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Laser experiments to simulate coronal mass ejection driven magnetospheres and astrophysical plasma winds on compact magnetized stars

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ABSTRACT

Laboratory experiments using a plasma wind generated by laser–target interaction are proposed to investigate the creation of a shock in front of the magnetosphere and the dynamo mechanism for creating plasma currents and voltages. Preliminary experiments are shown where measurements of the electron density gradients surrounding the obstacles are recorded to infer the plasma winds. The proposed experiments are relevant to understanding the electron acceleration mechanisms taking place in shock-driven magnetic dipole confined plasmas surrounding compact magnetized stars and planets. Exploratory experiments have been published [P. Brady, T. Ditmire, W. Horton, et al., Phys. Plasmas **16**, 043112 (2009)] with the one Joule Yoga laser and centimeter sized permanent magnets.

1. Planetary bow shocks

Magnetospheres and plasma shocks are ubiquitous in space and astrophysics, being formed from plasma winds streaming past planets and stars with strong permanent magnetic fields like the Earth, Jupiter, and the Sun. While unmagnetized and weakly magnetized planets with atmospheres, such as Venus and Mars, have gas dynamic shocks. From decades of spacecraft measurements in the solar system a great deal is known about the collisionless bow shocks and the magnetospheres formed by the solar plasma wind interaction with the magnetic dipole fields of the Earth [1] and Jupiter [2]. We use this knowledge in designing and interpreting the laboratory magnetosphere and astrophysical simulation experiments with high magnetic fields and laser-blow off plasmas. The scaling factor from the laboratory to the geophysical space scale is of order 10^9. The scaling factor from the laboratory to a magnetic white dwarf is 10^{12}, and for scaling to pulsars the factor is several orders of magnitude larger. Thus, we expect to find important information on using scaling models for this important class of magnetized plasmas.

2. Background physics of solar wind driven shocks and magnetospheres

Detailed models and simulations of the Earth's bow shock and magnetosphere as a magnetic obstacle in the plasma wind emitted from the sun have been developed. The solar wind interaction with the magnetic fields of Earth and Jupiter form large plasma–electrodynamic dynamos that accelerate electrons [3] and protons [4]. Recently, basic laboratory experiments with a one Joule laser produced blow-off plasma colliding with small permanent magnets and unmagnetized targets have shown the feasibility of creating these magnetospheres and shocks with lasers in the laboratory [5].

Because the plasma wind is supersonic and super Alvénic, a stationary magnetic dipole in the flow can be viewed as a piston that drives a shock in the rest frame of the inflowing plasma [6]. The electron acceleration mechanisms are not well understood, as examples see Refs. [7,8,9] compared with Refs. [10,11,12] for two different theoretical models. For the Earth's magnetosphere, several different types of theories are used to model the production of the 30 keV–1 MeV electron fluxes measured by instruments on spacecraft in the Earth's magnetosphere. The same type of electron acceleration phenomenon is also found in the magnetosphere of Jupiter, and similar processes probably account for the electron energy fluxes inferred from synchrotron radiation from magnetic stars [13,14].

Laser-blow off plasmas and laser-plasma diagnostics are described in the work of London and Rosen [15]. In this work we propose to carry out modern laser-blow off experiments in the laboratory with high-resolution diagnostics. We analyze the possibility of using high powered lasers-target experiments to investigate the nature of the interaction of the dipole with the plasma wind created by laser-blow off plasmas from plastic foils. Both front side and back side plasmas ejecta are candidates for different types of plasma winds. The planets are metal or plastic spheres with or without embedded dipole magnets. The expanding

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plasma will be created by laser ablation of a solid targets. Key objectives in the experiment are to create a shock from the obstacle, and to contrast the damage of the surfaces between magnetized and unmagnetized planets. Another objective is to create the dynamo electric field, and to measure the impact of the electrons on the surface of the sphere.

Small scale experiments were carried out on the YOGA laser at the University of Texas in 2005–2008 with laser pulses of up to 4 J and plasma pulse lengths of 400 ns. The findings were published by Brady et al. [5] as shown here in Fig. 1.

For a longer lasting solar wind pulse we constructed and used in this work a coaxial plasma accelerator with a seed plasma produced by a laser pulse striking an Al wire in the trapping region of the coaxial capacitor. This produced a similar set of data and conclusions for the coronal mass ejection (CME) interactions with the magnetized obstacle contrasted with interactions produced with an unmagnetized Al block. The plasma wind–obstacle interaction time is extended to 400 ns.

3. Bow shocks from plasma winds on magnetic stars and planets

Mildly supersonic $M_s = u/c_s \sim 1.4$–5 plasma winds, where u is the mean particle velocity and c_s is the sound speed, are commonplace in astrophysics and space physics. The winds may be associated with (A) accretion onto a central star; (B) the precursor phase to the Type Ia supernova (SNIa) where plasma is pulled into the magnetic white dwarf (WD) from the companion star; (C) plasma winds are intercepted by neutron stars (NS); after stars are ignited, the stellar wind outflow creates bow shocks at the magnetic planets; (D) and, at the termination of the stellar outflow where the thermal pressure jumps to match that of the interstellar gas. Here we report laboratory experiments for a plasma wind interaction with two obstacles: one magnetized and one unmagnetized to explore the physics of these plasma shocks.

Due to the 40 years' history of magnetospheric spacecrafts with bow shock passages, we know a great deal about the microscale structure of collisionless bow shocks. This field of science has taken another large step forward with the detailed correlation measurements with the extensive instrumentation on the Four-Cluster spacecrafts [16]. The Cluster mission is a European Space Agency mission in operation since February 2001 and has been extended until December 2009. The between-the-spacecraft distances have been 600, 2000, 100 and 5000 km. The bow shock [17] is now seen to consist of hundreds to thousands of microshocks that have widths, Δ_i, on order of the ion skin depth $\Delta_i = c/\omega_{pi}$, where ω_{pi} is the ion plasma frequency, which is comparable to the ion gyroradius $\rho_i = v_i/\omega_{ci}$ for the solar wind plasma which has $\beta_i = p_i/(B^2/8\pi)$ of order unity We define the ion cyclotron frequency as ω_{ci}, the ion thermal velocity as v_i, and the plasma beta as $\beta_i = 2/\mu_0 n T_i/B^2$. The compression ratios of the magnetic field in the microshocks is observed to $B/B_0 \sim \rho_l/\rho_0 \sim 2$–7 where B_0 and ρ_0 are the upstream magnetic field. We know how the microshock is formed from the Hall-MHD description of the plasmas [3]. The solar wind has dynamic pressure, ρu_{SW}^2, which balances the magnetospheripressure at the magnetopause (mp) at the stand-off distance R_{mp}. The pressure balance equation is given by $\rho u_{SW}^2 = B_{mp}^2/(2\mu_0) \sim B_s^2/(2\mu_0)\ (R_s/R_{mp})^6$. Where the dimensionless radius of the magnetopause is $R_{mp} = X_{mp} \cdot R_s$. The dynamo electric field is $E_{dyn} = -u \times B$ which gives a solar wind dynamo voltage $V_{SW} = L_y E_{dyn}$ of $E_{dyn} = u_{SW} B_{mp} = (2\mu_0 n_i m_i)^{1/2} u_{SW}^2$. Here we define the dynamo electric field E_{dyn} and the associated dynamo voltage V_{SW}.

A typical bow shock structure is propagating upwind with a speed of 250–300 km/s with respect to the rest frame mass density plasma which is flowing toward the planetary dipole with a speed of 400 km/s and the magnetic field Θ is at about 30° to the flow velocity. This bulk plasma flow speed is 5.7 times the sound speed (70 km/s) and 13 times the Alfvén velocity (30 km/s). The pulse shapes are well resolved by the four spacecrafts and there are hundreds of these nonlinear pulses in the overall bow shock region. This shocked plasma is swept around the magnetopause. The shocked plasma outside the magnetosphere is called the magnetosheath. The entry of plasma across the magnetopause into the magnetosphere proper is largely from a back flow from the downstream side of the planetary dipole. The spiky, nonlinear nature of the plasma in the bow shock was discovered earlier and named SLAMS for short large-amplitude magnetic structures [17], for which there are a variety of shapes.

4. Magnetic dipole properties

The plasma–magnetic dipole system must satisfy three key requirements to have the characteristics of a collisionless shock for solar wind simulations:

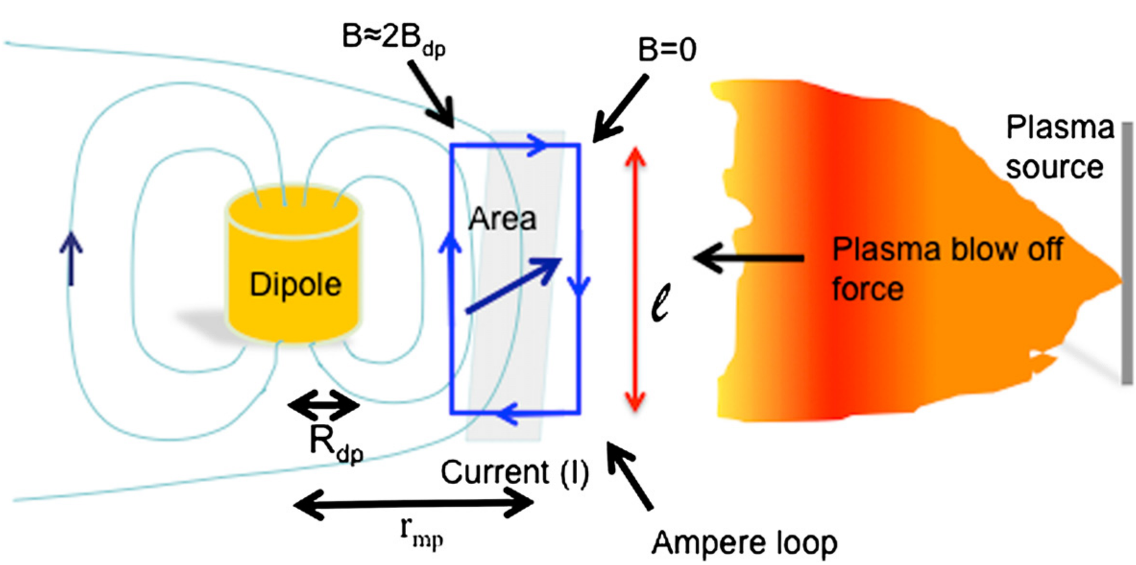

Fig. 1. Sketch of the laboratory experiment showing the blow-off plasma produced from a laser pulse irradiating an aluminum wire target. The obstacle on the left is alternately a magnetic dipole in the shape of 1 cm diameter permanent magnetic or an unmagnetized aluminum cylinder.