

On the analysis of the operation of a double electrostatic layer in the ion sail mode

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Abstract. The paper presents analytical estimates and numerical calculations of the pressure on a double electrostatic layer in the ion sail regime in low-Earth orbits and in interplanetary space. An estimate of the leakage current density for the system under consideration is also given.

Introduction

A logical step in the plans for further space exploration was the development of fundamentally new propulsion systems capable of operating with minimal consumption of on-board energy sources. Such systems, in particular, include various sailing structures: film [1, 2], electric [3-6] and magnetic [7-9]. The thrust of a magnetic sail arises as a result of the magnetostatic interaction between the solar wind and an artificial magnetic field, which is generated on board the spacecraft by an electric current flowing through an electrical circuit of a given shape. In this paper, another version of an electric sail is considered – the so-called dipole drive (double electrostatic layer), proposed in [10], which structurally consists of two parallel conductive surfaces made in the form of grids of conductive filaments. The conductive surfaces are separated by an insulating gap, the design of which is determined by the necessary electrical and mechanical strength and the minimum possible effect on the electric field between the conductive surfaces. To maintain a constant potential difference between the grids, a device is connected to a negatively charged surface that emits electrons into the surrounding space.

1. Calculation method and main results

The double electrostatic layer is capable of operating in the so-called ion sail mode. When the flow of ions and electrons comes from a negatively charged surface, the

positively charged ions, entering the space between the charged surfaces, receive an inhibitory effect from the electric field between them. With a sufficiently high accelerating potential difference, these ions are pushed back out. The effect of the dipole motor on each ion is similar to an elastic collision. Thus, the dipole engine rejects the incoming ion flow without changing their kinetic energy, acting as an ion sail (Fig. 1). In Figure 1, $\mathbf{E}$ is the electric field strength in the space between

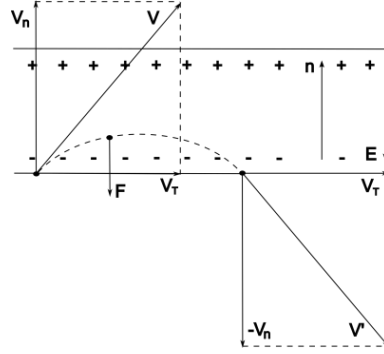


FIGURE 1. Device diagram

the grids, $\mathbf{V}$ is the velocity at the entrance to the gap, $\mathbf{V}'$ is the velocity at the exit from it, $\mathbf{V}_n$ is the normal component of the velocity. In the analytical evaluation of the ion sail, it is assumed that there is no field from the outside of the double electrostatic layer, but inside it is constant. Then the condition for the reflection of an ion with charge Z and mass m_i has the form $ZeU \geq \frac{m_i V_n^2}{2}$.

In this case, the change in the impulse of one ion will be determined by the expression $\Delta \mathbf{p} = -2m_i V_n \mathbf{n}$.

By defining the distribution of particle velocities by velocities and directions in the spherical coordinate system $dn(V, \varphi, \psi)$, it is possible to obtain a change in the impulse of the flow reflected during dt by a section dS of the conductive surface $d\mathbf{P} = -2m_i dn(V, \varphi, \psi) V_n^2 dS dt \mathbf{n}$.

The total pressure on the ion sail is obtained by integrating this value over all possible speeds and their directions.

The described approach does not take into account two important features of a real double electrostatic layer moving in a cosmic plasma: 1) charge distribution on a grid rather than on a solid plane, which leads to the penetration of an electric field into the outer space, and 2) shielding of the electric field by cosmic plasma.

Figure 2 shows the results of calculations of ion trajectories for a near-Earth plasma temperature of 10^3 K, the angle of incidence on the plane of the surface grid $\pi/6$ and a potential difference of 0.24 V. In conditions of solar wind (substorm) with a velocity of hydrogen H^+ and helium He^{++} ions of about 780 km/s, calculations have shown that it is necessary to supply a voltage of about 6700 V to the grid.

The trajectories are shown as blue solid lines, the grid is green, the flow is directed from bottom to top. According to a given ion velocity and direction distribution function, an ensemble is created to calculate the change in impulse $\Delta \mathbf{p}_k$ for the ion and the pressure on the ion sail by summing all calculated $\Delta \mathbf{p}_k$. Calculations of

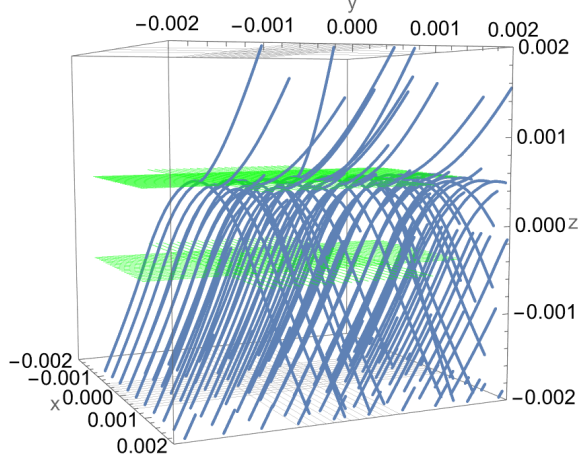


FIGURE 2. Particle trajectories

the pressure acting on the double electrostatic layer were carried out for spacecraft in low-Earth orbit and for spacecraft in near-solar orbit under the influence of the solar wind. The paper also provides an analytical estimate of the leakage current density of a double electrostatic layer in the ion sail mode $j = \frac{1}{2}n_e e \sqrt{\frac{8kT}{\pi m_e}}$ and a numerical calculation of the leakage current density was performed.

Conclusion

The efficiency of the double electrostatic layer in the ion sail mode has been evaluated. Estimates of the pressure forces on a double electrostatic layer in the ion sail regime in low-Earth orbits and in interplanetary space under the influence of the solar wind are given. Estimates of the leakage current density and the consumed electrical power of a double electrostatic layer in the ion sail mode are given. The work is supported by the Russian Science Foundation (grant No. 24-41-02031, <https://rscf.ru/project/24-41-02031/>).

References

- [1] Polyakhova E.N. Spaceflight with Solar Sail. 2-nd Edition, URSS (Lenand), Moscow, 2011. (In Russian)
- [2] Wright J. Space sailing. Abingdon: Routledge, 1992. 258 p.
- [3] Janhunen P., Sandroos A. Simulation study of solar wind push on a charged wire: Basis of solar wind electric sail propulsion // *Ann. Geophys.* 2007. Vol. 25. P. 755–767.
- [4] Janhunen P. Electric sail for spacecraft propulsion // *Journal of Propulsion and Power.* 2004. Vol. 20. N 4. P. 763–764.
- [5] Toivanen P., Janhunen P., Envall J. Electric sail control mode for amplified transverse thrust // *Acta Astronaut.* 2015. Vol. 106. P. 111–119.
- [6] Palos M. F., et al. Electric sail mission expeditor, ESME: Software Architecture and Initial ESTCube lunar cubesat E-sail experiment design // *Aerospace.* 2023. Vol. 10. P. 694–723.
- [7] Zubrin R. M., Andrews D. G. Magnetic sails and interplanetary travel // *Journal of Spacecraft and Rockets.* 1991. Vol. 28. N 2. P. 197–203.
- [8] Andrews D. G., Zubrin R. M. Use of magnetic sails for Mars exploration missions // *Papers of the American Institute of Aeronautics and Astronautics.* 1989. P. 202–210.
- [9] Zubrin R. M. The use of magnetic sails to escape from the low Earth orbit // *Journal of the British Interplanetary Society.* 1993. Vol. 46. P. 3–10.
- [10] Zubrin R. The Dipole Drive: A new Concept in Propellantless Propulsion / 70th International Astronautical Congress (IAC), Washington DC, 20-26 October 2019:

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