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Ionospheric plasma modification in the vicinity of a spacecraft by powerful radio pulses in topside sounding

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Abstract—A mechanism of strong turbulence is proposed for interpretation of the resonances observed by a wide-band receiver during topside sounding. The turbulence is created in the vicinity of the spacecraft due to the striction modulation instability. Experimental results obtained with the aid of a wide-band receiver on board the *Intercosmos-19* satellite are discussed in terms of strong wave–wave and/or wave–particle interaction, namely electron acceleration in Langmuir cavitons and non-linear generation of the electron Langmuir plasma waves and Tonks–Dattner resonances.

1. INTRODUCTION

When topside radio pulse sounding of the ionosphere from artificial satellites orbiting high above the $F2$-layer was carried out back in the early 60's, long-term excitations were observed at frequencies of the so-called main resonances: the electron Langmuir frequency f_{Pe}, the upper hybrid resonance f_{UHR}, the electron gyrofrequency f_{He} and its harmonics nf_{He} ($n = 1, 2, 3, \ldots$) (LOCKWOOD, 1963; CALVERT and GOE, 1963). The life-time of these resonances is one or two orders of magnitude longer than the duration of the sounding radio pulse itself ($\tau_0 \approx 10^{-4}$ s).

Later, FEJER and CALVERT (1964), MCAFEE (1973), PARKES (1974), BENSON (1977), KRUPINA (1977) and GERSHMAN *et al.* (1974) developed a theory of these resonances, attributing the long delays of the return signals to the low group velocities of the longitudinal electrostatic waves excited by the radio pulse. That the detected waves are electrostatic rather than electromagnetic is due to the high group velocities of the latter, whereby they rapidly leave the vicinity of the satellite. On the other hand, the longitudinal waves which are refracted at the natural concentration gradient with the scale height H (MCAFEE, 1973; KRUPINA, 1977) (for f_{Pe} and f_{UHR}) or magnetic field of the Earth (FEJER, 1964; GERSHMAN *et al.*, 1974) (for f_{He} and nf_{He}) travel a relatively short distance (10^2–10^4 m) with group velocities of $\sim 10^3$–10^5 m s^{-1} and return to the satellite.

Linear theory (MCAFEE, 1973) predicts two waves which have undergone refraction and returned to the satellite. Since the return conditions 'pick' them out of the radiated wave packet in the range $\Delta f \approx 1/\tau_0 =$ 10 kHz (where τ_0 is the transmitter pulse duration) and since the two waves picked out have different frequencies when the Doppler effect is taken into account, the theory predicts modulation of the observed signal. What is important is that the beat frequency must increase with the observed delay time.

In the real situation, however, since the radiating power of the satellite-borne transmitter is such that the HF energy density in the vicinity of the satellite is comparable with the thermal energy of electrons, one must take into account the non-linear effects under conditions of strong pumping (self-effect of the wave). Weak turbulence conditions were first considered by OYA (1971). The principle underlying the proposed mechanism is cyclotron heating of the plasma surrounding the satellite by the high-power transmitter pulse and development of the electron temperature anisotropy ($T_\perp/T_\parallel > 5$), which results in excitation of the Harris instability and then, due to the non-linear wave interaction mechanism, to the excitation of diffuse resonances. The major role in the proposed mechanism is played by the sounding pulse energy absorption near $2f_{He}$.

These ideas were further developed by KIWAMOTO and BENSON (1979) and BENSON (1982), who, on the basis of experimental data, considered the effects of plasma parameters, geophysical parameters and radiated wave power on the stimulation of resonances, and a non-linear Landau damping mechanism was proposed which the authors believed to be more appropriate than the 3-wave interaction mechanism.

In all these studies it was noted that the turbulent state of the plasma was due to the fact that the energy density W of the radiated ionosonde pulses becomes comparable with the thermal energy of the plasma $n_e T_e$. OYA (1971) reported that $W/n_e T_e \sim 10^2$.

However, at $W/n_e T_e > 1$ the plasma is strongly affected by its striction extrusion by the pumping wave field when there is an electric field gradient. The striction mechanisms are responsible for the appearance in the plasma of cavities (cavitons), the low density regions in which the Langmuir plasmons are accumulated. The cavitons may collapse and thereby cause acceleration of electrons and an increase of Langmuir oscillation energy density (Rudakov and Tsytovich, 1978).

2. STRONG TURBULENCE MODEL

The model proposed in this work is based on the fact that, on account of the striction modulation instability arising under the effect of the high power transmitted wave, a soliton array is formed at the pumping frequencies $f_0 \sim f_{Pe}$ and $f_0 \sim nf_{He}$, where f_0 is the pumping frequency. The solitons may appear both in the Langmuir waves (Degtyarev *et al.*, 1980; Petviashvili and Tsvelodub, 1980) and the cyclotron waves and their harmonics (Petviashvill, 1976). The velocities of the solitons are small [fast solitons soon cease their motion (Rudakov and Tsytovich, 1978)]. Thus the excitations which show a tendency for long delay can be interpreted as soliton HF oscillations received by the on-coming antenna of the satellite moving through the turbulence.

Apart from a rather stable soliton array (Kuo and Gheo, 1981), a high power pumping wave field will cause the development and collapse of cavitons (Rudakov and Tsytovich, 1978; Krasnoselskikh and Sotnikov, 1977; Kuznetsov, 1974; Burinskaya, 1979; Wong *et al.*, 1981); the collapse of a cavity, involving radiation of ion–acoustic waves (when the initial field is strong enough), is caused by the rise of energy density of the Langmuir plasmons in the cavity. When the collapsing cavity becomes the size of about the Debye radius r_D, the HF field dissipation (Landau damping) mechanism is switched on. The lifetime of cavitons (Rudakov and Tsytovich, 1978) is of the order $\tau_c = l_c/c_s$, where l_c is the caviton size, c_s is the ionic sound velocity. In the experiments [cf. the references in Rudakov and Tsytovich (1978)] the life-times of the observed cavitons were many times greater than l_c/c_s, which means that spatial dispersion effects must be taken into account in evaluation of the caviton collapse rate [in contrast to Krasnoselskikh and Sotnikov, (1977) Kuznetsov (1974) and Burinskaya (1979)]. Dispersion in the caviton is enhanced due to the decrease of density before Landau damping occurs.

The characteristic modulation instability development time at $W/n_eT_e > k^2r_D^2$ and $W/n_eT_e > m/M$ (the supersonic collapse conditions when ionosonic waves are generated) $\gamma_{\text{mod}}^{-1} = \omega_{Pe}^{-1}\,(Wm/n_eT_eM)^{-1/2} = 10^{-5}$ s. Here, and below, the estimates are for the conditions prevalent on the *Interkosmos-19* (IK-19) artificial satellite: $\omega_{Pe} = 2\pi f_{Pe} = 10^7\ \text{s}^{-1}$, $\omega_{He} = 4 \times 10^6\ \text{s}^{-1}$, $\tau_0 = 10^{-4}$ s, $P = 100$ W—the transmitted power, $T_e = 3000$K, $n_e = 3 \times 10^4\ \text{cm}^{-3}$—electron concentration, $r_D = 1.4$ cm, $T_en_e = 10^{-9}\ \text{J m}^{-3}$, $M/m = 1.6 \times 10^3$. The satellite altitude was 900 km (the region intermediate between O^+ and H^+ ions). In the case of very strong pumping at $W/nT \gg 1$, according to Silin (1965) $\gamma^{-1} = \omega_{Pe}^{-1}\,(m/M)^{-1/3} \approx 10/\omega_{Pe} = 10^{-6}$ s. Thus the duration of the transmitted pulse, about 10^{-4} s, is enough for the modulation instability effects to develop. The numerical simulation of the collapse under different conditions gives the typical HF field maximum delay time counted from the initial moment of pumping: $10^2 - 5 \times 10^3\ \omega_{Pe}^{-1}$ or $10^{-5} - 5 \times 10^{-4}$ s.

According to numerical simulation results (Degtyarev *et al.*, 1980) which we have applied to the case of satellite motion along the magnetic field, the initial stage of development of Langmuir turbulence is characterized by a 'pure', spatially periodic soliton structure which, on further constant pumping, is broken up into a set of arbitrarily located solitons. According to Degtyarev *et al.* (1980), the characteristic turbulence development time $\tau = 3M/\omega_{Pe}m = 5 \times 10^{-4}$ s and the space scale $x = 3r_D\sqrt{M/m} = 2$ m. The soliton array is periodic at times $t \leqslant \tau$. For $W/n_eT_e \geqslant 0.1$, the soliton width $l_s \approx 0.2x \approx 0.4$ m and the period $h = 1x$–$4x$.

It is essential that the portion of the HF energy W_k taken away from the pumping wave E_0, attains, according to Degtyarev *et al.* (1980), saturation at $E_0^2/8\pi\, n_eT_e = 3\sqrt{m/M}$ on the level 0.4–0.5 n_eT_e. Plasma concentration Δn and field E variations under such pumping conditions may be as large as 0.3 n_e and $10^3\ E_0$ (E_0 is the pumping wave field). Besides, plasma stratification with the scale $(r_Dc/\omega_{He})^{1/2}$ (Vas'kov and Gurevich, 1977), the formation in the ionosphere of artificial inhomogeneities (Bolenov *et al.*, 1977; Grach *et al.*, 1979; Vas'kov and Gurevich, 1976; Dimant, 1977; Belikovich *et al.*, 1977; Erukhimov *et al.*, 1982) occur within the plasma resonance region in the ordinary wave field.

The formation of artificial inhomogeneities in the lower ionosphere under the effect of high power radio wave vertical beams transmitted from the ground has been investigated in, for example, Bolenov *et al.* (1977) and Grach *et al.* (1979). The authors were chiefly interested in the thermal parametric instability mechanisms (Grach *et al.*, 1979; Vas'kov and Gurevich, 1976; Dimant, 1977). However, the dissipative instability is characterized by considerable inertia. In Belikovich *et al.* (1977) and Erukhimov *et al.* (1982) the possibility of stimulation of inhomogeneities by heating from the ground on account of the strictional forces is discussed and the conditions of ordinary mode backscatter and the competition between the thermal and strictional parametric instability mechanisms are considered.

We will now estimate the energy density of the wave transmitted from the satellite. For frequencies above the plasma frequency we have in the near zone of a long cylindrical source

$$W = \frac{P}{2\pi r l_0 v_{gr}} \approx \frac{P f_0}{2\pi r c l_0 \sqrt{f_0^2 - f_{Pe}^2}}. \qquad (1)$$

Then, $W = n_e T_e$ at the distance perpendicular to the dipole:

$$r_p \approx \frac{P f_0}{2\pi l_0 c n_e T_e \sqrt{f_0^2 - f_{Pe}^2}} \qquad (2)$$

(here, v_{gr} is the group velocity of the wave, c is speed of light, l_0 is the transmitting dipole length $l_0 = 50$ m). Substituting into (2) the value $f_0 = f_{Pe} + \Delta f_0$($\Delta f_0$ is the ionosonde frequency tuning step; for $f_0 > 1.5$ MHz, $\Delta f_0 = 50$ kHz), we obtain $r'_p \approx 5$ m. At $f_0 \gg f_{Pe}$, $r''_p = 1$ m. The length of the near turbulence zone can be found from the condition for the so-called 'superstrong turbulence' $W_T = n_e T_e (m/M)^{1/3}$ and in the above two cases $r'_T = 60$ m and $r''_T = 12$ m, respectively.

In general, the strictional modulation instability and soliton formation mechanism given in Degtyarev *et al.* (1980) is valid for small $W/n_e T_e$ ratios, however, its saturation at $W_c \sim 0.5\, n_e T_e$ permits the results of Degtyarev *et al.* (1980) to be extrapolated to $W/n_e T_e \sim 1$. The wavefront overturn effect taking place under these conditions does not substantially affect the space scale pattern but only renders the cavity boundaries steeper.

Since within the field of action of the potential force on quasi-neutral plasma its steady-state density is $n_{e,i} = n_e \exp(-W/n_e T_e)$, in the near zone (2) $n_{e,i} \to 0$, in the near cavitons $n_{e,i} \to n_e e^{-1/2}$, and on the boundary zone (2) where the HF field pressure and thermal pressure are equal $n_{e,i} \to n_e e^{-1}$.

For a better understanding of the energy transformation processes taking place in the frequency range $f_0 < f_{Pe}$ we will use the results of Galushko *et al.* (1975) and Singh and Gould (1971), where the radiation of a source in a magnetoactive plasma and absorption of HF radiation are considered, with allowance for the finite source dimensions, plasma temperature and its inhomogeneity. In those studies it was found [cf. the references in Galushko *et al.* (1975)] that for $f_0 < f_{Pe}$ the major portion of radiation is concentrated near the resonance cone whose axis is along the external magnetic field H_0 and a shadow zone appears on the directional pattern. (At $f_0 \geqslant f_{Pe}$ there is no such resonance cone.) Its apex angle is defined as $\cot^2 \theta_0 = |\varepsilon_\parallel|$, where $\varepsilon_\parallel$ is the longitudinal dielectric constant. The attenuation length, $l_\theta \sim \lambda_0^2/\pi^2 l_0 \cos\theta$, where λ_0 is the wavelength in vacuum. In Singh and Gould (1971) $\theta_0 = \cos^{-1}(f_0/f_{Pe})$ and the intensity decreases as r^{-1}, where r is distance from the source. On the resonance cone surface the intensity decreases as $r^{-\beta}$, where $\beta \approx 1/2$.

In the case of $f_{He} < f_0 < f_{Pe}$ we have what may be called a trapped electric field limited by the volume V_T. It should be noted that due to condition $\varepsilon < 0$ in this frequency band the non-resonant attenuation length d may be $\lambda_0/2$ (for $f_0 \sim 0.9 f_{Pe} \sim f_Z$) and $d \sim \lambda_0/10$ (for $f_0 \sim f_{Pe}/2$), i.e. $d_{\max} \sim 50$ m and $V_T \sim 10^6$ m. The resonance cone is then bounded by an angle $\theta_{\max} \approx 45°$. This may be concluded from the fact that in the case of a narrow directional pattern the $W/n_e T_e$ ratio increases along H_0, and therefore r_p, and at the end of the transmitted pulse action the value of $\varepsilon_\parallel$ within the resonance cone will be close to 1 and $l_{\theta_{\max}} = \sqrt{2}c^2/\pi^2 f_0^2 l_0 \approx 30$ m. Therefore, the perturbed region may be represented by a cylinder flattened in the direction $\mathbf{H}_0 \times \mathbf{l}_0$ and having its axis directed along $\mathbf{H}_0$. Its volume may be estimated roughly as

$$\begin{aligned} V_T &\approx \pi l_0^2 l_{\theta_{\max}} \cdot \cos^2(\mathbf{H}_0 \mathbf{l}_0) \\ &\approx 2\sqrt{2} l_0 c^2 \cos^2(\mathbf{H}_0 \mathbf{l}_0)/4\pi f_0^2 \\ &\approx 2 \times 10^5 \text{ m}^3. \end{aligned}$$

If this region is uniformly filled with the HF field, its redistribution would involve $W = P\tau_0/V_T \sim 5 \times 10^{-8}$ J m^{-3}, i.e. $W/n_e T_e \approx 50$. The directional isotropicity of the Poynting vector $\mathbf{P}$ is attained when the pure longitudinal waves are transformed to the intermediate waves (Krupina, 1977), which is due to the strong refraction at the inhomogeneity near the satellite resulting from the properties of the refractive index surfaces of longitudinal waves. It should be noted that one could expect the resonant enhancement of the wave emitted in the direction $\mathbf{l}_0$ with a group velocity of about $3 \times 10^{-3}\, c$ when the direction of $\mathbf{l}_0$ coincides with the resonance cone surface (Singh and Gould, 1971). Since during the transmitter pulse the striction force acting on a unit volume of plasma, $F = -(f_{Pe}/f_0)^2\, \partial W/\partial r$, where r is the distance along $\mathbf{H}_0$, then considering the above for $f_0 < f_{Pe}$ and putting $W = P/\pi r^2 v_{gr}$ we obtain an expression for the time of macroscopic striction extrusion of plasma to a distance r from the antenna

$$\tau = \frac{f_0}{2 f_{Pe}} \left(\frac{M n e \pi v_{gr}}{2P} \right)^{1/2} r^2 \qquad (3)$$

and for the distance r_e to which plasma will be extruded during the time τ_0

$$r_0 = \left(\frac{2\tau_0 f_{Pe}}{f_0}\right)^{1/2}\left(\frac{2P}{\pi M n e v_{gr}}\right)^{1/4}. \qquad (4)$$

For $r = l_{\theta_{\max}}$ and $f_0 \sim f_{Pe}$, $\tau \approx 1.5 \times 10^{-7}\ r^2 \approx 1.3 \times 10^{-4}$ s (comparable with τ_0).

On the boundary of the region under consideration the pressure of the HF field is higher than the thermal pressure of the plasma. This means that after termination of the transmitter pulse the broadening of the zone due to the slowing down and delay of the wave will continue until $W/n_eT_e \sim 1$ on its boundaries. The dimensions are thereby increased about three times. In order for such additional broadening to occur it is enough that the delay be about 1–3 ms. The time of diffusion dissipation of the inhomogeneities of such dimensions $\tau_D \sim L^2/D_\alpha \sim 10^{-1}$ s (D_α is the ambipolar diffusion coefficient).

According to KRASNOSELSKIKH and SOTNIKOV (1977), in the case of longitudinal propagation in a magnetic field the cavitons are formed within a narrow cone $\alpha \leqslant (f_{Pe}/f_{He})k \cdot r_D$ with the axis directed along the Poynting vector of the pumping wave. The cavities then look like 'pancakes' flattened along the v_{gr} of the pumping wave. Applying the results of DEGTYAREV *et al.* (1980) to the case of longitudinal propagation we obtain for $f_0 \rightarrow f_{Pe}$, $f_{Pe}/f_{He} = 5$ and $k = 0.6\ \mathrm{m}^{-1}$, $\alpha \approx 6°$. The minimum dimensions of the modified zone will be determined by the fraction of the pumping wave energy consumed to accelerate electrons. According to the estimate in GUSEV *et al.* (1980), this fraction η is several per cent of the radiated energy. The total volume of the accelerating cavitons may be estimated as $\eta \approx \sum V_c/V_T$ or $\sum V_c \sim 10^{-2}\ V_T \sim 10^4\ \mathrm{m}^3$, whence the minimum size is about 20 m.

Transformation of the transmitter radiation into slow plasma waves (GOLANT and PILIYA, 1971; GALEEV *et al.*, 1975) will, in this case, occur mainly on the boundary of the zones (2) and (4), where the concentration gradient is considerable.

3. COMPARISON WITH THE EXPERIMENT

The experimental results obtained on the *Interkosmos-19* (IK-19) artificial satellite have shown that, despite the short duration of the transmitted pulse, effective heating of the plasma surrounding the satellite takes place, especially at sounding frequencies below the local plasma frequency (GALPERIN *et al.*, 1981), and turbulization of the plasma.

Figures 1 and 2 present data obtained on IK-19 with the HFA-2 satellite-borne wide-band high-frequency analyzer (GUSEV *et al.*, 1980).

Figure 1 shows the time history of stimulation at $f_{Pe} = 2.5$ MHz with time resolution $\Delta\tau \approx 0.1$ ms. The time and frequencies corresponding to the f_0 frequency of

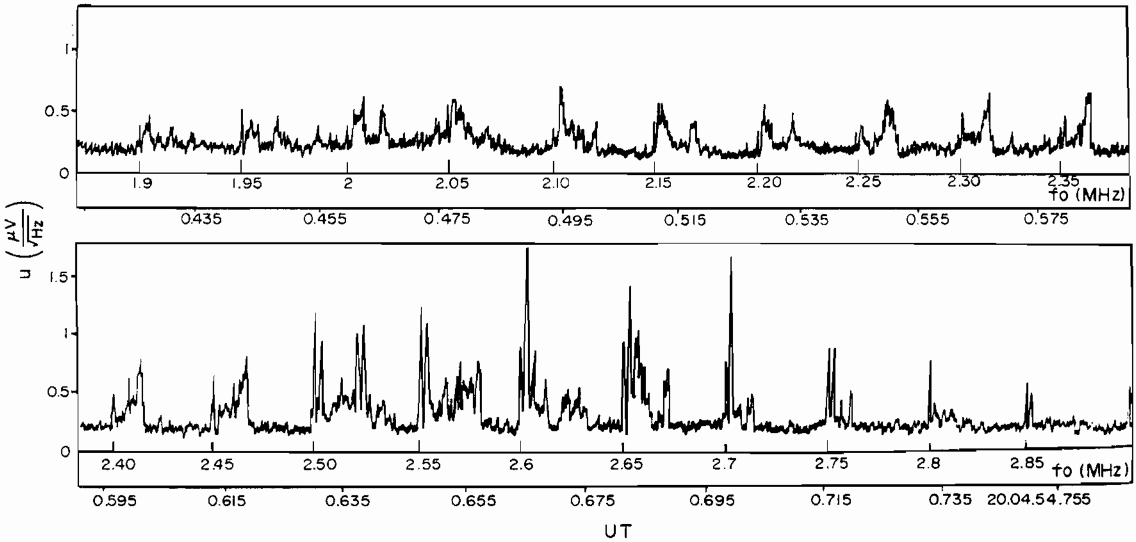

Fig. 1. Plasma response on local plasma frequency ($f_{pe} \sim 2.5$ MHz) as the frequency of emitted topside sounder pulses approaches f_{pe}. Pulses occur at the frequency markers. Revolution no. 840, 26 April 1979, 20.00 UT, longitude 337°, latitude 6°S, $H = 940$ km, $f_{pe} = 2.50$ MHz, $f_{He} = 485$ kHz, filter pass band $\Delta f = 50$ kHz, $\tau = 0.1$ ms.

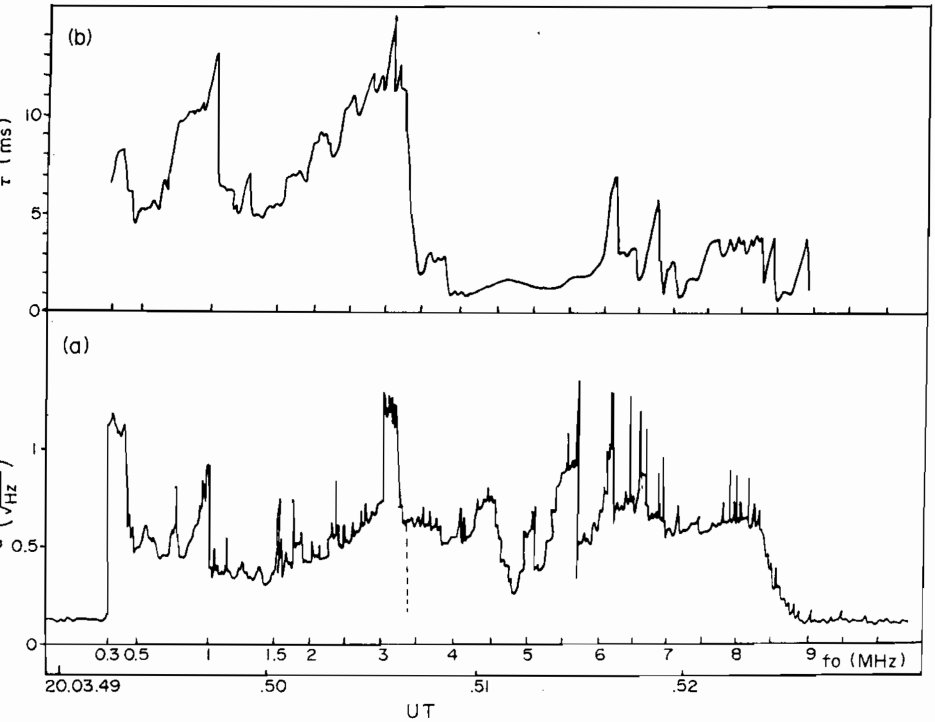

Fig. 2. Envelope of maxima (A) and duration (B) of plasma frequency ($f_{pe} \sim 3$ MHz) response on topside sounder pulses f_0 during one sweep of sounder. Revolution no. 840, longitude 337°, latitude 3°S, $H = 930$ km, $f_{pe} = 3.05$ MHz, $\Delta f = 100$ kHz, $\tau = 0.1$ ms. Both figures were obtained by filtering from the wide-band receiver HFA-2 signal with the help of a filter tuned to the local plasma frequency when the topside sounder transmitter sweeps from 0.3 to 16 MHz. The sounder tuning step is equal to 25 kHz in the 0.3–1.5 MHz band and 50 kHz in the 1.5–16 MHz band.

the IS-338 sounding transmitter (Vasiliev *et al.*, 1980) are plotted on the X-axis and the stimulated signal amplitude on the fixed frequency equal to local f_{Pe} is plotted on the Y-axis.

For $f_0 \geqslant f_{Pe}$ one can see the excitation is quasi-periodic with a period $\tau_1 \approx 1.2$ ms. At $f_0 < f_{Pe}$ the process becomes stochastic. However, when the measurements were carried out at f_{He} and $2f_{He}$, the excitations at $f_0 = f_{He}$ and $f_0 = 2f_{He}$ were again found to be modulated with the same period (Klimanova *et al.*, 1983). Furthermore, as one can see in Fig. 1, τ_1 does not vary with the delay time. This fact is inconsistent with the predictions of the linear theory (McAfee, 1973). The equality of modulation periods at f_{Pe}, f_{He} and $2f_{He}$ may be explained if one assumes that it is the above-mentioned strong Langmuir turbulence mechanism which is responsible for the long observed signal delays. At the same time, the modulation period τ_1 is the period of ion–acoustic waves $\tau_1 \sim \tau_s$ generated by the collapsing cavitons. It should be noted that τ is different from the proton gyroresonance period $\tau_{Hp} = 3.8$ ms ($f_{He} = 485$ kHz) [for more detail on the effects due to proton gyroresonance see Benson (1976)]. For heavier ions the period is even larger.

In the general case the condition for observability of the soliton array with wave vector k for the most unstable mode may be written as

$$k^2 \mp \frac{f_{Pe}}{31T_e}k \pm \frac{f_{Pe}}{3.9T_e\tau_{ob}} = 0, \qquad (5)$$

where τ_{ob} is the observable period of modulation in ms and f_{Pe} is in MHz, T_e in 10^3K and k in m^{-1}. The upper signs represent opposite satellite–soliton motion and the lower signs motion in the same direction. If $\tau_{ob} = \tau_1$, and corresponds to the most unstable wavelength at Langmuir oscillations (Degtyarev *et al.*, 1980), $\lambda_1 \approx 10$ m (it is about equal to the length of one arm of the receiving antenna $l_r = 7.5$ m) and $k_1 = 2\pi/\lambda_1 \approx 0.6\ \mathrm{m}^{-1}$, and the group velocity of this mode $\partial\omega/\partial k = 3 \cdot r_D^2 k\omega_{Pe} \approx 3\ \mathrm{km\ s}^{-1}$. In other words, the assumption that $v_{sat} > v_s$ or $v_{sat} > v_{gr}$ (where v_s is soliton velocity, v_{sat} is satellite velocity) is seen to be true. Thus the short modulation periods (Fig. 1) may correspond to oncoming motion of solitons and at the same time the long periods (up to 5 ms) to motion in the same direction. Moreover, the most unstable mode corresponds to $k \sim 0.6\ \mathrm{m}^{-1}$ too, and the boundary of the observable meaning of k is determined by $k > 0.3\ \mathrm{m}^{-1}$. For $v_{gr} \to 0\ \lambda_1 \approx 8\ \mathrm{m} \approx 4x$, which is consistent with the ideas of part 2. The satellite motion geometry is such that the directions of the magnetic field of the Earth $\mathbf{H}_0$, the satellite velocity vector $\mathbf{v}_{sat}$ and the receiving antenna of HFA-2 coincide, and the radiating antenna of the IS-338 transmitter makes an angle of 45° with this direction. The angle between $\mathbf{l}_r$ and $\mathbf{l}_0$ is always 45°. The 'shunting' effect of a long receiving antenna which crosses longitudinally the localized fields having the dimension $l_c < l_r$ should be noted. The invasion into the plasma of a metallic rod must strongly affect the dynamics and amplitude of the trapped plasmons.

At frequencies just slightly above f_{Pe} the estimate of the dimensions of the near turbulent zone r_T is seen to be rather accurate and $\tau_{Pe} \sim N^{-1/2}$ (where τ_{Pe} is the time of excitation at f_{Pe} during sounding at the frequency $f_0 = f_{Pe} + N\Delta f_0$), i.e. $\tau_{Pe} \sim r_T/v_{sat}$. It should be noted that since the upper hybrid resonance was near f_{Pe} ($f_{UHR} = f_{Pe} + \Delta f_0$), it is very difficult to account for the energy redistribution between the modes, and therefore the group velocities, in a more or less exact manner.

At $f_0 < f_{Pe}$, equation (4) for r_0 may be qualitatively illustrated by Fig. 1, with decreasing of f_0 the time of excitation at f_{Pe}, which we have interpreted as the time it takes for the satellite to cross the zone of strongly modified plasma, increases. The delay time at $f_0 \leqslant f_z$, where f_z is the cut-off frequency of the z-mode, equal to 2.25 MHz) corresponds to the crossing of the boundary of zone of size $l_{\theta_{\max}}$. The data we have presented correspond to satellite motion almost strictly with the field. When the movement was at larger angles to $\mathbf{H}_0$ (KLIMANOVA *et al.*, 1983), much smaller delay times f_{Pe} were observed both for $f_0 < f_{Pe}$ and $f_0 \approx f_{Pe}$ (in the latter case the number of solitons is often not greater than two or three). The reason may lie with the fact that the soliton array arranges itself, as noted above, substantially along the magnetic field of the Earth and they collapse substantially across the field.

Figure 2 shows the excitation amplitude and duration near f_{Pe} as a function of the pumping pulse frequency f_0. That the excitation of f_{Pe} is a strongly non-linear process is evidenced by the fact that the plasma resonance is stimulated by any ionosonde pulse, beginning from the first frequency $f_0 = 0.3$ MHz up to $f_0 \sim 3f_{Pe}$. An explanation of this effect is possible in terms of the theory of a periodic parametric action exerted on the resonance system. In the case of a periodic structure, which the pumping wave field is, the solution of the problem may be reduced to a Matthieu equation, and in the case of disturbance of a sufficiently large amplitude the Matthieu zones may overlap entirely. For the maximum possible pumping frequency $f_0 = 2f_{Pe}$, which corresponds to $n = 1$ for the eigen solutions $f_{Pe} = nf_0/2$, the excitations at frequencies of up to $3f_{Pe}$ may also be attributed to Matthieu zone broadening due to the large modulation amplitude. The f_{Pe} may, alternatively, be generated by the Cerenkov emission of electrons accelerated by the striction forces. In this case a superhot electron flux with a wide range of velocities may be stimulated by the transmitter radiation at frequencies $f_0 < f_{Pe}$, and the beam instabilities for which the condition $\omega - n\omega_{He} = kv$ is valid may be responsible for the generation of frequencies $f_{Pe} \leqslant f \leqslant f_{UHR}$ and frequencies near nf_{He}.

In Fig. 2 one may note peculiar behaviour near $f_0 \sim 2f_{Pe}$. The increase of excitation at $2f_{Pe}$ suggests the presence of non-linear parametric decays $f_{Pe} = f_0 - f_{Pe}$, $f_{Pe} = f_0 - f_{Pe} \pm f_{He}$. As shown in GUSAKOV and FYODOROV (1979), the thresholds of parametric decay instabilities are lowered in trapped plasmons. The increase of excitation at $2f_{Pe}$ may be regarded as confirmation of the fact that the ionospheric plasma is modified at double the Langmuir frequency (GALEEV *et al.*, 1972) as well as it is at frequencies $f_0 = f_{He}, f_{Pe}, nf_{He}$. At $f_0 < f_{Pe}$, the stimulation of f_{Pe} is also somewhat peculiar (Fig. 2), which allows us to assume the possibility of parametric confluence of the type $f_{Pr} = f_0 + nf_{He}$.

4. ON THE ELECTRON HEATING EFFECT IN THE VICINITY OF SATELLITE

We have noted already that cavity collapse entails dissipation of the HF field by the Landau damping mechanism, i.e. energy is transferred to the particles. What is important is that collapse in a magnetic field causes acceleration of electrons across the field. The ultimate result of these effects is that in the direction perpendicular to H_0 the electron temperature is increased by two or three orders of magnitude (DEGTYAREV *et al.*, 1980; KRASNOSELSKIKH and SOTNIKOV, 1977; GURERICH and ISTOMIN, 1979). Using an electron spectrometer, this fact was registered on the IK-19 satellite where IS-338 radiation stimulated intensive, soft electron fluxes with energies of about 150 eV were observed at angles of about 90° to H_0 (GALPERIN *et al.*, 1981). The maximum of these fluxes occurs at the frequency $f'_0 \approx 0.7\ f_{Pe}$ and extends through a rather wide band: at the level of 0.3 I_0 (I_0 is the maximum flux at f'_0) the stimulating frequency band extends from $0.3f_{Pe}$ to f_{Pe}. Weaker electron fluxes were observed at frequencies up to $f_0 \sim 3f_{Pe}$. The similarity between the envelope of electron fluxes and the envelope of the radiation at the plasma frequency (cf. Fig. 2) prompts the conclusion that these phenomena are somehow correlated, that it is the wave–particle interaction which is the precise reason for electron heating. In BENSON (1982) it was hypothesized that in the experiments on the IK-19 satellite the heating took place not at the frequency $0.7\ f_{Pe}$ but at the third harmonic of f_{He} [this assumption was prompted by the coincidence of $3f_{He}$ with $0.7f_{Pe}$ in some of the figures of GALPERIN *et al.* (1981). Nevertheless, the averaged curves of GALPERIN *et al.* (1981) plotted for f_{Pe} varying from 5 to 9 MHz do not support this assumption. One should note that the duration of the accelerated electron fluxes detected on the IK-19 satellite (GALPERIN *et al.*, 1981 (0.3–3 ms) correspond to the time of collapse of cavitons 0.1–1 m in size. Such cavitons must originate on the boundary of the central macroscopic cavity in which all the emitted radiation is trapped. Afterwards, this cavity will disintegrate into smaller ones due to thermal diffusion. Thus the most probable mechanism of the observed electron heating is, in our opinion, their acceleration by the HF field within the cavities; besides, electrons may undergo repeated acceleration (VAS'KOV *et al.*, 1983).

The fact that electrons are accelerated mainly at the frequency $0.7f_{Pe}$, rather than even at f_{He}, although a peak is observed there too, may be explained as follows. The acceleration by three-dimensional electric fields confined within the cavitons is more effective at pumping frequencies smaller than f_{Pe}, since all the pumping power will be localized near the satellite in this case, whereas at emitted frequencies $f_0 \geqslant f_{Pe}$ a considerable portion of energy is carried beyond the satellite vicinity by the ordinary and extraordinary electromagnetic waves, as well as by the longitudinal electrostatic wave. The decrease of electron concentration results in a reduction of the local plasma frequency and, therefore, an enhancement of local fields in cavitons at frequencies $f'_{Pe} = f_0 < f_{Pe}$. The range of f'_{Pe} will be determined from the condition that in a caviton $n_{e,i} = -n_e \exp(-W_k/n_e T_e)$ and may attain values of $(e^{-1/2}–e^{-1/4})f_{Pe} \approx (0.6–0.8)f_{Pe}$.

The scatter and absorption of electromagnetic waves at cylindrical inhomogeneities give rise to secondary Tonks–Dattner resonances (GOLANT and PILIYA, 1971) detected in a number of laboratory experiments [cf., for example, the references in GOLANT and PILIYA (1971)]. The maximum must occur at $f_{TD} = f_{Pe}/\sqrt{2}$. This result follows from the fact of the existence of surface waves near a plasma shock wave (which are transverse in the range $f_0 < f_{Pe}/\sqrt{2}$ and potential at $f_0 \to f_{Pe}/\sqrt{2}$) (GOLANT and PILIYA, 1971; KARPLYUK and KOLESNICHENKO, 1970; GINZBURG and RUKHADZE, 1975), for which the resonance condition has the form $\varepsilon_1 + \varepsilon_2 = 0$, where ε_1, ε_2 are the dielectric constants of the first and second media.

Since in the central zone $n_{i,e} \to 0$ when $f_0 < f_{Pe}$, as has been shown above, then $\varepsilon_1 \approx 1$, $\varepsilon_2 = 1 - f_{Pe}^2/f_0^2$ and, therefore, $\varepsilon_1 + \varepsilon_2 = 2 - f_{Pe}^2/f_0^2 = 0$, i.e. $f_0^2 = f_{Pe}^2/2$. If we now allow for the magnetic field according to GINZBURG and RUKHADZE (1975), we have to substitute f_{UHR} for f_{Pe}: $f_{TD}^2 = (f_{Pe}^2 + f_{He}^2)/2$. In the conditions which prevailed on IK-19, the ratio f_{Pe}/f_{He} was normally above 2 (in our case $f_{Pe}^2/f_{He}^2 = 25$). The results of GALPERIN *et al.* (1981) also relate to large f_{Pe}^2/f_{He}^2 ratios, when $f_{UHR} \to f_{Pe}$. In reality the resonance band is confined within

$$f_{Pe}/\sqrt{2} \leqslant f_{TD} \leqslant f_{UHR}/\sqrt{2},$$

depending on the magnetic field orientation in relation to the jump surface.

The life-time of a resonance on such surface waves must be short (less than 1 ms), since the effectiveness of absorption of the energy of these waves by electrons is higher than for 3-dimensional Langmuir waves (GINZBURG and RUKHADZE, 1975), and the attenuation decrement $\gamma_{surf} \approx -0.1 \cdot |k_z| \cdot v_{Te}$ in the region $f_0 \sim f_{Pe}/\sqrt{2}$, where $k_z > \omega/c$, takes values $\gamma_{surf}^{-1} \approx 5 \times 10^{-4}$ s. The enhancement of the surface mode on the central cavity boundary and its absorption results in violation of the r_s versus f_0 relationship given by equation (4). The absorption rate of the long wave portion of the surface mode is lower and its life-time may become much longer (up to 10 ms). Thus in the frequency range $f_{He} < f_0 < f_{UHR}/\sqrt{2}$ one should observe long lived resonances at the same frequencies. Obviously, they can be detected only if the antenna crosses the layer in which the surface mode has been stimulated. Therefore, in experiments using an ionosonde antenna which is both receiving and transmitting in the cases $\mathbf{l}_0 \parallel \mathbf{H}_0$ and $\mathbf{l}_0 \parallel \mathbf{v}_{sat}$ such excitations may not be detected. The wake may also play the role of a resonator of the surface mode, and, whenever the transmitted power is insufficient to cause considerable modification of plasma in the vicinity of satellite (as, for example, in the case of a reduction of the radiating antenna efficiency when $\lambda_0 \gg l_0$), it may bring about long lived resonances at these frequencies.

CONCLUSIONS

The results of wide-band investigations of the wave processes by external ionospheric sounding (KUSHNEREVSKY *et al.*, 1982), as well as the ionosphere modification mechanism proposed in this work, provide the first direct confirmation of the results obtained in laboratory ionospheric plasma simulation experiments (Boswell, 1981). They provide a basis for reconsidering the organization and interpretation of satellite sounding measurements. Further investigations will require the use of quick response particle detectors with a large dynamic energy range. We believe that a different attitude should be taken in interpretations of the plasma resonances recorded on the topside ionograms, especially the diffuse and nonlinear processes. Interpretation of the ionograms themselves should also be more sophisticated. For example, the modification of the ionosphere in the vicinity of a satellite by a high power wave emitted by a satellite-borne transmitter compels one to pass from plane-layer to cylindrical geometry in calculations of the beam paths for plasma and intermediate waves (Krupina, 1977) within the framework of geometrical optics.

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