Numerical modeling of behavior of high-energy plasmoid in upper ionosphere and geomagnetic field

A.S. Kholodov, Y.A. Kholodov[1], E.L. Stupitzki, A.Y. Repin[2]

[1]*Department of Applied Mathematics, Moscow Institute of Physics and Technology*
[2] *Central Institute of Physics and Technology, Sergiev Posad, Russia*

In the paper the numerical investigation of parameters of the plasmoid expands into rare ionosphere and the geomagnetic field is performed. The range of the initial energy change is $10^{19}\div10^{22}$ [erg] and of the mass change is M ~ $(0.3\div1)\cdot10^{6}$ [g]. These ranges conform to the well-known large-scale geophysical experiments “Argus” and “Starfish”. The all stages of the development of the plasma flow are considered: from 10^{-6} up to hundreds of seconds.

As the content of physical processes essentially varies, the developed numerical algorithm has complex structure and contains the following computational blocks. Radiation-gas-dynamics block allows determining the emission of thermal radiation from plasma at the initial stage of its expansion ($t \le 2\cdot10^{-5}$ [s]) on the basis of diffusion approximation and the amount of energy which remains in plasma. The calculations have been done for the different initial energy q [erg] and mass M_0 [g] of aluminium plasma. They are shown that the outgoing into radiation part of the initial energy is $\chi = \exp\left(-3{,}219/X^{n}\right)$, where $X = q/(M_0 \cdot 4.2\cdot10^{13})$, $n = 0.281 + 0.0713\cdot \lg X$ and $X \ge 1$. After the radiation stage plasma has the energy $(1-\chi)\cdot q$ which is divided on the internal, kinetic and ionization parts.

Another block calculates inertial scattering of plasma. The ionization structure of plasma is formed ($t \le 2\cdot10^{-3}$ [s]) as a result of nonequilibrium processes. This structure further determines the interaction between plasma and rarefied ionosphere and the geomagnetic field. As a result plasma is braking.

The calculations have shown that the averaged asymptotic value of the degree of ionization is $\alpha_\infty = \left(n_e/n\right)_\infty = 13\cdot\exp(-10.38\cdot X^{0{,}02-0{,}09\lg X})$. Thus the both parameters are mainly determined by the specific energy q/M_0.

At the stage of braking ($t \le 1$ [s]) one-dimensional spherical-symmetric plasma flow transforms into a three-dimensional one. At this stage if the classical diffusion coefficient is used in calculations the geomagnetic field becomes entirely superseded from plasma.

On the fig. 1 is shown the space distribution of the plasma electron and ion temperatures and magnetic field for q=$4.2\cdot10^{19}$ [erg] and M_0=10^{6} [g].

For the later stage ($t \ge 1$ [s]) we developed a three-dimensional MHD code on the base of the explicit monotone scheme high (2-3) order of approximation [1]. In this work we proved the adaptability of MHD approximation for calculations of all stages of plasma dynamics. The code uses the split procedures in the space and by the physical processes (gasdynamics and magnetodynamics steps). On the gasdynamics step we use the analog of the Godunov's scheme [2] with (2-3) order of approximation. For the magnetodynamics step we use the characteristic-based scheme [3]. This approach lets us to calculate the big discontinuities of the MHD flows in domain of integration.

The MHD approach is useful here because of the big space scale of plasma distribution and the small larmor radiuses of electrons and ions. The parameters and space scale of the problem are changing up to few orders during the problem solving. For this reason integration domain is also rebuilding by periodical reconstruction of the Cartesian Euler grid.

The plasma flow moving produces MHD perturbation that can spread out onto very long distances. If we get explosion on the altitude $h < 120$ [km] the air density is high and the size of plasmoid is not too large. If we get explosion on the altitude $h \geq 1200$ [km] the resulting plasma flow spreads out on too very long distances and these distances can be comparable with typical scale of the geomagnetic field changes. That leads to reducing of the energy flow density in the MHD perturbation. So the main goal of the work was to create 3D MHD code which allows us to calculate the characteristics of perturbed region for the explosions on the altitudes $h = 150 \div 1000$ [km].

In work [4] the 3D numerical simulations of the explosion on the altitude $h = 150$ [km] were done for the time up to 6 seconds first. On this altitude air density is high enough so the above-mentioned numerical scheme gives us the acceptable results (fig. 2). But for the extension of time and altitude range the 3D numerical algorithm had been elaborated. In particular, we have to adapt the algorithm of grid reconstruction in accordance with MHD perturbation spreading. As a result, we were able to essentially extend spatio-temporal range of the computed parameters.

On the fig. 3 is shown the structure of perturbed domain on the time moment $t = 14.6$ [s] in two mutually perpendicular directions. On the top it is shown the ratio of the calculated density to the density of unperturbed atmosphere. From the bottom it is presented the magnetic field vector projection B_{xz} onto the meridional plane (on the left) and the latitudinal plane (on the right).

The plasma has too much larger angular spread in the meridional plane then in the latitudinal plane. It is testify that the plasma flat jet is possible in this situation with the ejection of some plasma flow onto very large altitudes. On the fig. 4-5 is shown the common structure of perturbed domain on the long time moments $t = 36$; 80; 163 [s]. For hundreds seconds MHD perturbation becomes global and at the same time the plasma continues to spread out. However the plasma structure is highly non-homogeneous and this is because of formation of the instabilities and jet streams which lead to the plasma stratification.

If we get explosion on the altitude $h = 1000$ [km] the Alfven wave speed is faster then the initial speed of a MHD perturbation and it reaches the boundaries of the computational domain very fast. It demands from the numerical algorithm permanently to enlarge computational domain. On the fig. 6 is shown the structure of perturbed domain on the time moments $t = 16.6$ [s] in the magnetic meridional plane. The colour shows the parameters distribution in the meridional plane for the density (divide by the density of unperturbed atmosphere, onto the top left), specific internal energy - $\varepsilon / \varepsilon_*$ (onto the top right), velocity projection onto meridional plane $y = 0$ - V_{xz} / V_* (from the bottom left) and magnetic field projection onto meridional plane $y = 0$ - B_{xz} / B_* (from the bottom right). The parameters specific values are $\varepsilon_* = 1.46$ [km^2/s^2], $V_* = 1.21$ [km/s], $B_* = 0.0014$[Gs]. Initial radius of the perturbed domain is $R_0 = 25$ [km], the density is $\rho_0 = 8.06 \times 10^{-15}$ [g/cm^3], the temperature is $T_0 = 6.1 \times 10^{-4}$ [K] and the linear velocity profile has $V_0 = 1550$ [km/s].

In the region included by the global MHD wave the gas velocity and geomagnetic field have essential perturbations. Out of the plasmoid region the temperature of MHD wave is changing a little. For the calculations on the longer times it is necessary to allow that some plasma part is going away through the boundaries of a computational domain to the outer space.

The performed computations showed very comprehensive facilities of the developed numerical algorithm. This algorithm lets us to solve one of the more complicated classes of the plasma-dynamics problems. These are the problems of large-scale explosion processes then the parameters of the problem can change on many orders of values.

References

1. Y.A. Kholodov and J.V. Vorobjev, About One Method of Numerical Integration of Discontinuous Solutions in Gas Dynamics, *J. Math. Mod.*, 8, 77 (1996).
2. S.K. Godunov, A Finite Difference Method for Numerical Computation of Discontinuous Solutions of the Equations of Fluid Dynamics, *Mat. Sb.* 47, 271 (1959).
3. A.S. Kholodov, Construction of Positive Definite Difference Schemes for Hyperbolic Equations, *J. Comput. Math. and Phys.,* 18, 1476 (1978).
4. A.S. Kholodov, Y.A. Kholodov, E.L. Stupitzki, A.Y. Repin, Numerical Modeling of Behavior of High-Energy Plasmoid in Upper Ionosphere, *J. Math. Mod.*, V. 16, i. 8, p. 3-23 (2004).

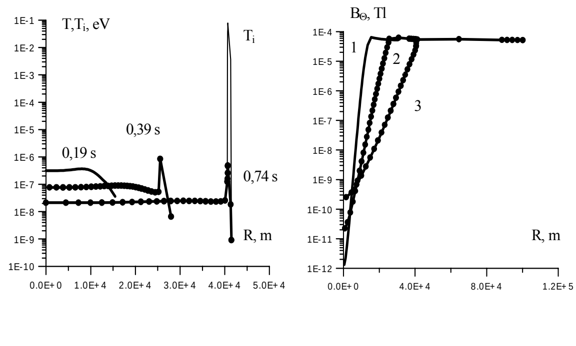

Fig.1. The radial distributions of the main plasma parameters at the deceleration stage in the different time moments.

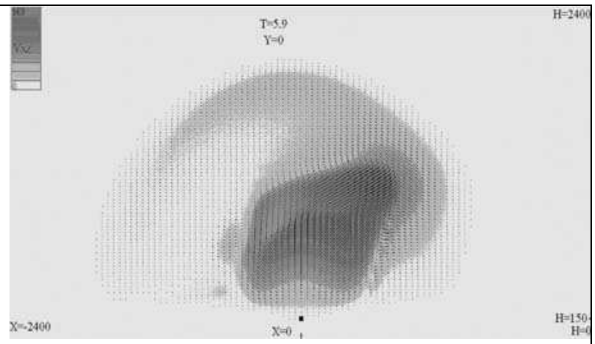

Fig.2. The velocity distribution in the middle meridian plane on the time moment $t = 5.9$ [s].

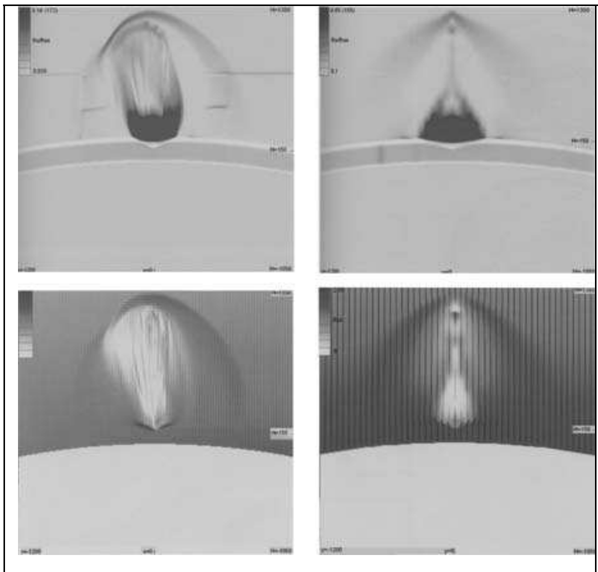

Fig.3. The distributions of the dimensionless parameters in the middle meridian plane (y=0, on the left) and in the latitudinal plane (x=0, on the right) on the time moment $t = 14.6$ [s].

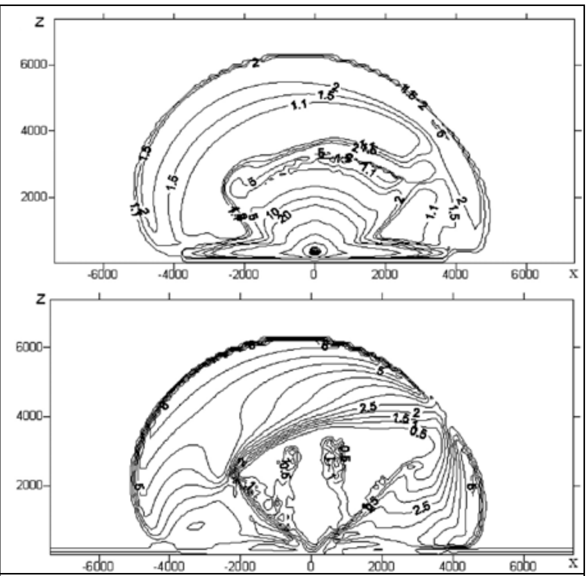

Fig.4. The isolines of the main parameterso (a –density and b - projection of the magnetic field vector) in the perturbed region on the time moment $t = 36$ [s].

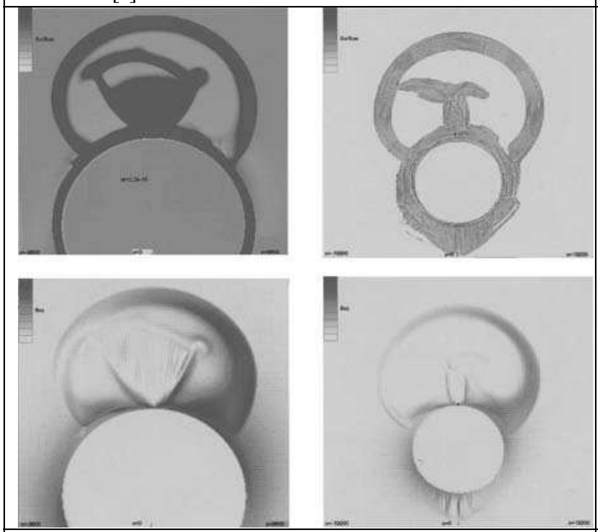

Fig.5. The distributions of the density and magnetic field in the meridian plane for the explosion on the altitude 150 [km] for $t = 80$ [s] – (a) and $t = 163$ [s] - (b)

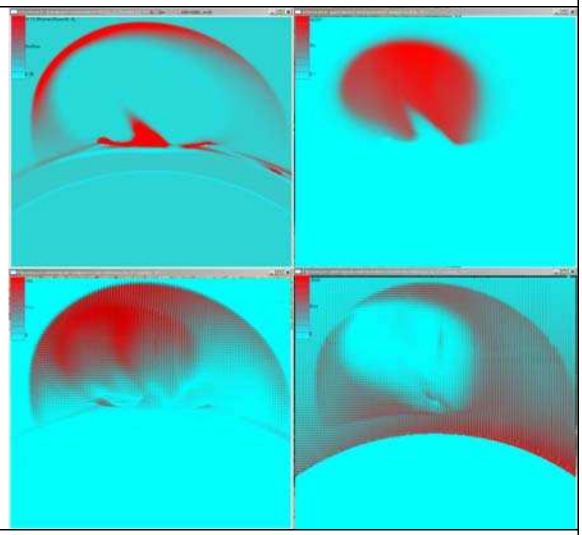

Fig.6. The parameters distributions in the meridian plane on the time moment $t = 16.6$ [s].