PIC simulations of collisionless shocks in laboratory-scaled mini magnetospheres

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Abstract

Available computational resources and laboratory plasma streams allow for an *ab initio* approach to the formation of collisionless shocks on the interaction between plasmas and magnetic obstacles of sizes on the order of the plasma kinetic scales. In this work, we resort to full particle-in-cell simulations to identify the critical obstacle size to generate a compressed plasma region ahead of these objects and show that their effective size depends on the relative orientation between the plasma's and the obstacle's magnetic fields.

Introduction

Interest has recently risen in the study of mini magnetospheres, mainly motivated by the observation of crustal magnetic anomalies on the lunar surface. The Moon does not possess a global magnetosphere or a bow shock like the Earth [1]. Interestingly, however, it does have localized regions of magnetic field of magnitude $B \sim 10-100$ nT over extensions of $L \sim 100-1000$ km [2]. The typical ion gyration radius around the solar wind magnetic field is of the order of $\rho_i \sim 100-1000$ km at 1 AU, i.e. it is comparable to the lunar magnetic obstacles' spatial scales [3, 4]. A similar scenario has been recently obtained experimentally [5]. Although available laboratory plasma streams have absolute parameters far from those of the solar wind (e.g. plasma density $n \sim 10^{14}-10^{15}$ cm^{-3} and $B \sim 10^{-1}$ T), these flows can share similar Alfvénic Mach numbers $M_A \sim 1-10$ and ratios $\rho_i/L \sim 1$, which allows for the investigation of scaled down space and astrophysical interactions between plasmas and magnetic fields in the laboratory. Correctly modelling the formation of mini magnetospheres and of magnetized, collisionless shocks thus implies understanding the kinetic-scale phenomena of the plasma. Whilst the global MHD dynamics of multi-scale magnetospheric systems is well understood, kinetic-scale physics such as finite Larmor radius effects on magnetized, collisionless bow shocks remain largely unexplored. Particle-in-cell (PIC) simulations play a critical role in this effort since they can capture the important microphysical processes underlying the formation of small-scale magnetospheres [6], as well as of collisionless shocks.

In this work, we perform PIC simulations of a magnetized plasma colliding with a dipolar magnetic field that stops the flow at a distance compared to its kinetic scales. We describe the microphysics of mini magnetospheres and determine the critical obstacle size for the formation of shocks in different 2D simulation planes.

PIC Simulations

The numerical experiments presented in this work were performed using OSIRIS [7], a massively-parallel PIC code. OSIRIS operates in normalised plasma units, the independent variable being the plasma density n_0. Distances are normalised to the electron skin depth c/ω_{pe} (where c is the speed of light and $\omega_{pe} = \sqrt{4\pi n_0 e^2/m_e}$ is the plasma frequency, with e and m_e representing the electron charge and mass, respectively) and times are normalised to the inverse of the plasma frequency $1/\omega_{pe}$.

In all the simulations, we use a cold plasma flow with reduced ion-to-electron mass ratio $m_i/m_e = 100$ and speed $v_0 = 100 v_{the}$, where v_{the} is the electron thermal velocity. By using these parameters (the realistic mass ratio is 1836 and the typical solar wind flow velocity is of the order of $10^{-3}c$), we can significantly reduce the computational effort to perform the numerical experiments, although it is still possible to infer about the microphysical properties of these systems. The grid resolution is 10 cells/(c/ω_{pe}). The simulation domain is filled with the plasma internal magnetic and electric fields $\mathbf{B}_{\rm IMF}$ and $\mathbf{E}_{\rm IMF}$ such that $\mathbf{E}_{\rm IMF} + \mathbf{v_0} \times \mathbf{B}_{\rm IMF} = 0$. The magnitude of $\mathbf{B}_{\rm IMF}$ is chosen such that the flow has an Alfvénic Mach number $M_A = v_0/v_A$, where $v_A = B_{\rm IMF}/\sqrt{4\pi n_0 m_p}$. The dipole magnetic moment μ is chosen such that the plasma ram pressure equals the magnetic pressure at a certain distance L, comparable to the plasma kinetic scales, given, to first order, by $L \simeq \left(\mu^2/2n_0 m_i v_0^2\right)^{1/6}$.

Figure 1 shows the results of 2D simulations where the interaction between a plasma of $M_A = 2$ and a dipolar magnetic field can be observed for different dipole intensities. Both the dipolar and the internal plasma magnetic fields point out of the simulation plane. The dipole magnetic moment increases from left to right, such that the density cavities have a size (a) $L < d_i, \rho_i$, (b) $d_i < L < \rho_i$ and (c) $d_i, \rho_i < L$, where ρ_i is the ion Larmor radius defined by $\rho_i = m_i c v_0/eB_{\rm IMF} = M_A d_i$. For $L < d_i, \rho_i$ (Fig. 1 a), the dipolar structure can only perturb the plasma creating a faint wake behind it. After the particles are deflected, they are rotated by the internal plasma magnetic field with a Larmor radius $\rho_i > L$, i.e. the plasma is not able to pile up in front of the cavity size and create a compressed (shocked) region of magnetic field. A similar result is observed for $d_i < L < \rho_i$ (Fig. 1 b), even though compressed plasma regions show an

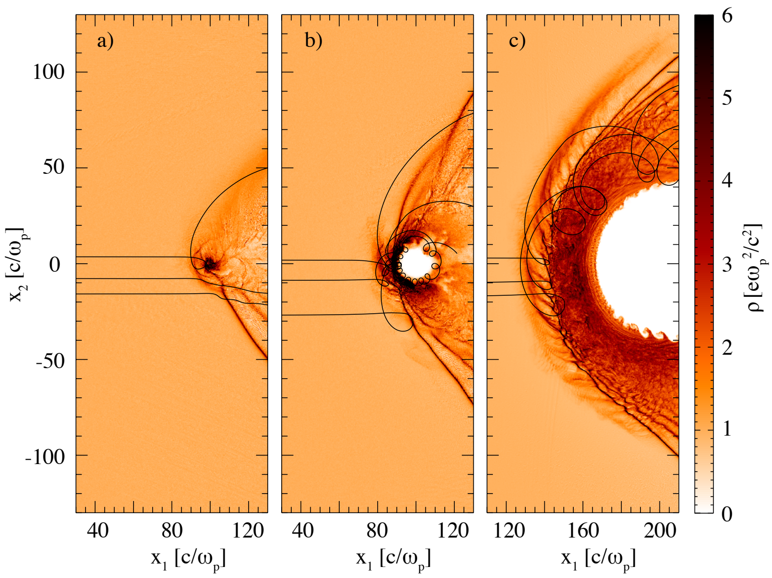

Figure 1: *Critical cavity size for formation of miniature magnetized shocks. A plasma flow with $v_0 = 0.2c$ and $M_A = 2$ interacts with magnetic dipoles that standoff the plasma at a distance (a) $L = 0.25\rho_i$, (b) $0.75\rho_i$ and (c) $2.5\rho_i$. The black lines represent ion trajectories and illustrate the typical Larmor radius scale after the particles are reflected.*

oscillatory dynamics ahead of the magnetic obstacle. In the case where $L > d_i, \rho_i$ (Fig. 1 c), the plasma ions can be reflected in front of the magnetic obstacle and thus counter-stream with the unperturbed flow, leading to the generation of turbulence via the modified two-stream instability [8]. A curved shock front, clearly identified by the sharp transition between the compressed and unperturbed plasma regions, is formed ahead of the density cavity. These results indicate that ρ_i is the critical kinetic scale that determines the shock formation in mini magnetospheres.

The magnetopause position is controlled by the balance between the plasma ram and the total magnetic pressure. Since the plasma is highly conductive, it compresses the dipolar magnetic field such that its internal magnetic field remains constant. Opposite orientations of $\mathbf{B}_{\mathrm{IMF}}$ can change the total magnetic pressure profile close to the magnetopause and thus inflate or deflate the density cavity. Although these changes may not be relevant in large-scale (e.g. planetary) systems, we find that for mini magnetospheres such inflation/deflation can be on the order of 100% the cavity size for low M_A flows and critically determine the formation of collisionless shocks. We find that the magnetic pressure gradient required to stop the plasma flow occurs farther from the dipole for anti-parallel $\mathbf{B}_{\mathrm{d}}$ and $\mathbf{B}_{\mathrm{IMF}}$ when compared to the opposite relative orientation (see Fig. 2 a, b). This difference is more evident when $\mathbf{B}_{\mathrm{IMF}}$, $\mathbf{B}_{\mathrm{d}}$ point out of the simulation plane. In an in-plane configuration (see Fig. 2 c, d), the field lines can reconnect in front of the magnetopause when $\mathbf{B}_{\mathrm{IMF}}$ and $\mathbf{B}_{\mathrm{d}}$ are anti-parallel. In this case, the simple pressure

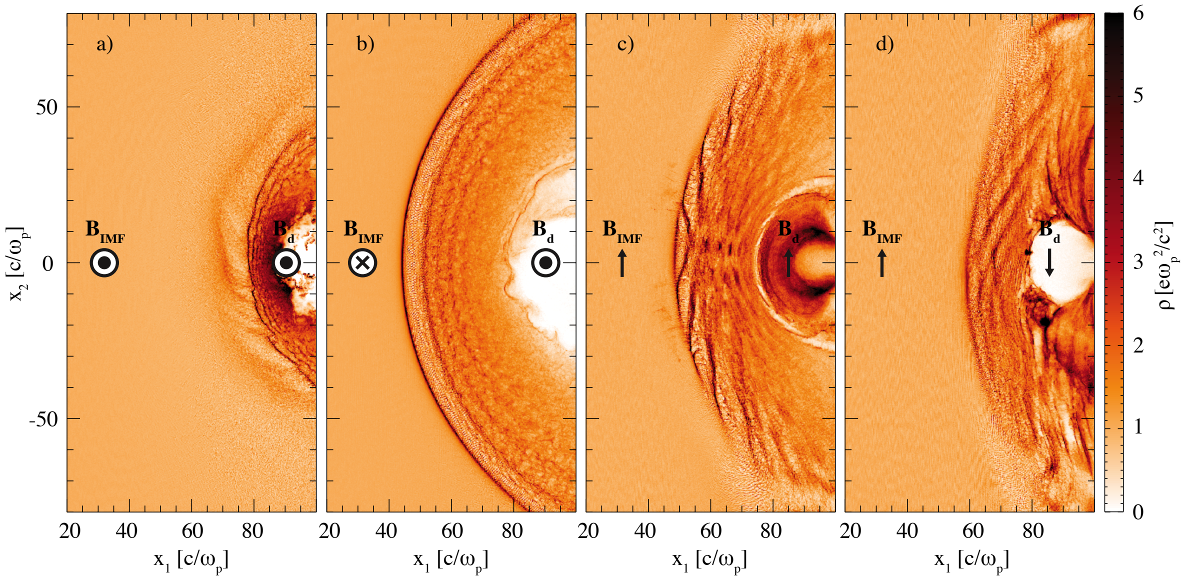

Figure 2: *Effective cavity size is sensitive to* $\mathbf{B}_{IMF}$ *orientation. A plasma flow with* $v_0 = 0.1c$ *and* $M_A = 1.5$ *is collided with a dipolar B-field parallel (a, c)/anti-parallel (b, d) to* $\mathbf{B}_{IMF}$*. The dipolar and plasma internal magnetic fields are set up in out and in-plane configurations in panels (a, b) and (c, d), respectively. The plasma is stopped at a distance* $L = 2d_i$ *according to the macroscopic pressure balance.*

gradient argument presented above is not sufficient to estimate the magnetopause position. In 3D, the interplay between the two planes will be critical to determine the cavity size. This will be investigated in a future publication.

Conclusions

We show that the critical obstacle size for the formation of shocks in mini magnetospheres is $L > \rho_i$. This result confirms that full PIC simulations are critical to describe the formation of collisionless shocks resulting from the interaction between plasmas and magnetic obstacles. We also observe strong variations of the effective obstacle size depending on the plasma magnetic field orientation. This shows that the global system behaviour can be determined by kinetic-scale physics and suggests that both space and laboratory systems may be highly mutable. Work supported by the European Research Council (Accelerates ERC-2010-AdG 267841).

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