The nature of the low-frequency electromagnetic radiation in the polar cap

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A region of increased electromagnetic radiation was observed in the earth's polar cap. It is shown that this radiation is generated by streams of low-energy electrons. The theoretically calculated level and spectral distribution of the turbulent noise agrees with the results of land-based measurements and of measurements with the aid of satellites.

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Fluxes of electrons of energy 100—200 eV and density 10^{-2}—10^{-3} cm^{-3} are constantly registered in the polar magnetosphere of the earth, in the region of the so-called polar daytime cusp.[1)] These solar-wind particles penetrate from the transition region through the daytime cusp into the earth's magnetosphere, up to altitudes on the order of 100 km.[1,2]. It was experimentally demonstrated with the aid of satellites that these streams generate a very low frequency (VLF) noise in a wide range of frequencies (up to 1 MHz).[3] We shall show below that the characteristics of the VLF noise in the cusp are directly connected with the parameters of the electron streams, i.e., measurements of VLF noise can be used for the diagnostics of the parameters of the solar-wind particles penetrating into the region of the daytime cusp. This is quite important, since the geometry and the state of the magnetosphere depend on the solar-wind parameters. A study of VLF noise can be carried out with the aid of a network of land-based stations without the use of outer-space apparatus.

To investigate the possibility of registering VLF radiation arriving from the daytime cusp, synchronous measurements were made, for the first time, of the characteristics of the VLF noise in the Antarctic on a mobile station that crossed several times the region of the cusp, and at two control stations, namely Mirnyĭ [at 77° geomagnetic latitude (GL)] and Vostok (the geomagnetic pole). These measurements revealed a zone of increased radiation in the region of the projection of the center of the polar cusp on the earth's surface (~79° GL in the case of weak magnetic activity). In the diurnal course of the VLF noise intensity (see the curve of Fig. 1) there were observed two maxima: the first at approximately 12:00 local magnetic time (LMT), and the second near 18:00 LMT. In addition to this curve, Fig. 1 shows the dependence of the probability of splitting out of electrons with energies up to 0.7 keV on the geomagnetic latitude and on the time of the day, plotted in accordance from the measurement results of the OGO-4 satellite.[4] The agreement, in time, between the bursts of VLF radiation and the maxima of the probability of the appearance of soft electrons indicates that the streams of the electrons in the daytime cusp generate the VLF oscillations that are subsequently recorded on earth.

A spectral analysis of the signals registered simultaneously in the zone of increased radiation (~79° GL) and outside this zone (in Mirnyĭ, ~77° GL), shows that their spectra differ qualitatively, namely, the increased-radiation zone contains a high-frequency component of noise from 5 kHz upward. This frequency (5 kHz) coincides with the extreme frequency of the lower hybrid resonance (LHR)[2)] $\omega_{L_i}(1+\omega_{L_e}^2/\Omega_e^2)^{-1/2}$ at an altitude on the order of 1000 km of the polar ionosphere.

The foregoing experimental facts allow us to conclude that the electron streams in the region of the polar cusp excite oscillations at the LHR frequencies. Part of the energy of these oscillations, converted into whistlers by the density inhomogeneities of the ionosphere, is registered by the land-based stations in the form of VLF noise. The spectral intensity distribution and the level of the VLF noise are determined by nonlinear processes that limit the exponential growth of the wave generated by the beam of waves, and by the same token saturate the instability.

We have developed a nonlinear theory for the saturation of LHR waves excited by an electron beam, and have regarded as the stabilizing effect the principal nonlinear

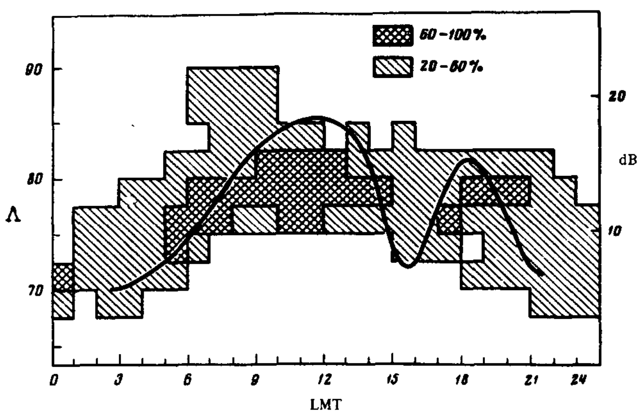

FIG. 1. Variation of the intensity of the VLF noise (in decibels) as a function of local magnetic time (LMT) (solid curve) at 79° geomagnetic latitude. Distribution of the probability of the spilling out of soft electrons as a function of the geomagnetic latitude Λ and the LMT (according to the data of the OGO-4 satellite[4]).

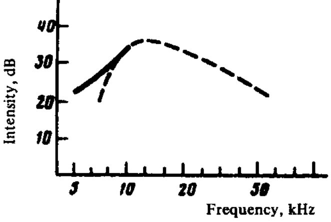

FIG. 2. Spectral distribution of the intensity of the VLF noise measured at 79° geomagnetic latitude (solid curve). The dashed curve shows the distribution calculated from formula (1) at $\omega_{L_e}/2\pi = 1$ MHz and $p = 5.4$.

process, namely induced scattering of the LHR oscillations by the electrons and ions of the ionospheric plasma (cf.[5]). The results of the theory and their comparison with the data obtained by the satellites Injun-5[6] and ISIS-1[7] are given in[8]. We emphasize that good agreement was obtained both with respect to the spectral composition and with respect to the total intensity of the VLF noise measured in[6,7]. The new data described above, obtained with land-based apparatus in the Antarctic, can also be interpreted with the aid of the theory of turbulence of LHR waves. Thus, according to the theory, the quasistationary LHR-wave spectral energy distribution $S(\omega)$ is determined by the excess $p = u_b/u_{\rm thr}$ of the beam velocity u_b over the instability-excitation threshold $u_{\rm thr} = 1.14\, r_{D_b}(\omega_{L_e}\nu_e)^{1/2}$, and is given by the formula (see[8])

$$S(\omega) \sim \left(\frac{\omega_{L_e}}{\omega}\right)\left(\frac{\omega}{\omega_{L_e}} - 1 - p^2 \frac{\omega}{\omega_{L_e}} \ln \frac{\omega}{\omega_{L_e}}\right), \qquad \omega_1 < \omega < \omega_{L_e},$$

where the lower limit of the spectrum is given by

$$\omega_1 = \omega_{L_e}[1 + p^2 \ln \omega_{L_e}/\omega_1]^{-1}.$$

The calculated spectral distribution $S(\omega)$ is shown by the dashed curve of Fig. 2. It is seen from this figure that in the range up to 10 kHz the experimentally observed growth (solid curve) of the VLF noise intensity corresponds to the growth of the spectral intensity (1) of the LHR waves. In the frequency region from 8 to 10 kHz, the experimental and theoretical noise intensities are in agreement. For a more complete comparison of the developed theory[8] with experiment, it is desirable to increase the upper frequency limit of the registered VLF radiation in the region of the daytime cusp. In addition, it is desirable to study the time variation of the intensity of the VLF radiation, inasmuch as in accord with the theoretical representations the relaxation of the noise to the distribution (1) oscillates in time with a frequency $0.3\nu_e u_b v_{T_e}^{-1}(p^2 \exp[p^{-2} - 1] - 1)$ (v_{T_e} is the thermal velocity of the electrons of the ionosphere plasma). Under the conditions of the upper polar ionosphere, this frequency amounts to ~100 Hz.

We emphasize that measurement of the temporal and spectral characteristics of the VLF noise on earth yields sufficient complete information on the parameters of the beam of the spilled-out electrons. Thus, measurement of the ratio of the frequency of the relaxation oscillations of the noise to their damping decrement, the theoretical value of which is $\sim 0.3 u_b/v_{T_e}$, makes it possible to calculate the beam-electron velocity u_b (we assume that we know the temperature of the ionospheric-plasma electrons). In addition, from the frequency corresponding to the maximum intensity of VLF noise we can obtain the value of $p = u_b/u_{\rm thr}$, and from the known u_b also the threshold beam velocity needed for the buildup of the instability, and by the same token the concentration of the spilling-out electrons.

Thus, if further observations confirm the correctness of the proposed theory, then a new possibility is uncovered, in principle, of measuring the parameters of electron beams in the polar regions by registering the VLF noise in a network of continuously operating land-based stations that cross the region of the cusp. These stations could also follow the space-time displacements of the cusp due to the dynamics of the geometry of the magnetosphere.

1)The daytime cusp is a narrow region in the earth's polar magnetosphere, where the magnetic field is weaker; it serves as the separation boundary between the closed force lines of the daytime magnetic field and the open force lines that go off into the tail of the magnetosphere.[1]

2)We use the following notation: Ω_e is the electron cyclotron frequency, ω_{L_e} and ω_{L_i} are the electron and ion Langmuir frequencies respectively, ν_e is the collision frequency of the plasma electrons with the ions and neutrals, and r_{D_b} is the Debye radius of the beam electrons.

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