Modeling of the interaction of charged micro satellite and thermal plasma by molecular dynamics method

Zinin, L. and Sharamet, A.

Immanuel Kant Baltic Federal University, Kaliningrad, Russia

INTRIDUCTION.

The presence of the electric charge of the satellite is a significant factor in the experimental measurements of near-Earth space plasma. The effect of this interaction on the results of measurement and processing are widely discussed, is being discussed in the literature (see., e.g., analyzing satellite Auroral probe measurements [1-3]). There are measurement model, including taking into account the temperature anisotropy [4-6]. As the analysis of experimental measurements and modeling of the thermal plasma measurements clearly indicate that the positive potential of the satellite greatly distorts the spatial pattern of the measured ion fluxes, and in conjunction with the temperature anisotropy can distort angles of arrival of ions [6]. Such bias can significantly affect the processing of data obtained by the direction of ion flow, and consequently on the value of field-aligned velocity of the ions and the speed of the magnetospheric convection.

Attempts have been to determine the theoretical the potential of the satellite, including by analyzing the current balance on the surface of the spacecraft. Widely known NASA model - NASCAP-2K [7], Japan - MUSCAT, ESA - SPIS [8,9] (their comparison in [10]).

Distortion of mass - spectrometric measurements of thermal plasma by charged satellite is one of the main problems for experimental studies low-energy plasma. To reduce the electric potential and to minimize surface currents using there are , for example, equipotentialization satellite surface [11]. There are a active methods of reducing electric potential. For example, in a project INTERBALL on the satellite Auroral probe for this purpose served RON experiment [12,13]. However, reducing the electric potential is likely to zero technically impossible, moreover, the capacity reduction methods themselves introduce significant perturbations in the surrounding plasma and affect the correct operation of the devices.

Some model satellite and plasma interactions were based on hydrodynamic approach and PIC method [14-16]. However, the use of hydrodynamic approach obviously limited to the case of dense plasma, and a PIC method is a compromise between the hydrodynamic approach of direct interaction and the simulation of "all to all particles." The molecular dynamics method (MDM) can be used for any parameters of thermal plasma, regardless of the magnitude of the Debye radius and, in spite of its computational complexity, can be a key to simulate the electric field distribution, the distribution of particle concentrations, their trajectories near the spacecraft.

DESCRIPTION OF THE MODEL

Classical molecular dynamics method is now widely used for the simulation of physical, chemical and biological systems. The first attempt at the use of MDM can be regarded as the work of Alder and Wainwright [17, 18]. Review of MDM in physics and chemistry is given in [19]. In the classic MDM quantum and relativistic effects are neglected, and the particles move according to the laws of classical mechanics.

Preliminary results of modeling the distribution of protons around a charged satellite in a 2D approach considered in [20,21]. Consider the problem of 3D modeling of charged microsatellite and thermal Maxwellian plasma interraction in detail. Assume that a plasma of consists of protons and electrons. Each particle move due to Lorentz force:

$$m\mathbf{a} = q\mathbf{E} + q[\mathbf{v} \times \mathbf{H}] \qquad (1)$$

here m - mass of a proton and an electron, q, **a**, **v** - its charge, acceleration and speed, respectively, **E** - electric field strength, **H** - magnetic field. The electric field at any point in the simulation area is calculated according to Coulomb's law, taking into account all n particles (electrons and ions) in the computational modeling region and electric field $\mathbf{E}_{sat}$ due to charge of satellite:

$$\mathbf{E} = \sum_{i=1}^{n} \frac{q_i}{4\pi\varepsilon_0 r_i^2} \frac{\mathbf{r}_i}{r_i} + \mathbf{E}_{sat} \qquad (2)$$

Thus, for each particle one can find the value and direction of force in the right side of the equation (1) to obtain the positions and velocities of the particles in the new time level.

The particles at the initial time of simulation are evenly distributed in space and have a Maxwell velocity distribution.

$$F(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} exp\left(-\frac{mv^2}{2kT}\right) \qquad (3)$$

where v - velocity of the particle, m - its mass, k - Boltzmann constant, T - temperature.

The number of particles N in the speed range [v, $v + dv$] for the density n is calculated as

$$N = \int_{v}^{v+dv} 4\pi n v^2 F(v) dv \qquad (4)$$

The model domain is a cube with edge of 1 m. In its center there is a microsatellite - ball of radius 5 cm.

The plasma velocity is directed along the x-axis. The magnetic field in this calculation assumed to be zero. The temperature of both protons and electrons is the same and equal to 5000 K. The total number of particles in the simulation field is 10^7. Therefore, the unperturbed concentration of protons and electrons is n = 5

cm^{-3}. plasma velocity relative to the satellite assumed to be 10 km/sec and 20 km/sec, and the potentials of the satellite U_{sat} +5 Volts and +10 Volts for the calculations presented below. The time step was 10^{-8} seconds. This small value due to the need to accurately calculate the trajectories of electrons whose thermal velocities of the order of 500 km/sec. Spatial step for the selected values of the time step does not exceed 5 mm.

For the numerical simulation system comprising such a large number of (~ 10^7), you must have significant processing power, allowing to realize parallel computing. In addition to the technological component, it requires the development of a special type of algorithms that optimize the use of memory and data exchange in the accounts. Description applied algorithms in this article will be published in a separate paper.

RESULTS OF NUMERICAL MODELING

Figures 1-4 show the results of numerical modeling of the interaction of a charged satellite and thermal Maxwellian plasma. Presents the spatial distribution of the concentration of hydrogen ions in the plane XOZ (y = 0) after 3500 time steps beginning from the numerical experiment, which represents 3.5 10^{-5} sec from the time the initial modeling. Each point represents a proton, crossed the XOZ plane of the two time steps. Initial conditions were only a spatially uniform distribution of protons and electrons with isotropic velocities Maxwellian distribution corresponding to the temperature 5000 K. The plasma relative satellite velocity V and consisted of 10 km / sec (Fig. 1 and 3) and 20 km / sec (Fig. 2 and 4) along the horizontal axis OX. U_{sat} satellite potential of +5 Volts (Fig. 1 and 2) and +10 Volts (Figures 3 and 4), was adopted.

In all the figures there is a strongly marked ion shadow of microsatellite. Spatial characteristics of the shadows become more clear with increasing relative velocity of the plasma and satellite and the satellite's positive potential. Thus, for a plasma speed of 10 km/s, and the electric potential of the satellite 5 Volts (Figure 1), the characteristic dimensions of the shadow of the satellite ion about 20 cm. Furthermore, before a satellite is also present in the region of a few cm greatly reduced ion concentration. By increasing the relative speed of 20 km/s at the same value of the satellite electric potential (Figure 2) ion shadow increases up to half of meter (maybe further, but we are limited in spatial scales of modeling the field).

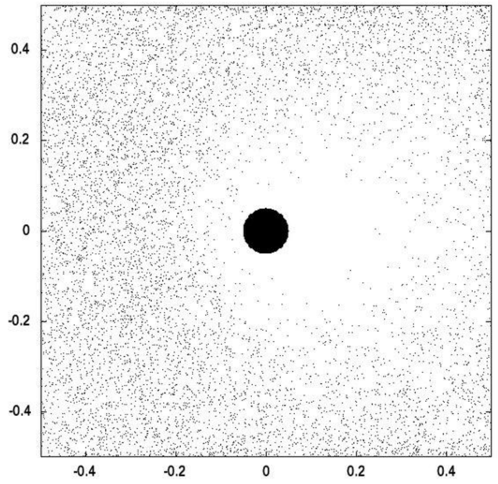

Fig.1

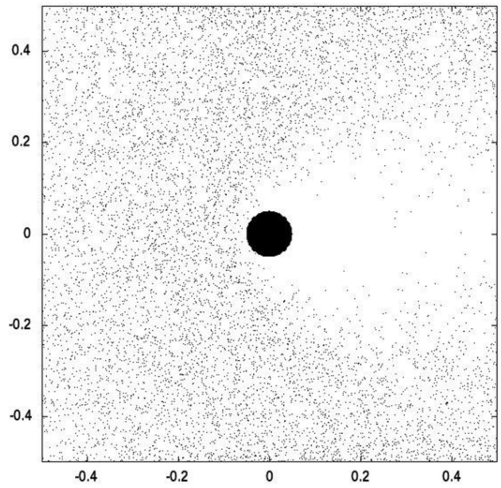

Fig. 2.

The spatial distribution of the concentration of hydrogen ions. The axes - the distance from the center of the microsatellite in meters. The plasma velocity is directed along the horizontal axis OX. V = 10 km / s (left figure 1) and 20 km/s (right figure 2). U_{sat} electric potential of satellite =+ 5 Volts

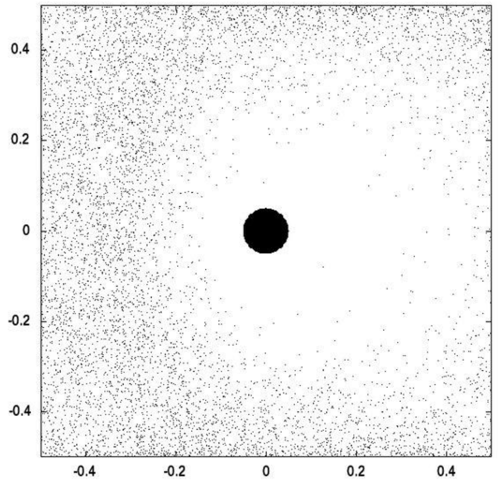

Fig. 3

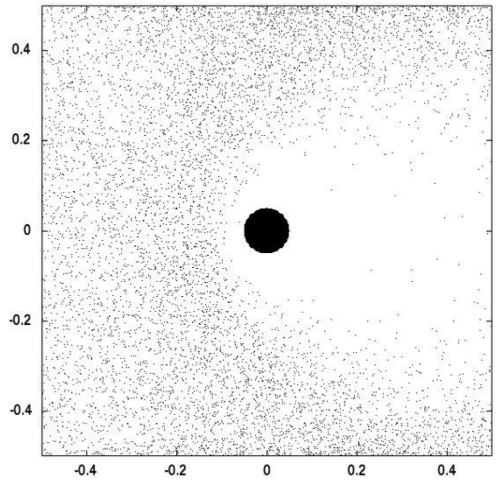

Fig. 4

The same as on Fig.1 and 2, but for U_{sat}=+10Volts

Consider the effect of increasing the positive potential of the satellite. When plasma speed of 10 km/sec region of reduced concentration increases significantly as a companion to and behind it. Before the satellite at a distance of about 10 cm concentration drops almost to zero. Shadow is greatly increased in the transverse dimension and the satellite extends almost to the boundaries of modeling region. A different picture is observed for twice the relative velocity of the satellite and plasma. Directly in front of the satellite observed a thin layer (3 - 5 cm) lower concentration of protons. But just before this layer exceeds the background concentration undisturbed conditions. The shadow of the satellite are clear and has about half a meter in diameter. The length of the shade clearly exceeds the spatial domain simulations and probably reach the meter and more. As expected pattern is symmetrical along axes OY (not shown), and OZ.

Thus, the numerical simulation results show a significant distortion of the spatial distribution of thermal ions in the presence of the positive potential of the satellite, which are expressed in the presence of an area of low concentration to the satellite and ion shadows behind him. These distortions are all the more pronounced, the greater the relative velocity of the satellite and plasma and the magnitude of the positive potential of the satellite.

This work was made by support of Russian Foundation for Basic Research, grant 15-01-00369

REFERENCES

1. *Hamelin M., Bouhram M., Dubouloz N., Malingre M., Grigoriev S.A., Zinin L.V.* Combined effects of satellite and ion detector geometries and potentials on the measurements of thermal ions. The Hyperboloid instrument on Interball // in Proc.7th Spacecraft Charging Technology Conference,23-27 April 2001.ESTEC. Noordwijk. The Netherlands. ESA SP-476. P. 569-574.

2. *Bouhram M., Dubouloz N., Hamelin M., Grigoriev S.A., Malingre M., Torkar K., Veselov M.V., Galperin Y., Hanasz J., Perraut S., Schreiber R., Zinin L.V.* Electrostatic interaction between Interball-2 and the ambient plasma. 1. Determination of the spacecraft potential from current calculations// Ann. Geophys., 2002. V. 20. N 3. P. 365-376.
3. *Hamelin M., Bouhram M., Dubouloz N., Malingre M., Grigoriev S.A, Zinin L.V.* Electrostatic interaction between Interball-2 and the ambient plasma. 2. Influence on the low energy ion measurements with Hyperboloid // Ann. Geophys. 2002. v. 20. N 3. P. 377-390.
4. *Zinin L.V., Galperin Y.I., Gladyshev V.A., Grigoriev S.A., Girard L., Muliarchik T.M.* Modelling of the anisotropic thermal plasma measurements of the energy-mass-angle ion spectrometers onboard a charged satellite // Cosmic Research. 1995. V. 33. P. 511
5. *Zinin L.V., Galperin Yu.I., Grigoriev S.A., Mularchik T.M.* On measurements of polarization jet effects in the outer plasmasphere // Cosmic Res. 1998. V.36. N 1. P. 39-48.
6. *Zinin L.V.* Modelling of thermal H+ ions on charged satellite taking into account temperature anisotropy // Vestnik IKSUR, 2009. N. 10. P. 56-63.
7. *Mandell M. J., Katz I., Hilton M. et al.* Nascap-2K spacecraft charging models: algorithms and applications // 2001: A spacecraft charging odyssey. Proceeding of the 7th Spacecraft Charging Technology Conference. 23—27 April 2001. ESTEC. Noordwijk. The Netherlands. ESA SP-476. P. 499—507.
8. *Hilgers, A., S. Clucas, B. Thiébault, J.-F.s Roussel, J.-C. Matéo-Vélez, J. Forest, and D. Rodgers* Modeling of Plasma Probe Interactions With a PIC Code Using an Unstructured Mesh, , IEEE Trans. Plasma Sci, Vol 36, No5 Part2, pp 2319-2323, DOI: 10.1109/TPS.2008.2003360, Oct 2008.
9. *Thiebault B.,·Jeanty-Ruard B.,·Souquet P.,·Forest J.,·Mateo-Velez J.-C., Sarrailh·P., Rodgers D., Hilgers A., Cipriani F., Payan D., Balcon N.·* SPIS 5.1: An Innovative Approach for Spacecraft Plasma Modeling. IEEE

Transactions on Plasma Sci,; Vol 43, No 9. DOI:10.1109/TPS.2015.2425300 Sept 2015

10. *Novikov L.S., Makletsov A.A., Sinolits V.V.*·Comparison of Coulomb-2, NASCAP-2K, MUSCAT and SPIS codes for geosynchronous spacecraft charging. Advances in Space Research; DOI:10.1016/j.asr.2015.11.003, Nov 2015
11. *Galperin Yu. I., Gladyshev V.F., Kozlov A.I et al.* Electromagnetic compatibility of scientific space complex ARCAD-3. M.: Science, 1984.
12. *Torkar K., Veselov M. V., Afonin V. V., Arends H., Fehringer M., Fremuth G., Fritzenwallner K., Galperin Yu. I., Kozlov A. I.. Perraut S., Riedler W., Rudenauer F., Schmidt R., Smit A., Zinin L. V.* An experiment to study and control the Langmuir sheath around INTERBALL-2 // Ann. Geophys. 1998. V.16. P. 1086-1096.
13. *Riedler W., Torkar K., Veselov M.V., Galperin Yu.I., Pedersen A., Schmidt R., Arends H., Rudenauer F.G., Fehringer M., Perraut S., Zinin L.V.* Experiment RON for active control of spacecraft electric potential. Cosmic Res. 1998. V. 36. N 1. P.49-58.
14. *Rylina I.V., Zinin L.V., Grigoriev S.A., Veselov M.V.* Hydrodynamic approach to modeling the thermal plasma distribution around a moving charged satellite // Cosmic Res. 2002. V. 40. № 4. P. 367-377.
15. *L. Zinin , Grigoriev S., Rylina I.* The models of electric field distributions near a satellite // Proceedings of the conference in memory of Yuri Galperin, eds:L.M.Zelenyi, M.A.Geller, J.H.Allen, CAWSES Handbook-001, Boulder, USA. pp 76-83, 2004.
16. *Kotelnikov V.A., Kotelnikov M.V., Gidaspov V.Yu. Котельников В. А., Котельников М. В., Гидаспов В. Ю.* Mathematical modeling of flow past bodies of collisional and collisionless plasma. // M.: Fizmatlit. 2010. 272 P.
17. *Alder B. J., Wainwright T. E. Phase* Transition for a Hard Sphere System // J. Chem. Phys. 1957. V. 27, P. 1208 - 1209

18. *Alder B. J., Wainwright T. E.* Transport processes in statistical mechanics / Ed. I. Prigogine. N. Y., 1958
19. *Kholmurodov H.T., Altaisky M.V., Pusynin M.V. et al* Methods of molecular dynamics to simulate the physical and biological processes // Physics of Elementary Particles and Atomic Nuclei. 2003. V. 34. N.2. P. 474-515.
20. *Zinin L.V., Ishanov S.A., Sharamet A.A., Matsievsky S.V.* Modeling the distribution of charged ions near the satellite method of molecular dynamics. 2-D approximation // Vestnik IKBFU. 2012. N 10. P. 53 – 60.
21. *Sharamet A.A., Zinin L.V., Ishanov S.A., Matsievsky S.V.* 2D modelling of a ion shadow behind charged satellite by molecular dynamics method // Vestnik IKBFU. 2013. N 10. P. 26—30.