Effect of Magnetic Reconnection on Earth's Magnetosphere

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Abstract
As we know, Sun is the place of solar activities such as solar flares, coronal mass ejections, solar wind, etc. The solar eruptions of plasma and magnetic fields reach near the Earth's magnetosphere, resulting in an interaction of plasma and magnetic field with Earth's magnetosphere. Magnetic reconnection is one of the major mechanisms causing the interaction between them as well as the eruption of plasma and magnetic field from the Sun. There are several impacts of the magnetic reconnection process on Earth. We have discussed here the magnetic reconnection process and its impacts on Earth's magnetosphere on the basis of previous research.

Keywords: Magnetic Reconnection, Solar Wind, Earth's Magnetosphere

1. Introduction

Magnetic reconnection is one of the most fundamental processes in space physics. It breaks the ideal MHD frozen-in conditions allowing magnetic field lines to rearrange and reconnect, thereby changing the magnetic topology of the plasma system. Reconnection converts stored magnetic energy into plasma heating, bulk plasma flows, and particle acceleration, making it a major energy release mechanism in space plasma. It is a major driver of space weather. It operates throughout the universe, including in the solar corona, planetary magnetosphere, heliosphere etc. **McKenzie (2011)** reviewed the recent findings about the empirical quantities in the reconnecting corona. Earth's magnetosphere is the region of space surrounding the Earth that is dominated by Earth's magnetic field. It acts as a protective shield against the continuous flow of charged particles from the Sun known as solar wind. The magnetosphere is generated primarily by the motion of molten iron within Earth's outer core, which creates the geomagnetic field. The magnetosphere has a highly dynamic structure that changes continuously in response to variations in solar wind conditions. On the Sun-facing side, it is compressed to form the dayside magnetopause, while on the night side it is stretched into a long magnetotail extending millions of km into space. Major regions of the magnetosphere include the bow shock, magnetosheath, magnetopause and magnetotail. The magnetosphere acts as a protecting shield for Earth's atmosphere. Previous studies suggested that the reconnection process could be expected to become the main driver for magnetospheric convection. (e.g. **Nishida, 1968**). **Fisher et al. (1998)** have done the statistical study of active regions; liberate the magnetic tension and triggering the eruption of magnetic flux ropes. **Yokoyama et al. (2001)** found a vital piece of evidence for magnetic reconnection inflow in a flare on

March 18, 1999. **Frey et al. (2003)** presented evidence that reconnection at Earth's high-latitude magnetopause is driven directly by the solar wind and can be continuous. **Cassak (2016)** emphasised on the physics of magnetic reconnection and diffusion regions. **Xue et al. (2016)** presented evidence of fast reconnection in a solar filament eruption using high-resolution H-alpha images from the New Vacuum Solar Telescope, supplemented by extreme ultraviolet observations. **Ojerheghan and Adimula (2020)** have examined the determinants for magnetic reconnection in a low-activity year, 2009, and a high-activity year, 2012, by using geomagnetic factors: solar wind plasma speed, B_z and the Dst index. **Trattner et al. (2021)** summarised the observational evidence for the location of magnetic reconnection at Earth's magnetopause. **Lu et al. (2022)** have provided observational evidence for the cascading magnetic reconnection process. **Yohkoh** observations have established the evidence for magnetic reconnection over the last decade. **Gershman et al. (2024)** discussed how the rates of energy transformation during reconnection scale throughout the solar system. The last thirty years have also seen the development of laboratory reconnection experiments at a number of institutions. In parallel with the efforts of experimentalists in both space and laboratory plasma physics, theorists have discovered the structure of the diffusion region and the factors governing the rate, onset, and cessation of reconnection, and the topological reconfiguration of the magnetic field and have all been found analytically and with the aid of increasingly potent MHD, hybrid, and kinetic numerical simulations.

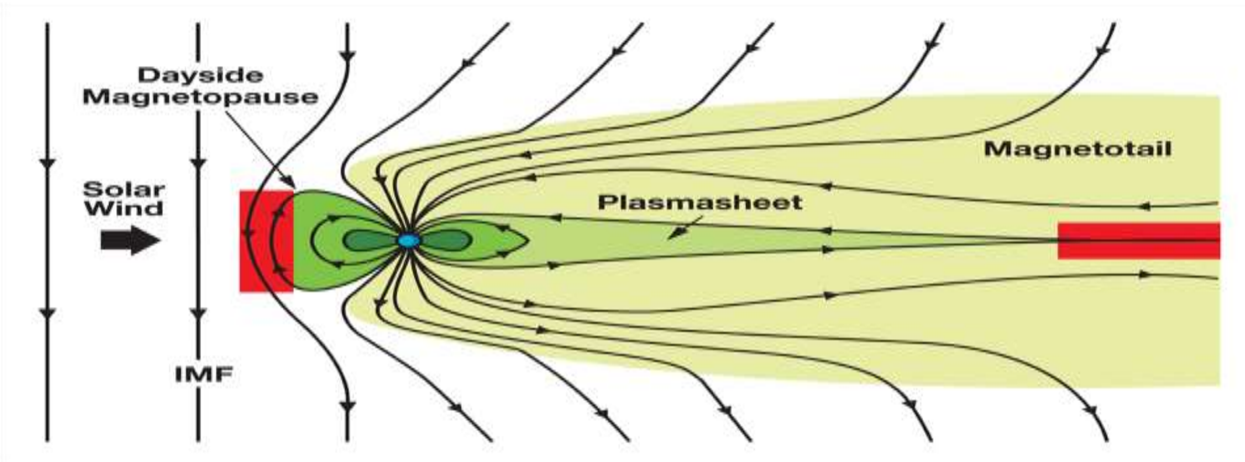

Figure 1: Schematic representation of magnetic reconnection in the Earth's magnetosphere
https://mms.gsfc.nasa.gov/images/science_page/science_1_lg.png

2. Effects of Magnetic Reconnection on Earth's magnetosphere

Magnetic reconnection is a basic plasma process in which magnetic field lines break and reconnect. The primary cause for research into magnetic reconnection involves its space weather implications. A deep understanding of space physics is essential to formulate responsible policy (e.g. **Cassak et al. 2017**). It has several major impacts on Earth's magnetosphere. Consequently it is a major cause of space weather events. It can trigger geomagnetic storms and auroras, which can further damage to power transmission systems and electric grids, disruption of satellite operations, degradation of radio communication, and navigational errors. **Sokolov (2011)** established that a geomagnetic storm can be defined in terms of changes in the Dst index. It was also immediately realized that magnetic reconnection could be happening in tokamaks (**Furth et al., 1963**). Magnetic reconnection reshapes the magnetosphere at the dayside of the magnetopause and the nightside magnetotail. It is the major energy transfer mechanism from solar wind. **Fig. 1** shows the magnetic reconnection in the Earth's magnetosphere. Key impacts of magnetic reconnection on the Earth's magnetosphere are the following:

1. **Energy Release and solar wind coupling**

The reconnection process occurs when the IMF carried by solar wind connects with the magnetic field of Earth on the dayside. In the magnetic reconnection process, stored magnetic energy is transformed into heat, kinetic energy, and particle acceleration. The primary mechanism by which plasma and solar wind energy enter the magnetosphere and produce a substantial amount of geomagnetic activity is reconnection. The solar wind carries the interplanetary magnetic field (IMF). When the IMF interacts with Earth's magnetic field, magnetic energy is stored at the magnetopause, especially when the IMF has a southward component. If the southward IMF encounters the northward geomagnetic field, oppositely directed field lines come together, break, and reconnect. This process creates new magnetic field lines linking the solar wind directly to Earth's magnetic field. The newly reconnected field lines allow solar wind plasma, momentum and energy to enter the magnetosphere. Since early research on magnetic reconnection at the magnetopause, it was anticipated that when the IMF was pointing in the opposite direction of the geomagnetic field, the solar wind would be able to transfer momentum and energy to the magnetosphere more effectively (**Arnoldy, 1971; Fairfield and Cahill, 1966; Sonnerup, 1970**). Thus, magnetic reconnection acts as a coupling mechanism between the solar wind and Earth's space environment.

2. **Magnetospheric Dynamics**

Dayside (Magnetopause): Solar wind's and magnetospheric's oppositely directed field lines merge, opening field lines that stretch into the magnetotail and increasing the size of the magnetosphere. The magnetosphere compresses on the dayside.

Nightside (Magnetotail): The reconnection process in the magnetotail releases energy and causes magnetospheric substorms, which cause auroras. Magnetic reconnection accelerates charged particles toward Earth, and these particles collide with atmospheric gases close to the poles, causing the auroral display and plasma circulation. It involves the mixing of solar wind plasma and ionospheric plasma, which impacts the composition and density in the key region.

3. **Space Weather**

The reconnection process occurs in the sun as well as near Earth's space. In the solar corona, it triggers the plasma eruptions, release of energetic particles, and magnetic clouds into space and near the Earth's space; the southward solar wind's magnetic field reconnects with the magnetosphere, entering the energy into the magnetosphere. Reconnection efficiently accelerates charged particles to high energies, contributing to radiation hazards for astronauts and spacecraft. Moreover, causes geomagnetic storms, energetic particle precipitation, and auroral displays, which can further damage satellites or power grids. Geomagnetic storms are caused by reconnection with the Earth's magnetosphere, and powerful reconnection-driven storms have the potential to interfere with technological impacts. **Fig. 2** shows the space weather impacts on technology. Reconnection accelerates charged particles towards Earth's polar regions, producing auroras and enhancing their intensity during storms.

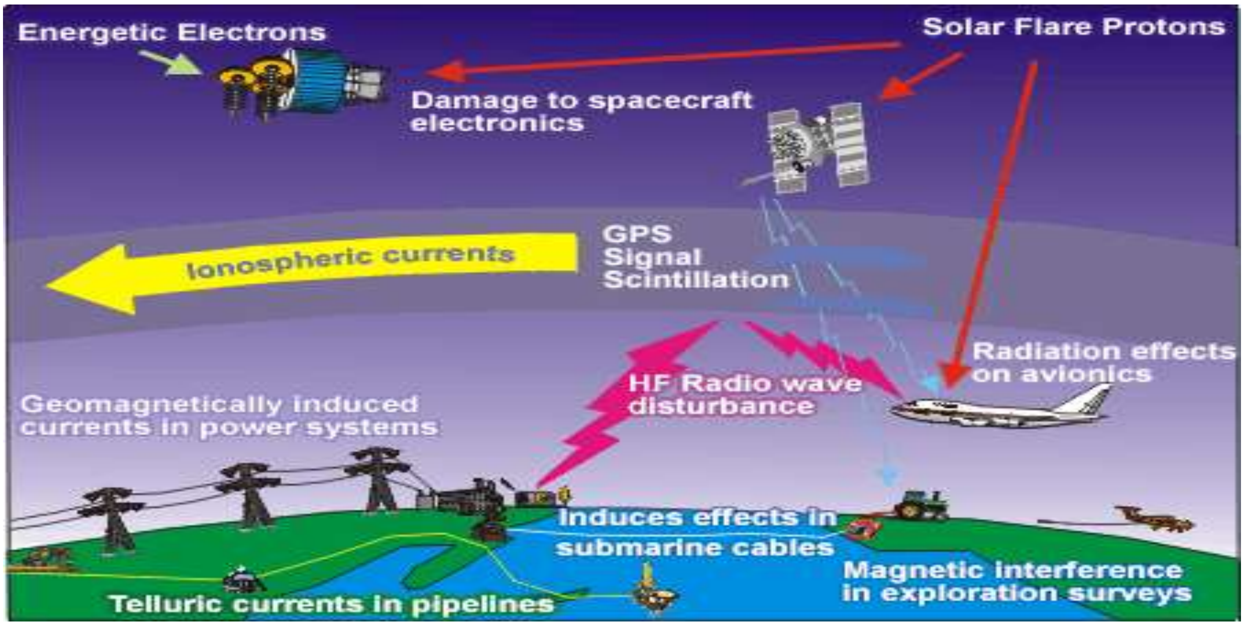

Figure 2: Space weather effects on technology
(https://www.spaceweather.gc.ca/images/tech/spaceeffects.gif)

4. **Particle Acceleration in Radiation Belt**

Reconnection processes accelerate electrons and ions to high energies and inject the particles into the Van Allen radiation belts by converting magnetic energy into particle kinetic energy and altering radiation belt intensity and structure. This majorly occurs in the magnetotail region during the period of geomagnetic disturbances. In the magnetotail, oppositely directed magnetic field lines come together and reconnect, forming an X-line and current sheet. The reconnection process produces the strong electric field near the X-line. These electric fields directly accelerate these electrons and ions to higher energies.

3. Summary

Magnetic reconnection is a basic plasma process in which magnetic field lines break and reconnect. It is a physical process with two different effects: topological rearrangement of magnetic field lines and the transformation of magnetic energy into heat and enormous kinetic energy (K. E.). It has several significant impacts on the Earth's magnetosphere. The main cause for research into magnetic reconnection is its space weather implications and hazards to human life. Despite the number of observations, there are still challenges in studying magnetic reconnection, such as multiscale coupling, limited observations, small-scale physics, etc. In the future we can achieve the higher resolution measurement of magnetic reconnection with advanced spacecraft missions and reproduce reconnection under controlled conditions in laboratory experiments. Understanding magnetic reconnection can be helpful for society to predict space weather and can better protect technological infrastructure.

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