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ORIGINAL ARTICLE

Laser-plasma simulations of artificial magnetosphere formed by giant coronal mass ejections

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Abstract We employed the laboratory (Laser-Produced Plasmas, LPP) and numerical (3D/PIC-code) simulations to study the resulting state of very strong compression of magnetopause (MP) by CME with effective energy $E_0 \geq 10^{34}$ ergs directed to the Earth. During probable formation of an Artificial Magnetosphere (AM, *in a flow of CME' plasma around the Earth*) with the MP stand-off at R_{mp} up to (2–3)R_E, many catastrophic phenomena could occur in a space and ground networks due to very high curl electric fields induced by world-wide magnetic field's changes with a SC-rate >50 nT/s. The laboratory models of AM (with $R_{mp} \sim 0.1$–30 cm) were formed around high-field, 1D and 3D magnetic obstacles, overflowing by LPP-blobs with E_0 up to kJ and magnetized ions. The shape and internal structure of a large-scale AM were studied at KI-1 facility of the Russian team using a set of B-dot magnetic probes, while the main goal of UT's small-AM experiment was to explore a possible shock's generation and relevant electron acceleration. Preliminary results of KI-1 experiments show that the both R_m-size and SC (E_0) of AM could be described by modified Chapman-Ferraro Scaling, while the whole SC-distribution (in front "one-half" of equatorial plane)—by well-known "Image Dipole" model of the Earth's magnetopause field.

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1 Introduction

More than 3-fold compression of the Earth's magnetosphere could be caused by giant Coronal Mass Ejections (CME), driven by recently discovered Mega Solar Flares with the total released energy $\geq 10^{34}$ ergs. Its potential after-affects should be so hazardous that advanced and detailed investigations, including modern laboratory simulations are required (Horton and Chiu 2004; Horton et al. 2007a; Ponomarenko et al. 2005, 2007b). Physical conditions of such rare and enormous phenomena could be understood based on the concept of a non-stationary "Artificial Magnetosphere"—AM (Nikitin and Ponomarenko 1996; Zakharov et al. 1996; Ponomarenko et al. 2007b) which is formed when an exploding plasma flows around a magnetic dipole μ. According to the MHD-model (Nikitin and Ponomarenko 1996; Zakharov et al. 1996; Ponomarenko et al. 2007b), the stand-off distance R_{mp} of AM magnetopause is determined by the main energetic parameter of the problem $K = 3E_0R_0^3/\mu^2$ (for effective plasma energy E_0 and distance R_0 between dipole center and plasma release's point). For the explored case of $K \gg 1$ it could be expressed (Ponomarenko et al. 2007b) approximately as $R_{mp} = R_m^* \approx 0.75R_0/K^{1/6}$. This type of scaling was confirmed for the fist time in the Laser-Produced Plasma (LPP) experiment of ILP (Zakharov et al. 1996) at KI-1 target chamber ∅120 cm and recently in our PIC-simulations (Ponomarenko et al. 2007a, 2007b) by 3D/Hybrid-code of Kyushu University (KU, Japan). Our first experiment on the simulation of AM-formation during anti-asteroid explosions (Zakharov et al. 1996) was characterized by unmagnetized ions as their directed Larmor radius $R_L = mcV_0/zeB_d^*$ at magnetopause (for $B_d^* = \mu/R_m^{*3}$) was larger than R_m^*, i.e. criterion $\varepsilon_m = R_L/R_m^* \sim 3(>1)$, similarly to pioneer work of Bostick et al. (1966) with plasma gun.

To correctly simulate AM-formation around the Earth we carried out Artificial Magnetosphere EXperiment (AMEX) in the required MHD range of dimensionless criteria $K \gg 1$ and $\varepsilon_m < 1$. So far the problem was explored in this range only in 2D/3D PIC—simulations, but only for stationary overflowing, while for the non-stationary and CME related phenomena, a 3D/MHD-code (Ridley et al. 2006) appears recently. To analyse our laboratory data and apply them to extreme geophysical phenomena we have used a 3D/PIC hybrid code of KU, which was verified in turn by AMEX data. Our laboratory simulation is based on the *principle of limited simulation* (Podgorny and Sagdeev 1970; Zakharov 2003) and one of its first goal was to reproduce the structure and dynamics of super-compressed magnetic field in the sunward part of highly-disturbed Earth's magnetosphere.

2 Large scale experiment AMEX and relevant 3D/PIC-simulation

Figure 1 shows a principal scheme of AMEX in the main cross-section of KI-1 target chamber (Zakharov 2003) with the length 5 m and high-vacuum up to 10^{-7} Torr. This stainless steel chamber is supplied by the ms-source of high-density plasma background's flow and external coil of steady uniform magnetic field B_0, while the whole KI-1 facility consists of a set of CO_2-laser generator and amplifier with the output up to 400 J in 100 ns-pulse. We used a flat or convex Nylon6 plastic target with a few cm^2 laser spot to produce a LPP with moderate front velocity $V_0 \approx 180$–200 km/s (maximal along to target normal, where $\theta = 0$), consisting of a H^+ and C^{+3}/C^{+4} ions with the average $\langle m/z\rangle \approx 2.5$ a.m.u. The initial shape of LPP appears as a sphere touched to target and consequently it had angular distribution like $V_0 \propto \cos\theta$, for which LPP of uniform density should have a total kinetic energy $E_k = E_0/16$, where $E_0 = (dE/d\Omega)_0 \times 4\pi$ is effective LPP energy for maximal $(dE/d\Omega)_0$ along to target normal. So for the real energy of LPP up to $E_k \approx 25$ J we have its effective value (into 4π) $E_0 \approx 400$ J.

This approach allows us to compare directly the results of our experiments with theoretical models of the interaction between expanding spherical plasma clouds (of energy E_0) and various magnetized media. It was based on the data of a KI-1 test experiment (Ponomarenko et al. 2007b) with an LPP-blob decelerated by uniform field $B_0 = 600$ G. As

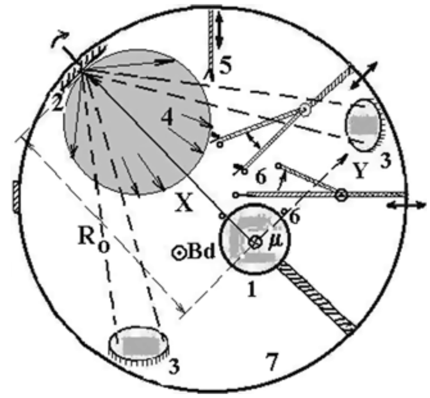

Fig. 1 General scheme of AMEX experiment at KI-1 facility of ILP: **1**—dipole; **2**—laser target; **3**—mirrors for beams of CO_2-laser; **4**—Laser-Produced Plasma (LPP); **5**—set of Langmuir probes; **6**—set of magnetic (B-dot) probes; **7**—chamber ∅120 cm; B_d—dipole field (in the shown equatorial plane). Axis of Gated Optical Imager (GOI) was directed into the paper

we recently reported (Zakharov et al. 2008) such LPP can be used as the model of giant CME in the laboratory simulation with LPP—dipole interaction, to test a new magnetopause scale R_m^* of AM, very important for the problem of probable catastrophic changes of the Earth's magnetosphere. Earlier we verified of R_m^*—scaling in the PIC-runs with a spherical plasma clouds (Ponomarenko et al. 2007a) and LPP-blobs (Zakharov et al. 2008), as presented below. A 3D/PIC-model of KU with our simple MHD-model are briefly described by Ponomarenko et al. (2007b) and we used up to 3 000 000 ions in the grid with a minimal size up to 4–5 mm for the PIC-runs. The most runs were conducted under the same conditions as for experiments AMEX, with the initial distance $R_0 = 75$ cm (mainly GOI photos for LPP with $E_0 \approx 300$–400 J) and its final value $R_0 = 61.5$ cm (for LPP with $E_0 \approx 200$ J), which was more appropriate for the detailed probe measurements along to main X-axis (Fig. 1). They were done for two main regimes (I and II) of dipole field with the moments $\mu = 1.1 \times 10^7$ and 2×10^6 $G \cdot cm^3$. Such 3D-fields were generated by many-turns coil (∅16 cm) covered by thin-wall metallic ended cylinder of ∅20 cm and supplied by ms-pulsed capacitor scheme for multi-kA current.

3 Results and discussion

Figure 2 shows a typical examples of AM-shape in AMEX with apparent non-MHD ($\lambda \le R_L$), flute-type instability, developing (at left) from the early stage ($t = 1.5$–2 μs) of LPP deceleration by field (Zakharov et al., 2006, 2008). It could be a reason of plasma penetration inside of MP, up to the dipole's surface at small $\mu \le 10^6$ $G \cdot cm^3$, since the gap ≈10 cm (between it and MP, here) is comparable with the directed ion Larmor radius $R_L \ge 10$ cm (at $B_d^* \approx 300$ G).

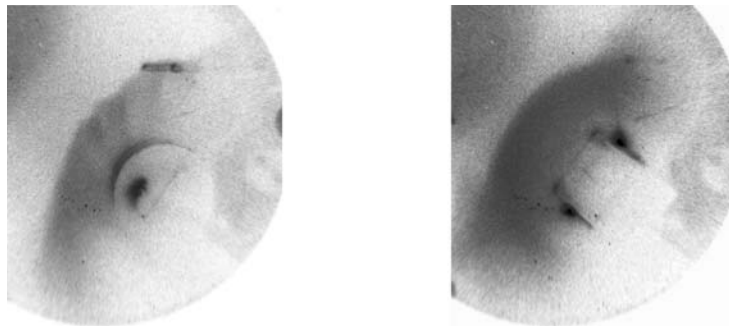

Fig. 2 Initial GOI data on the shape of magnetopause around dipole (∅20 cm) with the moment: $\mu = 1.1 \times 10^6\ \mathrm{G \cdot cm^3}$ (#35 at the left, $t = 4.2$ μs for $K \approx 4000$) and $2 \times 10^6\ \mathrm{G \cdot cm^3}$ (#41 at right, $t = 4.4$ μs for $K \approx 1000$, where dipole was rotated to show "meridional plane"). In both cases $R_0 = 75$ cm, $E_0 = 300$–400 J and H_2-gas added at 0.1 mTorr (to enhance luminosity of MP)

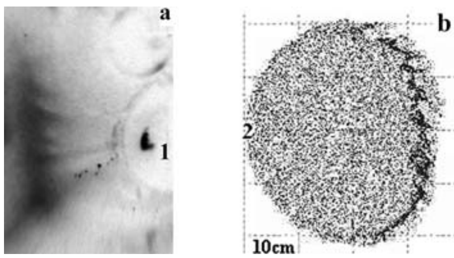

Fig. 3 Comparison at the same scale of AMEX #224 (**a**) with added $B_0 = 115$ G and data of its PIC-modeling (**b**). Here $K \sim 10$ (for $E_0 = 200$ J, $R_0 = 61.5$ cm and $\mu = 1.1 \times 10^7\ \mathrm{G \cdot cm^3}$) and such LPP's stop ($t = 2.2$–2.3 μs) at $R_{mp} \approx 26$ cm ($< R_m^*$) is better described by MHD-model; **1** is front part of dipole (with a spot of plasma penetrated along to B_d) and **2**—point of plasma release

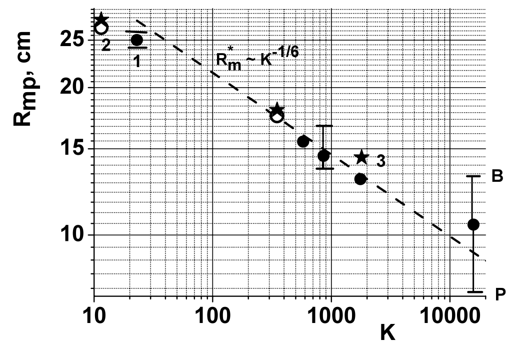

Fig. 4 Combined data on magnetopause stand-off R_{mp} in a flow of exploding plasma, ejected at $R_0 = 61.5$ cm: **1**—PIC-modeling for plasma energy $E_0 = 400$ J; **2**—PIC for $E_0 = 200$ J; **3**—AMEX laboratory simulation for $E_0 = 200$ J (and μ up to $1.1 \times 10^7\ \mathrm{G \cdot cm^3}$, at the left point); **P** and **B**—plasma boundary and its diamagnetic boundary (i.e. MP), correspondingly; R_m^*—is estimation of stand-off via scaling $R_m^* \approx 0.75 R_0/K^{1/6}$ for $E_0 = 400$ J

Figure 3(b) shows the result of PIC-run with the energy $E_0 = 200$ J and the same LPP-geometry, V_0 and $\langle m/z \rangle$ as in AMEX. The dipole-like field "was created" by one turn of radius 8 cm like in AMEX coil. PIC-modeling data demonstrate a similar LPP deceleration along to X-axis or development of flute instability and reveal that up to the moment of LPP's stop it excludes all magnetic field in accordance with AMEX experimental results (Zakharov et al. 2008). In result, a general relation $R_{mp}(K)$ for the case $R_0 = 61.5$ cm was obtained (Fig. 4) and important verification of suggested approximation $R_m^*(K)$ was done in a wide range of criterion K.

Beside expected and pronounced deviation from $R_m^*(K)$ at finite $K \sim 10$, a substantial difference between a plasma' (**P**) and magnetic field' (**B**) boundary at large K in the given case (of fixed E_0, V_0 and R_0) is apparent effect of low ion magnetization. To the definition of $R_{\mathrm{L}} \propto V_0/B_d^*$ and also due to fixed value of field $B_d^* \propto (E_0/R_0^3)^{1/2}$ at MP (as R_m^*), the value of ion Larmor also should be fixed, while the own MP's size essentially decrease to high K numbers (and small μ).

Therefore ion magnetization criterion $\varepsilon_m = R_{\mathrm{L}}/R_m^*$ became ≥ 1 (at $K > 10^4$), instead of minimal $\varepsilon_m \sim 0.3$ at $K \sim$ 10–20, where the difference between positions of plasma and field boundary is very small (Fig. 4). As result we had chosen for AMEX the intermediate regime of $K \sim 1000$, in which ε_m is enough small for MHD-like structure of MP, while its whole boundary could be enough bended around dipole (Fig. 2), similar to the case of Earth's MP.

So, for the main regime II of AMEX at $K \approx 350$ (with $E_0 = 200$ J, $R_0 = 61.5$ cm and $\mu = 2 \times 10^6\ \mathrm{G \cdot cm^3}$) it was shown, that the 1D-distribution of magnetic field' compressional disturbances $\Delta B(X)$ inside of AM could be described (Zakharov et al. 2008) by well-known model of "Image Dipole" (Shabansky 1968). It allows us to determine the magnitude of world-wide ΔB-effect for the given size $R_m^*(E_0)$ and shape of AM, if our simulative AMEX measurements out of X-axis also correspond to this model and the data of Fig. 5 do confirm this.

Another important magnetic disturbances were measured directly at the dipole' conductive surface (Figs. 1, 2), where an essential local amplification by factor 1.5 could be possible due to its "Telluric" currents and for its spherical shape (Shabansky 1968). We did not see such effect, most probably because of a shape of used dipole in a form of closed cylinder of finite height 14 cm $\sim$ ∅. Finally, according to "Image Dipole" model, for enough "bended" MP-shape (around the dipole), a global compression effect of dipole field could be evaluated in magnitude as a

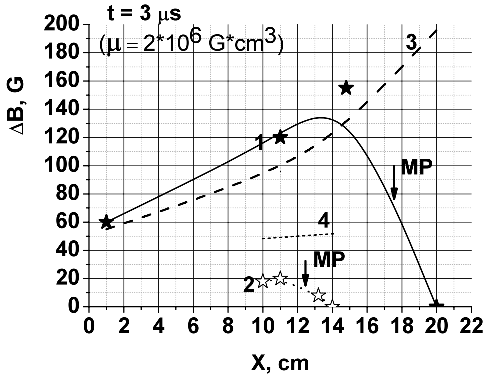

Fig. 5 Compression of magnetic field inside of Artificial Magnetosphere (in main regime II): **1** and **2**—AMEX data at Y = 19 cm and 34 cm; **3** and **4**—corresponding levels of the "Image Dipole" field for its $\mu_i = 7.7 \times 10^6\ \mathrm{G \cdot cm^3}$ suited at X = 49 cm (Y = 0); **MP**—*arrows* show locations of magnetopause (at Y = 0 it lies at 19.5 cm)

quasi-uniform addition of field ΔB^+, which we can express as $\Delta B^+ \approx B_d^* \approx (E_0/R_0^3)^{1/2} \sim 100$ G (comparable with observed, Fig. 5) for the tested scale R_m^* of our MP. This scale for explosive-type overflowing replaces the usual stand-off $R_m = (\mu^2/4\pi P_d)^{1/6}$ in a stationary flow with dynamic pressure P_d (of Background Plasma—BP) and therefore instead of traditional Chapman-Ferraro Scaling (CFS) for $\Delta B \propto P_d^{1/2}$ we should use in the CME's case a founded modified CFS as $\Delta B^+ \propto E_0^{1/2}$ that was tested for the first time by AMEX recently (Zakharov et al. 2008).

4 Conclusions

Thus, we validated the novel approach developed in recent laser experiments (Horton et al. 2007b; Zakharov et al. 2008) for simulation of various magnetospheric phenomena, opening new opportunities in this field. Moreover, the experimental capabilities of KI-1 facility (Zakharov 2003), supplied by source of Background Plasma (BP) allow us to plan a combined type of simulative experiment, when so called Terrella (model of stationary magnetosphere) would be compressed by BP-shock (from LPP) and the additional "erosion" of MP could occur due to reconnection between the dipole field and magnetic field frozen into shocked BP.

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