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Small-scale magnetosphere: what can be learned from laboratory experiments?

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Abstract

A problem of magnetosphere formation on the ion inertia scale $L_i=c/\omega_{pi}$ around weakly magnetized bodies is investigated by means of laboratory experiments. A specific magnetic field was observed which is non-coplanar to dipole field, doesn't change sign at dipole moment inversion and could be generated only via the quadratic Hall term J×B/ne. Magnetopause position and plasma stand off distance were found to be profoundly different between the experimental regimes with small and large ion inertia length. Results at conditions of large L_i could be interpreted as though plasma penetrates deep inside magnetosphere and moves there without advecting the dipole field. This suggests that while ions pass through magnetosphere, electrons overflow it along the magnetopause boundary.

1. Introduction

In recent years there emerged a number of related problems dealing with a mini-magnetosphere. Mini-magnetosphere forms when a small body like asteroid, or localized surface region like on Moon, or a spacecraft possesses an intrinsic magnetic field. At scales of the order of 100 km interaction of the Solar Wind with a localized magnetic field is different from the well-known planetary magnetospheres because of kinetic and two-fluid effects.

Galileo spacecraft encounter with asteroid Gaspra in 1991 and later with Ida in 1993 motivated studies of specific signatures that a weakly magnetized body produces in the SW. It was recognized that under ion scales incompressible whistler modes would dominate instead of magnetosonic waves. Since the discovery of lunar crustal magnetic fields in Apollo missions, their mapping by Lunar Prospector gave ample examples that SW does interact with lunar magnetic anomalous. On Moon a mini-magnetosphere might be useful as a shield against SW plasma. Since then other missions provided new data. SELENE Explorer [1] revealed distinct magnetic reflection of SW ions over the Aitken anomaly correlated with reduction of the ions reflected by lunar surface. Besides reflected ions Chandrayaan-1 spacecraft observed above the Crisium antipode anomaly a reduction of the backscattered hydrogen atoms [2] giving further evidence of a surface shielding.

Current understanding of the problem is based mostly on numerical studies by Hall MHD and hybrid codes. It was shown that a shocked upstream region roughly resembling magnetospheric bowshock appears only when pressure balance stand off distance R_M is larger than the ion inertia scale, while in the opposite case there is no ion deflection and density pile up [3].

2. Results

To achieve a wide range of kinetic scales in laboratory magnetosphere we used theta-pinch plasma operating on light hydrogen and heavy argon as well as laser-produced plasma with small ion density in the interaction region. Realized experimental regimes are shown in the table.

n_i, cm^{-3}	V_o, km/s	Ion	R_M/L_i
$4\cdot10^{13}$	40	H^+	3.3
$2\cdot10^{13}$	100	H^+	1.9
$1.5\cdot10^{12}$	120	H^+	0.75
$2\cdot10^{12}$	50	Ar^{4+}	0.4
$5\cdot10^{11}$	100	C^{4+}	0.4

At small L_i magnetopause position was measured near the expected pressure balance distance R_M. However, at $L_i>R_M$ it was found significantly farther from the dipole. Significant plasma penetration across magnetic barrier was observed as well, as shown in Fig. 1.

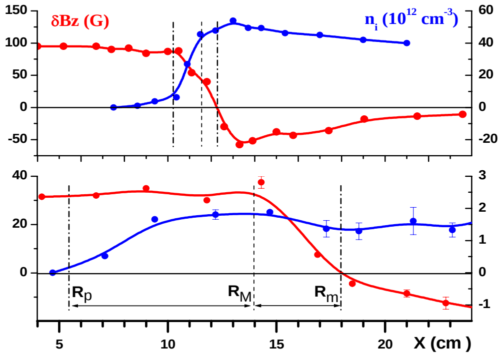
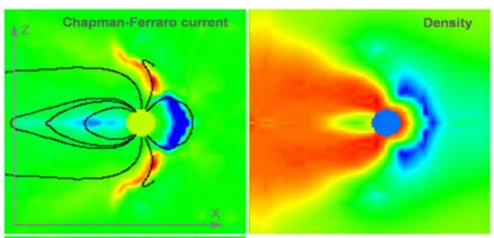


Figure 1: Profiles of magnetic field perturbation and plasma density measured along interaction axis for regimes with small (upper panel) and large L_i (lower panel). Dashed vertical line indicates a "sub-solar" stand off distance R_M calculated by conventional formula. Dash-dot lines indicate measured magnetopause position and boundary of plasma penetration inside magnetosphere.



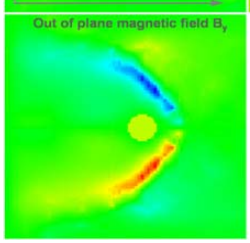


Figure 2: Meridian structure of laboratory magnetosphere. Spatial size of the shown region is 70×70 cm. Circle marks the dipole cover. Rainbow color plots of:

Current density J_Y, plasma density n_I (blue corresponds to 50% increase above upstream density, Red – zero) and magnetic component B_Y.

In the regime №2 for which $R_M/L_i \approx 2$ detailed grid measurements of magnetic field and plasma density were made. In Fig. 2 one can see meridian plane where magnetic field lines are mapped over color plot of Chapman-Ferraro current J_Y. Next plot of plasma density is presented. One can see the essential features of magnetosphere – Chapman-Ferraro current, cusps, tail, density cavity.

Detailed mapping revealed a presence of out of plane B_Y component of magnetic field that cannot be explained in the MHD frame. It is positive in the North hemisphere, negative in the South and doesn't change sign with magnetic moment inversion which indicates its quadratic nature. Its maximum value ±50 G is about 5 times smaller than the jump of field at the magnetopause $\triangle B_Z \approx 250$ G. The structure of B_Y field closely follows the Chapman-Ferraro current.

3. Conclusions

Obtained experimental data support the finding of numerical simulations that plasma isn't stopped by magnetic barrier in the regime $R_M/L_i<1$ and gives new insight on the process which is behind such behavior. Penetration of ions inside magnetosphere can be explained by currents associated with out-of-plane magnetic field generated due to Hall term. These in-plane currents can fully compensate electric field generated by ion motion: $c\mathbf{E} = -(\mathbf{V} - \mathbf{J}/ne)\times\mathbf{B} \approx 0$

Acknowledgements

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