Mid-latitude precipitation of energetic protons due to a pulsed disturbance of the magnetosphere

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Observations of a pulsed precipitation of protons with $E_p \geq 12$, 100, and 350 MeV on a high-altitude balloon are discussed. The relationship between these precipitation events and a pulsed disturbance of the magnetosphere is analyzed, as are possible precipitation mechanisms.

The detection of γ rays with $E_\gamma \geqslant 5$ MeV during a flight of the Nataliya-1 γ telescope on a high-altitude balloon on August 23, 1979, at a height of 30.0–33.5 km, at 46° N, and at a geomagnetic cutoff rigidity of 3.5 GV was accompanied by the detection, in three channels of digital ratemeters, of fluxes of the charged component of secondary cosmic radiation. The γ telescope is described in detail in Ref. 1. The channels of the ratemeters for the charged-particle fluxes in the Nataliya-1 can determine the total number of protons and electrons with the following energies in the telescope:

channel 1 ($J1$) — protons with $E_p \geqslant 100$ MeV, electrons with $E_e \geqslant 10$ MeV,

channel 2 ($J2$) — protons with $E_p \geqslant 350$ MeV, electrons with $E_e \geqslant 15$ MeV,

channel 3 ($J3$) — protons with $E_p \geqslant 12$ MeV, electrons with $E_e \geqslant 1.5$ MeV.

Service information as well as scientific information was obtained on the flight: specifically, the air pressure at the flight altitude, the temperature inside the container, the voltages from the power supplies, etc.

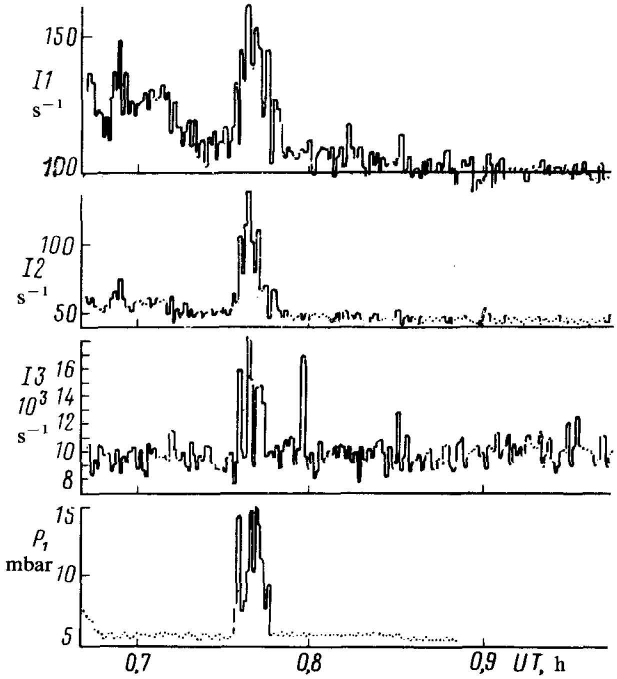

FIG. 1. Time record of the readings of ratemeters $J1$, $J2$, and $J3$ (averaged over 1-min intervals) and of the pressure at the flight altitude (P_1).

The flight occurred in a magnetically quiet environment corresponding to a Q day; the value of ΣK for Moscow was[2] 19. Despite this quiet environment, the γ telescope at the maximum heights of the ascent detected a substantial increase in the charged-particle count rate (averaged over 1 min); this increase was many standard deviations above the average value of the flux in adjacent time intervals (Fig. 1). The most significant deviation in the charged-particle flux was also accompanied by changes in the readings of the pressure gauge (shown in the same figure). This event began at 7 h 36 min. No systematic changes in the characteristics of the instrument were noted. The values of the service parameters other than the pressure of the surrounding air did not go outside their working ranges. An explanation of the increase in the detected fluxes on the basis of a change in the height of the balloon must be rejected, since the corresponding vertical velocity of the balloon would have to have been $\geqslant 4$ km/min, and such a velocity could not have failed to rupture the skin of the balloon. A finer temporal analysis reveals a complex structure in the time evolution of the intensity of the radiation detected (Fig. 2). The surges in the charged-particle fluxes last 5–20 s each, and the rate at which they appear increases to a maximum in 2–3 min and then decays to zero with a time constant ~ 5 min. Changes also occur in the amplitudes of the surges over time. Relatively high frequencies of the surges are associated with relatively large surge amplitudes, particularly for the high-energy particle fluxes (channel 2 of the ratemeters).

The duration of these increases in the fluxes of precipitated particles reaches 15-16 min, as can be seen in Fig. 2 for the most prominent of these increases. The pressure increase, which coincides in time with an increase in the fluxes of precipitated charged

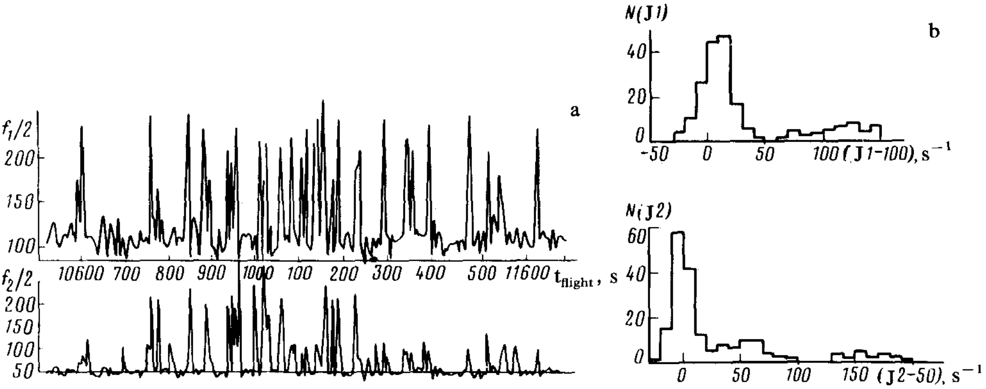

FIG. 2. a—Count rate in ratemeter channels $J1$ and $J2$ versus the flight time for the interval 10 500–11 700 s; b—distribution in count rate of the channels of ratemeters $J1$ and $J2$.

particles, can be attributed to a heating of the atmosphere (its upper layers) by these precipitated particles. The particles precipitated in the surges are apparently protons, since they do not increase the count rate of γ rays with energies $\geqslant 5$ MeV. For this case we can find a rough estimate of the spectral index for the additional flux of these protons associated with a surge, working from the extent to which the readings of ratemeters $J1$, $J2$, and $J3$ increase. This estimate yields a proton spectral index of 2.5 over the energy range 12–350 MeV.

We assume that the pressure increase corresponds to an increase in the energy of the thermal motion of the air atoms, i.e., that an increase in the pressure from 6 to 15 mbar ($\Delta P = 9$ mbar) corresponds to an increase in the energy of the atoms from 0.02 to 0.05 eV. This energy could be introduced at the balloon height (32 km) by a flux of precipitated particles, and the corresponding energy density would have to be $\geqslant 10^{15}$ eV/cm^3. The energy flux of the precipitated protons with $E_p \geqslant 12$ MeV corresponds to 3×10^{-4} erg/cm^2 at $H = 32$ km with a spectral index of 2.5.

Under the assumption that the spectral index of the precipitated protons does not flatten out beyond -2 at energies up to ~ 10 keV, we conclude that the total energy density introduced by the precipitated particles is $\geqslant 3 \times 10^{17}$ eV/cm^3, or two orders of magnitude greater than the energy input required to heat the upper layers of the atmosphere. Here we have ignored the thermal conductivity of the medium and the radiative energy loss. The observed increase in the fluxes of precipitated particles must have been accompanied by an increase in the ionization level in all layers of the ionosphere. In fact, such changes were observed at ionospheric stations at Moscow, Kiev, Gor'kii, Irkutsk, Novo-Kazalinsk, and Karaganda.

Analysis of the magnetograms from the high- and mid-latitude stations reveals some structural features that coincide in time with the surges in precipitation (Fig. 3). These structural features can be seen particularly well on a magnetogram from Heiss Island. Figure 1 shows the precipitations corresponding to pulses in the H component of the magnetogram from Heiss Island at 06 h 50 min UT and 7 h 36 min UT. We see that the pulse at 7 h 36 min is considerably larger than the preceding pulses at 6 h 30 min and 6 h 50 min, and it is also quite visible on the magnetograms from the Moscow,

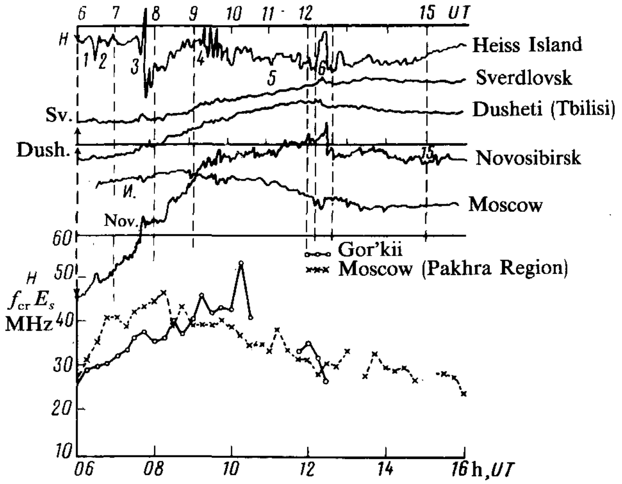

FIG. 3. Magnetograms from stations at Heiss Island, Sverdlovsk, Moscow, Dusheti, and Novosibirsk for the period 06.00–16.00 UT on August 23, 1979; time record of $f_{cr}E_s$ according to data from ionospheric stations at Gor'kii and Moscow (Pakhra Region).

Sverdlovsk, and Novosibirsk stations (Fig. 3). These times of the pulsed changes in the magnetic field and the increases that we detected in the fluxes of precipitated particles correspond reasonably well with structural features on the time record of the critical frequency of the sporadic layer (Fig. 3), according to data from the ionospheric station at Gor'kii.

Data from 18-NM-64 neutron monitors at Moscow, Sverdlovsk, Apatity, and Tbilisi also reveal increases of 1.2–1.5% in the cosmic-ray fluxes.[2] In other words, an increase in the fluxes of the hard component of the cosmic rays is observed in a longitude sector overlapping the region of observation of our own apparatus. Pulsed changes in the geomagnetic field of this type (Si) reflect a sudden contraction or expansion of the magnetopause by inhomogeneities of the solar wind.[3] Such pulses are particularly noticeable in a period in which the magnetosphere and the solar wind are becoming quieter; our experiment occurred during such a period. The transfer of energy of the pulse from the solar wind to the magnetosphere is not yet understood. The pulses are accompanied by pulsations with periods which depend on the observation latitude.[4] The event is characterized by a high propagation velocity of the pulsed signal in the magnetosphere,[3] and, as follows from the results of the present experiments, it is accompanied by an increase in the fluxes of precipitated protons.

An increase in the flux of precipitated protons over such a short time cannot be explained by the transport theory of Ref. 5. The pulsed nature of the particle precipitation is apparently evidence of some pulsed acceleration mechanism inside the magnetosphere on a shell with $L \sim 2$. This mechanism accelerates the particles to energies of at least 50–100 keV. Actually, we have two alternatives here: Either the fast protons observed during the surges are the accelerated particles themselves, or they are protons of the trapped radiation which are ejected from a shell with $L \simeq 2$ through resonant pitch-angle scattering. We have called upon this latter mechanism to explain some similar surges observed during the recovery phase of a moderate magnetic storm near the midnight meridian.[6]

The particles accelerated to 50–100 keV are then the source of ELF wave packets, which scatter the fastest protons of the trapped radiation. Several mechanisms for the acceleration of particles to these energies, 50–100 keV, are known; the mechanism which is being discussed most widely is the "double-layer mechanism."[7,8]

On the basis of the data available at this point we cannot reject the hypothesis that some magnetospheric mechanism may be operating to directly accelerate protons to energies ~400 MeV.

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