Pulsed precipitation of protons with $E_p > 500$ MeV from the $L = 2$ shell during a magnetic storm

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Experimental results revealing a pulsed precipitation of protons with energies of 100–500 MeV from the inner Van Allen belt during a magnetic storm are analyzed. The pulses had a length $\lesssim 5$ s. This precipitation is discussed in connection with time-varying processes in the midnight magnetosphere.

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On a high-altitude balloon on August 20, 1979, the Nataliya-1 γ telescope detected periodic changes in the flux densities of secondary cosmic particles: of protons with $E_p > 500$ MeV, and of electrons with $E_e > 20$ MeV. The period of these fluctuations was 10.4 min, and the amplitude of the periodic component was $\gtrsim 20\%$ of the constant flux density.[1] These periodic fluctuations were detected during a magnetic disturbance, and we believe that they can be attributed to an interaction of precipitating particles with ELF radiation and microfluctuations of the nighttime magnetosphere.[2] Quasiperiodic fluctuations in the flux density of secondary cosmic particles have been observed[3,4] in a magnetically quiet environment, and the appearance of such fluctuations can be attributed to internal gravity waves.[5]

During the same flight we observed short bursts ($\lesssim 5$ s) in the intensity of charged particles (Fig. 1). These bursts were detected most frequently near the midnight meridian, i.e., roughly from 23.00 LT to 01.30 LT (Fig. 2).

The ratio of the intensity in a burst to the average intensity varies from 3–4 for the $I1$ channel to 13–14 for the $I3$ channel of the rate meter. The rate-meter channels $I1$, $I2$, $I3$, and $I4$ correspond to the detection of the following particles: For $I1$, electrons with $E_e > 20$ MeV and protons with $E_p > 100$ MeV in the telescope aperture; for $I2$, electrons with $E_e > 20$ MeV and protons with $E_p > 500$ MeV in the telescope aperture, directed from the upper hemisphere; for $I3$, electrons with $E_e > 1.5$ MeV and protons with $E_p > 12$ MeV, moving in all directions; and for $I4$, the γ-ray count ("masters") over a time ~ 2 s after the operation of the γ telescope.

The height of a burst thus increases with decreasing energy of the detected particles.

By comparing the heights of the bursts in channels $I1$, $I2$, and $I4$, we can draw conclusions about the species of the particles forming the bursts in our case. Specifically, they are quite probably protons with $E_p > 100$ or even > 500 MeV at an intensity $\sim 10^5$ particles/(m$^2 \cdot$ s) during a burst. The additional flux of protons due to the bursts, averaged over the time (~ 2 h) corresponding to the region in which the bursts were detected most frequently, is 60–80% of the unperturbed proton flux density at the

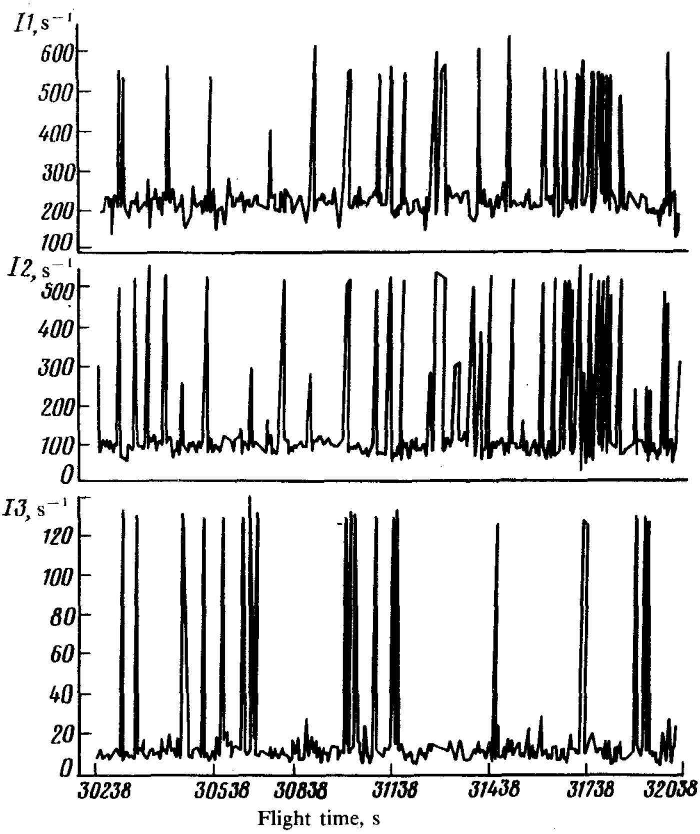

FIG. 1. Intensity bursts in the rate-meter channels *I* 1, *I* 2, and *I* 3.

geomagnetic latitude with a cutoff rigidity[6,7] of 3.5 GV. The contribution of electrons with $E_e > 20$ MeV to the count rate of the *I* 1 and *I* 2 channels is $\sim 10\%$, and even if we assume the opposite—that the burst is formed by electrons—then there should be a

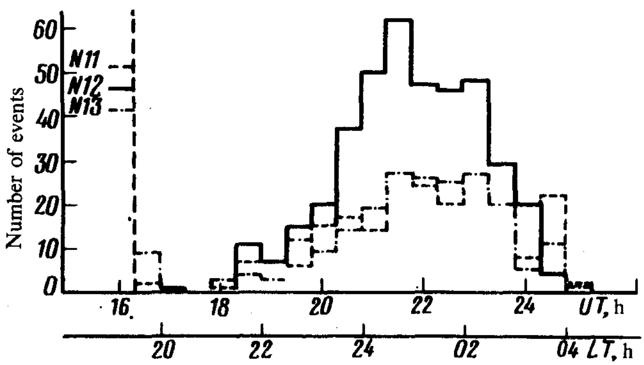

FIG. 2. Time evolution of the number of bursts in the *I* 1, *I* 2, and *I* 3 channels (LT is the local time, and UT is the universal time).

burst in channel $I4$ (the γ channel) with a magnitude $\sim 100\ \gamma/\mathrm{s}$, but this burst was not observed. We thus conclude that the particles causing the intensity burst in the $I1$ and $I2$ channels are protons with $E_p > 100$ MeV and $E_p > 500$ MeV, respectively. The duration of these bursts and their localization near the midnight meridian suggest that the bursts are associated with time-dependent processes in the tail of the magnetosphere. The perturbing process may be the acceleration of particles at the magnetospheric tail to energies ~ 100 keV upon the reconnection of magnetic lines of force during a magnetic storm. Beams of accelerated particles—electrons and protons—are captured to closed magnetic shells as they move into the magnetosphere.[8,9] Events unavoidably lead to conditions such that packets of VLF or ELF waves are excited, depending on the plasma density, the magnetic field, and the pitch-angle distribution of the accelerated particles. Events of this type have been detected repeatedly during magnetic storms.[10,11] Packets of ELF waves, if sufficiently localized in space, may be dissipated in an interaction with fast protons from the inner Van Allen belt at the $L = 2$ shell. In particular, one mechanism for the energy dissipation of a wave packet is the scattering of charged particles through pitch angle by waves with the frequencies ω corresponding to the Doppler-shifted cyclotron resonance,[12] $\omega - kv_{\parallel} = n\Omega_p$, where Ω_p is the proton gyrofrequency; $n = 0,1,2,...$ is the order of the resonance; k is the wave number; and $v_{\parallel}$ is the longitudinal component of the particle which is interacting resonantly with the wave. The precipitated proton fluxes may be put in phase in a certain way and may form packets of particles: bursts of duration corresponding to the characteristic time for the dissipation of the resonant ELF waves or the minimum proton lifetime on the shell. Packets of ELF waves with a duration of 3–5 s have been detected by satellite measurements[13,14] on the $L = 2$–4 shells during magnetic disturbances.

The proton diffusion time is determined by the diffusion coefficient D, which depends in turn on the amplitude of the ELF wave. We can estimate the amplitude of the ELF waves of the packet from[12] $b = \gamma_0 D B_0/\Omega_p F$, where γ_0 is the Lorentz factor of the particles, Ω_p is the gyrofrequency, and F is an anisotropy factor. Assuming that D corresponds to the case of pronounced diffusion, we find that b should be greater than $30\ \gamma$.

In the rapid-diffusion limit, the flux density of precipitated particles (J_{prec}) is approximately equal to the flux density of captured particles (J_{cap}); i.e., $J_{\mathrm{prec}}/J_{\mathrm{cap}} \sim 1$. If $J_{\mathrm{prec}}(E_p > 500\ \mathrm{MeV}) \cong 8 \times 10^4$ particles/$(\mathrm{m}^2 \cdot \mathrm{s})$, then the captured flux is also $J_{\mathrm{cap}}(E_p > 500\ \mathrm{MeV}) \sim 10^5$ particles/$(\mathrm{m}^2 \cdot \mathrm{s})$. Our estimates agree satisfactorily with the flux densities of captured protons on the $L = 2$ shell found from measurements taken on space vehicles.[15]

In explaining the pulsed precipitation of protons with $E_p > 100$–500 MeV we must also consider a possible effect of pulses of the magnetospheric electric field. A parallel electric field can increase the flux of precipitated particles by an order of magnitude at a moderate amplitude of the ELF waves.[16] Electric-field pulses are characteristic of magnetic-storm conditions, and according to the GEOS 2 data[17] they appear most frequently in the nighttime hemisphere. The average height of these bursts is ~ 10 mV/m. The motion of the plasma in association with the electric-field pulses is also accompanied by the appearance of VLF emission in the frequency interval 0.1–50 kHz, with an increase in the power toward lower frequencies, and by bursts of ELF emission. This circumstance could explain the observed fluxes of precipitated particles during the bursts.

In summary, we may say that our observations have revealed the existence of quasiperiodic precipitations of electrons with 20 MeV and of protons with 100–500 MeV (Ref. 1) in a magnetically disturbed environment. Our observations have also revealed precipitations in short bursts, lasting $\lesssim 5$ s, from the $L = 2$ shell near the midnight meridian. The appearance of these bursts is associated with time-varying processes in the magnetospheric tail, which sharply increase the intensity of ELF waves.

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