THESIS PROPOSAL

Title: Magnetic Reconnection at the Leading Edge of an Interplanetary Coronal Mass Ejection: A Data-Driven Simulation Study

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Field of study: Physics

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1 Introduction

Magnetic Reconnection is a magnetic field rearrangement in a microscopic scale to make the system achieve the lower energy state through transferring the energy that is stored in the magnetic field lines into a kinetic energy of the plasma.

The reconnection is well known to be the cause of several space weather phenomena near Earth such as auroras, which originate through reconnection at the Earth's magnetosphere. Reconnection also provide the energy for solar storms at the surface of the Sun. Such solar activity causes space weather phenomena at Earth.

Apart from the reconnection near Earth and the surface of the Sun, there is some interesting observational evidence of magnetic reconnection that was observed at the interplanetary region between the Sun and the Earth's magnetosphere by *Chian* and *Muñoz* (2011). On 2005 January 21, four *Cluster* spacecraft detected asymmetric reconnection at the leading edge of an interplanetary coronal mass ejection (ICME), a massive release of plasma and attached magnetic field lines from the solar corona which can also drive a geomagnetic storm that can cause several types of space weather phenomena. For this event their work shows characteristics of asymmetric reconnection, which is a type of the reconnection with a current sheet separating plasma with different magnetic field strength and density.

../Seminar/Pics/5a.png

Figure 1: This graph shows a plateau feature in the exhaust (outflow) from asymmetric reconnection when plotting the component of magnetic field in the L-direction (Direction along magnetic filed lines)[*Chain* and *Muñoz* 2011].

In this project we study asymmetric reconnection in the same event as *Chian* and *Muñoz* (2011). We will perform a data-driven simulation using a Particle In Cell (PIC) model, which treats both ions and electron as a particle. The result from the simulation will be used to compare with observational data. Finally, in this study we also have an opportunity to study mixing behavior between two plasma populations that were initially separated.

2 Objectives

- Learning more about asymmetric reconnection at the leading edge of an interplanetary coronal mass ejection through a data-driven simulation.
- Study mixing of the two plasma populations in a reconnection outflow region.

3 Background knowledge

Magnetic reconnection

An ideal properties of a plasma is quasi-neutrality, when plasma have a zero total charge. Plasma is a perfect conductor that means a plasma conductivity is nearly infinity or a plasma have no electrical resistivity. And the condition that we are interested in is called a frozen-in condition.

Frozen-in condition

The ideal magnetohydrodynamic plasma model, which is the plasmas and magnetic behave like fluid, have a frozen-in condition every where.

Under the frozen-in condition, the electric filed is zero in the plasma frame so the particles can only sense the magnetic field that drives particles to gyrate around the magnetic field line that make it like the particles are frozen in to the magnetic elements. However, if we transform into the lab frame to become a plasma observer and an element of plasma moves with the velocity $\mathbf{u}$, we will be able to observed the electric filed of the plasma element that occur by the frame transformation.

$$\vec{\mathbf{E}}_{\text{lab}} = -\frac{\vec{\mathbf{u}}}{c} \times \vec{\mathbf{B}}_{\text{lab}}$$

We can also show that,

$$\begin{aligned}
\vec{\mathbf{E}}_{\text{lab}} &= \vec{\mathbf{B}}_{\text{lab}} \times \frac{\vec{\mathbf{u}}}{c} \\
\vec{\mathbf{E}}_{\text{lab}} \times \vec{\mathbf{B}}_{\text{lab}} &= \left(\vec{\mathbf{B}}_{\text{lab}} \times \frac{\vec{\mathbf{u}}}{c}\right) \times \vec{\mathbf{B}}_{\text{lab}} \\
&= -\vec{\mathbf{B}}_{\text{lab}} \times \left(\vec{\mathbf{B}}_{\text{lab}} \times \frac{\vec{\mathbf{u}}}{c}\right) \\
&= -\vec{\mathbf{B}}_{\text{lab}} \left(\frac{\vec{\mathbf{u}}}{c} \cdot \vec{\mathbf{B}}_{\text{lab}}\right) + \frac{\vec{\mathbf{u}}}{c}\left(\vec{\mathbf{B}}_{\text{lab}} \cdot \vec{\mathbf{B}}_{\text{lab}}\right) \\
&= -\mathrm{B}^2 \hat{\mathbf{B}}_{\text{lab}} \left(\frac{\vec{\mathbf{u}}}{c} \cdot \hat{\mathbf{B}}_{\text{lab}}\right) + \frac{\vec{\mathbf{u}}}{c}\mathrm{B}^2
\end{aligned}$$

We can consider $\vec{\mathrm{u}}$ in to two component. Firstly, we consider a plasma bulk velocity in the same direction with a magnetic field ($\vec{\mathrm{u}}_{\|}$). Secondly, we consider a magnetic field perpendicular velocity ($\vec{\mathrm{u}}_{\perp}$). However, a $\vec{\mathbf{E}} \times \vec{\mathbf{B}_{\text{lab}}}$ need to be perpendicular to $\vec{\mathbf{B}}_{\text{lab}}$, so only $\vec{\mathrm{u}}_{\perp}$ is considered.

$$\begin{aligned}
\vec{\mathbf{E}}_{\text{lab}} \times \vec{\mathbf{B}}_{\text{lab}} &= \frac{\vec{\mathbf{u}}_{\perp}}{c}\mathrm{B}^2 \\
\frac{c\left(\vec{\mathbf{E}}_{\text{lab}} \times \vec{\mathbf{B}}_{\text{lab}}\right)}{\mathrm{B}^2} &= \vec{\mathbf{u}}_{\perp}
\end{aligned}$$

This means a plasma under frozen-in condition have a perpendicular velocity that drove only by an $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ drift.

Moreover, the conservation of magnetic flux due to this properties of a Maxwell's equation $\vec{\nabla} \cdot \vec{\mathbf{B}}_{\text{lab}} = 0$ have an importance roll in the studying of the magnetic reconnection. With the frozen-in condition the two magnetic flux tubes can not merge due to the condition that the magnetic flux within each tube before and after merging can not change. Under these conditions magnetic reconnection can not occur.

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Figure 2: All this is assuming the frozen-in condition show two magnetic fluxs are merging in 2 dimensional.a)Two flux tubes before merging. A first tube contain 3 magnetic units with into-the-page direction and 1 magnetic unit with out-of-the-page direction. When a second tube contain 3 magnetic units with out-of-the-page direction and 1 magnetic unit with into-the-page direction. b) Two flux tubes are merging. The first tube gains 1 magnetic unit with into-the-page direction. When the second tube gains 1 magnetic unit with out-of-the-page direction. c) When two magnetic flux tubes are under frozen-in condition, two flux tubes can not merge in order to conserves the amount of magnetic unit then two tubes can only press each other.

Current sheets

Due to the conservation of magnetic flux with the frozen-in condition for the ideal plasma, two magnetic flux tubes are not able to meet, merge, break, and reconnect. Therefore, the space between the two flux tubes with the different direction will create the into-the-page current ($\vec{\mathbf{J}} = \vec{\nabla} \times \vec{\mathbf{B}}$), which we call current sheet. From these properties we need to break a frozen-in condition in some region,

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Figure 3: Current sheet

which is called a magnetic diffusion region, for allowing the magnetic field line to break and reconnect again in order to study a magnetic reconnection. Then one way to determine a type of reconnection is how the frozen-in condition was broken. These following sections we will considering in two types of magnetic reconnection; collisional reconnection and collisionless reconnection.

Collisional reconnection

The collisional reconnection occur when the plasma fluid in some region is not a perfect conductor anymore. This region is called “diffusion region” or “reconnection region” means the magnetic field lines can be diffused inside this region. In this region ,there is an additional electric field from the collision of a plasma that make the MHD plasma gain the electrical resistivity. This type of reconnection is called Sweet-Parker reconnection.

$$\vec{\mathbf{E}} = -\frac{\vec{\mathbf{u}}}{c} \times \vec{\mathbf{B}} + \eta \vec{\mathbf{J}}$$

Sweet-Parker Reconnection(collisional).png

Figure 4: Sweet-Parker Reconnection

The collisional reconnection have a slow reconnection rate due to the large diffusion region.

However, the collisional reconnection not usually occur in the space plasma environment due to a low density plasma environment that can make the collision rate very small. In this project we interest to study the reconnection in the interplanetary plasma environment, so the type of reconnection that we interest is collisionless reconnection.

Collisionless reconnection

Same as collitional reconnection, the frozen-in condition need to be broken in order to have a collisionless reconnection. However, the plasma fluid is still a perfect conductor that means the electric field can not generate from the resisitivity. Therefore, another mechanism is needed for generating electric field.

The region under frozen-in condition in the environment that no collision, the plasmas move under $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ drift and plasmas are also attached to the magnetic field. However, when the plasmas move inside the hall region that frozen-in do not works, the plasma won't drift with $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ anymore.

../Seminar/Pics/MRE/Collisionless Reconnection.png

Figure 5: This picture shows a particle trajectory under the frozen-in condition when it moves out side the hall region(Yellow region) and the trajectory in side the region when the frozen-in condition is broken.

$$\vec{\mathbf{E}} = -\frac{\vec{\mathbf{u}}}{c} \times \vec{\mathbf{B}} + \frac{1}{nec}\left(\vec{\mathbf{J}} \times \vec{\mathbf{B}}\right)$$

In this equation shows that an electric field in the lab frame now do not contain only a transformation frame electric field but also have a Hall term that generates another electric field which breaks frozen-in condition because in the plasma frame an electric field is not zero anymore.

`../Seminar/Pics/MRE/Hall Reconnection(collisionless`

Figure 6: Hall reconnection

Asymmetric reconnection

Now we have an idea what the magnetic reconnection is, we will move next to an analysis step.

In this study we will focus on an asymmetric inflow (asymmetric reconnection), which there are unequal incoming and out going mass, momentum, and energy fluxes through the reconnection region. Because in reality, such as reconnection under a turbulent condition, the reconnection loses all of its symmetry.

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Figure 7: Asymmetric reconnection

In this study we will an reconnection at the leading edge of an interplanetary coronal mass ejection which we believe to be an asymmetric reconnection.

Interplanetary coronal mass ejection

Coronal mass ejection

A corona mass ejection(CME) is a massive release of plasma and attached magnetic field from the solar corona, which is a low density plasma (when comparing with other parts of the Sun.) that surrounds the Sun. The CME usually present during a solar prominence eruption and also following solar flares. This solar events mostly originate from active regions on the Sun's surface, such as grouping of sunspots.

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Figure 8: Corona mass ejection observed with coronagraph in white light.

Interplanetary coronal mass ejection

Interplanetary coronal mass ejection(ICME) is one of the large-scale interplanetary structures. ICMEs originate from closed field region at the Sun's surface that it is called coronal mass ejection(CME). CMEs drive shocks from close to the Sun then expand into the interplanetary medium, the shock become weaker when go further from the Sun. ICMEs are the interplanetary enlargement of CMEs. CMEs can be observed in white light with coronagraph. However, ICMEs can not be successfully observed the same way as CMEs. They are preferable to identified using plasma, magnetic and energetic particle signature, for example.

../Seminar/Pics/Schematic-of-an-interplanetary-coro

Figure 9: ICMEs are identified using plasma and magnetic properties.

Chian and *Muñoz* 2011

Interplanetary coronal mass ejection on 21^{st} January 2005

On 20^{th} January 2005 at 0654 UT, a huge coronal mass ejection erupt toward Earth that releases flare in X7-class that we can detect solar energetic particles immediately at the spacecrafts after the explosion. This CME is from sun spot number 720 that big enough to see at the Earth. This CME arrived at the *Cluster* spacecraft on 21^{st} January 2005.

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Figure 10: The coronal mass ejection at 3 o'clock location in visible light on 20^{th} January 2005 at 6.54 am observed by SOHO.

Result and Discussion

The results from their work show the evidence of the magnetic reconnection observe by four *Cluster* spacecraft at the leading edge of a ICME along with a bifurcated current sheet in both multi-spacecraft and single-spacecraft technique.

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Figure 11: Four *Cluster* spacecrafts.

../Seminar/Pics/1b.png

Figure 12: This graph shows two magnetic discontinuity that refer to the current sheets structure at the leading edge of an ICME

../Seminar/Pics/3.png

Figure 13: This graph shows magnetic reconnection at the leading edge of an ICME together with the current sheet SB1 and SB2. When $|\mathbf{B}|$ (nT) is the modulus of magnetic field, $|\mathbf{V}|$ (km s^{-1}) is the modulus of observed plasma velocity (black) and the plasma velocity(orange) from the magnetic reconnection theory, and $|\mathbf{J}|$ is the modulus of the current density compute by multi-spacecraft technique.

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Figure 14: This picture shows LMN coordinate system, L is a direction of the field lines, M is out-of-the-plane direction also the the current flow direction, and N is the perpendicular direction to L and M.

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Figure 15: These graph show the component of $\mathbf{B}$ and $\mathbf{V}$ measured by $Cluster - 1$ in the LMN coordinate. Both show observational evidence of bifurcated current sheet SB1 and SB2, with a plateau at the middle of each current sheet in B_L, and correlated/anti-correlated V_L and B_L.

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Figure 16: This graph shows a plateau structure that refer to a bifercated current sheet for a single spacecraft technique.($Cluster - 3$)

../Seminar/Pics/5b.png

Figure 17: This graph shows J_M calculate from B_L showing double peaks at both edges of the bifurcated current sheet SB1.

4 Methodology and Scope

Methodology

An introduction to Particle In Cell Model

A Particle-in-cell model is a model that we will use to study a reconnection. This model will consider the plasma as an individual particle. This model will separated into two part.

Firstly, there is an equation of motion for a plasma view point through the normalized relativistic form of Newton's second law equation.

Secondly, There is an time evolution for the electromagnetic feature through the normalized relativistic form of Maxwell's equation.

In this model both plasma and electromagnetic elements will change with time. And the model will govern all of the parameters through this following diagram.

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Figure 18: This diagram shows how plasmas and electromagnetic features behave under a Particle-In-Cell model. When the two different color circles represent two type of particles, every grid points contain the value of electric and magnetic field, and four nearest grid points (Yellow dash box) represent 1 cell

A data-driven simulation

In this project we choose to use a PIC model, so the next part is doing a simulation. A data-driven simulation is a simulation for comparing the model with the observation data by using initial variables for the simulation from the real event. From this study we will set the initial parameters to be the environment at the leading edge of an ICME on 21^{st} January, 2005.

Scope

- Current density(J)
- Electric field
- Density of ions and electrons
- Velocity of ions and electrons
- Magnetic field

5 Research planning

	Dec-Feb	Mar-Apr	May	Jun-Jul	Aug
Coding and Simulating a model					
Data analysis					
Conference					
Writing thesis					
Thesis defense					

6 Summary and Outlook

- Comparing simulation result with observable evidence.
- At the leading edge of an interplanetary coronal mass ejection can have magnetic reconnection.

References

[1] Abraham C.-L. Chian and Pablo R.Muñoz. *"Detection of current sheets and magnetic reconnections at the turbulent leading edge of an interplanetary coronal mass ejection."* Astrophysics Journal Letters 733: L34 (5pp), 2011 June 1.

[2] Malakit, K. *"Asymmetric magnetic reconnection: A particle-in-cell study."* PhD.Thesis, 2012.

[3] Space Weather, *" What's up in space−−21 Jan 2005."* http://spaceweather.com/archive.php?view=1&day=12&month=09&year=2017

[4] Gopalswamy, N. *" Properties of Interplanetary Coronal Mass Ejection."* Space Science Review (2006) 124: 145. https://doi.org/10.1007/s11214-006-9102-1