Magnetic Reconnection and Generation of Radio waves in Star-Planet Interaction

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Contents

Abstract

The study of exoplanet[3] has become one of the most important studies in the growing field of Astronomy. In this report we are going to have a brief overview on the Star-Planet interaction process and its consequences.
Here we shall discuss what happens when magnetic field from a star interacts with a obstacle nearby and how the auroras are formed. We will end this report by categorizing the types of obstacles and will have a brief discussion on how the process of reconnection and emission of Radio Waves take place for object of different categories.[15]

Chapter 1

Introduction

Finding exoplanets is one of the most important aims in the world of astronomy. Our closest exoplanet is Proxima Centauri-b, which is nearly 4.2 lightyears away from us. Even if using the most developed and advanced methods, there is no chances we can reach to our closest exoplanet within a human lifetime. So, detection of exoplanets and studying them in different EM waves are the crucial part for the dawn of exploration of extra-solar planets.

Till the date, there are several effective methods for the detection of exoplanets. Among them the most effective and popular one is the Transit Method, in which light curve of a star is studied. When a planet passes infront of the star, a drop in the light curve is observed. Using the dip in the light curve, we can get enough information to study the planet. Beside the transit method, there are also some methods, eg. Reflex motion (Radial velocityt), Gravitational lensing, direct imaging and etc.

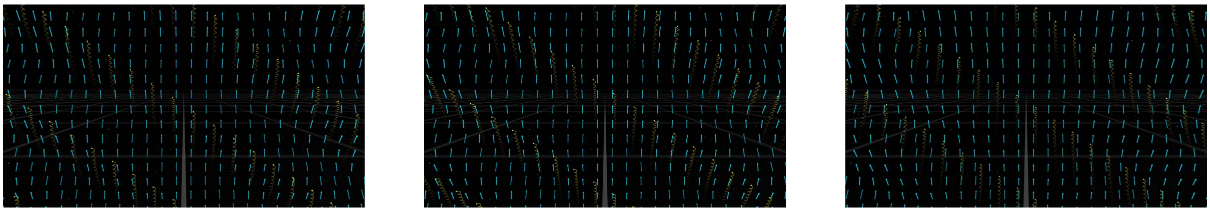
A new addition to the field of detecting the exoplanets is the study of the generated radio waves, due to the magnetic interaction between a host star and its planet.[14]

Before jumping into the topic, it's important to get familiarized with some definitions.

1.1 Terminologies

- **Plasma:** Plasma is one of the four fundamental states of matter. Plasma contains both ions and electrons, and its nature of carrying charged particles differentiate it from the other states of matter. At a certain temperature and density we get a partially ionized plasma, which has a certain amount of neutral particles along with charged particles.
  If in a plasma, a magnetic field is capable to change the trajectories of the charged particles, then it is a magnetized plasma.[13]

- **Alfven Waves:** A kind of plasma waves, which are transverse in nature. This transverse wave moves along a magnetic field line, carrying the ions and perturbed magnetic fields with it. The speed of Alfven wave is termed as Alfven speed. Related to the Alfven wave's speed, there is a term, called Alfven Mach number.



(a) (b) (c)

Figure 1.1: Three pics showing the movement of Alfven waves along magnetic field[2]

- **Mach number:** Mach number is a dimensionless quantity, which is basically the ratio between relative velocity of a flow (w.r.t. anything) and velocity of sound.

$$M = \frac{v}{c}$$

where, v = the relative velocity of a flow of a fluid and c = speed of sound in the fluid. The **Alfven Mach number** is related to the speed of Alfven waves. It is basically the ratio between the speed of plasma flow and Alfven speed.

- **Super-Alfvenic and Sub-Alfvenic:** A flow is Super-Alfvenic when the Alfven Mach number is grater than 1, and the flow is considered as a Sub-Alfvenic when the Alfven Mach number is less than 1.

- **Non-Maxwellian Distribution:** We can think it as a deviation from the Maxwellian distribution (most probable velocity of particles in a gas) of particles.

Chapter 2

Star-Planet interaction

2.1 Magnetic Reconnection

Every star has its own magnetic field, due to the motion of plasma inside it. Due to a stellar wind or other stellar phenomenon (eg. coronal mass ejection) the plasma from the star gets out from the sun, with a closed loop of magnetic field from the star. This loop after travelling all the way from the host star to its planet, collides with the magnetic field of it (the planet), and the collision between the two magnetic fields is known as **Magnetic Reconnection**[6][12].

Magnetic field lines are stretched and twisted, which carry a certain amount of potential energy with the configuration. During the reconnection process the stressed magnetic fields configuration relaxes and achieves the configuration of a lower potential. The excess magnetic energy are converted in the kinetic energy of the fluid and heating of the plasma.

From Ampere's law ($\nabla.\vec{B} = 0$) we know that magnetic field always exists in loop. So, we can never expect that a magnetic field will get disconnected by any means from the middle. But, in case of reconnection it happens, as during the time of reconnection laws of ideal Magneto Hydro Dynamics (ideal MHD) are violated.

The magnetic fields are snapped from the middle and gets connected with each other, in a manner (figure: 2.1).

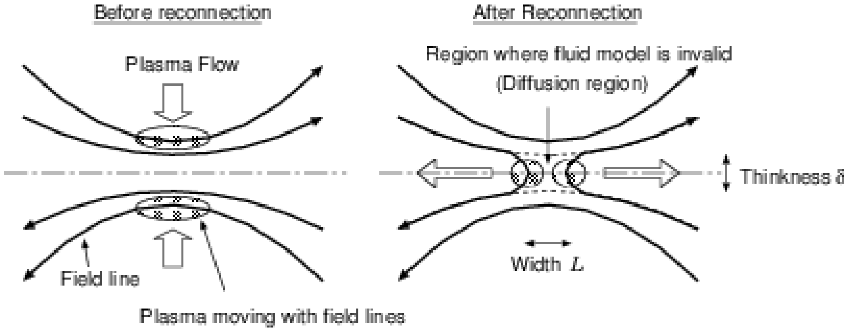


Figure 2.1: The reconnection of magnetic field liens

Due to the violation of laws of ideal MHD, as an example, we can see **finite resistivity effect**.
We can also, observe the conservation of magnetic flux doesn't hold at the scenario. The flux is annihilated and the flux is changed into kinetic energy of the flow and heat of the plasma.

[**Finite Resistivity effect:** In case of ideal Magneto Hydro Dynamics, the resistivity tends to 0, which implies that conductivity tends to infinite.]

When two magnetic field, opposite in direction of propagation collides with each other, something interesting takes place.

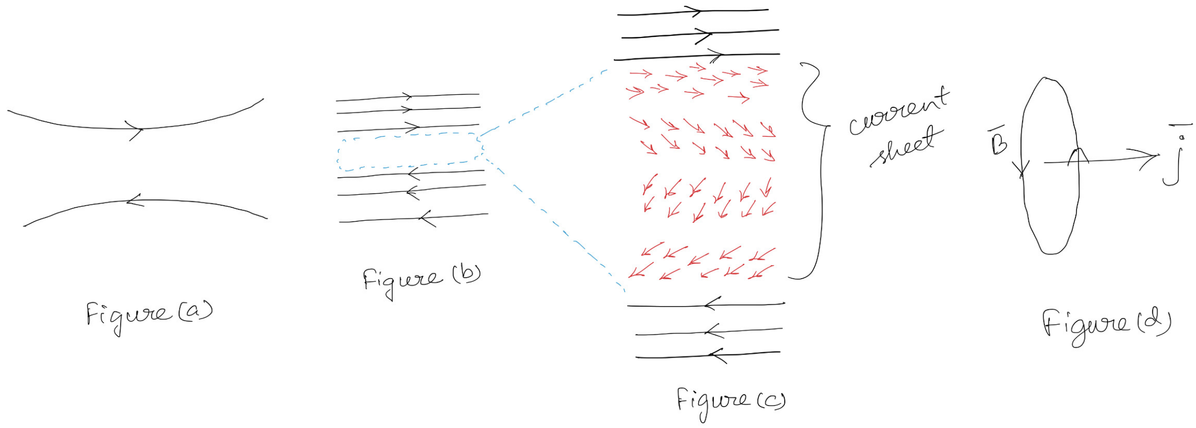


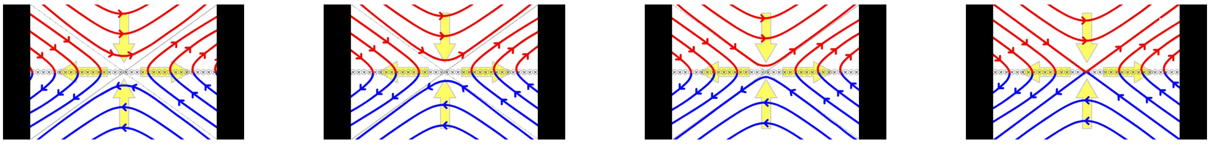
Figure 2.2: Generation of sheet current

From the figure above, we can see in figure a and b, oppositely propagating field lines are approaching each other. The gap in between them (dotted portion in figure b) can be interpreted like the orientation in figure c.
Figure d, represents the fourth equation Maxwell ($\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$).

We can say the scenarios in figure a and b can be compared as a looped magnetic field lines, like figure d.

So, there is the violation of the finite resistivity effect, and we can get some finite value of resistance. As, we are getting a presence of current, we can say from Ohm's law, $\vec{J} = \sigma \vec{E}$.
So, σ is no longer infinite and thus we can expect a value of resistance.[9][8]

As the reconnection takes place, the newly formed magnetic fields lines try to snap along the perpendicular direction of their initial velocity (figure:).



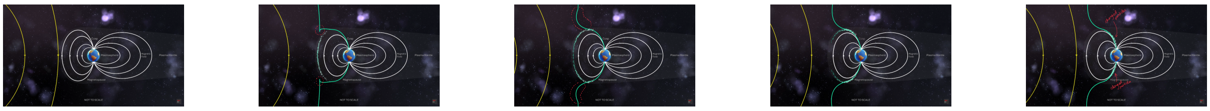
(a) (b) (c) (d)

Figure 2.3: We can see the newly formed fields are having a motion along the horizontal direction.

2.2 Star-Planet Interaction

When the newly formed magnetic fields try to snap along the perpendicular direction of their initial motion (i.e. when they snaps along the horizontal direction, as per figure 2.3), then due to the huge force of instantaneous snap of the field lines, perturbation is generated.
This perturbation in magnetic field lines, along with charged particles starts moving as Alfven waves.[4][10]

A pictorial representation:



(a) (b) (c) (d) (e)

Figure 2.4: The propagation of disturbance are dotted in the picture, which will follow the magnetic field lines. Also, we can see the charged particles, which are following the magnetic field lines to gather around the poles.[5]

Now, the obstacle with which the magnetic field with charged particles, arriving from the host star, is colliding, based on their nature, can be divided in two categories; **Magnetized Obstacle** and **Unmagnetized Obstacle**.

2.2.1 Magnetized Obstacle

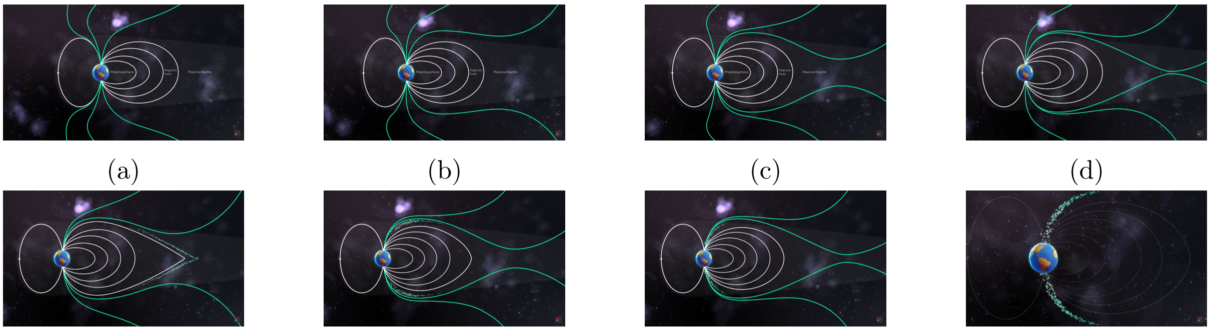
In case of a magnetized obstacle, it has its own magnetosphere around it, with which after the collision of magnetic field from the host star, due to the energy release (as mentioned in section 2.1), charged particles get accelerated. Due to the acceleration of the charged particles, along the magnetic field lines, radio emission can be observed. Alfven Mach number plays an important role, while understanding the propagation of charged particles and perturbation of magnetic field lines.

Super Alfvenic flow

If the incoming flow, from the host star is Super Alfvenic then due to a formation of bow shock[11], it gets transferred into Sub Alfvenic.
Due to the generation of the bow shock[1], the magnetic field lines get disconnected from the host star. Now those disconnected magnetic fields gains the orientation of the already existing

magnetic fields around the obstacle. Thus the charged particles can't anymore return to the host star (the source), and accumulates at the region where, the magnetic field lines end, the polar region of the obstacle, which after interaction with the atmosphere of the obstacle, appears as Aurora.

These images can describe, what happens to the orientation after the magnetic field lines, get disconnected from the source:



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 2.5: Flow of magnetic field lines after a bow shock formation by obstacle[5]

Sub Alfvenic flow

When the flow from the host star is not super alfvenic (i.e. the speed has a Mach number less than 1), then the magnetic field lines do not get disconnected from the source, as the obstacle has not formed any bow shock.
In this situation, the magnetic field lines, after reconnection, will remain connected with the source and as well with the obstacle. In this scenario, wings are formed, for Alfven waves to propagate. These wings are also called the **Magnetic Flux tube**.

In our Solar System, we can spot Magnetic flux tube between Jupiter and its satellites (IO, Ganymede).

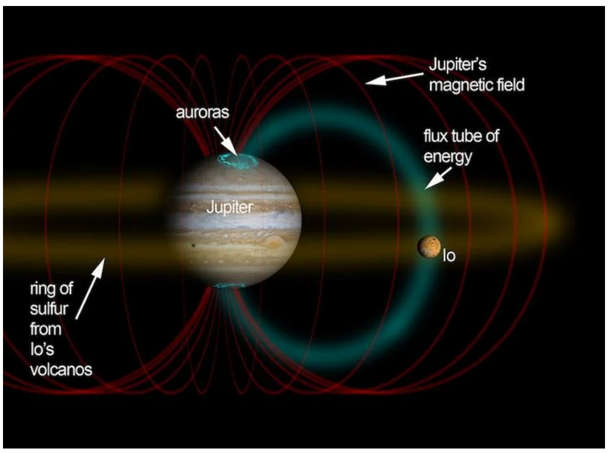


Figure 2.6: Generation of sheet current[7]

If the flow that is coming from the source is strongly magnetized, then from the Alfven waves, we can spot Radio emission. However, in case of our Solar system, the flow is not so strongly magnetized, so we can't spot it in Sun-Earth system.
But, in Jupiter's flux tube with its satellite, we can spot radio emission. In presence of the flux tube, the rotation of strong magnetic fields of Jupiter results in reconnection and radio emission.

2.2.2 Unmagnetized Obstacle

In case of an unmagnetized obstacle, the scenario can be different from a magnetized obstacle. This in turn depends on the conductivity of the obstacle.

Conducting Body

In case of an obstacle, which is conductive in nature, an induced magnetosphere is formed, if the flow from the source is Super Alfvenic. But, the focusing of charged particles in the polar region does not take place and no radio emission is detected.

If the flow is Sub Alfvenic in nature, then there will be no excpetion than the previous mentioned case for a Magnetized obstacle. We can observe the formation of a Magnetic flux tube. But, the difference due to the conducting body will be that, the perturbation in magnetic field will be not due to the reconnection phenomena that will take place, but it'll be due to the deviation by the obstacle.

Insulating Body

In case an obstacle, which is insulating by nature, it'll absorb the incoming flow. For absorption of the flow, a plasma cavity is created, which gets filled by the charged particles in motion. For insulating bodies also no radio waves are produced.

Chapter 3

Conclusion

This review report is basically a study of magnetic reconnection and the generation of Radio waves due to the interaction between a Star and its planets. We had a detailed discussion on Magnetic reconnection, where we came across the fact that Ampere's law is violated in non-ideal MHD. Also, we got to see the generation of current, thus electric field at the moment of reconnection.
After having a brief overview on reconnection, we proceeded to the formation and the topology of Alfven waves. We also encountered the reason of generation of Radio waves (that is due to accelerated charges).
How Auroras are formed also is an important result of magnetic reconnection and its topology after.
Finally we had a brief review on what happens for Magnetized and Unmagnetized body. There we discussed about different scenarios, such as reconnection and generation of radio waves for magnetized obstacle in Super and Sub Alfvenic flow. Then, we moved on to Unmagnetized obstacles and had a short discussion about what happens for a conducting and insulating body. Study of radio emissions from exoplanets can be a crucial step in their detection and study.

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