Acceleration of ions in the plasma environment of the earth by the radiation from a low-frequency transmitter on the ground

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An acceleration of H^+, He^+, and O^+ ions has been observed experimentally during the application of an electromagnetic wave from a low-frequency transmitter on the ground to the ionospheric and magnetospheric plasma.

Previous studies[1–5] have revealed that the radiation from a low-frequency transmitter can stimulate a precipitation of electrons and protons from the earth's magnetosphere into the ionosphere. The experiment reported here as part of the joint Soviet-French project ARKAD-3 was carried out in order to search for inverse effects, specifically, a heating of ionospheric ions and their ejection into the magnetosphere by intense low-frequency electromagnetic waves from an external source.

The radiation source was the Soviet subauroral low-frequency transmitter UPD-8 (Ref. 6; geographic latitude $\varphi = 64°24'$N; geographic longitude $\lambda = 41°32'$E; McIlwain parameter $L = 4$; transmitted power $W = 300$ kW). This transmitter was working in accordance with a special program at a carrier frequency $f_0 = 19.1$ kHz with amplitude modulation (8-s transmission with an 8-s pause).

The properties of the plasma and the electromagnetic waves were measured by a scientific package carried on the OREO-3 satellite.[7] In the present letter we are reporting measurements of the ion mass composition ($M = 1$–32 units) in the interval $E/Q = 0.01$–3.5 keV/charge, carried out by the ION1 and ION2 instruments. When the satellite passed near the transmitter, the ION1 and ION2 were able to detect ions with pitch angles $\theta \approx 85°$ and $\theta \approx 145°$, respectively (θ is the angle between the velocity of the particle and the magnetic-field vector). As a control of the electromagnetic field in the frequency range from 10 Hz to 20 kHz we used measurements taken with the ONCh-TBF instrument.

Figure 1 shows the fluxes of H^+, He^+, and O^+ ions with energies of 250–330 eV, along with the amplitude of the electric component of the electromagnetic field perpendicular to the external magnetic field at frequencies of 15 kHz and 4.5 kHz. The amplitude of the signal from the transmitter was determined by means of a wide-band filter with a central frequency of 15 kHz. Since the measurements were carried out in a setting of a relatively weak geomagnetic activity ($D_{st} = -10$ nT), the zone of natural

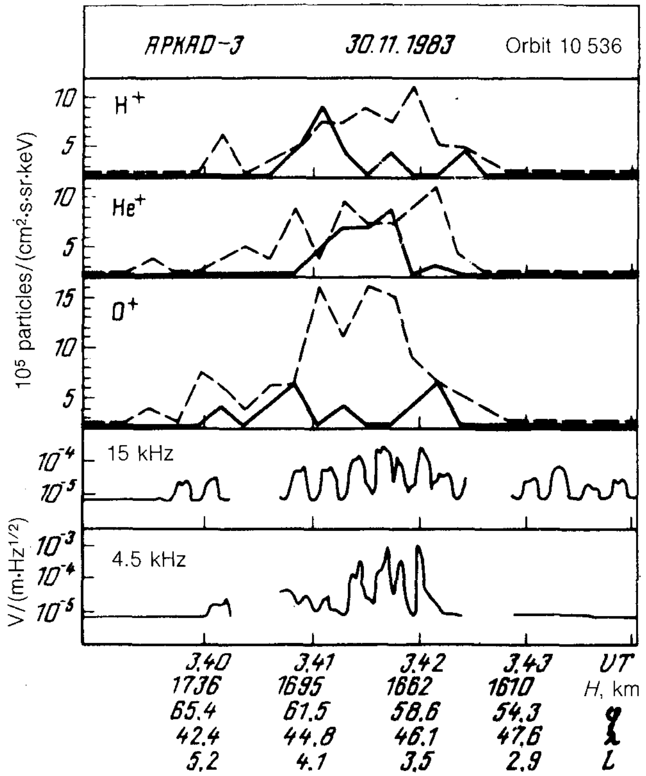

FIG. 1. Differential fluxes of H^+, He^+, and O^+ ions and the electric fields at frequencies of 15 kHz and 4.5 kHz according to measurements on orbit 10 536. The three upper plots show the ion fluxes with pitch angles $\theta = 85°$ (dashed lines) and with $\theta \approx 145°$ (solid lines). The breaks on the curves in the two lower plots are a result of a lack of data due to on-board calibration of the ONCh-TBF instrument. UT—Universal time; H—height of the satellite; φ and λ—geographic latitude and longitude of the projection of the orbit of the satellite; L—McIlwain parameter. The flux densities (the three upper plots) are given in linear scale, while the electric fields are given in logarithmic scale.

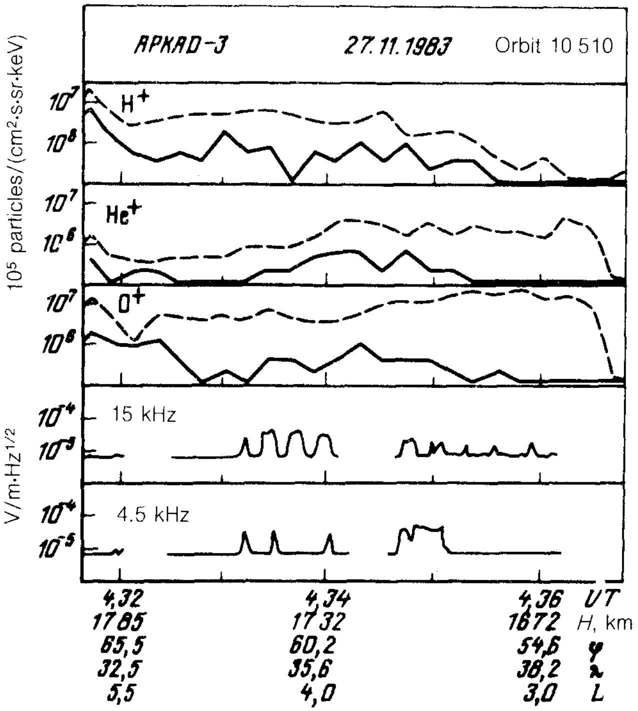

FIG. 2. Measurements of the same type as in Fig. 1, carried out on orbit 10 510. The particle fluxes are shown in logarithmic scale.

auroral precipitation was at a higher latitude (not shown in Fig. 1). It can be seen from Fig. 1 that a mid-latitude increase in the ion fluxes, of about an order of magnitude above the background level, occurs in the zone in which the transmitter signals are detected. Simultaneously, radiation appears at frequencies ~4.5 kHz, which lie near the local lower-hybrid resonance frequency; this radiation is correlated with the 8-s transmissions from the transmitter.

On orbit 10 510 (Fig. 2), measurements were taken at a time of a high geomagnetic activity ($D_{\rm st} = -30$ nT). Accordingly, the zone of natural precipitation had shifted to smaller L shells (Fig. 2) and partially overlapped the zone acted upon by the signals from the transmitter. On this orbit, as in the preceding case, a significant increase in the quasitransverse and upward ion fluxes was observed in the transmitter zone (up to 10^6–10^7 cm^{-2}·s^{-1}·sr^{-1}·keV^{-1}); the effect was particularly pronounced in the case of He$^+$ ions. We should point out that, while the ion flux densities with $\theta \approx 85°$ and $\theta \approx 145°$ were approximately the same under quiet geomagnetic conditions, under perturbed conditions they differed by a factor of several units. Another distinction is the shift of the low-latitude boundary of the ion fluxes from $\theta \approx 85°$ to smaller L shells. Figure 3 shows the geographic positions of the regions in which anomalous fluxes of ions were observed to flow out of the ionosphere into the magnetosphere ($\theta \approx 145°$) on five orbits of OREOL-3. The asterisk in this figure marks the position of

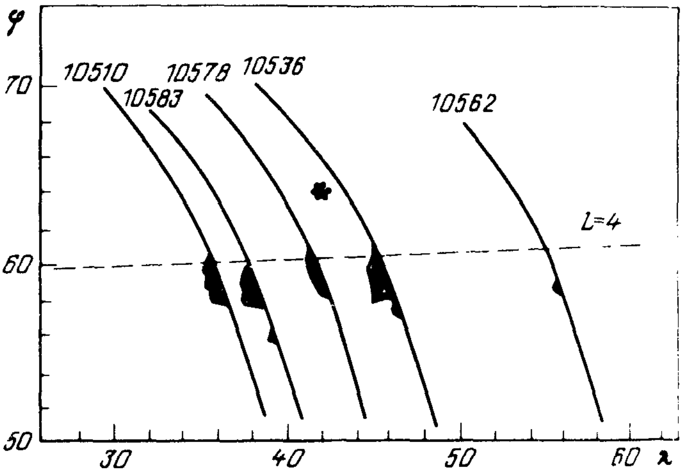

FIG. 3. Projections onto the earth of satellite orbits which passed near the transmitter. Shown on the projections of the orbits are the fluxes of He^+ ions with $\theta \approx 145°$ (fluxes from below). The curves are labeled with the satellite orbit number. Dashed line—intersection of the satellite with the L shell of the transmitter; φ and λ—geographic latitude and longitude.

the transmitter; the dashed line is the $L = 4$ shell. As in some earlier experiments,[3,5] the "influence" region of the transmitter is limited to a latitude band of 5–7° and is displaced away from the L shell of the transmitter toward the equator.

It thus follows from these experimental results that intense electromagnetic waves from a low-frequency, ground-based transmitter stimulate the occurrence of the following physical processes in the mid-latitude ionosphere and in the magnetosphere of the earth: 1) an acceleration to energies on the order of or greater than 300 eV and the ejection into the magnetosphere of ionospheric O^+, He^+, and H^+ ions; 2) an excitation of an intense ELF-VLF noise in the region in which the quasitransverse ion fluxes are observed.

Because of the high phase velocity of whistlers, their interaction with superthermal ions ($E \lesssim 1$ keV) in the upper ionosphere is inconsequential. It thus seems reasonable to consider a two-step process as an explanation of these results: a nonlinear conversion of a whistler transmitted by the low-frequency transmitter on the ground into other plasma-wave modes, followed by an interaction of these secondary waves with ionospheric ions. In the upper ionosphere, two nonlinear processes involving whistlers occur most efficiently: (1) an induced scattering of whistlers into low-frequency plasma waves (or lower-hybrid waves) in a process involving thermal ions; (2) a decay of whistlers into low-frequency waves and electrostatic ion-cyclotron waves.[8,9]

Litvak and Trakhtengerts[10,11] have called attention to the importance of nonlinear induced scattering for the heating of plasmas, including the ionospheric plasma. The high efficiency of low-hybrid and ion-cyclotron waves for accelerating ions across an external magnetic field has been demonstrated in several studies, dealing with both the auroral plasma[12–14] and plasmas in the laboratory.[15,16]

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