Precipitation of protons from the earth's magnetosphere stimulated by artificial low-frequency radiation

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The results of an experiment on the action of low-frequency radiation on the magnetospheric plasma are presented. Such action stimulates precipitation of protons. A preliminary interpretation of the data is given.

Over the course of many years, different groups in our country and abroad attempted to observe directly the precipitation of particles from the earth's magnetosphere stimulated by low-frequency waves injected by ground-based transmitters. Since it is energetically easier to change the electron distribution function than the distribution function of heavy ions, considerable efforts were directed toward observing stimulated precipitation (SP) of electrons. Such precipitation was recently observed.[1,2] However, in our experiment, we observed not only the expected SP of electrons but also SP of high-energy protons. This paper concerns this phenomenon.

The experiment and the apparatus for analyzing electron precipitation are described in Ref. 1. The fluxes of precipitating protons were observed with the help of SÉS-14 apparatus placed on board the Aureole-3 satellite. This apparatus measures proton fluxes in the energy range 66–216 keV, separated into four differential channels.[3]

Figure 1 shows the intensities of protons with energies 91–122 keV (RD2) and 159–216 keV (RD4) on the ascending revolution at altitutdes of 1500–2000 km in the after-midnight sector. The observations were performed on December 22, 1981, under quiet geomagnetic conditions $K_p = 0+$. To separate out SP of protons from the background formed by their intensity fluctuations, the measured quantitites were

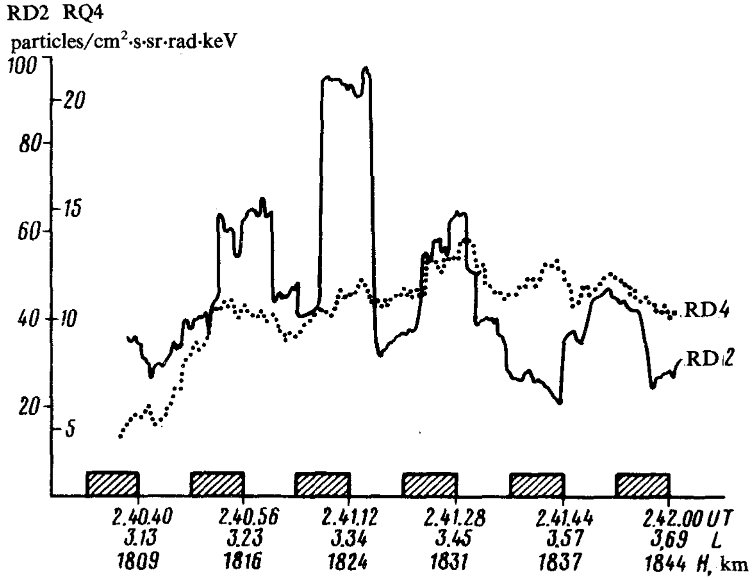

FIG. 1. Flux intensities of 91- to 122-keV protons (curve RD2) and 159- to 216-keV protons (curve RD4), recorded on December 22, 1981 on the Aureole-3 satellite during quiet geomagnetic conditions ($K_p = 0+$).

smoothed with an 8-sec moving average. A chronogram of the transmitter operation is shown at the bottom of the figure (transmission for 8 seconds, pause for 8 seconds). Periodic bursts of intense protons, associated with transmissions from the transmitter, are clearly evident on the curve RD2 in Fig. 1. Stimulated precipitation of protons with energies 159–216 keV (RD4) are less appreciable than for RD2, but, for example, a burst correlated with the transmission is clearly evident beginning at 2.41.24 UT.

We call attention to the following.

a) The region of SP of energetic protons is located on L shells 3.2–3.5, and is displaced toward the equator from the transmitter ($L = 4$);

b) SP of high-energy protons was observed for ~50 s, i.e., the latitude extent of the region of SP is 350–400 km, which is comparable to the diameter of the region illuminated in the ionosphere by the transmitter;

c) bursts of SP high-energy photons arrive at the satellite with a delay of 3–4 s relative to the transmissions of the transmitter. These delays are apparently explained by the time required for the waves to propagate to the region of interaction and by the transit time of protons from the region of interaction to the satellite.

To compare the SP of high-energy protons and electrons, Fig. 2 shows the results of observations performed on December 13, 1981, with moderate geomagnetic activity $K_p = 3+$. The displacement of the zone of SP of particles toward lower L shells and the increase in the intensity of precipitation in this case (compared with Fig. 1) is apparently related to the well-known effect of excitation of protons in the ring-current belt during magnetospheric substorms. It can be said that the characteristics of the region of SP depend strongly on the geomagnetic environment. We note that regions

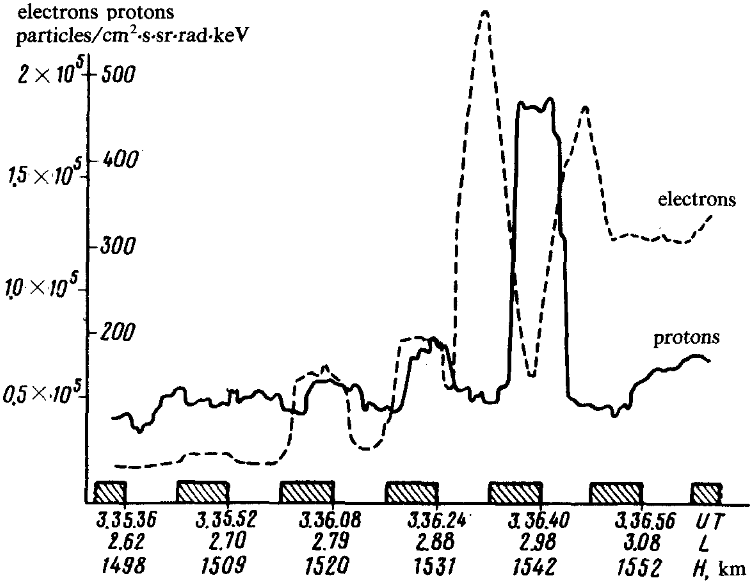

FIG. 2. Flux intensities of 91- to 122-keV protons (solid curve) and fluxes of electrons with average energy 1.85 keV (dashed curve), recorded on December 13, 1981.

of SP for 1.85-keV electrons and for 91- to 122-keV protons do not coincide, although the dimensions of these regions are close. Analogous appearance of SP of protons and electrons toward the equator from the transmitter was also recorded on some other revolutions passing near its meridian.

In theoretical papers concerning the mechanism of the interaction of intense VLF waves with high-energy particles in the magnetosphere, as a rule, only the cyclotron interaction of waves with high-energy electrons was examined and field-aligned propagation of waves ($\psi = 0$, ψ is the angle between the wave vector **k** and the direction of the earth's magnetic field) was assumed.[4,5] Estimates using these assumptions lead to fluxes of precipitating particles greatly exceeding the measured fluxes[1,2] and they do not correspond to present models of the propagation of VLF waves in the magnetosphere,[6] according to which the wave is not field-aligned ($\psi \neq 0$).

For $\psi \neq 0$, in addition to the cyclotron interaction with electrons $v_{\|,e} = (\omega_{Be} - \omega)/k_{\|}$, where $v_{\|,e}$ is the field-aligned velocity of electrons, $\omega_{Be} = eH/me$ is the gyrofrequency of electrons, ω is the frequency of the transmitter, and $k_{\|}$ is the component of the wave vector along the magnetic field), it is also necessary to take into account the Cerenkov interaction of the VLF wave with electrons and protons $(v_{\|,e,i} = \omega)\, k_{\|}$, where $v_{\|,e,i}$ is the field-aligned velocity of electrons or protons). The most intense interaction, which depends on the angle ψ and which leads to pitch-angle diffusion of particles in the loss cone, occurs near the equatorial plane of the magnetosphere. Figure 3 shows the computed values of the equatorial resonance energies for Cerenkov interaction (solid lines) and cyclotron interaction (hatched area) with non-field-aligned propagation of the wave and different models of the plasma density,

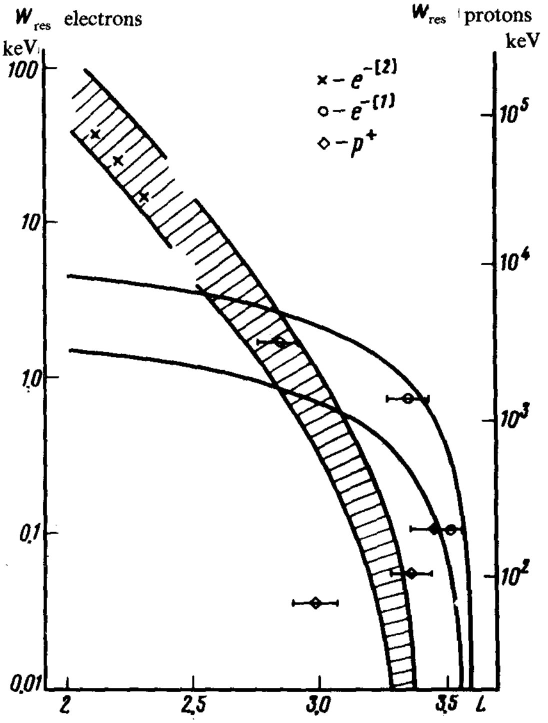

FIG. 3. Comparison of theoretical and experimental particle energies for cyclotron and Cerenkov interaction mechanisms.

together with the experimental values of the L parameter for maximum precipitation of electrons (○) and protons (◇) corresponding to the energy of the ring current. This figure also shows the data on the localization of the region of SP for high-energy electrons from the region of the internal radiation belt in the American experiment with VLF transmitters (×) from Ref. 2. It is evident that in our experiment the observation of SP of high-energy particles from the ring current ($L \simeq 2.5$–3.5) is related primarily to the Cerenkov resonance. The precipitating flux of particles in each field tube is calculated by integrating the perturbed particle distribution function within the loss cone along the length and cross section of the resonance region. The calculated values are in satisfactory agreement with the experimental data. Detailed comparisons of the computed and measured particle fluxes accompanying SP will be published separately.

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