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ENERGETIC CRITERIA OF ARTIFICIAL MAGNETOSPHERE FORMATION

S. A. Nikitin and A. G. Ponomarenko

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Analyzing the efficiency of the use of explosive methods in space, which are presently considered as a means for the antiasteroid protection of the Earth [1, 2] and as a possible way of exerting an effect on the Earth's ozone layer with the aim of restoring it [3], it is important to determine the scales of magnetospheric disturbances related to expansion of a giant high-energetic plasma cloud formed in the place of explosion [4, 5]. As an estimation, we neglect the influence of the background plasma [6] and restrict ourselves only to the interaction of the plasma products with the magnetic field, considering their expansion at the initial time moment to be spherically symmetric and their velocity to be nearly equal to or less than Alfven's velocity (inside the magnetosphere $\lesssim 10^8$ cm/sec [7]). The problem is close to the known fundamental problem of magnetosphere formation as a result of the interaction of the magnetic geodipole with the solar wind [8] and can be resolved within the scope of a common hydrodynamic approach.

Using the ideal MHD-approximation, we consider deceleration of an expanding diamagnetic plasma in the field of a point magnetic dipole with moment $\mathbf{m}$ as a function of the joint initial kinetic energy of particles $\mathcal{E}_0$. Earlier [9], we established the dependence of the boundaries of the deceleration region (DR) and of the nature of plasma motion on the energetic interaction parameter $\text{æ} = 3\,\mathcal{E}_0\,R_0^3/\mathrm{m}^2$ (R_0 is the distance from the dipole to the explosion location). The case of extremely high magnitudes of this parameter ($\log \text{æ} \gtrsim 1$) is investigated below, the explosion-induced magnetospheric disturbances being comparable or considerably greater than the effect of the "solar wind" pressure.

The characteristic deceleration radius r_* of the plasma front in the direction to the dipole from the explosion point located in the equatorial plane can be evaluated from the energetic balance equation, which is representable in a sector approximation and in the approximation of self-similar expansion of a plasma volume element with a uniform particle density distribution [9, 10]:

$$\mathcal{E}_0 - \frac{1}{2}\int_0^{r_*} \mathbf{H}_s^2\, r^2\, dr = \mathbf{H}_s^2\, r_*^3/40. \tag{1}$$

Here the integral describes the work of deceleration forces as a result of interaction of surface currents induced in plasma with the external magnetic field; the right member is the internal (radial) motion energy remaining in the given element of the plasma volume and determined from the balance of the kinetic and magnetic pressures. The disturbed field on the cloud boundary $|\mathbf{H}_s(r)|$ can be approximated by the expression for the angle-dependent mean-square field on the surface of a superconducting sphere placed into a uniform magnetic field [10]. The latter, according to the sense of the approximation used, coincides, in magnitude and direction, with the local dipole field $\mathbf{H}_d(\mathbf{r})$ [9]:

$$\mathbf{H}_s^2 \approx \frac{3}{2}\mathbf{H}_d^2.$$

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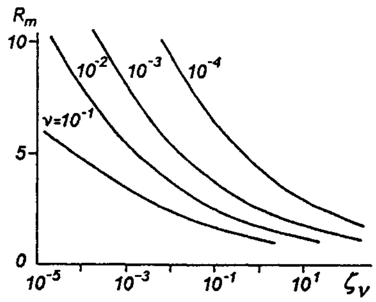

Fig. 1

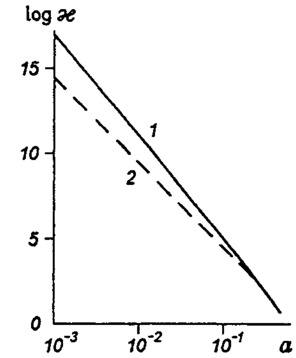

Fig. 2

Integrating (1) in view of the explicit dependence $\mathbf{H}_d(\mathbf{r})$ and using the definition of the parameter æ, we obtain the energetic balance equation in normalized form

$$æ = \frac{9}{4}\left(\frac{a^{-3}}{3} - \frac{a^{-4}}{2} + \frac{a^{-5}}{5} - \frac{1}{30}\right) + \frac{9}{80}\frac{(1-a)^3}{a^6}, \tag{2}$$

where $a = 1 - r_*/R_0$ is the relative (in units of R_0) spacing between the dipole and the frontal stop point of the plasma front. Equation (2) is sufficient to determine the size a at various combinations of geometrical, R_0, and energetic, $\mathcal{E}_0$, factors of explosion and the dipole moment magnitude $\mathbf{m}$, incorporated in one parameter æ. Nevertheless, to take into account the finite sizes of the dipole field source, having, for example, a spherical form with radius R_d (for the Earth $R_d = R_E \approx 6400$ km), it is convenient to "split" the parameter æ by introducing an additional geometrical factor $\nu = R_d/R_0$ and the modified energetic parameter

$$\zeta_\nu = \frac{\mathcal{E}_0}{2\mathcal{E}_*}[1 - (1 + 9\nu^2)^{-1/2}].$$

The latter is equal to the ratio of the energy of the plasma, moving into a solid angle, at which one can see from the explosion point a spherical region around the dipole with radius $3\,R_d$, to the characteristic energy magnitude $\mathcal{E}_* = \mathrm{m}^2/3\,R_d^3$, constituting the dipole magnetic energy in a spherical layer $R_d \leqslant R \leqslant 3\,R_d$ with an accuracy of 4%. The farther the spherically symmetric explosion from the dipole ($\nu \to 0$ at $\mathcal{E}_0 = \text{const}$), the less the magnetic field resistance to relative propagation of the plasma front (in units of R_0). On the other hand, fixing ν, one can change ζ_ν and, hence, the size a at the expense of change in $\mathcal{E}_0$. Using the ratio

$$æ = \mathcal{E}_0/\mathcal{E}_*\nu^3,$$

from (2) a family of curves $\nu = \text{const}$ is constructed in Fig. 1 on the plane $\zeta_\nu, R_m = a/\nu$, where R_m is the distance between the dipole and the stopping boundary (in units of R_d). These curves enable one to carry out an analysis of the magnetospheric disturbance scale relative to the dipole size as a function of the energy $\mathcal{E}_0$ and location ν of the explosion.

At energy magnitudes $\zeta_\nu \ll 1$, for computation of an approximate form of DR in various sections one can use the method of sector (differential) balance of the initial energy and the work of ponderomotive forces. In particular, in Eq. (2) we neglect the term that describes the contribution of the pressure balance. For comparison, the dependences $\log æ(a)$ with (curve *1*) and without (curve *2*) regard for this factor are shown in Fig. 2. If the plasma moves to the dipole in near-crosswise directions to the disturbed force lines of the dipole field, we can neglect the pressure balance up to $\log æ \lesssim 10$, where the computational error of the value of a reaches $\sim 50\%$.

For the case of an equatorial injection, the appropriate equation of the DR boundary in an equatorial section has the form [9]

$$æ = 3 \int_0^{\xi_*} \frac{\xi^2 \, d\xi}{(1 + 2\xi \cos\varphi + \xi^2)^3}. \tag{3}$$

Here $\xi_*(\varphi) = r_*(\varphi)/R_0$ is the dimensionless deceleration radius; φ is an angle formed by the radius-vector $\mathbf{r}_*$ and the dipole–explosion direction.

Using (3), we shall consider the approximate behavior of DR at $æ \to \infty$. According to [9], at $æ \gtrsim 1/10$ the plasma does not undergo marked deceleration in the direction of angles $|\varphi| \geqslant \varphi_0$, where φ_0 is determined by the expression

$$æ = 3 \int_0^{\infty} \frac{\xi^2 \, d\xi}{(1 + 2\xi \cos\varphi_0 + \xi^2)^3} = \frac{3}{16 \sin^5 \varphi_0} [2\varphi_0(2 + \cos 2\varphi_0) - 3 \sin 2\varphi_0], \tag{4}$$

in other words, in the cone with a half-angle of opening φ_0 (Fig. 3) the plasma propagates in the "blow-out" regime (at $æ \ll 1/10$ the regime of "quasi-trapping" of the plasma by the dipole field at a scale of $\sim R_0\, æ^{1/3}$ takes place). In the cone, supplementing the above-mentioned solid angle up to 4π, with the opening angle $\alpha = \pi - \varphi_0$, the idealized plasma, on the contrary, does not penetrate beyond the deceleration boundary, which at $æ > 3\pi/16$ is a line with a negative curvature ($\varphi_0 > \pi/2$) relative to the injection (explosion) point. Thus, with an increase in the plasma energy the DR surface will envelop the dipole, which gives such a model a nonstationary structure that is closer to the actual form of the Earth's magnetosphere in its frontal side turned to the Sun.

Let us introduce a parameter b, which is equal to the ratio of the magnetosphere cross size (Fig. 3) to the radius R_0. The parameter a is determined from (2) with the rejected last term on the right side (approximation $\log æ < 10$):

$$æ \simeq 3\left(\frac{a^{-3}}{3} - \frac{a^{-4}}{2} + \frac{a^{-5}}{5} - \frac{1}{30}\right). \tag{5}$$

As in (3), the factor 3/4 [9] before the bracket in (5) is replaced by 1. Equating (4) to (5), we get ($æ \to \infty$, $\alpha \to 0$)

$$b/a = (15\pi/8)^{1/5} \approx 1.4.$$

Thus, at $æ \to \infty$, the DR cone, or the "artificial magnetosphere," tends to "collapse" in a beam with the vertex in the point dipole at the mentioned ratio of sizes a and b, which is close to the one in the known two-dimensional magnetosphere models [11].

By taking into account the finite size of the dipole R_d, which under natural conditions coincides with the Earth's radius ($R_d = R_E$), one obtain the following restrictions on the explosion energy, related to the geometrical features of DR.

First,

$$b \gtrsim \nu = R_d/R_0$$

or

$$\alpha \gtrsim \alpha_\nu = \arctan \nu.$$

From the relationship (4) between α and $æ$, we obtain the appropriate energetic condition

$$æ \lesssim æ_b = \frac{3}{16 \sin^5 \alpha_\nu} [2(\pi - \alpha_\nu)(2 + \cos 2\alpha_\nu) + 3 \sin 2\alpha_\nu].$$

Second,

$$a \gtrsim \nu$$

or, taking into account (5),

$$æ \lesssim æ_a = 3\left(\frac{\nu^{-3}}{3} - \frac{\nu^{-4}}{2} + \frac{\nu^{-5}}{5} - \frac{1}{30}\right).$$

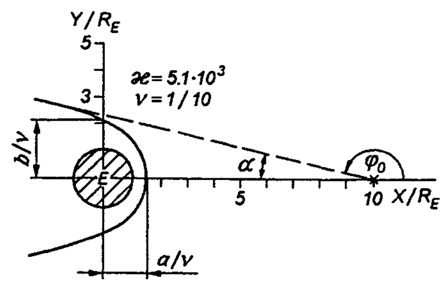

Fig. 3

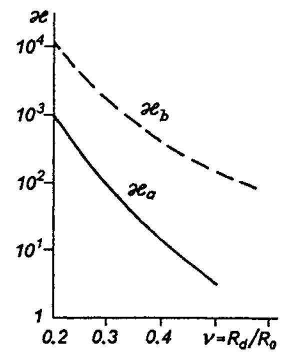

Fig. 4

From analysis of the functions $æ_a(\nu)$ and $æ_b(\nu)$ in Fig. 4 in the interval $0.1 < \nu < 1$, and also from the results of analysis of their asymptotes, we obtain the following restriction on the explosion energy:

$$æ \lesssim æ_a(\nu) = \min\{æ_a, æ_b\},$$

which is connected with the requirement that the deceleration boundary at the frontal point should be located a distance $R > R_d = R_E$ from the dipole.

Let us consider a numerical example whose parameters meet the critical range of possible applications of global space explosions to the purpose mentioned above. Let the kinetic expansion energy of plasma in the quantity $\mathcal{E}_0 = 10^3$ Mtons be released on the magnetosphere boundary, i.e., at $R_0 = 10R_E$ ($\nu = 0.1$). For the appropriate magnitude $\zeta_\nu \simeq 0.12$ ($æ = 5 \cdot 10^3$) from Fig. 1 we find $R_m = 1.7$, and, hence, the explosion energy is a critical value in this case. According to (3), for $æ = 5 \cdot 10^3$ the equatorial section of DR is shown in Fig. 3 in relative cartesian coordinates X/R_E, Y/R_E with "magnetopause" size $R_m = 1.6$. The form and sizes of the "magnetosphere" in the meridional section of DR [9] are little different from the equatorial case within the scope of the approach stated.

Thus, the dependence of the parameters of the artificial magnetosphere formed by the plasma cloud of a space explosion on the energy ($\sim \mathcal{E}_0$) and location of this explosion is obtained. We have established a criterion for the excess of the pressure balance effect over the effect of the work of the deceleration force in determining the plasma front stopping boundary in the direction to the dipole ($\log æ \gtrsim 10$). We have obtained the critical plasma energy parameter $æ_a$, related to the approach of the artificial magnetopause to the Earth's atmosphere. In particular, for explosions on the natural magnetosphere boundary an energy level of $\mathcal{E}_0 \sim 10^3$ Mtons ($4 \cdot 10^{18}$ J) corresponds to it.

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