GUIDE-FIELD MAGNETIC RECONNECTION: FIRST HYBRID SIMULATIONS OF HIGH ION TEMPERATURE PLASMAS

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Abstract

Magnetic reconnection is a fundamental plasma process that occurs throughout the heliosphere and can be responsible for high velocity plasma jets and energetic particles through the release of magnetic energy. Historically reconnection theory has predicted that the bulk flow and thermal energization is set by the available reconnecting magnetic energy, however, recent simulations, observations and theoretical works have shown the released magnetic energy in anti-parallel reconnection is inhibited by the upstream plasma beta (the relative thermal energy normalized to magnetic energy per particle, $\beta = 2\mathrm{T}/(\mathrm{B}^2/4\pi n)$). Using kinetic theory and hybrid particle-in-cell simulations of magnetic reconnection we extend this result for guide field reconnection. Preliminary works suggested that the influence of β was suppressed for a guide field, however we find that the outflow reduction is recovered for a sufficiently large total β based on the guide field and the reconnecting field. This suggests that the efficiency of reconnection as an energization process is limited in high β regimes such as well developed turbulence or in the downstream of shocks.

Keywords Magnetic Reconnection · Plasma Physics · Astrophysics · Computational astrophysics · Magnetohydrodynamics (1964)

1 Introduction

Magnetic reconnection is the process through which energy stored in the magnetic fields of (generally collisionless) plasmas is transformed into kinetic and thermal energy via rearrangement of the field line topology [1]. Magnetic reconnection occurs at places like stellar accretion disks, the magnetotail of the Earth, or the Sun's surface and is thought to be behind many space weather phenomena such as coronal mass ejections and the solar wind.

Reconnection is preceded by the concentration of magnetic flux in increasingly thin current sheets where the direction of the magnetic field lines changes abruptly over a small spatial scale. As oppositely directed field lines are pushed closer together by the inflowing plasma, they tear and conjoin, generating a stretched field line that relaxes and releases energy in the form of a plasma jet [2].

Many observational events [3] as well as simulations suggest that the speed at which these bulk plasma outflow jets travel is smaller than the expected Alfvén speed. The firehose instability is believed to be the reason for the outflow speed reduction, which arises from a pressure anisotropy in the diffusion region and can be interpreted as a centrifugal force where the component of the pressure that's parallel to the field lines ($P_\parallel$) pushes the particles towards the x-line, the point at which reconnection occurs, beating the magnetic tension force that creates the outflow. When the value of the firehose parameter $\epsilon = 1 + 4\pi(P_\perp - P_\parallel)//B^2$ is below 0 the instability is triggered and the outflow speed gets reduced.

Progress has been done in the pursuit of understanding how this instability gets triggered in anti-parallel reconnection, and an empirical equation (Eq. 1) that relates the initial ion exhaust temperature to the outflow has been derived empirically from simulations [4] and theoretical predictions for it have also been made [5].

$$v_0 = \frac{\epsilon}{3} \frac{c_{Ar}^2}{\sqrt{T_{i\parallel}/m_i}} \tag{1}$$

Despite these efforts, the aforementioned studies were limited to anti-parallel reconnection. The effects of high initial ion exhaust temperature in guide-field reconnection remain unbeknownst to us.

In this paper, we follow the work of Haggerty et. al [4] to perform and compare hybrid simulations of both nearly anti-parallel and guide-field reconnection with different upstream initial ion β_i values to ultimately analyze the general behavior of the outflow in guide-field reconnection as this variable increases.

2 Methodology, Simulations, and Observations

In order to study the outflow velocity, quasi-2D simulations of both, anti-parallel and guide-field reconnection were performed using kinetic hybrid particle-in-cell code ***dHybridR*** [6]. Lengths in simulations are normalized to the ion inertial length $d_{i0}=c/\omega_{pi0}$. The reconnecting magnetic field B_0 and particle number density n_0 are normalized to arbitrary characteristic values. Time is normalized to the ion cyclotron time $\Omega_i^{-1} = eB_0/m_i c^{-1}$. Speeds are normalized to the Alfvén speed $c_{A0} = \sqrt{B_0^2/4\pi m_i n_0}$. Electric fields and temperatures are normalized to $E_0 = c_{A0}B_0/c$ and $T_0 = m_i c_{A0}^2$. The simulation box has doubly periodic boundaries, with box size and grid scale that vary depending on the parameters set for the simulation and the and the coordinates $\hat{x}$ and $\hat{y}$ correspond to the outflow and inflow respectively.

Each simulation consisted of two force-free current sheets with magnetic profile $\mathbf{B} = B_{x0}(tanh((y - 0.25L_y)/\lambda) - tanh((y - 0.75L_y)/\lambda))$ where L_y is the dimensions of the box along $\hat{y}$, B_{x0} is the strength of the reconnecting magnetic field, and λ is the half-thickness of the current sheet.

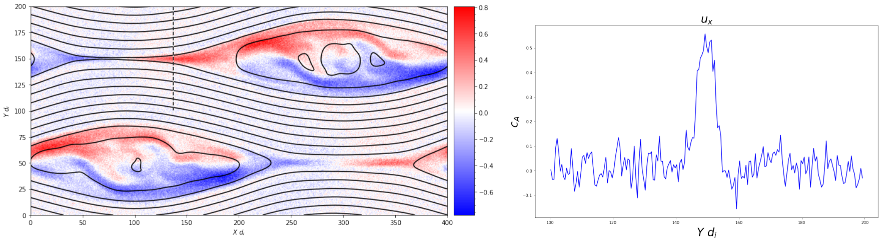

Figure 1: 2D plot of a reconnection simulation with initial ion temperature $T_i = 4$, and cut along y axis on the upper left reconnection region. The red and blue areas represent the asymptotic $E \times B$ drift which translates as the outflow in the positive and negative $\hat{x}$ direction respectively

In Figure 1 (a) and (b) we show the cut downstream along the $\hat{y}$ direction that is taken for every simulation at 40 to 70 d_i upstream to analyze the asymptotic $E \times B$ drift outflow as well as density, temperature, pressure, magnetic and electric field strengths, and other quantities such as mirror and firehose instabilities.

As found in previous works, the anti-parallel reconnection simulations carried out with the code dHybridR exhibited a similar reduction in the outflow speed that agrees with the prediction stated in Eq. 1 and the ones derived in the papers cited above.

In the case of guide-field reconnection, we observe a similar behaviour in the reduction of the outflow whose reduction factor appears smaller than that of anti-parallel reconnection. As the initial ion exhaust temperature becomes larger, the reduction in the outflow speed seems to scale with $\frac{1}{\sqrt{\beta_i}}$. Likewise, as the guide-field gets larger, the reduction of the outflow also seems to get smaller, yielding a faster outflow. It is also possible to distinct a tendency for reconnection of $\beta_i < 1$ to approach a constant value for any initial β. As the reconnecting magnetic field gets larger, the threshold for reconnection to transition into one that scales with the square root of β_i is placed at a higher inflowing reconnecting β.

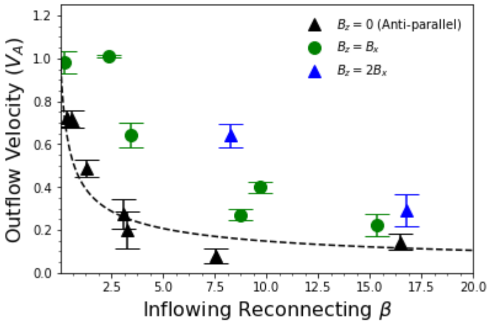

Figure 2: Compilation of all the simulations run. The black dashed line shows the prediction by Haggerty et al.[4] for anti-parallel reconnection. It is important to point out that the inflowing reconnecting β does not equal β_{tot}

2.1 Headings: second level

3 Theory

To be developed

4 Conclusion

In this paper, we have explored what occurs in guide-field reconnection and shown that it indeed exhibits a reduction in its outflow speed. We found that the reduction in the outflow speed cannot be explained by the predictions and empirical derivations made previously for anti-parallel reconnection events. The behaviour of the reduction seems to scale similarly to the anti-parallel case with additive that the factor by which it gets reduced is less. This factor remains constant as the initial β approaches the value of 1 after which it starts to decrease as a function of the magnitude of the magnetic field strength which gets larger by virtue of the guide-field strength. This threshold is present in simulations of any guide-field strength.

This study leaves open the possibility to develop a theoretical framework that accurately predicts the outflow speed as a function of the initial ion temperature T_i and the guide-field strength. If accomplished, this would expand the knowledge we have on how the partition of energy occurs in magnetic reconnection.

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