Observation of evidence of reconnection and plasma acceleration at a distance of about 5×10^5 km in the tail of the earth's magnetosphere

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The distributions of beams of fast particles in the high-latitude ionosphere have been studied on the basis of measurements taken on the satellite Oreol-Z. The generation of a beam is associated with reconnection in the remote regions of the magnetospheric tail. The subsequent drift of the accelerated plasma in the transverse electric field gives rise to structures of precipitating particles with an energy dispersion.

The reconnection of magnetic fields which results in a conversion of magnetic energy into the thermal and kinetic energy of a plasma is responsible for many important phenomena that occur at the sun (flares), in plasmas in the laboratory (the disruptive instability in tokamaks), and in the earth's magnetosphere. An important question for magnetospheric physics is the mechanism by which the plasma of the solar wind is heated and accelerated during the recovery phase of a substorm, in which particles that are convecting out of the plasma envelope begin to replenish the loss of the emptied plasma sheet. The possibility that this phenomenon is of a permanent nature—replenishing the plasma sheet at other times also, at a greater or lesser intensity—is not ruled out. According to the present understanding, the source of the particle production and acceleration lies at a distance on the order of 5×10^5 km [or $(70–100)R_e$, where R_e is the earth's radius], depending on the conditions in the magnetosphere. It is believed to correspond to a region of a quasisteady reconnection of the geomagnetic and interplanetary magnetic fields (see Refs. 1–3 and the bibliographies there). This region is considerably more distant in the geomagnetic tail than the "near" reconnection zone, which arises in the main phase of a magnetospheric substorm.[4]

Simple calculations of the trajectories of protons[5] show that the pitch-angle distribution of the particles in the remote tail consists of two components. The larger component contains particles with pitch angles $>0.2°$, which are reflected from the magnetic mirrors at heights above $2R_e$ and then move back toward the source. The other component consists of particles with pitch angles $\leqslant 0.2°$, which may precipitate into the auroral ionosphere. The remote reconnection zone projects onto the earth's ionosphere at the highest-latitude rim of the auroral zone, in which the characteristics of the precipitated particles accumulate information on the physical processes that occur in the plasma reservoir of the tail. Studying the structure of this part of the auroral zone at comparatively small heights was the purpose of the study which we are reporting here.

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Measurements were taken on the satellite Oreol-Z (the joint Soviet-French project ARKAD-Z). This satellite was launched on 21 September 1981; the apogee was $H_\alpha = 2000$ km, the perigee was $H_p = 410$ km, and the inclination of the orbit with respect to the equatorial plane was $i = 82.5°$. Scientific apparatus carried on this satellite was used to measure the thermal and superthermal plasma, fast particles, VLF waves, magnetic and electric fields, and radiations during aurorae. The apparatus is described in detail in Ref. 6, where use was made of data from the ROBE instrument (measurements of protons and electrons in the range 0.2–21 keV) and the ION-1 and ION-2 instruments (measurements of the mass composition of the ions with atomic mass units in the range from 1 to 32 and with values $E/Q = 0.01$–5 keV/charge).

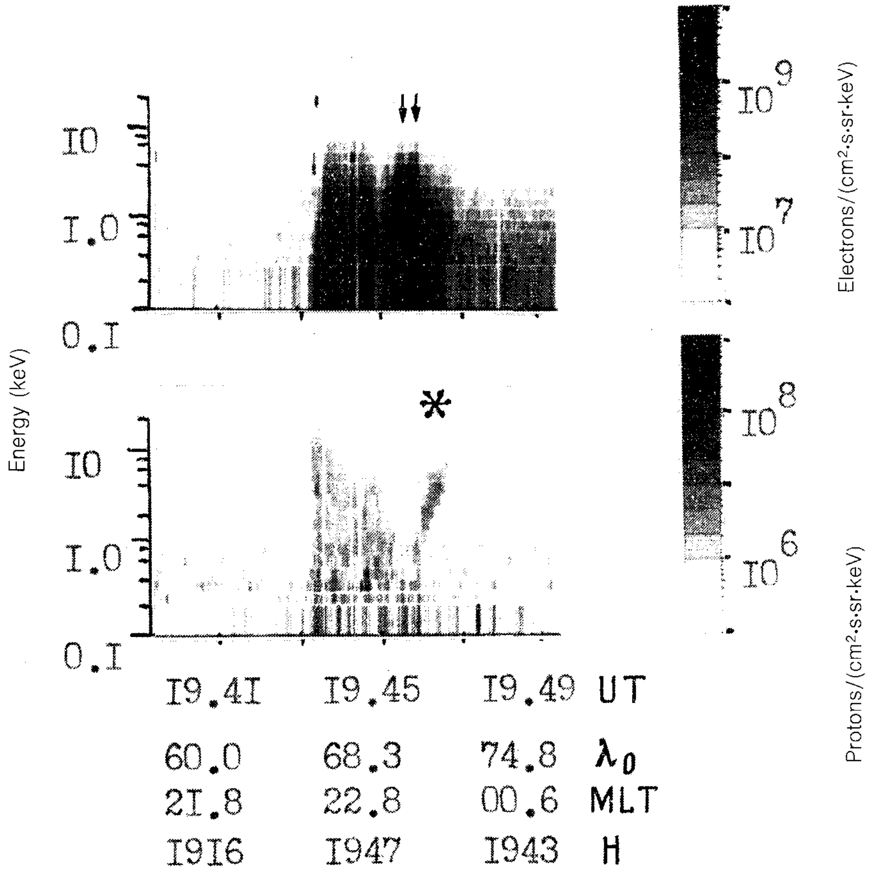

FIG. 1. Energy-time spectrogram of electrons (upper spectrogram) and ions (lower spectrogram) for orbit 5002 of the satellite Oreol-Z. The arrows show the inverted-V structures above the electron spectrogram. The asterisk above the ion spectrogram marks an auroral velocity dispersion structure.

In the course of this study, an examination was made of about 500 intersections of Oreol-Z with the auroral zone in the nighttime magnetosphere under various geomagnetic conditions. During 20 transits of the satellite, the characteristic dispersion band of particles precipitations was observed: ion energy versus invariant latitude (the lower spectrogram in Fig. 1). At the polar rim of the precipitation zone ($\lambda = 71.5°$) the maximum of the differential ion flux is at an energy E_p; with decreasing invariant latitude, the energy for the maximum of the ion flux decreases, reaching $E_p = 0.7$ keV at the latitude $\lambda = 69.7°$. Closer to the equator the average energy of the ions in the precipitations increases, presenting the classical picture of the acceleration of ions in the plasma sheet as the earth is approached as a result of betatron and Fermi mechanisms (Ref. 7, for example).

The following characteristic features can be seen in the observed auroral velocity dispersion structure:

1. It can be concluded from measurements of the ion mass composition (with the ION-1 and ION-2 instruments) that the ions observed in the structures are protons.

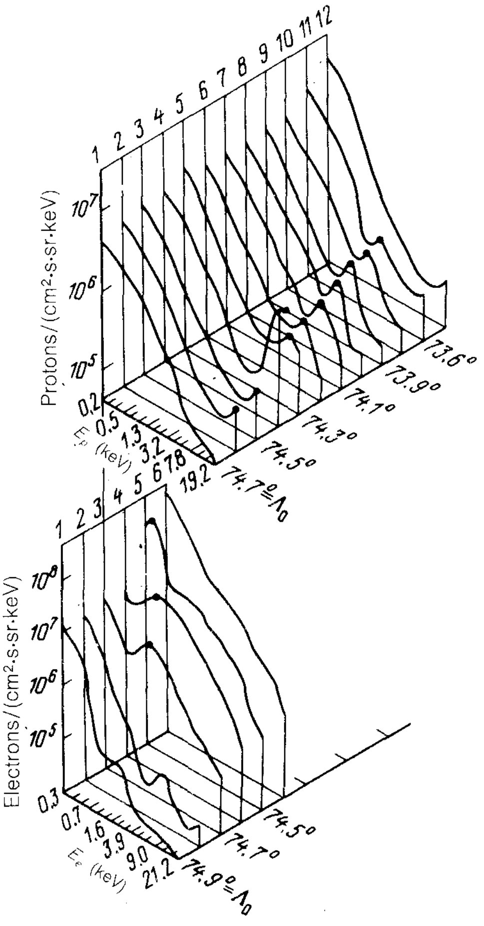

FIG. 2. Spectra of (a) protons and (b) electrons on orbit 2427 of the satellite Oreol-Z. In part a, the energy of the proton "peak" on spectra 1–3 lies outside the measurement range of the instrument; spectra 4–11 shows a pronounced auroral velocity-dispersion structure; spectrum 12 shows the background spectrum beyond the equatorial rim of the auroral velocity-dispersion structure. Spectra 1 and 2 in part b are characteristic of the polar cap; spectra 3–5 are characteristic of the aurorae velocity-dispersion structure.

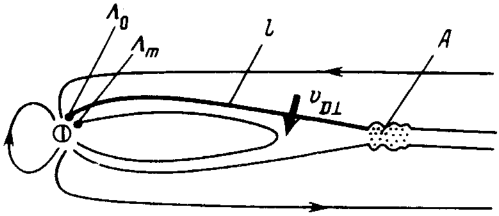

FIG. 3. Formation of the latitude-energy dispersion of a beam as the beam moves out of the tail of the magnetosphere as a result of electric drift (A is the reconnection region; the rest of the notation is explained in the text proper).

2. At the polar rim of the auroral velocity dispersion structure the maximum of the proton flux lies at an energy higher than at the equatorial rim, regardless of whether the satellite crosses this zone moving from the equator toward the pole (nine cases) or moving from the pole toward the equator (11 cases). This result proves that the auroral velocity-dispersion structure is a spatial, rather than temporal, phenomenon. Specifically, if this structure were a consequence of a time-dependent effect, then as the particles moved from the production region to satellite heights, the faster protons would be detected before the slower protons. As the satellite moved from the equator toward the pole (orbit F5002 in Fig. 1), however, the slow protons, rather than the fast ones, were detected first.

3. The maximum number of events of the auroral velocity-dispersion structure is observed in the premidnight sector of the magnetosphere (eight cases at MLT = 22–24^h).

4. Events of an auroral velocity-dispersion structure are observed in the recovery phase of substorms. Most of these events are detected during weak magnetospheric substorms (with a maximum AE index of about 300 nT).

5. In some cases the energy at which the maximum of the proton flux is observed at the polar rim of the auroral velocity-dispersion structure is higher than can be measured by the ROBE instrument. In Fig. 2a (orbit 2427), the flux does not reach a genuine maximum at an energy of 20 keV on spectra 1, 2, and 3. Examination of the electron spectra for this orbit (Fig. 2b) shows that the dispersion structure is indeed also observed at higher latitudes.

The energy-latitude dispersion in the auroral velocity-dispersion structures can be explained in terms of a filtering of the particles during their transverse displacement under the influence of the electric drift as they move out of the magnetospheric tail toward the observation point in the ionosphere (Fig. 3). For the displacement in invariant latitude we can write

$$\frac{2\pi(R_Z + H)}{360^\circ}(\lambda_0 - \lambda_m) = \int v_{D\perp} d\tau \cong \int v_{D\perp} \frac{dl}{\sqrt{2E_\parallel/m}} \cong \bar{v}_{D\perp} l / \sqrt{2E_\parallel/m} \sim E_\parallel^{-1/2},$$

where H is the height of the satellite, λ_0 is the invariant width of the particle production source, λ_m is the invariant latitude of the observed peak in the particles, R_d is the drift velocity, $E_\parallel$ is the longitudinal energy of the particles, and l is the distance from the source (the acceleration region) to the ionosphere.

The data from all the measurements conform well to the straight line

$1/\sqrt{E} = f(\lambda_m)$. We thus worked from the boundary latitude (see point 5 above) to estimate the maximum energy of the proton "peak." It turns out to be $\lesssim 100$ keV (in particular, for orbit 2427 the maximum energy of the proton peak should be $E_p = 70$ keV at $\lambda = 74.7°$).

The auroral velocity-dispersion structure is therefore an ionospheric autograph of particle beams coming from the boundary plasma sheet, where reconnection of the interplanetary and geomagnetic fields is believed to occur. We should point out that a dispersion pattern similar to the auroral velocity-dispersion structure has been observed[8] in the geomagnetic tail, for protons with energies above 25 keV at distances of $(14\text{–}15)R_e$. At auroral heights, however, this has been the first successful observation of this phenomenon, which can be credited to the high spatial resolution of the plasma experiments of the satellite Oreol-Z.

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