Electron acceleration in the front of a strong collisionless shock wave

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We investigate the excitation of plasma turbulence at frequencies on the order of the lower hybrid frequency by ion beams reflected from a shock-wave front, and the acceleration of electrons by the oscillations. The relaxation of the ensuing strongly anisotropic electron distribution is accompanied by excitation of oscillations having frequencies several times lower than the electron cyclotron frequency. Measurements of the low-frequency plasma turbulence and of the plasma-particle velocity distributions are in satisfactory agreement with the theoretical model developed in the present paper.

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1. INTRODUCTION

Magnetohydrodynamic analysis of the structure of strong shock waves propagating across a magnetic field in a collisionless plasma has shown that when the critical Mach number is exceeded the wave profile breaks and multivelocity ion flow sets in.[1] In the kinetic description this corresponds to the instant when part of the incident plasma-stream ion is reflected from the electric-potential jump in the shock-wave front. It was predicted theoretically in Ref. 1 that owing to excitation of lower hybrid oscillations of frequency $\omega\sim\omega_{LH}=(\omega_{ci}\omega_{ce})^{1/2}$ ($\omega_{cj}=e_j/H_0/m_jc$ is the cyclotron frequency of the particles of species j in the magnetic field H_0) by the opposing streams of the incident and reflected streams of the incident and reflected ions, part of the energy of the ion directional motion will be converted into thermal energy of the plasma. Direct measurements of the plasma parameters and of the lower-hybrid oscillations in the front of the departing shock wave produced in the supersonic solar wind ahead of the earth's magnetosphere have confirmed that this energy-dissipation mechanism, together with the occasionally realized anomalous ion-sound viscosity, is basic for strong collisionless shock waves and can explain the observed thermalization of the ions behind the wave front.[2]

On the other hand, since the phase velocity of the propagation of the excited lower-hybrid oscillations along the magnetic field is much larger than the thermal velocity of the electrons, they can effectively accelerate electrons along the magnetic field.[3,4] In the case of a shock wave near the earth, the accelerated electrons easily go off along the magnetic force lines fromthe shock-wave-front region into the interplanetary space and can be easily registered there in an energy range of the order of several keV,[5] comparable with the energy of the ion streams.

In Sec. 2 of this paper we propose a theoretical model of electron acceleration on the front of a strong collisionless shock wave in a magnetized plasma. The model is based on a self-consistent description of lower-hybrid plasma turbulence and of the velocity distributions of the beams of ions and superthermal electrons, within the framework of a quasilinear approximation. This model permits not only an estimate of the characteristic energies and fluxes of the accelerated electrons, but also indicates the mechanism of the anisotropic velocity distribution of the electrons accelerated in the manner described above. The theory developed describes satisfactorily the results of measurements of plasma turbulence having a very low measurements were made on the "Prognoz-8" satellite and are discussed in Sec. 3.

2. EXCITATION OF LOWER HYBRID OSCILLATIONS AND ELECTRON ACCELERATION

When constructing a model of electron acceleration in the front of a strong collisionless shock wave in a magnetized plasma, we start from the firmly established fact that a significant fraction of the ions is reflected from the shock-wave front and forms a beam that goes off, along the magnetic force lines, from the wave front into the region of the incident supersonic stream. This beam is the main source of energy for the accelerated electrons. The acceleration mechanism consists of excitation, by the ion beam, of plasma oscillations having very low frequency and propagating almost across the magnetic field. The dispersion equation of these oscillations is well known:

$$\varepsilon(\omega,\mathbf{k})=1+\frac{\omega_{pe}{}^2k_\perp{}^2}{\omega_{ce}{}^2k^2}\left(1+\frac{\omega_{pe}{}^2}{k_\perp{}^2c^2}\right)-\frac{\omega_{pi}{}^2}{\omega^2}-\frac{\omega_{pe}{}^2k_\parallel{}^2}{\omega^2k_\perp{}^2}\times\left(1+\frac{\omega_{pe}{}^2}{k_\perp{}^2c^2}\right)^{-1}+\frac{\omega_{pi}{}^2}{k^2n_0}\int\frac{\mathbf{k}\partial f_b/\partial\mathbf{v}}{\omega-\mathbf{kv}+i0}d^3\mathbf{v}+\frac{\omega_{pe}{}^2}{k^2n_0}\int\frac{k_\parallel\partial f_{Te}/\partial v_\parallel}{\omega-k_\parallel v_\parallel+i0}dv_\parallel=0, \quad (1)$$

where $\omega_{pj}=(4\pi n_je_j^2/m_j)^{1/2}$ is the plasma frequency of the particles of species j, ω is the wave frequency, $\mathbf{k}$ is the wave vector, $k_\parallel$ and $k_\perp$ are the wave-vector components along the across the unperturbed magnetic field, $f_0(\mathbf{v})$ is the beam-ion velocity distribution function, and $f_{Te}(v_\parallel)$ is the longitudinal-velocity distribution function of the superthermal electrons in the drift approximation. In the derivation of the dispersion equation it was assumed that the frequencies and the wave vectors of the oscillations lie in the intervals

$$\omega_{ce}\gg\omega\gg\omega_{ci},\quad \operatorname{Im}\omega\gg\omega_{ci},$$
$$k_\perp r_{Li}\gg1\gg k_\perp r_{Le},\quad \omega\gg kv_{Ti},\quad \omega\gg k_\parallel v_{Te}, \quad (2)$$

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where $v_{Tj} = (2T_j/m_j)^{1/2}$ is the thermal velocity of the particles of species j, and $r_{Lj} = v_{Tj}/\omega_{cj}$ is the Larmor radius of the particles of species j. The inequalities (2) allow us to neglect the influence of the magnetic field on the ion motion and use the drift approximation for the description of the electrons. In this paper we confine ourselves to a discussion of the limiting case $\omega_{pe} \gg \omega_{ce}$, which is typical of solar wind and of most laboratory experiments. In this limit, the short-wave oscillations are electrostatic and their frequency is equal to (at $k_\parallel = 0$) or higher than (at $k_\parallel \neq 0$) the lower-hybrid resonance frequency. With increasing wavelength the deviation of the oscillations from potential becomes appreciable and they are transformed into the well known whistler oscillations.

The condition that Čerenkov resonance exist between the reflected-ion beam and the indicated ions

$$\omega = \mathbf{k}\mathbf{v}_b$$

determines the phase velocity of the waves along the magnetic field as a function of the transverse component of the wave vector and of the projection of the beam velocity on the oscillation-propagation direction:

$$\frac{m_e\omega^2}{k_\parallel^2} = m_i v_b^2 \cos^2\theta_b \left(1+\frac{\omega_{pe}^2}{k^2c^2}\right)^{-1}\left[\frac{v_b^2\cos^2\theta_b}{v_{Ai}^2}\left(1+\frac{k^2c^2}{\omega_{pe}^2}\right)-1\right]^{-1}, \tag{3}$$

where v_b is the beam velocity, θ_b is the angle between the wave propagation direction and the beam-velocity vector, and $v_{Aj} = H_0(4\pi n_0 m_j)^{-1/2}$ is the Alfven velocity. Since the reflected-ion velocity is 2–3 times larger than the velocity of the super-Alfven plasma flux ahead of the shock wave, the ratio v_b/v_{Ai} is usually large. For small angles θ_b, the phase velocity of the wave propagation along the magnetic field turns out to be of the order of the electron Alfven velocity v_{As}. This means in turn that in a typical cosmic plasma with $\beta \sim 1$, where

$$\beta = 8\pi n_0 (T_i + T_e)/H_0^2$$

is the ratio of the plasma and magnetic-field pressures, such oscillations cannot be excited because of the Landau damping by the thermal electrons. The only oscillations that can build up in such a plasma are those propagating at a large angle θ_b to the ion beam, when $\cos\theta_b \ll v_{Ai}/v_b \ll 1$. The growth rate of the instability reaches then a maximum

$$\gamma_m \sim \omega_{LH}(v_{Ai}/\Delta v_b)^2 n_b/n_0$$

at $k = \omega_{pe}/c$, and in the case of strong shock waves with $n_b \lesssim 0.5n_0$ it turns out to be large enough ($\gamma_m \gg \omega_{ci}$) to justify neglect of the effect of the magnetic field on the motion of the ions in the wave field (ω_{LH} is the cyclic frequency of the lower-hybrid oscillations).

In the quasilinear approximation, the complete system of equations that describes the kinetics of the waves and of the plasma particles consists of the following equations:

$$\mathbf{v}\nabla f_i + \frac{e}{m_i}\left\{\mathbf{E}_0 + \frac{1}{c}[\mathbf{v}\times\mathbf{H}_0]\right\}\frac{\partial f_i}{\partial \mathbf{v}} = \frac{\pi e^2}{m_i^2}\int\frac{d^3\mathbf{k}}{(2\pi)^3}\mathbf{k}\frac{\partial}{\partial\mathbf{v}}\frac{|E_\mathbf{k}|^2}{k^2}\delta(\omega-\mathbf{k}\mathbf{v})\mathbf{k}\frac{\partial f_i}{\partial\mathbf{v}}, \tag{4}$$

$$\frac{v_\parallel}{H_0}\mathbf{H}_0\nabla f_{Te} = \frac{\pi e^2}{m_e^2}\frac{\partial}{\partial v_\parallel}\int\frac{d^3\mathbf{k}}{(2\pi)^3}\frac{k_\parallel^2|E_\mathbf{k}|^2}{k^2}\left(1+\frac{\omega_{pe}^2}{k^2c^2}\right)^{-2}\delta(\omega-k_\parallel v_\parallel)\frac{\partial f_{Te}}{\partial v_\parallel}, \tag{5}$$

$$\frac{\partial\omega}{\partial\mathbf{k}}\nabla|E_\mathbf{k}|^2 = \frac{\pi\omega_{LH}^2}{k^2}\left(1+\frac{\omega_{pe}^2}{k^2c^2}\right)^{-1}\left\{\int\mathbf{k}\frac{\partial f_i}{\partial\mathbf{v}}\delta(\omega-\mathbf{k}\mathbf{v})d^3v + \frac{m_i k_\parallel}{m_e|k_\parallel|}\left(1+\frac{\omega_{pe}^2}{k^2c^2}\right)^{-1}\frac{\partial f_{Te}}{\partial v_\parallel}\bigg|_{v_\parallel=\omega/k_\parallel}\right\}|E_\mathbf{k}|^2 = 0, \tag{6}$$

where $|E_\mathbf{k}|^2/8\pi$ is the spectral energy density of the electric field of the excited plasma oscillations.

The first of these equations describes the ion dynamics near the shock-wave front with allowance for the quasilinear relaxation of the ion velocity distribution by the excited plasma oscillations. Since this solution has not yet been solved even with a computer, the ion-beam density n_b and the velocity v_b and temperature $T_b \approx m_i\Delta v_b^2/2$ of the ions will be assumed known and have typical values recorded in cosmic experiments (see, e.g., the review[6]). Equations (5) and (6) determine then respectively the distribution function of the superthermal electrons and the spectral energy density of the excited wave. They can be easily solved at low electron energies and accordingly at short oscillation wavelengths. In this limit, expression (3) for the phase velocity of the oscillations along the magnetic field takes the simple form

$$m_e\frac{\omega^2}{k_\parallel^2} = m_i v_{Ai}^2\left(1+\frac{k^2c^2}{\omega_{pe}^2}\right)^{-1}. \tag{7}$$

Equation (6) simplifies correspondingly to

$$\frac{n_b v_{Ai}^2}{n_0\Delta v_b^2} + \left(v_{Ae}^2 - \frac{\omega^2}{k_\parallel^2}\right)\frac{\partial f_{Te}}{\partial v_\parallel'}\bigg|_{v_\parallel=\omega/k_\parallel} = 0. \tag{8}$$

We have neglected here the weak departure of the oscillations from the region in which they are generated. The solution of Eq. (8)

$$f_{Te} = \frac{n_{Te}}{2v_{Ae}}\left(\ln\frac{v_{Ae}-|v_\parallel|}{v_{Ae}+|v_\parallel|} + \text{const}\right), \tag{9}$$

where $n_{Te} = n_b v_{Ai}^2/\Delta v_b^2$, is valid only at $|v_\parallel| \lesssim v_{Ae}$, so that the constant it contains cannot be determined. This expression permits nevertheless a determination, from Eq. (5), of the behavior of the spectral energy density of the electric field of the excited oscillations at short wavelengths:

$$\int\frac{dk_\parallel}{(2\pi)^2}\omega_\mathbf{k}|E_\mathbf{k}|^2 = \frac{\omega_{ce}^2}{\pi\omega_{pe}^2}\frac{v_{Ae}H_0^2}{k^2}\left(1+\frac{\omega_{pe}^2}{k^2c^2}\right)^{-2}\left|\frac{\nabla_\parallel f_e}{f}\right|. \tag{10}$$

We see thus from (9) that the most superthermal electrons have rather low energies $m_e v_\parallel^2/2 \lesssim H_0^2/8\pi n_0$. This does not mean, however, that the main contribution to the energy content is made by just these low-energy electrons. Existence is quite possible of superthermal electron-distribution tails that fall off more rapidly than (9) but still slowly enough to make a large contribution to the energy content. Since Eq. (6) can as yet not be solved in the region of such tails, we confine ourselves to estimates of the density and average energy of the superthermal electrons, using the wave and particle energy conservation laws, as was done for the first time in the problem of the onset of a superthermal ion tail when electron-sound turbulence was excited by an electron current.[7] The first equation we need is obtained from the condition (6) of the energy balance of the excited waves:

$$\frac{n_b}{n_0}\left(\frac{v_{Ai}}{\Delta v_b}\right)^2 \approx \frac{n_{Te}}{n_0}\frac{m_e v_{Ae}^2}{\mathscr{E}_e}, \tag{11}$$

where $\mathscr{E}_e$ and n_{Te} are the average energy and density of the superthermal electrons. For the second equation we use the requirement that the energy flux of the reflected ions in the electron-acceleration region balance the flux of the accelerated electrons from this region. This condition can be easily obtained as a corollary of Eqs. (4) and (5) with account taken of the wave balance (6)

$$n_b m_i v_b^2 \Delta v_b \approx n_{Te}\mathscr{E}_e(\mathscr{E}_e/m_e)^{1/2}. \tag{12}$$

We have neglected here the wave energy flux, using the estimate (10) for the wave energy density. From (11) and (12) we get

$$\mathscr{E}_e \approx (m_e/m_i)^{1/5}(m_i v_b^2)^{2/5}(m_i \Delta v_b^2)^{3/5}, \tag{13}$$

$$n_{Te} \approx n_b (m_e/m_i)^{1/5}(v_b/\Delta v_b)^{2/5}. \tag{14}$$

For typical parameters of the ion beams[2,6] reflected from the front of the leading shock wave ahead of the earth's magnetosphere ($m_i v_b^2/2 \sim$ 1–5 keV, $m_i \Delta v_b^2/2 \lesssim 10^2$ eV, $n_b \sim 0.1 n_0$), the average energy of the thermal electrons turns out to be on the order of a hundred electron volts. At the same time, a small fraction of electrons can be accelerated to significantly higher energies, but to obtain such high energies in this case the turbulent acceleration should take place over much larger length. An estimate of the length needed to accelerate an electron to an energy $\mathscr{E}_e$ is obtained from the quasilinear equation (5)

$$L_\parallel \approx 16\pi^2 n_0^2 \mathscr{E}_e^2 (\mathscr{E}_e/m_e)^{1/2} \times \left[\omega_{LH} H_0^2 (\omega_{pe}^2/\omega_{ce}^2) \int |E_\mathbf{k}|^2 d^3\mathbf{k}/(2\pi)^3\right]^{-1}.$$

When dealing with kilovolt energies, this length is found to be of the order of 10^5–10^7 km.

Inasmuch as when electrons are accelerated only their mtion energy along the magnetic force line increases, the resultant electron distribution becomes strongly anisotropic:

$$f_{Te} = \frac{n_{Te} m_e}{2\pi T_\perp}\exp\left(-\frac{m_e v_\perp^2}{2T_\perp}\right) f_0(v_\parallel), \tag{15}$$

where the characteristic electron energy is $m_e v_\parallel^2/2 \gg T_\perp$ and $f_0(v_\parallel)$ is the longitudinal-velocity distribution function. Since the electrons are accelerated in the immediate vicinity of the shock-wave front, at a certain distance from the front the electrons moving away from it will predominate. Assume that $v_\parallel > 0$ in this direction. Even though $\partial f_0/\partial v_\parallel < 0$ at $v_\parallel > 0$ in this case, one can expect for a sufficiently general form of f_0 the distribution (15) to be unstable to excitation of oscillations as a result of cyclotron resonance in the anomalous Doppler effect[8]:

$$\omega - k_\parallel v_\parallel + \omega_{ce} = 0 \tag{16}$$

(the so-called "fan" instability). The frequency of these oscillations is $\omega = \omega_{ce} k_\parallel/k$ and $v_{\parallel r} = (\omega_{cd}/k)(1 + 1/\cos\theta)$, where $\cos\theta = k_\parallel/k$. (This is valid at $ck/\omega_{pe} \sim \omega_{ce} c/\omega_{pe} v_\parallel \cos\theta \gtrsim 1$, when the excited oscillations can be regarded as electrostatic. At $ck/\omega_{pe} \ll 1$ the excited oscillation branch goes over into the whistler mode.) The stabilizing contribution to the growth rate from the resonance with the normal Doppler effect $\omega - k_\parallel v_\parallel = \omega_{ce}$ is small, since the number of electrons moving towards the front ($v_\parallel < 0$) is small, since the number of electrons moving towards the front ($v_\parallel < 0$) is small. In addition, the parameter ω_{ee}/k should exceed by two or three times the thermal velocity of the cold electrons if the stabilizing effect of the Čerenkov damping of the oscillations by thermal electrons is to be small.

The quasilinear electron-"tail" relaxation due to the development of "fan" instability leads to diffusion of the resonant particles along the lines:

$$v_\perp^2 + v_{\parallel r}^2 - 2\int\left(\frac{\omega}{k_\parallel}\right) dv_{\parallel r} = \text{const}, \quad v_{\parallel r} = \frac{(\omega + n\omega_{ce})}{k_\parallel}, \tag{17}$$

i.e., to a "turn" of the electron tail of the transverse velocities. We shall assume (this will be confirmed by subsequent calculations) that the spectral energy density of the oscillations has a sufficiently narrow maximum with respect to the angle θ, so that higher resonances with $n > 1$ can be neglected. We assume in addition that the oscillation spectrum is monochromatic in k ($k = \bar{k}$). Then the "quasilinear" relaxation of the resonant electrons leads in final analysis to establishment of a "plateau" along the diffusion lines:

$$w = v_\perp^2 + (v_\parallel - v_{min}/2)^2 = \text{const},$$

where $v_{\min} = 2\omega_{ce}/\bar{k}$ is the minimum velocity of the resonant electrons. The correspnding distribution function is of the form

$$f_\infty(v_\parallel, v_\perp) = \frac{1}{2\pi} f_0(u)\left[(u - v_{min})(u - v_{min}/2)\right]^{-1}, \tag{18}$$

$$u = v_{min}/2 + \sqrt{w}.$$

The quasilinear relaxation is accompanied by excitation of plasma oscillations whose electric field has a spectral energy density given by

$$\frac{|E_\mathbf{k}|^2}{8\pi} = \frac{8\pi^2 m_e}{\bar{k}^2}\frac{\omega_{ce}^4}{\omega_{pe}^2}\frac{\sin^2\theta}{\cos^2\theta}\int_{v_{min}}^{v_{max}} dv_\parallel \int v_\perp dv_\perp (f_\infty - f_0), \tag{19}$$

$$v_{max} = (\omega_{ce}/\bar{k})(1 + 1/\cos\theta).$$

The total energy of the oscillations excited as a result of the fan instability is

$$\langle E^2/8\pi\rangle \sim n_{Te}\mathscr{E}_e(\omega_{ce}^2/\omega_{pe}^2)(\bar{\omega}/\omega_{ce}). \tag{20}$$

In this equation, $\bar{\omega}$ is the frequency at which the spectral density of the electrostatic oscillations has a maximum.

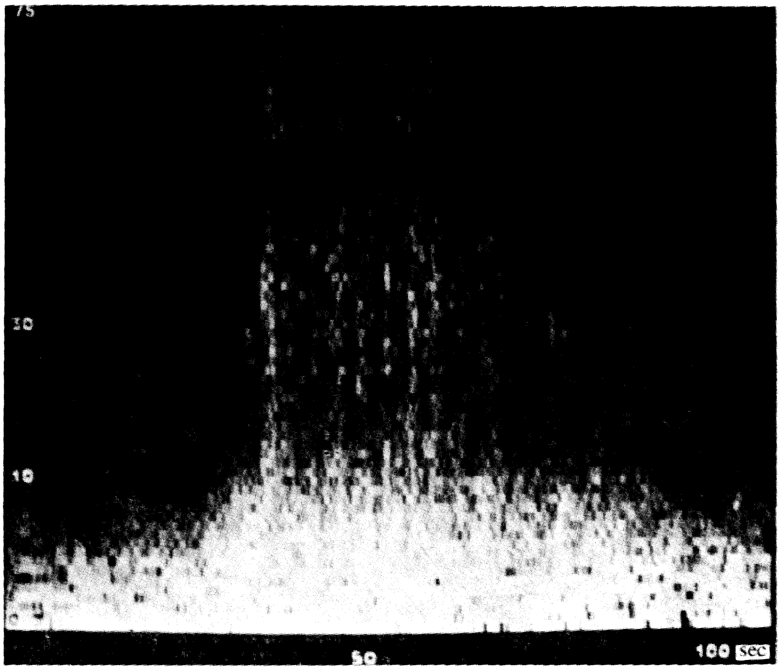

FIG. 1. Dynamic spectrum of electric extremely low-frequency oscillations when the front of a near-earth shock wave is crossed (the departure from the transition region to the solar wind took place at 13:33:55 hr Moscow time on 11 February 1981). The spectrum was obtained by the method of fast Furier transformation of the wave shape of the oscillations.

With the aid of (19) it can be shown that

$$\bar{\omega} = \frac{1}{4}\omega_{ce}\frac{v_{min} f_0 [\mathscr{E}_e^{1/2}/m_e^{1/2}]}{\int dv_{\|} f_0(v_{\|})} \approx \frac{v_{min}\omega_{ce}}{4(\mathscr{E}_e/m_e)^{1/2}}. \qquad (21)$$

3. COMPARISON WITH DIRECT MEASUREMENTS ON THE FRONT OF A SHOCK WAVE NEAR THE EARTH

Measurements of the spectra of the low-frequency electric-field oscillations and of the energy spectra of the ions and electrons were made with the "Prognoz-8" satellite, launched on 25 December 1980 on an elliptic orbit with approximate apogee 200 000 km. These measurements permit verification of the cited theoretical premises and indicate new paths for the development of the theory. The electric-field sensor was a twin floating probe. Decoupling high-capacitance capacitors connected directly to the inputs of preamplifiers located near the sensors ensured separation of the dc component of the signal from its fluctuations. The ac component was then amplified and fed to a set of band-pass filters (5–30, 85–125, and 640–800 Hz). The signal from a separate output was fed to a spectrum analyzer in which for nine frequencies in succession. The analyzer ensured simultaneous analysis of the electric-field and ion-flux signals in a frequency band of effective width $\Delta f = 3$ Hz centered at the frequencies 2, 4, 8, 12, 18, 25, 45, 70, and 105 Hz.

In addition, the signals from the input of the spectrum analyzer were transmitted to earth, at individual time intervals of duration up to 1.5 hr, at a scannign frequency 150 Hz. In the land-based data reduction, a spectral anaysis of these signals was carried out to obtain the dynamic spectra (the time—frequency—intensity dependences).

In the primary operating regime of the assembly, the

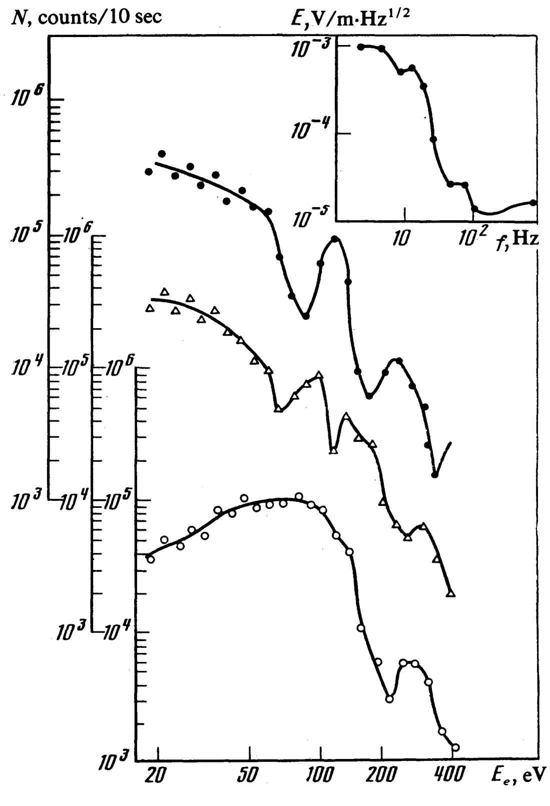

FIG. 2. Successive spectrograms of electrons obtained near the front of a near earth shock wave at 23 hr Moscow time on 29 December 1980. An electrostatic analyzer oriented perpendicular to the satellite rotation axis is directed towards the sun and ensures a spiral trace of the distribution function in the plane. The upper spectrum was obtained in solar wind (23:09:29 to 23:13:24 hr), and the lower in the transition region (23:13:55–23:17:30 hr). Inset—electric-oscillation spectrum recorded at wave-front crossing at 23 hr 12.5 min.

spectra of the electric-field fluctuations were measured continuously during the entire operating time of the satellite every 30.72 sec. In the high-speed signal transmission with land-based reduction, we calculated the fluctuation of the electric field in the frequency range from 0.3 to 75 Hz with a time resolution from 3.5 sec at 0.3 Hz to 0.8 sec at frequencies higher than 10 Hz.

Figure 1 shows an electric-field spectrum obtained during the crossing of a shock wave near the earth on 11 February 1981. The high intensity of the electric-field oscillations corresponds to the lighter sections. The instant $t = 40$ sec at which the maximum intensity was reached corresponds to the instant when the wave front was crossed (to the jump of the magnetic field). In the solar wind ahead of the shock-wave front (to the right of the point $t = 40$ sec), an increased level of the electric field oscillation is observed for a long time in the lower-hybrid frequency band. This is due to the presence of ion beams reflected from the potential jump in the wave front.[2] At the same time one can see clearly here a second intensity maximum at $f \sim 30$ Hz. This maximum may be due to excitation of high-frequency $f \sim f_{ce}/3$) oscillations on account of the anisotropic velocity distribution of the electrons accelerated by the aforementioned lower-hybrid turbulence. To verify this assumption, we analyzed nine crossings of the near-earth shock-wave, during the time of which we measured the spectrum of the oscillations at nine frequencies from 2 to 105 Hz. Only two of these spectra turned out to be perfectly smooth in the frequency range from 10 to 70 Hz. The other spectra have either clearly pronounced peaks at frequencies 20–40 Hz or shelves in this frequency region. Three of these spectra are shown in Figs. 2–4, each together with the two successive electron spectra (behind the wave front, in the front, and in the solar wind ahead of the wave front). Disregarding the singularity in the frequency region 20–40 Hz, the intensity of the oscillations decreases in the high-frequency region like f^{-2}. It is interesting to note that this agrees with the previously obtained solution (10) of the quasilinear equation (5).

To estimate the energy of the accelerated electrons and their density, we can use relations (13) and (14) assuming that up to 10% of ions with energy ~ 5 keV and temperature ~ 100 eV are reflected from the front, and the region of deceleration of these ions is $L_{\parallel} \sim v_b/\omega_{ci} = 10^8$ cm. As a result we obtain $\mathscr{E}_e \sim 100$ eV. Electrons of this energy were indeed observed earlier[5] and are present in our measurements (Figs. 2–4). The estimate of the intensity of the oscillations responsible for the electron acceleration is also found to be reasonable ($(\langle E^2 \rangle)^{1/2} \sim 10^{-3}$ V/m·Hz$^{1/2}$). Owing to the anisotropy of the electron velocity distribution, the electron energy spectrum measured with a cylindrical electrostatic analyzer is found to be modulated at the satellite-revolution frequency

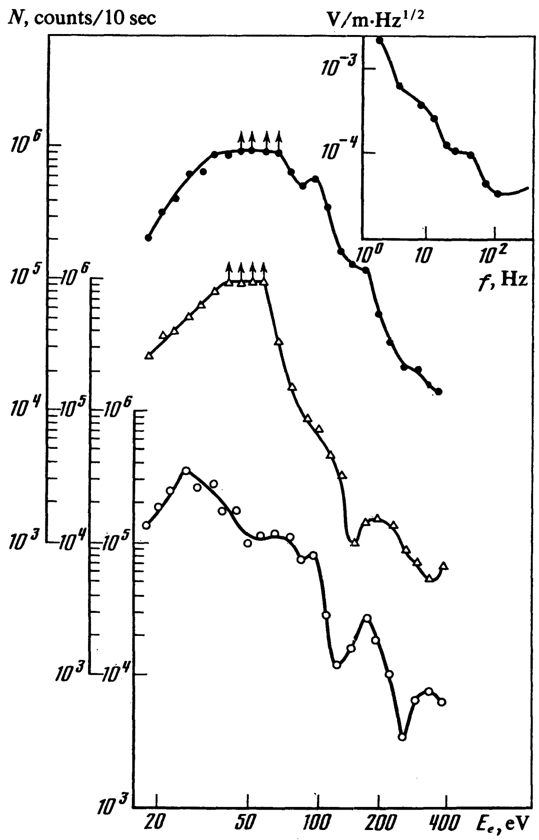

FIG. 3. The same as in Fig. 2 for the crossing of the near-earth shock wave at 01:26: hr Moscow time on 30 December 1980. The upper spectrogram was obtained in the transition region (01:20:33–0.1:24:29 hr), the front crossing occurred during the recording of the second spectrum (01:24:39–0.1:28:45). Inset—electric-oscillation spectrum recorded for the wave crossing at 0.1:26.

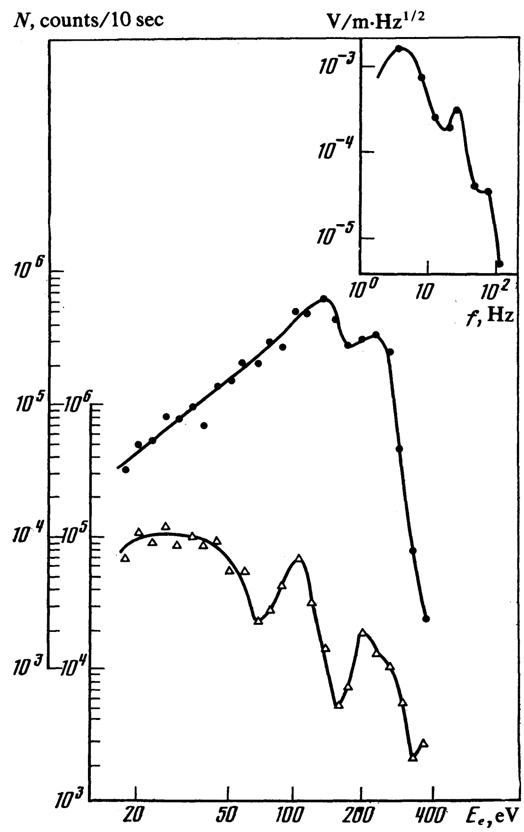

FIG. 4. The same for the crossing of the front on 31 December 1980 at 19:51. The upper spectrum was obtained in the transition region (19:47:08–19:51:03), the lower in the solar wind (19:51:14–19:55:09). Inset—electric oscillation spectrum obtained for crossing of wave front at 19:51.

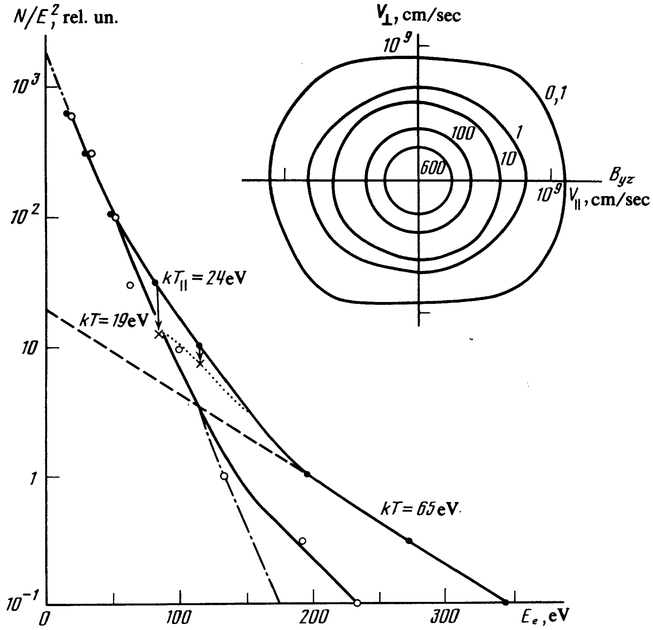

FIG. 5. Sections of three-dimensional electron distribution function for the case illustrated in Fig. 2.

(during the 4 minutes that the spectrum is plotted the satellite executes two revolutions about an axis directed towards the sum). The minima in the spectrum correspond to an analyzer direction perpendicular to the magnetic field.

Figure 5 shows an intersection of the three-dimensional distribution function of the electrons in the solar wind ahead of the shock wave with a plane perpendicular to the direction to the sun at the instant of time shown in Fig. 2, as well as the energy spectrum of the electrons. The light and dark circles were obtained respectively in the direction perpendicular to he vector of the interplanetary magnetic field and along the projection of the magnetic-field vector on this plane. The temperature of the core of the distribution function is 10 eV, and the superthermal component of the electrons in the direction of the anisotropy maximum and in the energy range 200–350 eV can be roughly approximated by a Maxwellian distribution with temperature 65 eV. The dotted curve in Fig. 5 is the excess of the electron density above the core. The average energy ≈ 65 eV of the accelerated electrons agree with the theoretical estimate (13).

To estimate the effectiveness of the mechanism described in Sec 2 of the isotropization of the electron distribution, we estimate numerically the oscillation intensity in the frequency region 20–40 Hz, assuming that in this region the low-frequency electric-field oscillation intensity spectrum, which decreases smoothly like f^{-2}, receives contributions also from the higher-frequency oscillations. In the case when distinct intensity peak appears in this region at 25 Hz (the crossing at 19 hr 51 min on 31 December 1980, Fig. 3), the intensity of the electric field of the oscillations can be estimated at $E \sim 10^{-4}$ V/m·Hz$^{1/2}$. This value agrees with the rough theoretical estimate (20).

The appearance of this intensity peak correlates with the onset of the anisotropy of the directions ($v_{\parallel} > 0$ and $v_{\parallel} < 0$) on the distribution funciton of the superthermal particles. For the crossing shown in Fig. 2, the directions $v_{\parallel} > 0$ and $v_{\parallel} < 0$ are symmetrical and there is no peak in the oscillation intensity. The onset of the direction anisotropy for the crossing shown in Fig. 3 is accompanied by a distinct intensity peak. As already noted in Sec. 2, the fan instability is possible only if $f_0(v_{\parallel} < 0) < f_0(v_{\parallel} > 0)$ for the fast particles. In the opposite case the instability is eliminated because of the contribution made to the growth rate in the normal Doppler effect.

CONCLUSION

Direct measurements of low-frequency oscillations of the electric field and of the energy spectra of electrons confirm the theoretical premises concerning the energy dissipation and particle acceleration in the fronts of collisionless shock waves with large Mach numbers $M \sim 10$. The sequence of the processes that occur on the front of such a wave reduces to the following:

1. Part of the incident-flux ions is reflected from the potential jump in the wave front and excites intense electrostatic oscillations with frequencies of the order of the lower-hybrid resonance frequency in a plasma. The primary dissipation of the energy of the supersonic plasma flux is due to interaction with these beams.

2. Part of the energy of the excited low-frequency oscillations is absorbed by electrons; this results in anisotropic superthermal tails of electrons with energy from 100 eV upwards.

3. Collisionless relaxation of the velocity anisotropy of the superthermal electrons is due to excitation of oscillations having frequencies several times lower than the electron cyclotron frequency.

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