Laboratory modeling of a field-aligned currents system generated by a flow of inner magnetospheric plasma

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Abstract. For the first time in laboratory conditions, an experiment to simulate a system of field-aligned currents arising on planets such as Hot Jupiters in the presence of dense inner-magnetospheric plasma was carried out. The magnitude and transit time of field-aligned currents were measured as a function of the magnetic field using flat electrodes. The geometry of the expansion of plasma streams was pictured by gated camera. Also, in a first approximation, the efficiency of energy transfer from plasma flows to field-aligned currents was calculated. The results obtained create a basis for future laboratory experiments on this topic and improve existing numerical models.

1. Introduction

Despite the great interest shown today in the study of space, many of its processes still remain difficult for studying. One of such processes is a formation of global field-aligned currents in presence of dense plasma flows in the planetary magnetospheres. This phenomenon is typical of Jupiter, and has recently gained relevance due to the discovery of exoplanets such as Hot Jupiters. The magnetospheres of hot exoplanets are characterized by ionization and outflow of the upper atmosphere.

Field-aligned currents transfer energy from the boundary layer and the magnetodisk to the polar ionosphere, causing various effects. The presence of planetary plasma or planetary wind, formed by the upper atmosphere ionization and held by the planet's magnetic field, with a plasma density several orders of magnitude greater than the external stellar plasma density, can lead to new phenomena that at the moment can only be detected in a laboratory experiment, because numerical modeling of such a system remains difficult due to the complex topology.

This paper presents the results of experiment on modeling of strong field-aligned currents, which are generated inside the magnetosphere [1] and make a closure at the planet poles. The experiment was carried out at the Laboratory of High Power Lasers of ILP SB RAS using the KI-1 facility [2-3]. A distinctive feature of the experiments is the use of energetic plasma flows generated by a powerful pulsed CO₂ laser. In previous laboratory experiments on laser plasma flow around a magnetic dipole [4-8], it was shown that, in addition to the formation of a clearly defined frontal region of the magnetosphere, the external plasma flow generates at the poles an intense system of field-aligned currents. Detailed measurements of the total magnitude and local density of field-aligned currents, magnetic disturbances at the poles revealed their similarity to the currents of Region-1 in the Earth magnetosphere. Laboratory field-aligned currents were observed only if they could be closed through the conducting surface of the dipole. The novelty of these experiments lies in the fact that field-aligned currents are formed this time by an inner-magnetospheric plasma flow.
2. Experimental setup
A dipole magnetic field source (Fig. 1) was placed inside a large cylindrical vacuum chamber of 5 × 1.2 m size with a residual pressure of to 10⁻⁶ Torr. The source consisted of two solenoids connected serially each of which could create a magnetic moment of up to 10⁶ G·cm³ powered by pulsed ~ 200 μs voltage generator. The magnetic moments of the coils were directed parallel to each other, creating a common dipole field. This dipole configuration made it possible to obtain magnetic fields with a large moment at a lower applied voltage. Polyethylene (C₂H₄) targets were fixed on both sides of the dipoles housing at the magnetic poles. Targets were symmetrically and simultaneously irradiated with two 100 ns pulses of a CO₂ laser with an energy of E = 200 J, creating plasma flows with a concentration of up to n = 10¹⁴ cm⁻³, velocity v = 100 km/s and total kinetic energy E = 25 J. The plasma ablated from the target simulated an inner-magnetospheric plasma of exoplanets called hot Jupiter.

To measure the electric potential and field-aligned currents, flat copper electrodes were used, fixed in pairs on the target at each dipole pole (U1 and U2 in Fig. 1b). One pair of electrodes was electrically gaped to measure the potential, and the second was short-circuited with a copper bus, which passed through the Rogowski coil to measure the current I. To obtain plasma images, high speed four gated camera HSFC PRO was used.

Figure 1. Scheme (a) and photo (b) of targets-dipole system with a generated plasma. 1 - laser beams, 2 - polyethylene targets, 3 - plasma flow, 4 - dipole magnetic field source, U1 и U2 – copper measuring electrodes.

3. Results
The field-aligned currents arising during the expansion of plasma flows inside the dipole magnetic field with the moment M = 10⁶ G·cm³ reached a magnitude of 1.77 kA (Fig. 2a). The value of such currents directly depended on the magnetic moment of the dipole field (Fig. 3 - black curve). The transpolar potential reached 275 V. For comparison, measurements were carried out without dipole field producing a relatively small current I = 77 A between the electrodes (Fig. 2c), apparently caused by a photo-current because of uneven irradiation of copper electrodes with laser radiation. The images demonstrate that in the presence of the dipole field the plasma expands along the field lines (Fig. 2b), while without magnetic field the quasi-spherical plasma clouds are formed (Fig. 2d).

It was found that the time duration of field-aligned linearly depends on the dipole magnetic moment (Fig. 3 - red curve). For example, at a magnetic moment M = 0.23 · 10⁶ G·cm³, the current existed 2.5 μs, and at M = 10⁶ Gs · cm³, it was 3.9 μs. This may be due to the fact that a magnetic field with a larger moment captures the plasma flow for a longer time, allowing it to form field-aligned currents for longer duration.
Figure 2. a and c - The current measured by the Rogowski coil (left axis) and the electric potential from two electrodes (right axis) during the expansion of laser plasma inside the dipole field with a magnetic moment of $M = 10^6 \text{ Gs} \cdot \text{cm}^3$ and without magnetic field, respectively. c and d – plasma images obtained at a time of 1.8 $\mu$s after irradiation of the targets.

Also, as a first approximation, it is possible to determine the total energy transferred from the plasma flow to the field-aligned currents. The energy of the plasma flow can be obtained as

$$E_p = 4\pi R^2 \int 0.5 \, n_i \, m_i (R/t)^3 \, dt \approx 25 \, J,$$

where $n_i$ – plasma density measured by Langmuir probe at a distance $R$ from the focal spot, $m_i$ - ion mass. The measured value of the transpolar potential and total current allows to determine the electric energy of the field-aligned currents

$$E_c = \int I U \, dt \approx 1.1 \, J,$$

where $I$ - total current, $U$ - transpolar potential. That is, the energy transfer efficiency from plasma flows to field-aligned currents was about 4.4%.
4. Conclusion
In recent years, planets such as hot Jupiters have been actively discovered in large numbers, which can have inner-magnetospheric plasma flows inside the intrinsic magnetic field. On such planets, various new physical phenomena can be expected, one of which is field-aligned currents caused by the motion of plasma along the expanding lines of force of the magnetic field. Field-aligned currents are an important element of planetary magnetospheres, transferring energy from the faraway regions and magnetodisk to the polar ionosphere, causing such a key effect as the generation of radio emission.

Currently, the study of planets such as hot Jupiters is mainly carried out using numerical modeling, the input data for which are obtained using spectral observations of such planets. For a full-fledged numerical simulation of complex processes occurring on hot Jupiters this information is insufficient, and laboratory simulations can be used to provide additional data and physical insight.

This work was the first to demonstrate the possibility of laboratory modeling of field-aligned currents arising on planets such as hot Jupiters. To create inner-magnetospheric plasma flows, irradiation of polyethylene targets with a powerful laser pulse was used. During the plasma flows expansion in a dipole field with a magnetic moment of up to M = 10^6 G⋅cm^3, field-aligned currents were measured reaching I = 1.77 kA. The amplitude and duration of field-aligned currents directly depended on the magnetic field. The results obtained in this work create the basis for future laboratory experiments on this topic, which will improve the models of planets such as Hot Jupiters.

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