Observation of particle precipitation from the ring-current zone stimulated by a powerful ground-based VLF transmitter

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Fluxes of precipitating particles, initiated by VLF radiation from a ground-based transmitter ($L = 4.0, f = 19.1$ kHz), are observed.

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In November–December 1981, we performed an experiment on the observation of stimulated precipitation of low-energy electrons from the ring-current zone ($L = 3$–5). This experiment was performed within the framework of the Soviet-French project "ARKAD-3", and the waves and particles were observed from the Aureole-3 satellite.[1] A Soviet ground-based subauroral VLF transmitter ($L_t = 4.0$, $f = 19.1$ kHz) was used.[2] Pulses with a duration of 8 s and a repetition period of 16 s were used. In designing the experiment, we expected unchanneled propagation of VLF waves in the magnetosphere ($\psi \neq 0$) and efficient generation of turbulence of plasma electrons in the region of absorption of VLF waves ($\omega \sim \omega_{\rm Be} \cos\psi, \omega_{\rm Be}$ is the gyrofrequency of electrons near the equatorial plane of the magnetosphere), where the starting whistler-type wave transforms into the electrostatic electronic cyclotron mode.[3] The idea of the experiment is analogous to the idea of cyclotron turbulent heating in a laboratory plasma.[4] Accordingly, we chose $\omega \gtrsim \omega_{\rm Be}$. Estimates show that in this case electrons with energies $E < 3$ keV are subjected to the greatest modifications.

In this paper, we shall restrict our attention to the results of detection of fluxes of

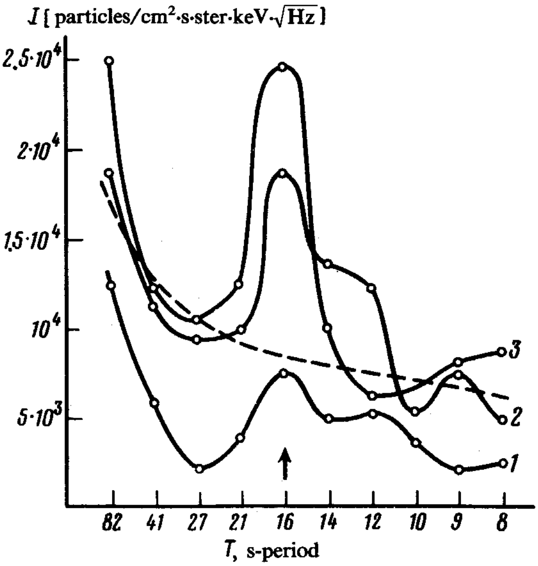

FIG. 1. Temporal spectra of electron fluxes, recorded on December 13, 1981 during revolution No. 1088 near the transmitter. Curve 1 corresponds to measurements at $L_{av} \approx 2.72$, 2—$L_{av} \approx 2.85$, 3—$L_{av} \approx 2.95$.

electrons and protons with energies $E = 0.75 \pm 0.15$ keV and $E = 1.8 \pm 0.25$ keV, obtained with the help of the RIP-2802 device.[1] Particles with pitch angles $40 \pm 10°$ were measured. Seventeen runs were made in the region above the VLF transmitter during the morning hours. The stimulated precipitation of electrons and protons was observed in seven runs. To separate the component related to the operation of the VLF transmitter, and therefore varying with the repetition period of its transmission, from the background formed by the natural particle fluxes, we calculated the temporal spectra of the particle intensity. Several such spectra of electrons for the run on December 13, 1981 (revolution 1088, altitude 1600 km, MLT$\sim 7^h$, $E = 1.8$ keV) are shown in Fig. 1. The peak corresponding to a period of 16 s, whose amplitude varies from one spectrum to another, is clearly visible. For comparison, the typical temporal electron spectrum for the same region during periods when the VLF transmitter did not operate (dashed curve) is also shown here. Figure 2 shows the behavior of the intensity of the stimulated component of the electron flux (with period 16 s) as a function of the L parameter of the observations for two revolutions and different energies. The peak in the intensity for $E = 1.8$ keV occurs at $L_m = 2.6$–2.8 (revolution 1088), while for $E = 0.75$ keV, it occurs at $L_m = 2.9$–3.0 (revolution 1193, altitude 1650 km, MLT$\sim 7^h\ 30'$). The stimulated precipitations reached magnitudes of $\sim 7 \times 10^4$ (cm^2·s·keV)$^{-1}$. If we make the usual assumption that the most intense interaction of the VLF wave with electrons occurs near the equatorial plane of the magnetosphere, then the values of E are resonant energies of electrons at the apogee of the lines of force with parameter L_m. It is easy to find the equatorial values of ω_{Be} and the value of the parameter $\kappa = \omega/\omega_{Be}$ from the values of L_m. It turns out that in both cases $\kappa > 0.5$ and, as is well known, the VLF wave cannot be channeled. We note that

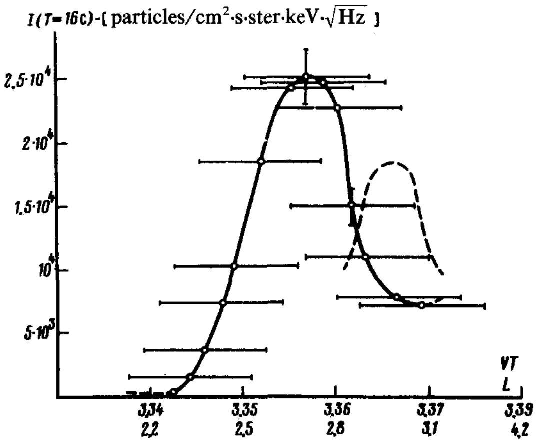

FIG. 2. Behavior of the 16-second component of the spectrum as a function of the time and position of the satellite. The continuous line shows the results of measurements of electron fluxes on December 13, 1981 during revolution No. 1088 ($K_p = 4-$). The dashed line denotes measurements of electron fluxes during revolution No. 1193 on December 21, 1981.

theoretical estimates[5,6] give magnitudes of fluxes of high-energy electrons (with energy $E = 2\text{–}40$ keV) $10^7\text{–}10^8$ $(\text{cm}^2\cdot\text{s}\cdot\text{keV})^{-1}$.

During May-November 1982, an experiment in which a S81-1 satellite and a NAA transmitter ($L = 3{,}2$; $\omega = 17.8$ kHz) were used, was performed in the USA.[7] The characteristic electron energies were $E = 17\text{–}30$ keV, and the maximum value of the integrated flux, ($E > 6$ keV) 10^3 $(\text{cm}^2\cdot\text{s})^{-1}$, was recorded at the latitudes of the inner radiation zone ($L = 2.1\text{–}2.3$).

For non-field-aligned propagation, it is necessary to take into account the possibility of both cyclotron and Čerenkov resonances. Simple calculations based on different models of the electron density distribution in a warm plasma, including the model proposed in Ref. 7, lead to the conclusion that the conditions for the cyclotron resonance cannot be satisfied for our values of E and L_m. At the same time, these values are consistent with the conditions of the Čerenkov resonance for electrons with the additional condition $\psi \cong 25\text{–}45°$. We shall discuss the results of the numerical calculations of the trajectory characteristics of VLF waves using the technique presented in Ref. 8 as well as the particle fluxes in a subsequent paper, but it should be noted that the values of ψ indicated are the usual values for such calculations. The displacement of the electron precipitation zone toward small-L shells relative to the transmitter, which was noted both in our experiment and in Ref. 7, can be explained in a logical way.

Thus, as far as we know, artificial precipitation of low-energy electrons and protons from the ring-current zone, initiated by powerful VLF radiation, has been observed for the first time. The precipitation is apparently due to quasilinear interaction of these particles with the VLF wave propagating in a nonfield-aligned manner at the Čerenkov resonance.

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