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Planetary magnetospheres formed by flows of hot collisionless dense plasma and kinetic plasma parameters governing topology reconfiguration

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Abstract

We consider formation of 3D magnetospheres of the magnetized exoplanets which are under action of the charged particles flow. Particles are characterized by certain shape of the velocity distribution function (VDF). New dimensionless kinetic parameters govern topolology and scales of the magnetosphere. These parameters are dependent from the VDF shape.

1. Introduction

Magnetospheres of the exoplanets - the 3D dynamic electromagnetic topological structures permanently are under the forming action from time-varying star-wind plasma flows loaded with CME clouds perturbations. Plasma flow as a medium is characterized by varying parameters describing the plasma electromagnetic properties such as dielectric and magnetic permittivity, conductivity. These parameters define the effects of electromagnetic inductive interaction of the internal magnetization of the planet $\mu(\vec{X})$ with the external plasma flow and the resulting skin by electric currents. Theory of the magnetosphere modeling and theory of magnetic topology substorm/CME transition from the open configuration with magnetotail to the closed dipolized configuration without tail is very sensitive to the methods of plasma properties definition and to the correct determination of the magnetization $\vec{\mu}(\vec{X})$ structure. Magnetization includes magnetic dipole and magnetic toroid components with their moment vectors in any orientation and any ratio. We consider 3D magnetospheres in the non-MHD terms via large scale kinetic (LSK) Vlasov/Maxwell approach to plasma where new spatial scales, new governing parameters and new functions for spatial structures determination appear.

2. Magnetospheres in 3D kinetics

The regions with high plasma β flow in the magnetospheres are the key regions for magnetic topology reconfiguration, they can occupy partly magnetosphere (Earth) and can occupy all magnetosphere (exoplanets). The exoplanets are fully transportable for star plasma flows here.

2.1. Collisionless plasma approach

The flows emitted from the star vicinity are characterized by a high temperature. Under these hot conditions, plasma behaves as a rarefied (collisionless) medium. Free path of the particles remains large in comparison with the dimensions of the observed magnetosphere and plasma e.m. structures. We get flyby particles (“resonant” and “nonresonant”) and partly trapped particles participating in part of the magnetization $\mu(\vec{X})$ formation. Such a plasma as a flow of groups of different in properties particles can’t be considered a simple MHD fluid with prescribed conductivity and viscosity.

2.2. Dimensionless plasma flow parameters in kinetics

Direct velocity of plasma flow near exoplanets remains rather small in relation to the thermal velocity of the electrons and often remains subsonic (Mach number $M < 1$), so it is smaller than the thermal velocity of ions. In this regime, strong e.m. kinetic plasma effects appear for flyby electrons and ions.
We operate with a plasma flow in the magnetosphere in terms of the particles velocity distribution function (VDF) $f_\alpha(\vec{v})$, which is self-consistent with e.m. fields. In such a regime, two groups of “flyby” particles separated in the velocity phase space have different dynamics in e.m. fields. There is a group of the “resonance” particles which are moving slowly to the planet and to the stationary magnetic field and a group of “nonresonant” particles which are in fast motion relative to the planet and magnetic field. The first group of particles is defined via the parameter κ_G of “momentum” anisotropy of the VDF, expressed via a local value of the VDF and the second group of particles is defined via the parameter κ_D of energy anisotropy and is expressed via the integral value of the VDF.
These effects we consider via Vlasov equation solution in terms of the tensor dielectric permittivity.

2.3. Governing parameter for topology of magnetosphere

We introduce a parameter G_V governing the e.m. part of magnetosphere topology. It is the ratio of the “energy” anisotropy parameter to the “momentum” anisotropy parameter of the VDF. Parameter G_V characterizes the external flow as diamagnetic ($G_V >> 1$) or resistive media ($G_V << 1$). The value of G_V depends purely on the shape of the external VDF and it is calculated for the "Maxwellian" and "kappa" distributions with parameters of the VDF variations modeling star CME in the flow. Parameter G_V is an e.m. analog of the acoustic Mach number. Note here that kinetic magnetic Reynolds number Re_m is independent from G_V e.m. parameter for characteristic of resistive effects in relation with spatial scale of the magnetization $\mu(\vec{X})$ distribution.

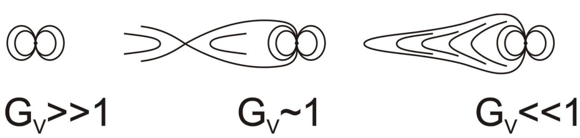

Figure 1: Magnetosphere of the planet governed by kinetic parameter G_V characterizing e.m. properties of the incoming plasma flow. We get a transition from the dipolized state (diamagnetic flow) to the magnetotail state (conductive flow).

2.4. The large scale parameters of plasma

We introduce two induced by flow LSK parameters r_G and r_{DM} ("thin" and "thick" scales) a special characteristic function $M_G(\vec{X}, G_V, \mathrm{Re}_m)$ for determination of magnetosphere spatial resistive and diamagnetic structures (magnetic ropes, current sheets, magnetic islands) with scales $L(X, r_G, r_{DM})$ and topology reconfiguration. The anomalous skin depth r_G and magnetic Debye scale r_{DM} are expressed via a ratio of the e.m. skin depth to the momentum and energy anisotropy parameters. Due to the small values for anisotropy ($\kappa_G, \kappa_D << 1$) we get the large values in plasma for the scales r_G and r_{DM} .

2.5. Conditions for permanent plasma penetration by flyby particles

Magnetic field forced the particles to gyro oscillations on some scale and provides a β parameter of the plasma for a magnetospheric plasma flow. We get an Earth type internal magnetosphere without flyby particles with stop flow border at $\beta\kappa_D \approx 1$ and at $\beta\kappa_G \approx 1$. The exoplanets magnetospheres considered here are in the state of permanent plasma penetration by dense flow of the flyby particles under the conditions $\beta\kappa_D >> 1$ and $\beta\kappa_G >> 1$, the conditions realized near Mercury.

3. Summary and Conclusions

We introduced kinetic approach to magnetosphere formation by high β plasma flows. It is hot, dense collisionless plasma. Effects of magnetosphere topological reconfiguration are provided by shape reconfiguration of the VDF. Under constant shape of the VDF we have constant topology with possibility to change magnetospheric scales (selfsimilar decrease and increase) due to change of hydrodynamical plasma parameters. Isotropic shape of the VDF provides positive values of the governing parameter G_V . Flows with anisotropic VDF provide negative value of the G_V . This case is subject of the next consideration.

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