Pergamon

Adv. Space Res. Vol. 15, No. 12, pp. (12)95–(12)98, 1995

0273–1177/95 $9.50 + 0.00

0273-1177(95)00022-4

EFFECT OF HF EMISSION OF THE TOPSIDE SOUNDER TRANSMITTER ABOARD THE COSMOS-1809 SATELLITE ON THE IONOSPHERIC PLASMA

N. V. Baranets,* V. A. Gladyshev** and V. V. Afonin***

* *IZMIRAN, 142092 Troitsk, Moscow Region, Russia*
** *Institute of Earth Physics, Moscow, Russia*
*** *Space Research Institute, 117810 Moscow, Russia*

ABSTRACT

The experiment on investigation of effect of the HF emission (300 W) by the dipole antenna on the ionospheric plasma was carried out onboard the COSMOS-1809 satellite (1987). The sounder accelerated particles (SAP) at the electron cyclotron harmonics $n \cdot \omega_{ce}$ and in the frequency region of antenna resonance were detected by the charged particle spectrometer.

INTRODUCTION

One of the most interesting results on board the COSMOS-1809 satellite was obtained when the dipole antenna was oriented almost along the magnetic field lines. In this case the stimulated bursts of electrons were recorded by the charged particle spectrometer on harmonics of the electron cyclotron frequency $n \cdot \omega_{ce}$ in the process of frequency scan of the topside sounder transmitter within the range of $f_0 = 0.3 - 5,0$ MHz, where n is the number of harmonic and $f = \omega/2\pi$.

SCIENTIFIC INSTRUMENTS

The COSMOS-1809 satellite was launched on 18 December 1986 into an almost circular orbit at a height of 980 km. The topside ionospheric sounder IS-338 was mounted on board the satellite. The sounder operates at 338 fixed frequencies within the range of 0.3–15.95 MHz. The main technical characteristics of the sounder are given in Table 1. Auroral and SAP electrons and ions in the energy range of $\varepsilon_e = 0.01$-10.2 keV and $\varepsilon_i = 0.01$-9.6 keV, respectively, were measured by the electrostatic analyser SF-3M /1/. The particles were detected in four angular sectors with an effective aperture angle of about 30°. Measurements of electron density n_0 and the temperature of the unperturbed plasma T_e has been made with the help of IZ-2 impedance probe and KM-9 rf probe. The working frequency of the IZ-2 instrument was 5.03 MHz. To determine the electron gyrofrequency ω_{ce} and the orientation of Earth's magnetic field in the satellite coordinate system, the data of onboard magnetometer and magnetic field model were used. Figure 1a shows the relative arrangement of the sensors and the two mutually perpendicular dipole antenna pairs.

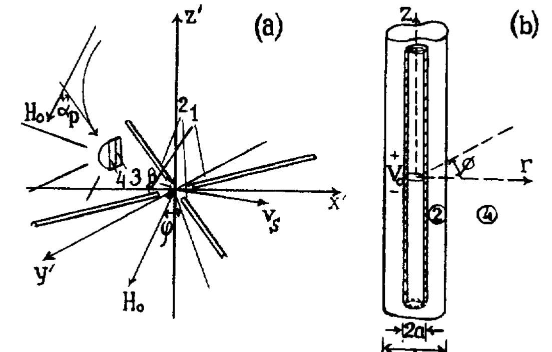

TABLE 1. The main characteristics of the topside sounder transmitter IS-338

antenna length (2h):	
0.3-5.0 MHz	50 m
5.0-15.95 MHz	15 m
antenna tube radius	0.012 m
pulse duration	0.133 ms
repetition frequency	58.6 Hz
frequency scanning step:	
0.3-1.5 MHz	0.025 MHz
1.5-15.95 MHz	0.095 MHz

FIG. 1. (a) The sensors arrangement of the SF-3M spectrometer and two dipole antennas in the satellite coordinate system - x', y', z': 1) long dipole 50m, 2) short dipole 15m, 3,4) the sensors of ions and electrons, $\vec{v}_s$ - satellite velocity vector; β -angle between $\vec{H}_0$ and z'-axis; φ - angle between $\vec{H}_o$ and a plane perpendicular to the antenna axis. (b) Geometry of antenna: region 2, cylindrical sheath; region 4, external medium; a, b - radii of antenna tube and region 2; z, r, ϕ - cylindrical coordinate system.

NEAR FIELDS OF A DIPOLE ANTENNA

To calculate the radiation characteristics of a dipole antenna in the ionospheric plasma, we used the model of finite-length antenna with insulated tips and surrounded by an infinite cylindrical region (Fig.1b). To

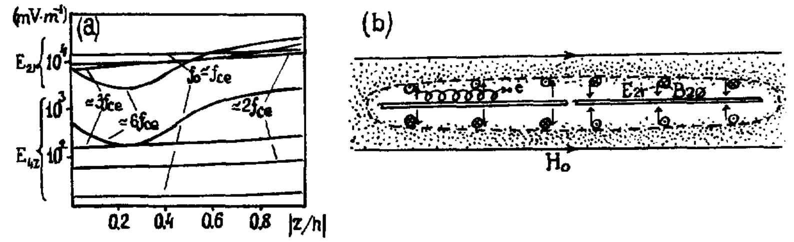

FIG. 2. (a) Frequency dependence of calculated values of the electric field component E_{2r} ($r = 2.0$ m) and E_{4z} (r=3.5 m) on z coordinate for $f_{pe} \approx 0.62$ MHz, $f_{ce} \simeq 0.64$ MHz, $T_e \approx 0.3$ eV; (b) Structure of electromagnetic field components E_{2r}, $B_{2\phi}$ for the case when the dipole is oriented along the H_0 field.

determine a sheath thickness b, we assumed that electron density n_0 changes from 0 to $n_0/2$ on the boundary of the cylindrical sheath. At high values of applied voltage V_0 RF forces lead to evacuation of electrons from surrounding region and exert an appreciable influence on the sheath thickness b. To calculate b, we used a rather rough estimation taking into account the general dependence on V_0, n_0 and T_e for unperturbed plasma, i.e. $b = 0.1 \cdot \eta r_{De}$ /2,3/, where r_{De} is an electron Debye radius and $\eta = eV_0/\kappa T_e$. For region 4 a cold homogeneous collisionless plasma model was used. We also assumed that the electron density in the sheath approximately corresponds to value $10^{-2} n_0$. The calculations of the input impedance and the current distribution in the antenna were carried out in accordance with the magnetohydrodynamic theory /4/. The refractive index of the waves for the isotropic model in the region 4 was estimated by expression $n_4^2 = 1 - \omega_{pe}^2/\omega_0^2$, but in the presence of magnetic field for the ordinary (O) and extraordinary (X) waves, we used the Appleton-Hartree formula. For the region 2 the refractive index of the waves in a plasma was estimated from $n_2^2 = 1 - \omega_{pe}^2/100\omega_0^2$. The wave numbers in the regions 2 and 4 are equal $k_2 = (\omega_0/c)n_2$ and $k_4 = (\omega_0/c)n_4$, respectively, and the wave resistance for the region 2 is $\zeta_2 = (\mu_0/\varepsilon_0 n_2^2)^{1/2}$, where ε_0, μ_0 - electric and magnetic constants, $c = 3 \cdot 10^8$ m/s. The sinusoidal antenna current was calculated as

$$I(z) = -\frac{iV_0 \sin k_0(h - |z|)}{2\, Z_c \cos k_0 h}, \tag{1}$$

where $i = \sqrt{-1}$, this expression is valid for $|k_4 h| \ll 1$ and $|k_4^2/k_2^2| \gg 1$. The wave resistance Z_c and wave number k_0 were determined from the expressions:

$$k_0 = k_2 \left\{ \frac{k_4^2 \left[H_0^{(1)}(k_4 b) + k_4 b \cdot \ln(b/a) H_1^{(1)}(k_4 b) \right]}{k_2^2 H_0^{(1)}(k_4 b) + k_4^2 \cdot k_4 b \cdot \ln(b/a) H_1^{(1)}(k_4 b)} \right\}^{1/2}, \tag{2}$$

$$Z_c = \frac{\zeta_2 k_4}{2\pi k_2} \left[\ln(b/a) + \frac{k_2^2 H_0^{(1)}(k_4 b)}{k_4^2 \cdot k_4 b \cdot H_1^{(1)}(k_4 b)} \right], \tag{3}$$

where $H_0^{(1)}$ and $H_1^{(1)}$ are Hankel' functions of the first kind. To calculate the dipole antenna input impedance $Z_v = R - iX$, one can write $Z_v = V_0/I(0) \approx i2Z_c \mathrm{ctg} k_0 h$. In the region 2 the lateral and longitudinal components of electric field $E_{2r}(r, z)$ and $E_{2z}(r, z)$ relative to the antenna are equal

$$E_{2r}(r, z) \approx \frac{i}{2\pi r \omega_0} \frac{dI(z)}{dz} \approx \frac{V_0 k_0 \cos k_0 (h - z)}{4\pi \omega_0 r n_2^2 Z_c \cos k_0 h}, \tag{4}$$

$$E_{2z} \approx \frac{V_0 \sin k_0 (h - |z|) \ln(r/a)}{4\pi Z_c \cos k_0 h} (k_0^2/n_2^2 \omega_0 - \mu_0). \tag{5}$$

For the magnetic component, one can take $B_{2\phi}(r, z) \approx (\mu_0/2\pi r) I(z)$. The electromagnetic components in the near field can be obtained from the boundary conditions at the sheath surface $B_{4\phi}(b, z) = B_{2\phi}(b, z)$; $E_{4z}(b, z) = E_{2z}(b, z)$; $E_{4r}(b, z) = (n_2^2/n_4^2) E_{2r}(b, z)$. The calculation results are presented in Figure 2a.

EXPERIMENTAL RESULTS

The antenna resonance. The earlier experiments with HF emission in the ionospheric plasma revealed the existence of the main peak for the SAP ions' intensities at frequencies close to, but lower then the local plasma frequency ω_{pe} /5/. The statistics of the recorded bursts of ions exclude an error due to the incorrect determination of the resonance frequencies values in a plasma. To get the required data set from the two instruments SF-3M and IS-338 operating with independent scanning modes, a special data reducing method was applied. The main point consists in the selection of flux particle data with an energy $\varepsilon_{e,i}$ during a

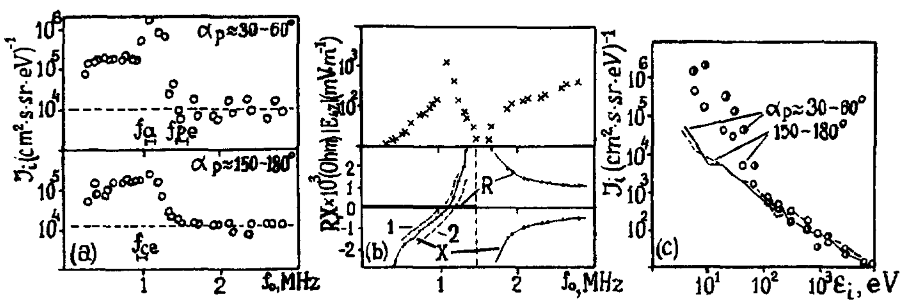

FIG. 3. (a) Dependence of the SAP ion fluxes on frequency f_0. The values of $\varepsilon_i \approx 9$eV, $\beta \approx 160°$, $\varphi \approx 15°$; dashed lines are the intensity level of unperturbed flux of ions; f_a is a frequency of antenna resonance. (b) Calculated electric field E_{4z} in the near field, r=3.5 m; R,X - resistance and reactance of antenna; dashed curves are the reactance for different parameters of region 2: 1 - $b = 0.05\eta r_{De}$, $n_2^2 = 1 - \omega_{pe}^2/500\omega_0^2$; 2 - $b = 0.20\eta r_{De}$, $n_2^2 = 1 - \omega_{pe}^2/50\omega_0^2$; vertical dashed lines is a mean value of frequency f_{pe}; latitude $L_{dip} \approx 59° - 66°$, Orbit 554 (27 Jan 1987). (c) Energy spectra of flux ions for different pitch angles at the frequency f_a. Signs o, • - perturbed fluxes, solid and dashed curves - unperturbed fluxes.

3-4 minute interval of operation of the scientific instruments on board the Cosmos-1809 satellite with a simultaneous computation of the emission characteristics and the following arrangement of these values as a function of the frequency f_0. One of the most characteristic cases of the observed bursts of ions of the energy $\varepsilon_i \approx 9eV$ for the two pitch angle sectors of about $30 - 60°$ and $150 - 180°$ are presented in Fig.3a. In the frequency range of $\omega_o < \omega_{pe}$ one can see a distinct maximum of the flux intensity J_i for two pitch angle sectors. This maximum is well correlated with the so-called antenna resonance ($\text{Im}Z_o \simeq 0, f_0 \simeq f_a$) and with the maximum of calculated electric field of the component E_{4z} (Fig.3b). This correlation allows to evaluate an effective thickness b of region 2 using the expression (3) for $Z_c = 0$ in the form $\ln(b/a) - (k_2/k_4)^2 \ln(1.1229/k_4 b) = 0$. For the ionosphere parameters corresponding to the presented case (Fig.3), the thickness was found to be equal $b \simeq 1.5$–2.5 m for the electron temperature of about $T_e \approx 0.2$–0.4 eV. The dashed lines in the lower part of Figure 3b show the reactive impedance component X for different values of the parameters b and n_2 in region 2. The energy spectra of ions for the pitch angles of $30 - 60°$ and $150 - 180°$ are shown on Figure 3c when the frequency of the pumping wave was $f_0 \approx f_a$. It is needed to emphasize that the observed amplitude of stimulated ion fluxes depends on pitch angle α_p.

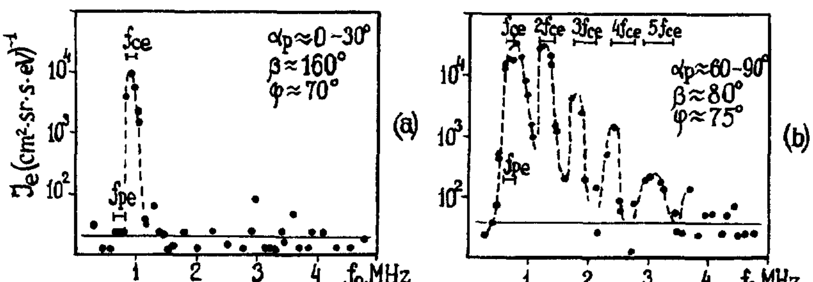

FIG. 4. Resonant increases of electron fluxes for $\varepsilon_e \approx 238$ eV at cyclotron harmonics $n \cdot f_{ce}$: (a) $L_{dip} \simeq 61° - 67°$, Orbit 675 (30 Jan 1987); (b) $L_{dip} \simeq 27° - 35°$, Orbit 43 (2 Dec 1986). Horizontal straight lines are the intensity level of the unperturbed flux of electrons.

Gyroresonance. Figure 4 shows the SAP bursts of electrons with energy $\varepsilon_e \approx 238$ eV observed on electron gyrofrequency harmonics $n \cdot \omega_{ce}$. Case (a) is for $\beta \approx 160°$; $\varphi \approx 75°$; $q = \omega_{pe}^2/\omega_{ce}^2 \approx 0.5$ (Fig.4a). The orientation of the dipole antenna to the magnetic field is almost normal. Intensive bursts of electron fluxes are observed on the first cyclotron harmonic in the region of $\alpha_p \approx 0 - 150°$; this case corresponds to the resonance condition $\omega_0 \approx \omega_{ce} + k_0^{\parallel} v^{\parallel}$, where $k_0^{\parallel}$, $v^{\parallel}$ are projections of wave number and particle velocity on the magnetic field. The data on Figure 4a are plotted only for pitch angles of $\alpha_p \approx 0 - 30°$. Figure 5a presents the energy spectrum of the SAP electrons in a wide range of energies with a maximum of about 400-500 eV when $f_0 \approx f_{ce}$. The disturbances of fluxes in this case are mainly caused by the interaction with the X-wave because the effect of an O-wave on the electrons at frequency ω_{ce} is negligibly small at the quasinormal orientation of antenna to the magnetic field H_0 and $k_0 h \ll 1$. It is obvious that the electron acceleration by the O-wave can occur only for longitudinal orientation of dipole antenna relative to the field H_0, or for an inclined orientation and at distances of about a few wave lengths from the antenna /6/. In the last case the electrons can be also detected by the SF-3M spectrometer.

b) $\beta \approx 80°, \varphi \approx 75°, q \approx 0.9$ (Fig.4b). The dipole antenna is oriented practically along the magnetic field. The resonance electrons recorded by the spectrometer at harmonics $n \cdot \omega_{ce}$ (n=1,2,3,4,5) could be subjected to strong disturbances only in the region 2 around the antenna with a radius $\sim 3-3.5$m and length ~ 25m. At this orientation of $\vec{H}_0$ and the dipole, the electrons were recorded in the range of $\alpha_p \approx 20-90^o$. Figure 5b demonstrates energy spectra of electrons only for one sector $\alpha_p \sim 60-90^o$. One can say that in this case the interaction of electrons occurs with waveguide modes (TEM modes). The similar electrodynamic system ("cocoon") and the field structure in it are schematically shown in Fig.2b. This phenomenon is of interest first of all because in case when the system slows down electrons, such system is a peculiar analogy of the microwave generator based on the induced cyclotron emission by electrons. The near field structure of the dipole at very large frequencies is very inhomogeneous and thus it can be one of the reasons why we observed the resonances up to n=5 (see Fig.2a, $f_0 \simeq 6f_{ce}$).

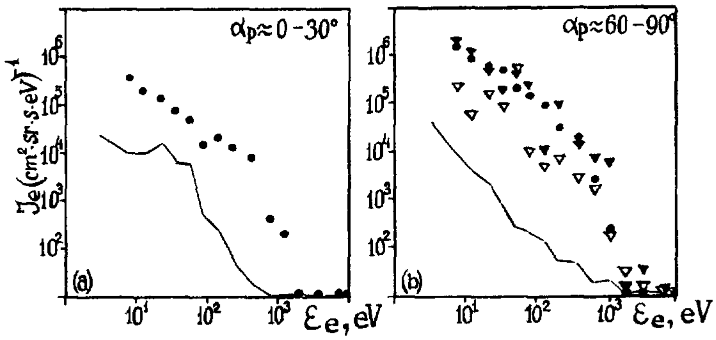

FIG.5. Energy spectra perturbation of electron fluxes. Signs •, ∇, ▼ correspond to perturbed fluxes at frequencies of f_{ce}, $2f_{ce}$, $3f_{ce}$ respectively. The solid line is a spectrum of the unperturbed flux of electrons. Panels (a,b) correspond to the cases presented in Fig.4a,b, respectively.

The variable along the coordinate z fields $B_{2\phi}(r,z)$ and $B_{4\phi}(r,z)$ can play a role of the equivalent irregular structure. In such structure the electron flux can be subjected to phase bunching and became modulated both in density and in velocity; the incoming electrons can be also slowed down (i.e. they can "reemit" the energy along the channel). Figure 5b shows the energy spectra of electrons in a wide range of energies from ~ 7eV to 1-2 keV. These spectra evidence the existence of a broad spectrum of oscillation modes interacting with electrons which have gyroradii $r_{ce} \approx 0.3-2$m.

CONCLUSIONS

This paper presents the results of an experimental study of the effects of HF emission by a dipole antenna on the near-satellite plasma. The main results can be summarised as follows:

1) For the case of $\omega_{ce} < \omega_{pe}$ the maximum intensity of SAP ions occurs in the frequency range of antenna resonance ($\mathrm{Im}Z_c \approx 0$) calculated for cold homogeneous plasma model without a magnetic field. This evidences that the interaction of HF emissions with ions occurs in the near field of antenna and the magnetic field does not exert an essential influence on the character of this interaction (at $\omega_{ce} < \omega_{pe}$).
2) Enhancement of ion fluxes in the energy range from $\sim$7eV (the beginning of range) to $\sim$100 eV takes place within the whole observed range of pitch angles $\alpha_p \approx 30-180^o$ at frequency of the antenna resonance.
3) The result 1 allows us to evaluate a sheath thickness b. For exapmle, at $f_{ce} \approx 0.64$ MHz, $f_{pe} \approx 0.62$ MHz ($n_0 \simeq 4600\,\mathrm{cm}^{-1}$) and $T_e \approx 0.2-0.4$ eV the sheath thickness is $b \simeq 2.8-3.5$m;
4) At quasinormal dipole orientation to the magnetic field, HF emission accelerates electrons at the first electron cyclotron harmonic ω_{ce} within the range of $\alpha_p \approx 0-150^o$. A peak intensity on the energy spectrum is observed in the range of $\varepsilon_e \approx 400-500$ eV; this confirms analogous earlier obtained results, see /5/.
5) At longitudinal dipole orientation to the magnetic field, the disturbed fluxes of electrons are observed at harmonics of $n \cdot \omega_{ce}$ (for n=1,2,3,4 and 5) in the range of $\alpha_p \approx 20-90^o$, i.e. in the waveguide-type region around the dipole;
6) First registered result 5 is evidence in favour of intensive interaction of electron fluxes in the energy range of ~ 7 eV - 2 keV with a wide spectrum of near field spatial harmonics in the channel.

Acknowledgments. The authors are very grateful to Professor Yu.I.Galperin as organizer of experiment "IS-338 - SF-3M" on board COSMOS-1809 satellite, and to the founders of scientific instruments IS-338 and IZ-2 G.V.Vasilev and G.P.Komrakov. We also wish to thank to Dr. Yu.V.Chugunov for useful discussion.

REFERENCES

1. N.V.Baranets, V.A.Gladyshev, T.M.Mularchik, V.A. Notkin, R.N.Suncheleev, Yu.P. Sharko, Cosmic Res.,30(1), 67-68 (1992).
2. J.P.Lafon, J. Plasma Phys.,10(3),383-396 (1973).
3. J.G.Laframboise, J.Rubinnstein and F.N.Palmer, Radio Sci., 10(8,9), 773-784 (1975).
4. Ronold W.P.King and Glenn S.Smith, Antennas in matter, Cambridge Univ. Press, London (1981).
5. Yu.I.Galperin, R.Z.Sagdeev, F.K.Shuiskaya, Yu.V.Lissakov, V.V.Migulin, Yu.V.Kushnerevskii, M.D.Fligel and G.V.Vasilev, Cosmic Res., 19(1), 34-44 (1981).
6. E.V.Suvorov and A.A.Freimann, High-school Proc., Radiophys., 20(1), 67 (1977).