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INTERPRETATION OF MAGNETIC MEASUREMENTS ON "PIONEER-1" AND ITS GEOPHYSICAL CONSEQUENCES

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SUMMARY

A collisionless shock wave near earth is possible only because it is oblique. An oblique shock wave consists of oblique solitary pulses. The properties of these pulses (amplitude, polarization) as functions of velocity and angle 0 are analyzed in the first part of the paper. The hypothesis is developed in the second part that the acceleration of soft electrons ($E \sim 1$ kev, third radiation belt, aurora electrons, electrons ionizing the night ionosphere), and also of electrons with energies $E \gtrsim 40$ kev (outer radiation belt) precisely takes place in oblique pulses.

Experimental corroborations of this hypothesis are brought up together with its morphological consequences.

author

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1. STRUCTURE OF OBLIQUE PULSES

A continuous registration of the magnetic field in the region from 12 to 14 R_E has been achieved on the rocket "Pioneer-1" [1] The observed magnetic field pulses were interpreted by the authors as isolated pulses running across the magnetic field ($\theta = \pi/2$), and the curves of the magnetic field, inherent to such pulses, were brought out. We would like to note that with such an interpretation,

* INTERPRETATSIYA MAGNITNYKH IZMERENIY NA "PIONERE = 1" I YEYE GEOFIZICHESKIYE SLEDSTVIYA

the theory of [2, 3] does not agree with the experiment of [1]:

1) The maximum field amplification in the transverse pulse is equal to 3. For subsequent field increase the pulses are destroyed. Meanwhile, a pulse height between 50 and 100γ is observed in the experiment; consequently, for an initial field of 5γ, the amplification constitutes 10 — 20, and not 3.

2) In the transverse pulse the field direction remains invariable, only its magnitude varies. Meanwhile in the experiment both the variation of the value as well of the field direction was always observed, and at times they even changed sign.

3) Transverse pulses are possible for Mach numbers $\mathfrak{M} \leqslant 2$, and in the corpuscular stream $\mathfrak{M} = 5 - 8$. This is why we interpreted these pulses in [4] as oblique, that is, running at a certain angle to the initial field H_0 $(\Theta = \pi/2)$. Oblique pulses differ essentially from the transverse ones: in them electrons do not drift strictly across the field as in the case of transverse pulses, but move at an angle $\Theta = \pi/2$ to the field, and, at the same time with much greater velocity (there is a velocity component along the field), inducing a large current, and consequently, a greater magnetic field gradient and a greater field amplification in the pulse $(H_{\max}/H_0 \sim \sqrt{M/m} \sim 40$ as against $H_{\max}/H_0 \leqslant 3$ in transverse pulses).

We shall bring forth the basic characteristics of oblique pulses. Let us introduce the following denotations: $\lambda = (1/2\mathfrak{M})(H/H_0)$, λ_+ is the maximum value of the field in the pulse, $\delta = 2\sqrt{M/m}\,u_0/c$ (u_0 is the pulse rate), $r = (v_A/c)\cos\theta\, M/m$, v_A is the Alfvén velocity, n is the plasma concentration ($n_e = n_i = n$, i.e. in the non-relativistic case the plasma is quasi-neutral), $v_\perp$ is the absolute value of the transverse velocity of electrons. We denote by a dot above the derivative over the coordinate, multiplied by the ratio $(n_0/n)\cdot\delta$, $n(\infty) = n_0$. The equations for the two-fluid magnetohydrodynamics provide for the modulus λ of the magnetic field the following equation [5]

$$\dot{\lambda}^2 = \delta^2\lambda^2(\lambda_+^2 - \lambda^2), \tag{1}$$

* I avail myself of the opportunity to correct the error in the first equation of [4]: instead of $1 + i\sqrt{\pi}\{\ldots$. We should read $2 + i\sqrt{\pi}\{\ldots$, which will modify the subsequent operations without, however, altering the conclusion on the existence of hydrodynamic instability.

where $\lambda_+^2 = 1 - r^2/\delta^2$, that is, the amplitude of the pulse rises with the increase of the angle θ.

From the equality $\mathrm{rot}\, H = (4\pi/c)j$ follows

$$v_\perp^2 = \dot\lambda^2 + r^2\lambda^2. \qquad (2)$$

For $\lambda_+^2 \to 1/2$ the density $n = u_0/(1 - 2\lambda^2)$ rises to infinity, so that the upper pulse amplitude limit is $H_{\max} = \sqrt{2} H_0 \mathfrak{M} |_{(\lambda_+^2 = 1/2)}$. The physical sense of $n \to \infty$ is the following: at subsequent rise of the amplitude the motion passes to the two-fluid type, the ions are reflected from the pulse's peak. At such a flow the equation of motion (1) is inapplicable.

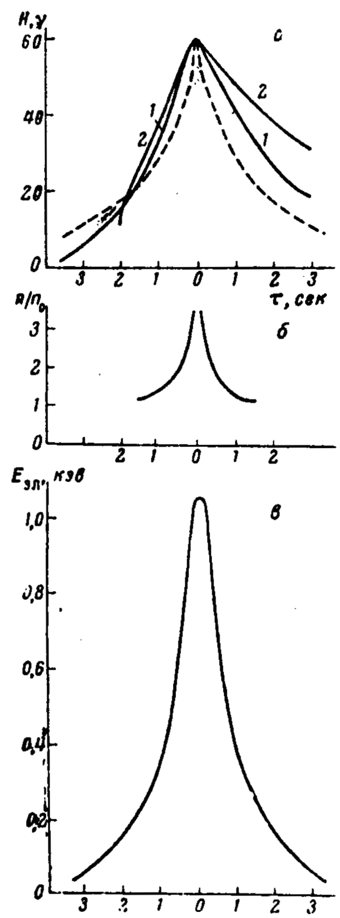
Thus $\lambda_+^2 < 1/2$. But from below amplitude λ_+ is not limited by anything. For $r = \delta$, $\lambda_+ = 0$. Thus, at $\lambda_+^2 = 0$

$$1 \geqslant \cos\theta = \cos(\theta_{\min}) = 2\mathfrak{M}\sqrt{m/M}, \quad \text{i. e.}\ \mathfrak{M} < \frac{1}{2}(M/m)^{1/2} \sim 20\ldots$$

for $\lambda_+^2 = \frac{1}{2}$. i. e. $H_{\max} = H_0\sqrt{2}\,\mathfrak{M}$, $1 \geqslant \cos\theta = \cos(\theta_{\max}) = \sqrt{2}\,\mathfrak{M}\sqrt{m/M}$,

that is,

$$\mathfrak{M} < 1/\sqrt{2}(M/m)^{1/2} \sim 30. \qquad (3)$$



Therefore, the experimental values of the amplitudes of pulses and of the Mach number in the flow correspond precisely to oblique and not to transverse pulses.

Plotted in Figure 1 are the graphs for n, H and $E_{el} = mv_\perp^2/2$, following from formulas (1), (2); they are compared with the data from "Pioneer-1" ([1], p. 1268, Figures 3 and 4); Here 1 and 2 are the experimental curves, T is the theoretical curve. The plasma parameters are borrowed from measurements on "Explorer-18" ($n_0 = 5\ \mathrm{cm}^{-3}$, $u_0 = 500\ \mathrm{km\ sec}^{-1}$, $H_0 = 5\gamma$), and the amplitude is taken maximum ($\lambda_+^2 = 1/2$) respectively for $\mathfrak{M} = 8{,}6$) $\theta_{\max} = 76^\circ$, but even such a small difference $\pi/2 - \theta = 14^\circ$ is sufficient for the amplitude

$$H_{\max} = 0{,}7\, H_0\, \mathfrak{M} = 61\ \gamma.$$

The quantity $\theta_{min} = 70^{\circ}$, that is, the range of angles for the given parameters is only 6°. The propagation of oblique pulses nearly perpendicular to the magnetic field of the flux agrees well with the direction of the latter; disregarding the inhomogeneities $(H^2/8\pi < n\kappa T)$, the field in the given region is perpendicular to the line earth-sun, along which the flow moves and the oblique pulses propagate. As we see, the agreement of theory with experiment is quite satisfactory.

2. ACCELERATION OF ELECTRONS IN OBLIQUE PULSES*

As may be seen from Figure 1, in the experimentally detected pulses of the magnetic field the electrons accelerate to energies of the order of 1 kev.

We assert that the electrons with energies of the order of 1 kev, detected from the subsolar side of the magnetosphere on "Explorer-12" [8], represent either the electrons of oblique pulses, or the electrons accelerated in oblique pulses, but then poured into the plasma at destruction of the latter.

This conclusion is also corroborated by the estimates of intensity. Assume that the density of the plasma between pulses is 10 cm^{-3} (compressed plasma between the shock wave and the magnetosphere). We shall postulate the additional compression inside the pulse of the order of two; then the flux of particles with average energy of 1 kev through an area of 1 cm^2 inside the pulse will be $\psi = 1{,}6\cdot10^{-9}\cdot1{,}3\cdot10^{9}\cdot2\cdot10 = 40$ ergs, which coincides by order of magnitude with the flux of 10^2 ergs cm^{-2} sec^{-1}, measured in [8].

Let us estimate the minimum dimensions of the pulse in a plane perpendicular to its velocity. The pulse's thickness is $d \approx c/\omega_{0,e} \approx 2$ км, $u_0 = 5\cdot10^7$ cm sec^{-1}, whereas the stay time of the pulse in the given volume of plasma is $\tau = d/u_0 \approx 0.0004$ sec. During that time the electrons of 1 kev will cover a path $S \approx 5\cdot10^6$ cm ≈ 50 km in the transverse plane; thus the dimensions of the pulse are 1 x 100 km. According to the field structure measured in [1], the pulse heights are visibly different. Inasmuch as to each amplitude corresponds its own propagation velocity u_0 or its angle θ, the difference in amplitudes implies difference in velocities or in the propagation directions. The pulses collide and interact, forming a certain nonstationary structure accelerating the electrons and ions. Substituting (2) into (1), we find $v_\perp^2 = \lambda^2\delta^2(1-\lambda^2)c^2$. Hence determining λ^2, and

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* See also the preliminary communication 6 .

substituting it in the relation $n_0 = n\,(1 - 2\lambda^2)$, we obtain the distribution function of the electron pulse by energies

$$f(E)=\left(1-\frac{E}{E_0}\right)^{-1/2}, \tag{4}$$

where E_0 is the maximum possible kinetic energy of electron in the given pulse; $E_0=\frac{mu_0^2}{2}$ Such a dependence must be given by rocket measurements of the electron spectrum inside the pulse in the region from 10 to 15 earth's radii.

Formulas (1) follow subsequently also from the equations of two-fluid magnetohydrodynamics without pressure. They are valid at $H^2/8\pi \gg p = n\varkappa T$ or, for the abiabatic process, at

$$\frac{n}{n_0} \ll \sqrt[\gamma]{\frac{Mu_0^2}{2\varkappa T}}$$

where $\gamma = C_p/C_v$ and, correspondingly, formula (4) are valid at (insert *) $E/E_0 \lesssim 1-\left(\frac{2\varkappa T}{Mu_0^2}\right)^{2/\gamma}$ At $T = 2\cdot 10^5\ {}^{\circ}K$, $u_0 = 5\cdot 10^7$ cm sec^{-1}, $\gamma = 5/3$, this gives $n/n_0 \ll 8{,}5$; $E/E_0 \ll 0{,}85$.

Inasmuch as $\frac{\partial v_\perp^2}{\partial \lambda^2} = \delta^2(1-2\lambda^2)$,

for $\lambda^2 < 1/2$, the curve $v^2(x)$ has at the peak of the pulse At

$$\lambda_+^2 = \frac{1}{2},\ r^2 = \frac{\delta^2}{2} \quad \text{and} \quad v_{\perp\,\max}^2 = \frac{\delta^2}{4}c^2,$$

that is,

$$E_{\max} = \frac{mv_{\perp\,\max}^2}{2} = \frac{Mu_0^2}{2} = \frac{1}{2}\frac{H_{\max}^2}{8\pi n_0} \tag{5}$$

is the greatest energy that may be obtained in the pulse by electrons, which does not exceed the kinetic energy of ions. In the experiment [1] $H_{max} = 105\gamma$, that is, $E_{max} = 3$ kev. If the pulse is steady relative to earth, E_{max} is the kinetic energy of ions of the corpuscular stream.

Considering the interaction of the corpuscular stream with the magnetosphere, geophysicists have been searching for a long time for the transfer mechanism of kinetic energy from ions to terrestrial plasma flux. As may be seen, oblique pulses constitute that mechanism. At the same time the energy is at first transferred to electrons, and then these electrons, penetrating into the magnetosphere, yield this energy to the terrestrial plasma (low-frequency radiation) and to neutral atmosphere, exciting polar

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* the angular point $v_{\perp\,\max}^2 = r^2\lambda_+^2c^2$.

aurorae and inducing the ionization of the night ionosphere. The energies of 10^1 ergs. cm^{-2} sec^{-1} are exactly sufficient for creating such physical effects [9]. Inasmuch as electrons move along the lines of force of the geomagnetic field, there takes place a focusing effect toward the ground surface of electrons having invaded various areas of the magnetosphere, and consequently also a focusing effect of their energy flux.

An indirect corroboration of such a hypothesis is given, in particular, by the experimental results of the work [10] consisting of measurement of X-ray bremmstrahlung emission in the atmosphere. Experiment has shown [10] that the X-ray emission consists also of separate pulses of 0.5 sec. duration that is, of same order as the oblique pulses in the drawing.

At resolution in the time of 10^{-3} sec, a uniform background is obtained instead of pulses, in the form of oscillations with a period $\tau \sim 6 \cdot 10^{-3}$ sec. This value is close to the period of Langmuir ionic oscillations at $n = 9$ cm^{-3}, $\tau_i = 2\pi/\omega_{0,i} = 1.5 \cdot 10^{-3}$ sec. Meanwhile it is well known [4] that $\omega_{0,i}$ is the characteristic frequency of oscillations occurring in the plasma of a solitary pulse at motion of electrons relative to ions. Thus, the experiment of [10] points indirectly to the character of dissipation in the pulse. A receiver in the frequency of $\sim 10^3$ cps would measure these plasma oscillations directly inside the pulse.

In oblique pulses the plasma is unsteady relative to oscillation build up with frequency $\omega_{0,i}$ (at $\omega \ll \omega_{0,i}$ this is a purely aperiodical instability). During the time of field stay in the given volume of plasma (τ) these oscillations have to accrue. Their increment is $\sim \omega_{0,i} = 1/\tau_0$, the pulse thickness is $d \sim c/\omega_{0,e}$, that is, $\tau_0/\tau = (\omega_{0,e}/\omega_{0,i}) \cdot (u_0/c) = \sqrt{M/m}\,u_0/c$, i.e. for $u_0 < 7 \cdot 10^8$ cm sec^{-1}, $\tau_0 < \tau$. They heat the electrons, also destroying the pulses. The experimental corroboration of electron heating in oblique pulses is given by measurements on "Explorer-18" ([11], Figure 19).

The acceleration in oblique pulses is an essentially nonstationary process still for another reason: at pulse's peak because of plasma compression, $8\pi n \varkappa T > H^2$, and the considered stationary solutions obtained in the approximation of cold plasma hydrodynamics, are no longer valid. But we still shall utilize them for the illustration of the physical mechanism of onset of vortex electric fields ($c \cdot \mathrm{rot}\,E = -\partial H/\partial t$), accelerating the particles, and for qualitative estimates of maximum energy of accelerated particles and its dependence on the angle.

When heating the electrons in pulses to temperatures $T_e \leqslant mv_\perp^2/2 = Mu_0^2/2 \gg T_i$ the flow past the magnetosphere becomes transonic, and the requirement of velocity jump of the shock wave type drops off ($\mathfrak{M} = u_0/c_s \sim 1$, where cs = T_e/M is the ionic speed of sound).

The variable magnetic field of the pulse transfers also its energy to protons (see (5)). These fast protons (0.05 — 1 Mev) induce a ring current around the earth.

The solar wind protons, reaching for example the moon, are decelerated in solitary pulses, while the pulse-accelerated electrons constitute one of the parts of lunar ionosphere.

Behind the magnetosphere the plasma flow velocity in the turbulent earth's tail ($u = 3 \cdot 10^7 \div 10^8$ cm/sec) is much greater than the Alfven velocity*and there correspondingly emerge in it oblique pulses in which the electrons are accelerated. This is the way we explain the electrons with energy $E \sim 1$ kev detected on the side of the earth by K. I. Gringauz et al [12] .

As pointed out above, the energy of the magnetic field and the energy of electrons are maxima for solitary pulses travelling along the field ($\theta = 0$). A natural question arises as to whether it would be possible to explain also the origin of hard electrons with $E \geqslant 40$ kev (electrons of the outer radiation belt) by acceleration in solitary pulses.

The first to draw attention to the importance of solitary pulses for the theory of radiation belts was V. A. Tverskoy in 1961 [13]. However, at that time very little was known about the turbulent supersonic flow past the earth and this is why he was compelled to limit himself to only a rather general remark, whereby "such events as the acceleration and the heating of electrons in solitary pulses, offer interest for the theory of the origin of the outer radiation belt, in which so far, only fast electrons have been detected". The experimental data accumulated for the past four years allow to develop this remark into the hypothesis expounded below, according to which the electron component of the outer radiation belt with energies $E \geqslant 40$ kev is induced by acceleration in solitary pulses and analogous nonstationary structures.

At pulse's peak to energies of 50 kev corresponds a magnetic field $H_{\max} = (16\pi n_0 E)^{1/2} \approx 400$ while maximum amplitudes measured by

* ($\mathfrak{M} = 6 \div 20$)

Pioneer-1 and Pioneer-5 did not exceed 105γ. However, this contradiction is only apparent. The parallel pulses (by which we imply the pulses travelling along the field) propagate with a velocity $u_0 = (20 \div 30)\, v_A = 800-1200$ km$\cdot$sec^{-1} (see section 1, (2) and (3)) and this is why they cannot be fixed relative to the earth; the duration of such a pulse's passage through a practically geostationary satellite ($u_{sat} \approx 1.6$ km sec^{-1}) is less than 1/100 sec, and the Pioneer-1 magnetometer was not able, according to its technical data, to register such rapid processes. But the very speed of these processes allows to register them not by a rotating but by a fixed coil in which such a pulse induced a substantial electromotive force (EMF).

In a turbulent plasma around the magnetosphere the unperturbed magnetic field is $\sim 10\gamma$ ($H_{0\ aver} = 5\gamma$, but at turbulent motion the fluctuation of the field is of the order of itself, that is $H_{0,\max} = 10\ \gamma$). At $n_0 = 5$ cm^{-3} we obtain the upper threshold of electron energy (section 1 (5)): $E_{max} =$ 45 kev.

The proper geometry (solar plasma flow along the magnetic field, $u_0 \parallel H_0$) and the plasma velocities required for parallel pulses ($u_{0\ max} \sim u_{0\ aver} + \Delta u$, $\Delta u \sim u_{0,\ aver} \sim 400$ km sec^{-1}, $u_{0,\ max}/v_A \sim 20$) in the process of turbulent large-scale pulsations ($R_H \sim 10^3$ km) is also materialized (see [14–16]) in the turbulent transitional region on the subsolar side, as well as in the magnetic tail. The emerging pulses, having attained $\lambda_+^2 = 0.5$, are soon tipped over, pouring out the particles accelerated in them. The nonlinearity of plasma flow leads in this way to magnetic field gradient increase, and hence to the appearance of electric fields accelerating the particles.

According to measurements on the AES "Injun-3" [17] the curves of soft ($E \gtrsim 10$ kev) and hard electrons' ($E \gtrsim 50$ kev) count as a function of time coincide in their shape, that is, hard electrons are accelerated by the same mechanism as soft electrons.

Pulses in 400γ may penetrate to geocentrical distances $r \sim 3R_E$, accelerating the particles inside the magnetosphere.

The upper energy threshold E_+ of electrons accelerated in pulses is determined from the relativistic theory: $E_+ = mc^2\sqrt{1+\lambda_+^2 r^2}$, at the same time $r < \delta < 4$, that is, $E_+ \leqslant 3mc^2 = 1{,}5$ Mev. Such high values as $v_A \gtrsim 650$ km/sec and the generation of hard electrons are possible inside the magnetosphere during magnetic storms, and also on the sun.

Any change of angle between H_0 and u_0 in the solar wind changes the structure of the transitional region, and though the energy of the interplanetary field is much less than the kinetic energy of the solar plasma, but the transition conditions of the latter, for example, from ions to electrons, (acceleration of electrons) are determined precisely by this field, that is, its direction and magnitude.

At Mach numbers $\mathfrak{M} > 1/\sqrt{2}\sqrt{M/m}\cos\theta$ $(u > u_{0,\text{крит}})$ solitary pulses, and alongside with them the shock wave, tip over, the motion becomes "two-fluid", electrons are not more extensively heated, but ions are. In the near-ground plasma $v_A \sim 50$ km/sec and u_0, crit $= (1 \div 1.5) \cdot 10^3$ km/sec. If $\cos\theta \neq 1$, u_0, crit $< 10^3$ km/sec. When the flow velocity u_0 rises, or the angle 0 between the interplanetary magnetic field H_0 and u_0 increases (and such variations take place systematically at the boundary of interplanetary field sectors [18] and sporadically, every few hours [16]), the head wave tips over.

The acceleration in solitary pulses is by no means the only acceleration mechanism. (For other acceleration mechanisms, see [19 – 21]).

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REFERENCES

1. Sonett, C., and Abrams, I.: J. Geophys. Res., 68, 1233, 1963

2. Adlam, J., and Allen, J.: Phil. Mag., 3, 488, 1958

3. Sagdeyev, R. Z.: Sb. "Voprosy teorii plazmy," vyp. 4, Atomizdat, 1964

4. Gintsburg, M. A.: Kosmich. issled., 2, 64, 1964

5. Kazantsev, A. P.: (ZHETF), 46, 1293, 1963

6. Gintsburg, M. A.: Phys. Rev. Lett., 14, 625, 1965; 16, 1966; Gintsburg, M. A.: Kosmich. issled., 3, 340, 1965

7. Saffman, P.: J. Fluid. Mech., 11, 16, 1961

8. Freeman, J., Van Allen, J., Cahill, L.: J. Geophys. Res., 68, 2121, 1963

9. Ivanov-Kholodnyy, G. S.: Space Res., 5, 19, 1965

10. Anderson, K., and Milton, D.: J. Geophys. Res., 69, 4457, 1964

11. I. G. Bulletin, No. 84, 1, June, 1964

12. Gringauz, K. I. i dr.: Dokl. A. N. SSSR, 131, 1301, 1960

13. Tverskoy, B. A.: (ZHETF), 42, 833, 1962

14. Wolfe, J., Silva, R., Myers, M.: Preprint on IMP-II, (COSPAR, 1965)

15. Cahill, L.: Preprint on "Explorer 14" (COSPAR, 1965)

16. Ness, N., Scearce, C., Seek, J.: J. Geophys. Res., 69, 3531, 1964

17. Fritz, T., and Gurnett, D.: J. Geophys. Res., 70, 2485, 1965

18. Ness, N., and Wilcox, J.: J. Geophys. Res., 70, 1965

REFERENCES (Continued)

19. Skuridin, G. A., and Pletnev, V. D.: (UFN), 45, 605, 1965

20. Pletnev, V. D., Skuridin, G. A., Shalimov, V. P., Shvachunov, I. N.: Sb. "Issledovaniya kosmicheskogo prostranstva." Izd-vo "NAUKA," str. 285, 1965

21. Tverskoy, B. A.: Ibid. 314

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