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# The physics of mini-magnetosphere: laboratory experiment, numerical simulation and analytical model

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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 experiment, analytical analysis and 2D Hall MHD simulation. Experimental evidence of specific Hall magnetic field is presented. Direct comparison of regimes with small and large $L_i$ revealed striking differences in measured magnetopause position and in plasma dynamics. Developed analytical model shows how two-fluid physics changes the scaling of cavity size from MHD pressure balance distance to a particle Stoermer radius when $L_i$ is large. It also predicts that because of plasma penetration across magnetopause there is a threshold value of $L_i$ at which upstream bow shock disappears. Numerical simulation is found to be in a good agreement with experiment and analytical model.

## 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. Hall MHD and hybrid simulations [2] revealed that whistler and magnetosonic wake is generated behind the body while ahead there is no ion deflection and density pile up. A shocked upstream region appears only when pressure balance stand off distance $R_M$ becomes larger than $L_i$. 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.

Revealing and fundamental results came from numerical investigations of a magnetic sail concept. Parametric study by hybrid simulation [1] showed that the size of mini-magnetosphere equals to MHD stand off distance when $L_i<R_M$ and to a Stoermer radius otherwise with a sharp transition in between. Thus, in kinetic regime plasma behaves like individual orbiting particles. How it happens while plasma is still strongly collective wasn't analyzed in any of the works.

## 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 [3]. Strong plasma penetration across magnetic barrier was observed as well, as shown in the figure. A presence of out of plane magnetic field $B_Y$ in the meridian plane of magnetosphere was discovered that can't 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. Detailed mapping by magnetic probes in the intermediate regime $L_i \approx R_M$ revealed that out of plane field is generated at the location of Chapman-Ferraro current and is smaller but comparable in value to the main component of dipole field at magnetopause.

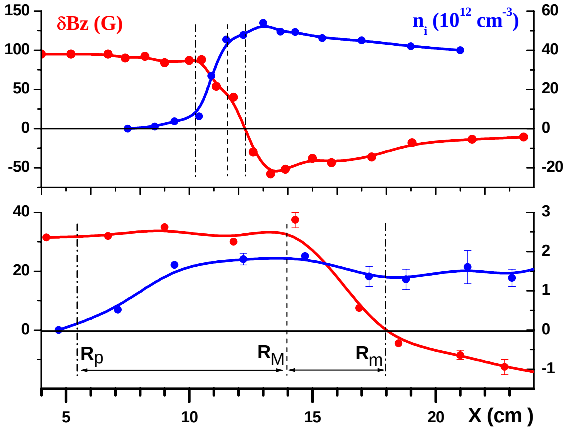

Figure 1: Profiles of magnetic field perturbation and plasma density measured along interaction axis for regimes with small (upper panel) and large $L_i$ (lower panel). Dashed vertical line indicates a "sub-solar" stand off distance $R_M$ calculated by conventional formula. Dash-dot lines indicate measured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

We explain experimental results in the frame of Hall MHD. The Hall electric field is the one that decelerates plasma $E_X \sim J_Y B_Z$. Because of latitude dependence, Chapman-Ferraro current $J_Y$ generates new component of magnetic field directed along it:

$$\frac{\partial}{\partial t} B_y \approx -\frac{\partial}{\partial x} V_x B_y + \frac{\partial}{\partial z}\left( V_y - \frac{J_y}{ne} \right) B_z \qquad (1)$$

Current $J_X$ associated with Hall field is maximal at the interaction axis X and flows like plasma towards dipole. Due to this Hall current advection of the main field component $B_Z$ accordingly changes:

$$\frac{\partial}{\partial t} B_z \approx -\frac{\partial}{\partial x}\left( V_x - \frac{J_x}{ne} \right) B_z \qquad (2)$$

Because in stationary state plasma velocity has to be equal to current velocity $V_X \approx J_X/ne$, plasma should penetrate across magnetopause. As the jump of velocity across magnetopause becomes smaller, kinetic pressure and jump of magnetic field decreases. To accommodate this change magnetopause should move farther away from the dipole. Exactly these tendencies have been observed in experiments. The other important consequence of (2) is that, while ions move across the mini-magnetosphere, electron population is at rest there and is separated from SW electrons by magnetopause barrier.

For numerical simulation we use Hall MHD with electron mass $m_e = m_i/1836$ included. 2D problem in X-Z plane is considered in Darwin approximation. Results on generation of Hall $B_Y$ field, magnetopause position and plasma penetration into magnetosphere are in good agreement with experiments and model. Simulation demonstrates disappearance of frontal bow shock at large $L_i$ and stopping of plasma near Stoermer limit as it was found out in previous numerical studies. It gives details of spatial structure of min-magnetosphere which supplement analytical model.

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