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EMISSIONS STIMULATED IN THE UPPER IONOSPHERE BY THE SURA HEATING FACILITY

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ABSTRACT

Results of two satellite experiments with the ground-based SURA heating facility are reported. The HF radiospectrometers onboard the APEX and CORONAS satellites registered within the topside ionosphere stimulated HF emissions while passing over the SURA heating facility, though the heating frequency was lower than the critical frequency f_0F2. The recorded spectra differ for the two experiments, and different geophysical and plasma conditions are regarded as a reason of the observed difference. Highly anisotropic fluxes of suprathermal electrons accelerated in the turbulence, stimulated by the heater, are considered as a source of wide-band Bernstein mode emission, which was registered onboard the satellites.

EXPERIMENTAL BACKGROUND

In a series of experiments with onboard satellite HF radiospectrometers the wide-band noises were registered within the topside ionosphere, associated with ground-based broadcast transmitters and other HF emitters on the Earth's surface (Kłos et al., 1990). The main feature of the observed phenomena was that the noise appeared also on frequencies lower than the critical frequency f_0F2. So one should look for a mechanism of energy transport through the wave barriers. One of the possible sources of the recorded wide-band radiation could be suprathermal electrons, which appear as a result of interaction of the HF radiowaves at the reflection point of the bottom side F-layer. Due to multiple acceleration within the resulting turbulent region (Vas'kov et al., 1983), the suprathermal electrons escape into the upper ionosphere.

To model the effects observed under natural conditions, experiments with the SURA heating facility were planned. The facility, situated near Nizhny Novgorod at the point with coordinates 56.12° N, 46.07° E, L-shell – 2.65, was operating while the satellite passed over it. Two such experiments were successful: one with APEX (Intercosmos-25) satellite on June 14, 1992, and the second one with CORONAS-I satellite on May 12, 1994. Ionospheric conditions were checked by a "Bazis" digital ionosonde. The heating frequency f_{ht} was selected lower than the critical frequency f_0F2. In the first case f_{ht} = 5.828 MHz and f_0F2 = 7.2 MHz, and in the second one f_{ht} = 4.785 MHz and f_0F2 = 5.4 MHz. The effective power of the heater (taking into account the antenna directivity) was PG ~ 160 MW. In both projects the heating experiments were conducted during evening hours when conditions for penetration of accelerated electrons in the upper ionosphere were optimal (F-layer peak and heating radio wave reflection level were situated sufficiently high, but absorption of the heating wave in the lower ionosphere was weak). In both cases the heater was operating in pulse mode: 4 s ON, 4 s OFF in the first case and 1 s ON, 1 s OFF - in the second one. Geomagnetic conditions in both cases were very quiet: $Kp \leq 2$. The most complex task was to select passes when the satellite trajectory deviation in longitude was minimal in relation to the facility longitude. One should keep in mind that the corresponding geophysical conditions should be fulfilled simultaneously with exact passing over heating facility (at least nighttime and low geomagnetic activity). For APEX experiment the minimal distance in longitude between heater an satellite ground projection was near 2°, but the heater transmitter was switched on 12 s after the satellite passed the minimal distance, and stimulated emissions were registered when longitudinal distance varied from 3 up to 5 degrees. In CORONAS-I case the longitudinal distance between heater and satellite projection was less then 1°.

In both cases the HF emission was registered by an electrical dipole of 15 m tip-to-tip length with the help of an HF radiospectrometer sweeping in the frequency band 0.1 - 10 MHz in the APEX experiment (PRS-3 device) and 0.1 - 30 MHz the CORONAS-I experiment (SORS-A device). The frequency step was 50 kHz ($\Delta f \approx 15$ kHz) in APEX and 25 kHz ($\Delta f \approx 15$ kHz) in CORONAS-I, respectively. The full spectrum was collected by 2.16 s in the APEX experiment and by 6.4 s in the CORONAS-I experiment.

RESULTS OF THE MEASUREMENTS

The dynamic spectra of radiospectrometer measurements are presented in Figure 1. The upper panel represents the APEX results: one can see the wide-band bursts of noises associated with the SURA heating pulses, observed even in whistler frequency band ($f < f_{He}$). The SURA pulses were resolved because the sweep period of the radiospectrometer was shorter than the duration of heater pulse. In the lower panel the CORONAS-I measurements are shown. The high telemetry sample rate was switched on when the heater was already in operation, and we can observe only the heater switching off. The most outstanding phenomenon observed in the figure is amplification of emission near the 3[rd] and 5[th] harmonics of the local gyro-frequency shown in the figure by white dashed lines. The individual pulses of the heater were not resolved by the radiospectrometer. In this case the sweep period of the radio-spectrometer was much longer than the heater pulse (6.4 s and 1 s respectively). At first glance the presented dynamic spectra differ to a great extent for two satellite experiments, but if we compare individual spectra, we will find the main similarity: amplifi-cation of noise in the vicinity of odd harmonics of the local gyrofrequency (see Figure 2).

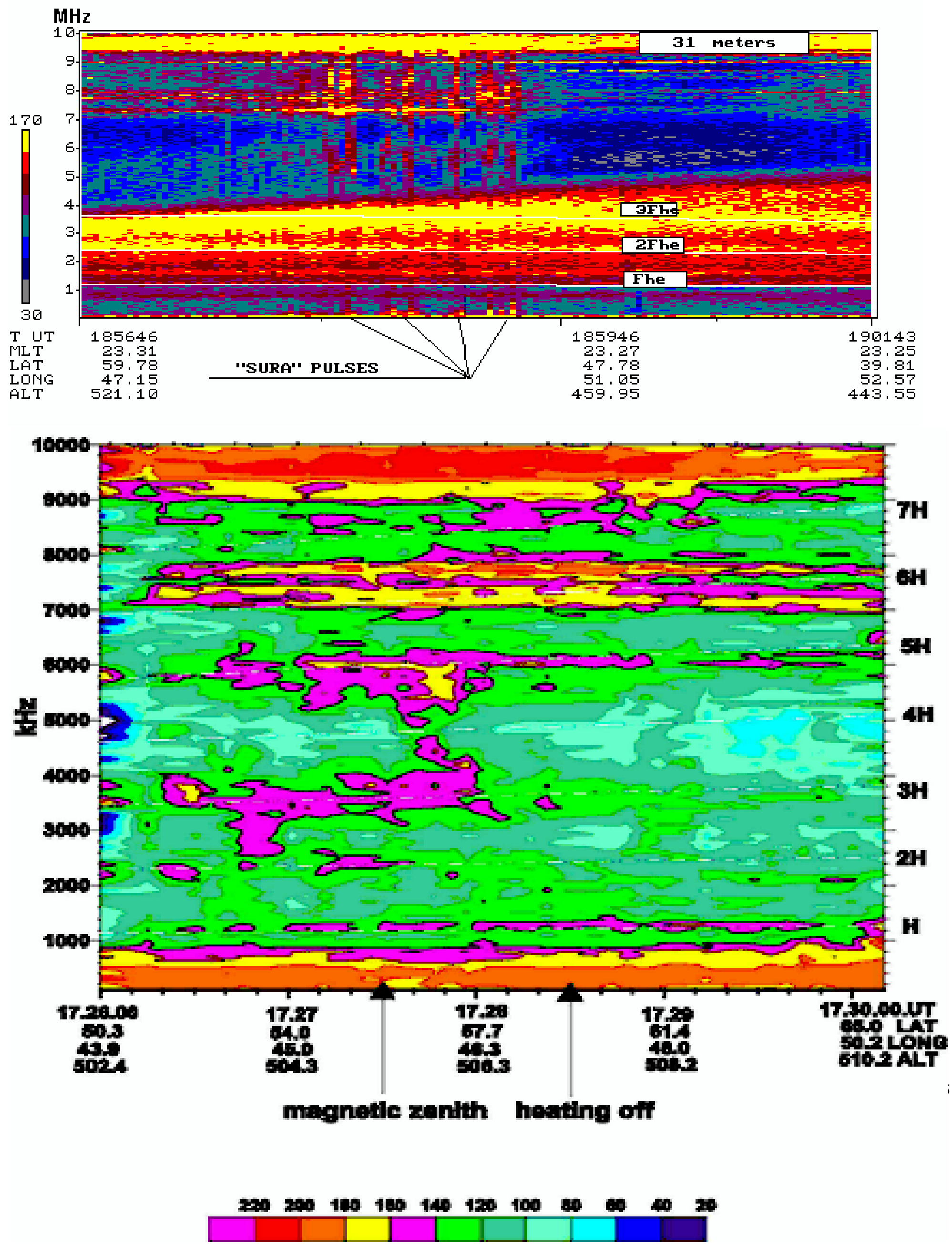

Fig. 1 Dynamic spectra of plasma radio spectrometer PRS-3 (APEX project) - upper panel and solar radio spectrometer SORS-A (CORONAS-I project) - bottom panel, during ionosphere modification experiments with "SURA" heating facility. White lines mark the electron gyroharmonics in both panels. At the bottom panel by vertical arrows the time of magnetic zenith and the time of "SURA" heating facility turn off are marked.

We can note that in the APEX spectrum the 3 rd harmonic is even more sharply amplified than in the CORONAS one. The greatest similarity is observed in the vicinity of the fifth harmonic. In both cases the heating frequency is slightly lower than the fifth harmonic, and in both cases the disturbed spectrum lies to the lower frequency side from the 5 th harmonic of gyrofrequency.

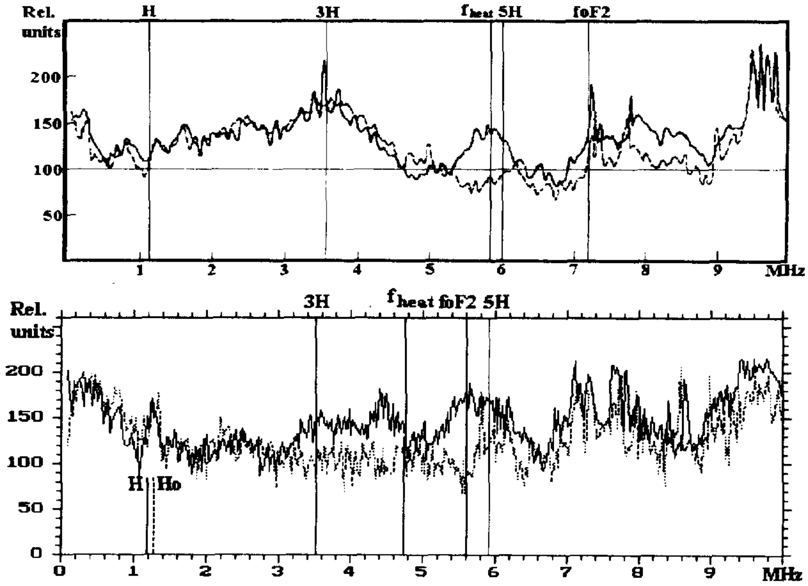

Fig.2 Examples of RF individual spectra during the heating experiments (APEX-upper panel, CORONAS – lower panel) are presented. Dashed lines show the undisturbed spectra (heater OFF). By vertical lines are marked main frequencies: gyroharmonics, the heater operation frequency (f_{heat}) and the critical frequency (f_oF2). At lower panel H_0 and H letters mark gyrofrequencies for undisturbed and modified spectra respectively.

DISCUSSION

The distribution function for the accelerated electrons is unknown. The only known experimental result (Rose et al., 1985) is increasing of accelerated electrons fluxes (~10 eV) over the heating facility. Vas'kov et al. (1983) supposed that collisions make the distribution function of the accelerated electrons isotropic, but this argument can be invalid in conditions of rather large reflection height. Anisotropy of the distribution function facilitates excitation of the Bernstein modes with $k_{II}=0$. It is convenient to model the distribution of the accelerated electrons by a distribution of the Dory-Guest-Harris type with flux

$$F_b(v_\perp, v_{II}) = n_b (j!\pi^{3/2} w_b^{2j+2} u_b)^{-1} v_\perp^{2j} \exp\{-\frac{(v_{II}-v_0)^2}{u_b^2} - \frac{v_\perp^2}{w_b^2}\} \qquad (1)$$

where n_b is the density of accelerated electrons, w_b and u_b are their transversal and longitudinal thermal velocities, j is the index of the anisotropy, and v_0 is their flux velocity along the magnetic field. Let $n_b \ll n_0$, where n_b is flux density of the accelerated electrons and n_0 is density of background plasma which is supposed collisionless. The dispersion relation for the background plasma could be written as:

$$\varepsilon_1(\omega,\mathbf{k})=1+D(F_0)=1-\frac{\omega_{pe}^2}{\omega_c^2}\sum_{n=-\infty}^{\infty}\frac{nA_n(x)}{x(\nu-n)}+\frac{\omega_{pe}^2}{\omega_c^2}i\sqrt{\pi}\sum_{n=-\infty}^{\infty}\frac{A_n(x)}{x}e^{-z_n^2}=0 \qquad (2)$$

under the conditions of low damping $z_n=\frac{\omega-n\omega_c}{|k_{II}|v_T\sqrt{2}}\gg 1$. Here $\nu=\frac{\omega}{\omega_c}$, $A_n(x)=e^{-x}I_n(x)$, $x=\frac{k_\perp^2 v_T^2}{2\omega_c^2}$.

Neglecting exponentially low damping, one can easily solve equation (2) in the limiting cases $x \ll 1$ or $x \gg 1$ when the eigenwave frequencies are clasped to the cyclotron harmonics (Akhiezer and Akhiezer, 1983). If $x \ll 1$, $m>1$, where m is the number of the cyclotron harmonic, the solution would be:

$$\nu = m+\frac{\omega_{pe}^2}{\omega_c^2}\frac{(m^2-1)x^{m-1}}{2^m(m-1)!(m^2-1-\frac{\omega_{pe}^2}{\omega_c^2})} \qquad (3)$$

It is supposed that the upper hybrid frequency is not close to the cyclotron harmonic ($\nu_{UH}=\sqrt{\frac{\omega_{pe}^2}{\omega_c^2}+1}\neq m$). If $m<\nu_{UH}$, electron cyclotron waves for small x are close but below the m th cyclotron harmonic frequency; if $m>\nu_{UH}$, their frequency is close to the cyclotron harmonic but higher than the frequency of the mth harmonic. If x>>1 one can easily find the asymptotic solution:

$$\nu = m + \nu_0(x) = m + \frac{\omega_{pe}^2}{\omega_c^2}\frac{m}{\sqrt{2\pi x^3}} \tag{4}$$

For x values close to 1, the contribution from neighborhood harmonics is essential and only a numerical solution of dispersion relation is possible. For waves with z_n>>1 the damping is exponentially small. This condition means quasi-perpendicular propagation of the waves with low damping.

The technical details of operation with Dory-Guest-Harris function one can found in Karpman et al. (1975). Addition of the beam into dispersion relation (2) could be expressed by the plasma dispersion function Z(z):

$$D(F_b) = \frac{2\omega_{pb}^2}{k^2u_b^2}\left\{1 + \frac{(-1)^j}{j!x_b^{j+1}}\sum_{n=-\infty}^{\infty} z_{b,n}Z(z_{b,n})* \left[(\frac{\partial}{\partial\frac{1}{x_b}})^j + \frac{u_b^2}{w_b^2}\frac{n}{\nu_b - n}((\frac{\partial}{\partial\frac{1}{x_b}})^j + jx_b(\frac{\partial}{\partial\frac{1}{x_b}})^{j-1}\right]A_n(x)\right\} \tag{5}$$

where $x_b = \dfrac{k_\perp^2 w_b^2}{2\omega_c^2}$, $\nu_b = \nu - \dfrac{k_{II}v_0}{\omega_c}$, $z_{b,n} = \dfrac{\omega - k_{II}v_0 - n\omega_c}{|k_{II}|u_b\sqrt{2}}$. When the imaginary part of the dispersion relation is small, the imaginary part of the frequency can be easily obtained analytically:

$$\gamma = \frac{\mathrm{Im}\{D(F_0) + D(F_b)\}}{(\frac{\partial \mathrm{Re}\varepsilon_l}{\partial\omega})_{\omega=\omega(k)}} \tag{6}$$

The growth rate of this type for excitation of cyclotron harmonics was numerically calculated in many papers. This case is not interesting because the possible kinetic growth rates of instability $\gamma \propto n_b/n_0$ are small. The case were this decomposition is invalid in the vicinity of the solution crossing for background plasma and beam mode oscillations is more interesting, when the real part of the dispersion equation admits a growth rate of instability of a hydrodynamic type $\sim\sqrt{\dfrac{n_b}{n_0}}$. We shall consider this situation for large x and x_b. The waves with large k recorded onboard the satellites can result in significant Doppler widening of emission stimulated near the cyclotron harmonic frequencies.

Let $|z_n| >> 1$, $|z_{b,n}| >> 1$, $x_b >> 1$. The dispersion relation for the mth cyclotron harmonic under j≠0 could be expressed as:

$$1 - \frac{\omega_{pe}^2}{\omega_c^2}\frac{m}{\sqrt{2\pi x^3}}\frac{1}{\nu - m} + \frac{\omega_{pe}^2}{\omega_c^2}\frac{i}{\sqrt{2x^3}}e^{-z_m^2} + \frac{\omega_{pb}^2}{\omega_c^2}\frac{\alpha_j}{(2j-1)}\frac{m}{\sqrt{2\pi x_b^3}}\frac{z_{b,m}Z(z_{b,m})}{(\nu_b - m)} = 0 \tag{7}$$

Here $\alpha_j = \dfrac{(2j-1)!!}{2^j j!}$. Using the asymptotic expansion of the plasma dispersion function for large $z_{b,m}$ we study the solution of the real part of the dispersion equation in this limiting case. At $\nu_0(x)=\nu_b$ the beam mode and Bernstein solution for the background plasma intersect. One can obtain an estimation for maximum growth by supposing $\nu_0(x)=\nu_b$ and $\nu=\nu_0(x)+i\gamma/\omega_c$:

$$\gamma = \frac{\omega_{pe}^2}{\omega_c^2}\sqrt{\frac{n_b}{n_0}\frac{\alpha_j}{2j-1}\frac{m\omega_c}{\sqrt{2\pi x^3}}\frac{v_T^3}{w_b^3}} \tag{8}$$

We should note that in the absence of anisotropy the beam-type amplification for the cyclotron harmonics excitation does not exist.

Strictly speaking, the presence of such complex solution at the real part of the dispersion relation means the existence in the vicinity of the solutions crossing of a point, in which $(\frac{\partial \mathrm{Re}\varepsilon_l}{\partial\omega})_{\omega=\omega(k)}=0$, so the expression (6) for growth rate in its vicinity is not valid. In this case, while looking for the correction to frequency, caused by a small imaginary part of the dispersion relation it is necessary to decompose the real part with an accuracy to second order which results in an expression for the correction

$$\delta\omega = \sqrt{\frac{2i\,\mathrm{Im}\{D(F_0)+D(F_b)\}}{\left.\frac{\partial^2 \mathrm{Re}\varepsilon_1}{\partial\omega^2}\right|_{\omega=\omega cr}}} \qquad (9)$$

where ω_{cr} is frequency, for which $\partial \mathrm{Re}\varepsilon / \partial\omega = 0$. For the case of large $z_{b,m}$ it is easy to find the critical point; in this point $\nu_0(x) \approx \frac{k_{II} v_0}{\omega_c}(1+\sqrt{\frac{n_b}{n_0}\frac{\alpha_j}{2j-1}\frac{x_b^{3/4}}{x^{3/4}}})$. We note that the condition $z_{b,m} >> 1$ used for simplification of the analysis, imposing strong restrictions on parameters of a beam of accelerated electrons, is unessential for the presence of a critical point. It should exist at $z_{b,m} \sim 1$ also, which is possible to see from the equation (7), but this case is difficult for analysis. In the vicinity of a critical point the growth rate is $\propto \sqrt{\frac{n_b}{n_0}}$ and can reach considerably higher values, than in a kinetic case (6).

We can conclude that the wide band emission in the vicinity of electron cyclotron harmonics observed in the experiments could be explained by excitation of Bernstein waves with large $k_\perp$ by anisotropic beams of electrons accelerated by heater emission.

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