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Investigation of planetary magnetospheres in laboratory experiments

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Abstract

We report on laboratory simulation of planetary magnetospheres conduced at KI-1 Facility. A program of investigations is based on a fundamental and practically important problem of extreme compression of the Earth magnetosphere under impact of super energetic CME plasma. The second and closely related topic concerns such particular aspect of planetary magnetospheres as field aligned currents that connect boundary layers with ionosphere. Besides Earth type, we consider exoplanets with intense surface evaporation of ionized gas. Experiments on magnetosphere inflation by plasma issuing from dipole are described.

1. General set up

The installation vacuum chamber 5 m long and 1.2 m in diameter includes theta-pinch source generating quasi-stationary plasma flow with velocity ~100 km/s and ion density up to 10^{14} cm^{-3}. A special feature of the facility is powerful $C0_2$ laser system capable of delivering up to 1 kJ of energy in a short pulse. Laser beams focused at a solid target produce energetic plasma expanding with velocity a few hundred km/s. A range of magnetic dipoles is used to study the interaction. The smallest dipole with radius 2.5 cm generates moment $5{\cdot}10^5$, while the largest (R_D=10 cm) – up to 10^7 $G{\cdot}cm^3$. Diagnostics consists of electric and three component magnetic probes and short time imaging. Typical magnetosphere size in experiments varies in the range 10-25 cm.

2. Description of experiments

Giant solar flares are the most powerful phenomena in the solar system, which can strongly affect various geospheres and technical systems in the near Earth's space or its surface. During the space era a record inward shift of magnetopause down to $5.2{\cdot}R_E$ was observed following the 4 August 1972 Flare. Its CME energy per unit solid angle was estimated to be $3{\cdot}10^{32}$ erg. MHD calculations show that at energy $\sim10^{34}$ erg the magnetopause could shift down to radiation belts $<3{\cdot}R_E$. At the initial stage of magnetosphere deformation the SSC index will reach ~1000 nT in a time of only ~1 min. The similarity scaling of natural and laboratory phenomena we base on energetic dimensionless parameter [2] that combines a release of energy E_o occurring at a distance R_o from the dipole with magnetic moment μ:

$$\chi = 3E_o R_o^3 \big/ \mu^2 \quad (1)$$

For the problem under discussion this parameter is very large. Based on laboratory data the physical scaling can be verified and estimation made of the minimum size of disturbed Earth magnetosphere that could be expected at most energetic Solar flare events. In the preliminary experiment to simulate such event we created magnetosphere by theta-pinch source and compressed it by laser-produced plasma [3]. The realized energetic parameter was χ>100 and a twofold compression of magnetosphere has been reached. By varying laser-beam energy a clear dependence of the size of deformed magnetosphere and corresponding SSC index on the energy of ejected plasma cloud has been observed [5].

In the second topic of the report we present results of laboratory study of Field Aligned Currents in planetary magnetospheres. FAC is a key element in the Earth magnetosphere-ionosphere coupling. The magnetospheric currents can flow into the ionosphere via the Birkeland currents, and closer through the ionosphere transverse to magnetic field due to finite Pedersen conductance. Region-1 current at the dayside maps in the Plasma Sheet Boundary Layer and is a direct result of the Solar Wind interaction with the Earth magnetic field. In experiments on magnetic dipole interacting with laser-produced plasma a generation of intense FAC system was observed for the first time in a laboratory [4]. Detailed measurements of total value and local current density, of magnetic field at the poles and in the equatorial magnetopause, and particular features of electron motion in the current channels revealed its similarity to the Region-1 current system in the Earth magnetosphere. Such currents were found to exist only if they can closer via conductive cover of the dipole. Comparison of conductive and dielectric cases revealed specific magnetic features produced by FAC and their connection with electric potential generated in the equatorial part of magnetopause. Results could be especially important for investigation of the Mercury as magnetic disturbance due to FAC could be exceptionally large because of small size of the Hermean magnetosphere. The other implication concerns hot exosolar planets. At conditions of good electric conductivity of planet surface total field aligned current appears to be saturated and reaches high values comparable to total magnetospheric current even in the absence of strong loading by interplanetary magnetic field.

In the last topic we describe experiments on a novel type of magnetospheric interaction. A localized source produces plasma which expands from the surface of the dipole, interacts with magnetosphere and changes its characteristics. Such scenario can be applied to weakly magnetized Hot Jupiters in a close orbit. Intense erosion and evaporation of atmosphere and subsequent gas ionization by EUV radiation may produce sufficiently strong plasma outflow to influence overall particle loss balance and magnetopause stand off distance [1]. The other implication is a concept of inflated magnetosail proposed for interplanetary travel by R. M. Winglee (2000). In laboratory experiment stationary magnetosphere was formed by theta-pinch plasma with density $3{\cdot}10^{13}$ cm^{-3} and velocity 30 km/s overflowing dipole with moment $3{\cdot}10^{5}$ $G{\cdot}cm^{3}$. Stand off distance was measured at $R \approx 15$ cm. Plasma outflow from the dipole cover was generated by surface discharge in two dielectric coils placed symmetrically around magnetic axis. The overall diameter of dipole with installed coils was 5 cm. The density of plasma from the surface source was measured as $6{\cdot}10^{13}$ cm^{-3} at magnetopause position. Its expansion induced the outward shift of magnetopause to a location at $R \approx 23$ cm. Thus, a direct experimental evidence of magnetosphere inflation and significant increase of stand off distance by a factor of 1.5 was obtained.

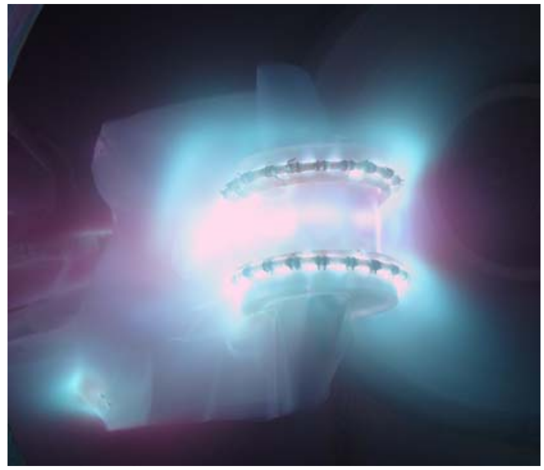

Figure 1: Plasma generated by surface discharge using two coils placed around magnetic dipole.

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