Laboratory simulation of Hot Jupiters atmosphere expansion

P A Prokopov, I F Shaikhislamov, Yu P Zakharov, V G Posukh, A V Melekhov, E L Boyarintsev, A G Ponomarenko
Institute of Laser Physic (ILP) SB RAS, Novosibirsk, Av. Lavrentyeva 15 b, 630090, Russia
paprok312@gmail.com

Abstract. Hot Jupiters (HJ) are exoplanets, gas giants with low orbits (≤ 0.1 a.u.). The stellar X-ray and ultraviolet (XUV) radiation energy deposition result in heating ionization and the consequent expansion of planetary atmosphere. Expansion of upper atmosphere under certain conditions could be so large that the majority of light atmospheric constituents overcome the gravitational binding and escape from the planet in a form of hydrodynamic wind. Besides interaction of two counter-streaming plasma flows (stellar wind and ionized upper layers of planet atmosphere), each of this flows interact with planetary magnetic field. In such complex situation laboratory simulation can provide data that can’t be obtained by computer simulation or observation. Experiment was carried out on KI-1 facility: high-vacuum chamber 5m long, 1.2 m in diameter with pressure ~ 10^{-6} Torr. Magnetic dipole with two attached laser targets played the role of a planet, and background plasma from θ-pinches used for simulation of stellar wind. As a result, data on a behavior of plasma density and magnetic field were obtained. The novel phenomenon was registered: magnetic field is transferred by the cloud of laser plasma, which was not observed before in experiments or calculations.

1. Introduction
Observation and study of planets outside the Solar System is a popular and rapidly developing field of modern physics [1]. Significant portion of discovered planets are close-orbits (≤0.1 a.u.) gas giants \((0.2M_j< M_p<8M_j)\), so-called Hot Jupiters. Upper layers of atmosphere are extremely heated by intense X-ray and ultraviolet radiation (XUV) of a host star. Expansion of ionized upper layers of atmosphere can overcome the gravitational binding and escape from the planet surface in a form of hydrodynamic wind (similar to the solar wind). This plasma stream interacts with solar wind and planetary magnetic field.

In such complex situation (counter-streaming plasma flows with a presence of magnetic field) laboratory simulation can provide new information, which cannot be obtained by computer simulations or observation of exoplanets. This work represents the description and results of experiment, which simulates all principal aspects of Hot Jupiters: relatively uniform solar wind, planetary magnetic field and plasma stream originates from inside of this magnetic field.

2. Experimental setup
Simulation experiment was carried out on KI-1 facility [2] of ILP SB RAS (figure 1). High-vacuum chamber 5 m long and 1.2 m in diameter with pressure in working mode ~10^{-6} Torr. Solenoid, which covers almost the entire outer surface of the chamber, created magnetic field \(B_0\) inside the chamber with
magnitude ~20 G at its axis. Chamber was filled with H\(^+\) background plasma (BP) from \(\theta\)-pinch plasma-source with density \(\sim 0.5 \cdot 10^{13} \text{ cm}^{-3}\), represents the stellar wind. Magnetic dipole with magnetic moment \(\mu = 7.5 \cdot 10^5 \text{ G/cm}^3\) and a fall of time \(\sim 250 \mu\text{s}\), oriented perpendicular to the chamber axis simulates the exoplanet with magnetic field. To simulate plasma flow from upper layers of planetary atmosphere, two polyethylene laser targets were attached to its surface. CO\(_2\) laser beam with specific form (\(\sim 70\) ns peak and \(\sim 1\mu\text{s}\) tail with energy \(\sim 150\) J for each) was focused symmetrically on each target into a spots with diameter \(\sim 2\) cm to produce a laser plasma cloud (LP).

Each cloud propagated along the normal to laser targets surface. At certain distance from the target these two clouds of plasma merged into a single cloud, which represents planetary wind. Figure 2 is a picture from image converter that illustrates expansion of laser plasma in a presence of a dipole magnetic field inside the background plasma flow. Coordinate system: X axis directed along the symmetry axis of the vacuum chamber, Z axis oriented vertically along the magnetic moment of dipole, and corresponding Y axis.
Two Langmuir probes with attached three-dimensional magnetic probes at a distance 40÷90 cm from the target were used for plasma diagnostic. Three-dimensional magnetic probe is a three small coils made of tungsten wire, oriented in three orthogonal directions with effective area \( \sim 1 \text{ cm}^2 \). There was also Langmuir probe and directed ion collector [3, 4] at a distance 207 cm from the target (90 cm from 0-pinch aperture).

3. **Experimental results**

LP consisted for the most part of ions \( \text{H}^+ \) and \( \text{C}^{4+} \) in approximately equally proportion. The front of LP propagates along the chamber axis at the speed \( \sim 170 \text{ km/s} \) in a cone with half-angle \( \sim 30^\circ \). A total number of electrons per solid angle, measured far from the target (where both clouds of LP already merged), was about \( N_e \Omega \approx 2.2 \cdot 10^{18} \text{ sr}^{-1} \), and the kinetic energy of ions was about \( W_\Omega \approx 32 \text{ J/sr} \). Typical form of LP signal is presented on figure 3, hereafter time \( t = 0 \) corresponds to the laser pulse. LP density had a three bunches, divided by 550 ns between the peaks (interval at the moment of LP generation; time interval between the peaks increases during the LP propagation, and reaches 3 – 5 \( \mu \text{s} \) at the moment of registration). Second peak was the biggest one, and had a twice smaller speed, than first one.

![Figure 3. Typical signal of LP density in vacuum in absence of magnetic field, measured by Langmuir probe at a distance 67 cm from laser target. It can be seen that typical LP cloud consist of three peaks of different amplitude](image1)

Figure 4 represents density distribution of BP at two different distances from the target. \( X = 207 \text{ cm} \) is near to 0-pinch aperture, so plasma density there is several times greater than at \( X = 67 \text{ cm} \). During its propagation from the source, the density of BP decrease by a cubic law, which is confirmed by measurements, presented on figure 5.

![Figure 4. Signal of unperturbed background plasma without magnetic dipole, measured by Langmuir probes at distances 67 and 207 cm. Ion probe current is proportional to the plasma density](image2)

![Figure 5. Spatial distribution of BP density along the X axis (black dots). Dashed line show cubic law.](image3)

Figure 6 illustrate interaction between LP and BP. Solid black line shows density distribution of unperturbed BP. Dashed line density distribution in case of LP propagates inside the BP, a sharp jump
of concentration corresponds to arrival of LP to the probe. Grey line represents the data obtained from directed ion collector; its construction allows us to detect ions, whose speed vectors are close to one direction. Here collector was oriented to detect only ions of BP, so the gray line coincidence with the black up to the time of arrival of perturbation caused by LP. After this moment collector shows partial displacement of BP. All measurements, presented on figure 6, were made at a distance 67 cm from the laser target.

Despite the expulsion of BP the interaction between LP and BP is rather weak. An evidence of a weak interaction between LP and BP is well demonstrated on figure 7, which illustrate the plasma density behavior in different modes (LP in vacuum; LP in BP; LP in BP with dipole magnetic field), at a distance 67 cm (figure 7a) and 207 cm (figure 7b) from the target.

![Figure 6](image1.png)

**Figure 6.** Demonstration of interaction of LP and BP. Solid black line represents unperturbed background. Dashed line – laser plasma in background, sharp peak, caused by laser plasma, can be seen. Grey line allows to see the expulsion of BP, it represents data from directed ion collector, which is oriented toward 0-pinch aperture and doesn’t register LP ions.

![Figure 7](image2.png)

**Figure 7.** Ion probe current in different modes at distances 67 cm (a), 207 cm (b). LP (solid black) – laser plasma in vacuum in absence of magnetic field; LP+B_d (dash) – laser plasma and dipole field; LP+BP+B_d (short dash) – laser plasma in background plasma with dipole; BP (solid grey) – background plasma without dipole.
Data obtained at a distance 67 cm shows a little difference in different modes, significant difference appears only at a distance 207 cm, where presence of BP causes almost 3 times reduction of LP density. Measurements in absence and in presence of dipole magnetic field give similar results, which demonstrate, that interaction takes place due to Coulomb collisions regardless the presence of magnetic field.

Let’s consider the behavior of magnetic field. Magnetic moment of the dipole is directed along the Z axis, so $B_z$ is largest component of magnetic field. Figure 8 illustrates the behavior of $B_z$ in three modes: LP with BP without dipole; LP with dipole without BP; LP with BP and dipole. In the first two cases the variation of magnetic field is not higher than 2÷3 G. In the first case it could be an irregular magnetic field carried by θ-pinch plasma and swept by LP. Magnitude of magnetic field in second case correspond to undisturbed dipole magnetic field, calculated by $B = \mu/\chi^3$. In the third case, when dipole and θ-pinch are on, variation of magnetic field is about 23 G which is much larger than in the other two cases. This is a novel experimental result, generation of such powerful magnetic field by counter-streaming plasma flows has not been observed before.

Magnetic field at such significant distance from dipole should be displaced by BP, which is confirmed in our previous experiments.

Figure 8. Perturbations of magnetic field at X=67 cm in different experimental modes. LP+BP (solid) – laser plasma in background plasma; LP+Bd (dash) – laser plasma in vacuum with dipole; LP+BP+Bd (short dash) – laser plasma in background plasma with dipole.

Figure 9. Measurements of ion probe current and magnetic field in rarified (solid) and dense (dash) BP at X = 67 cm. Stronger perturbations of magnetic field are observed in dense plasma.

Figure 10. Correlation of ion probe current (solid) and magnetic field (dash), measured at different distances. At X = 44 cm (a) three peaks of density and magnetic field can be seen (dipole magnetic field at this distance ~9 G); at X = 63 (b) first peak of density has fallen but magnetic field still has three peaks (dipole magnetic field at this distance ~3 G); at X = 90 cm (c) only the second peak of density and magnetic field can be seen (dipole magnetic field at this distance ~1 G).

Obviously, this magnetic field is not generated only by interaction of LP and BP, because significant magnitude is observed only when dipole is switched on, which means that magnetic field of 23 G at a
distance 44 cm from dipole was generated near the dipole and was transferred at that distance by LP. Figure 10 illustrates in more detail, that magnetic field is transferred by LP, simultaneous measurements of plasma density and variation of magnetic field shows that peaks of magnetic field correlated with density peaks at each three distances.

Another important result is dependence on the plasma density of the magnetic field. The comparison of magnetic fields in rarified and dense BP is presented on figure 9. In rarified plasma the magnitude of magnetic field is smaller but it corresponds to first peak of LP, whereas in dense plasma the twice greater magnetic field transferred by second peak of LP.

4. Discussion and conclusions

Summing up the results of experiment, weak interaction of LP and BP, due to the Coulomb collisions, takes place, and the measurements with directed ion collector shows that BP is expulsed by LP. Perturbations of B_z component of magnetic field about 23 G were detected at significant distance from dipole, when dipole is switched on and in presence of θ-pincho plasma.

Since a strong magnetic field is observed only in mode, when dipole is switched on and LP propagates in BP, a possible explanation of a presence of such strong magnetic field at this distance, is the transportation of magnetic field by LP away from dipole. The approximate possible scenario of this mechanism is described below.

BP ions are captured by magnetic field of dipole when they reached a certain distance. BP ions create a mini-magnetosphere around dipole with frozen magnetic field. After a laser pulse expanding cloud of LP expulse ions of BP with frozen magnetic field due to Coulomb collisions. Magnetic field is carried by electrons, which move with ions to keep plasma quasi-neutral. Perturbations of B_z corresponds the peaks of LP density in area close to dipole, when LP density is greater than BP density. But at larger distances, where BP ions are dominant, dynamic of magnetic field is governed by BP density. For this reason, the first peak of LP and corresponding peak of magnetic field are not observed already at a distance >70 cm.

Illustration of two stages of this process is presented on fig. The first stage is formation of magnetosphere before the laser pulse and creation of LP. The second stage is after the laser pulse, expanding LP carries with it ions of BP with magnetic field at significant distance, where magnetic field is approximately zero in unperturbed background.

Figure 11. Schematic illustration of expansion of magnetosphere. On the left picture BP ions are captured by dipole magnetic field and create mini magnetosphere. On the right picture expanding LP takes away BP ions and magnetic field.
Earlier experiments at KI-1 facility [5, 6, 7] showed that dipole magnetic field is expelled by background almost everywhere inside the vacuum chamber. In uniform magnetized background the cloud of super-Alfvénic LP decelerates and generates non-linear magnetosonic wave [8] or shockwave [9] (if there is enough energy). The present conditions principally differ from previous experiments, in the present case magnetized background creates the mini-magnetosphere, and magnetic field is localized in a small shell. LP generated inside this magnetosphere expands and takes away from dipole background ions with magnetic field at significant distance.

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