Magnetic Reconnection in Poynting-Dominated Plasma and the Effect of Turbulence

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Introduction

Various relativistic outflows from astrophysical objects are thought to be dominated by Poynting flux rather than kinetic energy flux. However, observations frequently imply the existence of an efficient dissipation mechanism of the energy contained in the fields. Provided the plasma is sufficiently dense to be described by MHD, magnetic reconnection is the most promising candidate. Although the classical steady state model predicts a faster reconnection rate than the Ohmic dissipation, it is still not enough to explain high energy astrophysical phenomena due to the large Lundquist number S. For this reason, a lot of effort has gone into finding a process which makes magnetic reconnection more efficient.

Turbulence has long been considered as a key process for fast reconnection in non-relativistic work. In 2-dimensional case, it has been reported that current sheets with sufficiently large Lundquist number evolve into a so-called *plasmoid-chain* which is a sheet filled with a lot of plasmoids. Interestingly, it has also been noted that reconnection rate of a current sheet reaching plasmoid-chain becomes very fast and independent of the resistivity [1, 2, 3].In 3-dimensional, the non-relativistic case, there are indications that turbulence can enhance magnetic reconnection rate since turbulent diffusion can induce a much larger effective resistivity in current sheets [4, 5]. In this theory, magnetic reconnection rate is much faster than the classical theory, and is independent of the resistivity.

Here, we extend the above non-relativistic work into the relativistic plasma which is Poynting-energy dominated as is the case of many high-energy astrophysical objects. It is reported that, because of the relativistically strong magnetic tension force, magnetic reconnection rate in a Poynting-dominated plasma can be enhanced by a factor $\sqrt{\sigma}$ where $\sigma = B^2/4\pi\rho h c^2\gamma^2$ is the magnetization parameter [6, 7]. Although this enhancement is numerically shown in the case of the relativistic Petschek reconnection, it was unclear if this process works in the case of including turbulent processes. We used a newly developed numerical technique to solve the relativistic resistive magnetohydrodynamic equations, and investigated both 2-dimensional plasmoid-chain and 3-dimensional turbulent reconnection. We confirm that the resistivity independent reconnection rate is obtained in the Poynting-dominated plasma case. We also show that the

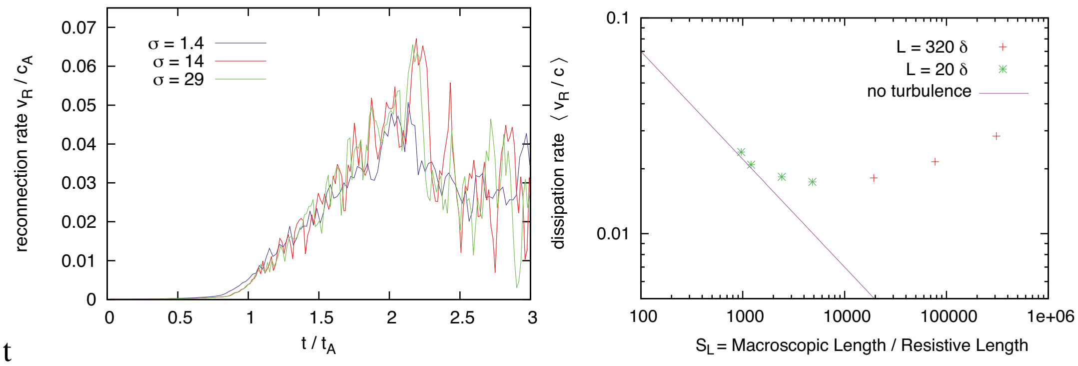

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Figure 1: *Reconnection rate of 2D relativistic plasmoid-chain. Left: temporal evolution of reconnection rate. Right: Plot of reconnection rates with respect to Lundquist numbers. Because of the plasmoid-chain, the reconnection rate is drastically enhanced, and becomes independent of the Lundquist number S when S exceeds a critical value.*

obtained reconnection rate is enhanced comparing with the non-relativistic case due to an effect of Poynting-dominated nature of plasma.

Method

We model relativistic current sheets using the relativistic resistive magnetohydrodynamic (RRMHD) approximation. We solve their temporal evolution using a RRMHD numerical scheme developed by Ref. [8] which fully takes into account the relativistic Ohmic dissipation law. This scheme preserves the divergence free constraint on the magnetic field using the constrained transport algorithm. We calculate the RRMHD equations in a conservative fashion. The relativistic ideal equation of state is assumed. For simplicity, we use a constant resistivity. We prepare a square domain, and divide it into homogeneous numerical meshes. For the model of relativistic current sheet, we prepare initially the relativistic Harris current sheet.

2D Reconnection with Plasmoid-Chain

To study effects of the plasmoid-chain in the case of large Lundquist number, $S = Lc_A/\eta > 10^3$, we consider the evolution of a current sheet in a 2-dimensional x-z domain whose length along the sheet is typically 320 times of the sheet width. Here, L is the length of the current sheet, c_A is the Alfvén velocity, and η is the resistivity.

For the upstream region of the current sheet, we consider a cold plasma with temperature: $k_BT/mc^2 = 0.1$; for the inside of the sheet, we consider a relativistically hot plasma $k_BT/mc^2 = 1$. To trigger the initial tearing instability at the origin $(x,z) = (0,0)$, we add a small divergence free perturbation to the magnetic field. To model magnetic reconnection in high energy astrophysical phenomena, we consider magnetically dominated plasma with typical magnetization parameter $\sigma = 14$.

3D Reconnection with Turbulence

To study effects of 3-dimensional MHD turbulence on the reconnection rate, we consider the evolution of a current sheet in a 3-dimensional domain.

We consider a plasma with uniform relativistic temperature $k_B T/mc^2 = 1$ in whole domain. In the upstream region, a moderately Poynting dominated plasma, $\sigma \sim 2$, is considered. To drive MHD turbulence, random velocity field with fixed velocity dispersion are injected locally around the central region of the current sheet for every fixed timesteps, Δt_{inj}. The injected velocity field is divergence-free, and its 1-dimensional power spectrum is flat ($k^2 P(k) \propto k^0$).

Results

Figure 1 is the reconnection rate of the numerical results. The left-panel is the temporal evolution of the rate with different magnetization parameter σ. This figure shows that the evolution of reconnection rate initially grows exponentially following the linear tearing instability. After one-Alfvén wave crossing time along the sheet, $t_A = L/c_A$, the sheet gradually starts to be filled with plasmoids. Around $t = 2t_A$, the sheet is completely filled with a lot of plasmoids, and becomes the so-called *plasmoid-chain*. The reconnection rate reaches about 0.03, and this is very fast comparing with the Sweet-Parker value, $v_R/c_A \sim 1/\sqrt{S}$. This can also be seen in the right-hand side panel of Figure 1. This is a plot of the averaged reconnection rate in the statistically steady state with respect to the Lundquist number. The solid line is the Sweet-Parker reconnection rate. This figure clearly shows that the reconnection rate becomes independent of the Lundquist number when the Lundquist number of systems is larger than a critical value, $S_c \sim 2 \times 10^3$. Note that this value is smaller than the non-relativistic value, $S_{c,NR} \sim 10^4$, [1, 2, 3].Theoretically, this non-relativistic critical value is inferred from the linear growth rate of the tearing instability and the Sweet-Parker law; substituting the Sweet-Parker sheet width, $\delta_{SP} \sim L/\sqrt{S}$, into the maximum tearing instability growth rate, $\gamma_{max} = (\tau_R \tau_A)^{-1/2}$, where $\tau_R = \delta^2/\eta$ is the resistive time scale, and $\tau_A = \delta/c_A$ is the

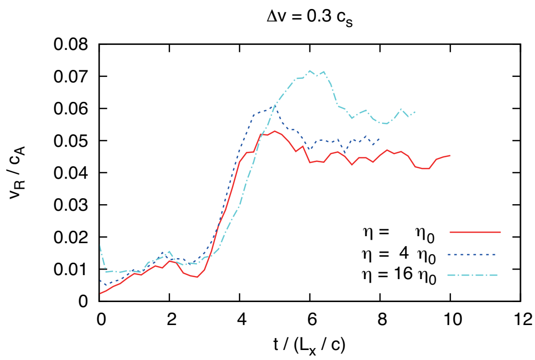

Figure 2: *Temporal evolution of reconnection rate of 3D relativistic turbulent reconnection. In those calculations, the resistivity is changed 1-order of magnitude but it shows the reconnection rate is nearly independent of the resistivity.*

Alfvén crossing time of the sheet width δ, the following expression can be obtained:

$$\gamma_{max}\tau_{A,L} \sim S_L^{1/4}, \quad (1)$$

where $\tau_{A,L} = L/c_A$ is the Alfvén crossing time along the sheet length L, and $S_L = Lc_A/\eta$. This means that the growth rate of the plasmoid-chain becomes comparable to the Alfvén crossing time when $S_L > 10^4$. Our smaller critical value, $S_c \sim 2\times 10^3$, may be due to a relativistic effect which gives a factor $\sqrt{\sigma}$ increase to the Sweet-Parker law, $v_R/c_A \sim \sqrt{\sigma}/\sqrt{S}$, and this changes the non-relativistic growing time of the plasmoid-chain into: $S^{1/4}\sigma^{3/4}$. More comprehensive discussions are given in the paper [9].

Figure 2 is the temporal evolution of reconnection rate of the plasma with the 3D turbulence case. In this calculations, the resistivity be changed more than 1-order of magnitude, but the reconnection rates are nearly independent of the resistivity. This indicates that the magnetic reconnection is not driven by just a local X-point but strong turbulence induces multiple X-points in the sheet and accelerate magnetic reconnection drastically, as predicted in the non-relativistic case [4].

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