}{7{\cdot}64\pi^2}\cdot n_e\cdot\frac{V_T^5}{V_{max}^{9/2}}\cdot\frac{\omega_c}{\omega_p}\cdot\left(1+\frac{\omega_p^2}{\omega_c^2}\cdot\frac{W}{n_eT_e}\right)^{-1}\cdot\left(\frac{m}{M}\right)^{1/2}\cdot\left(\frac{n_eT_e}{W}\right)^{5/2}. \qquad (7)$$

According to the expressions (4), (6) and (7) under strong Langmuir turbulence the pumping of spectrum in the direction of large k takes place, i.e. in the short-wavelength region $k > k_*$, cavern collapse is stopped because plasma oscillation Landau damping on local tail electrons.

Using (4) one can define maximum number of particles in tail interacting with wave:

$$n'_\infty = 8\pi A\left(V_{min}{}^\infty\right)^{-1/2}. \qquad (8)$$

Consequently, from energy balance equation it follows that asymptotic law of tail upper limit growth has the form:

$$V_{max} = \left(\frac{3}{4\pi}\frac{P{\cdot}t}{mA}\right)^{3/2}. \qquad (9)$$

Here $P = \gamma_m W$ is power absorbed in long-wavelength region of turbulence, t - time.

Above performed investigation is applicable until one can neglect the tail influence on Langmuir oscillation dispersion. Corresponding condition has the form $\int(mV^2 f/2)\,d\vec{V} < n_eT_e$ and is fulfilled for times $t \simeq n_eT_e/P$.

4. Discussion of results

Solutions obtained in previous sections allow to perform the calculation of descending electron flux in night ionosphere F-region generated by Langmuir wave collapse.

Long-wavelength Langmuir fluctuation energy density can be defined from the plasmon trapping condition - $W \simeq 2n_e T_e^2/mV_b^2$. For plasma in conjugate ionosphere at an altitude 250-300 km resonant photoelectron energy $mV_b^2/2 \simeq 40\ eV$, $T_e \simeq 1500°K$, $n_e \simeq 10^5\ sm^{-3}$, $\omega \simeq 10^7\ sec^{-1}$, $\omega_c \simeq 10^6\ sec^{-1}$, $m/M = 0,5 \cdot 10^{-4}$,$V_{min} \simeq 2V_T$, $V_T \simeq 10^7\ sec^{-1}$. Under indicated parameters from the formulas (9) and (7) we will obtain the value of generated fast electron maximum velocity $V_{max} \simeq 2 \cdot 10^8\ sm \cdot sec^{-1} \sim 20V_T$; at the same time maximum density of these electrons defined by the relation (8) is $n_\infty \simeq 10^4\ sm^{-3}$. Consequently, for descending electron integrated flux maximum value $\Phi_{max} = n'_\infty V_{max}$ we get the estimation $\sim 10^{12} sm^{-2} sec^{-1}$.

Estimation of integrated flux of fast electrons generated by Langmuir collapse strongly exceeds ($10^4 - 10^5$ times) the required value for the explanation of observed pretwilight enhancement of midlatitude ionosphere F-region red airglow $\sim 10^8 sm^{-2} sec^{-1}$. However, this is integrated estimation of total flux generated by resonant photoelectron descending beam. Resonant electron tail length $\triangle V \simeq V_{max} - V_{min}$ can be quite large. Thus, number of particles with energy 40 eV can be much smaller than total number of particles in tail. Reserve contained in total flux ($\sim 10^{12} - 10^{13} sm^{-2} sec^{-1}$) allows to suppose that part of flux coming on particles with energy 40 eV can provide the observed pretwilight enhancement (by 40-60 R) of 6300 A airglow.

From above mentioned it follows that direct transport of photoelectrons from conjugate points to local ionosphere is quite difficult mainly because of plasma wave generation by photoelectron beam. At the same time photoelectron flux energy is practically totally transferred to the generated waves. These waves excited in conjugate ionosphere themselves can generate in local ionosphere observed flux of descending electrons ($10^7 - 10^8 sm^{-2} sec^{-1}$) and provide observed level of red line 6300 A airglow intensity enhancement.

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