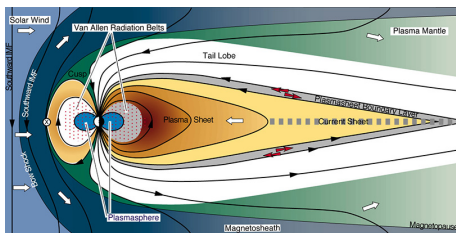


# Space Weather

## Lecture 3: Interaction with Interplanetary Magnetic Field and Reconnection

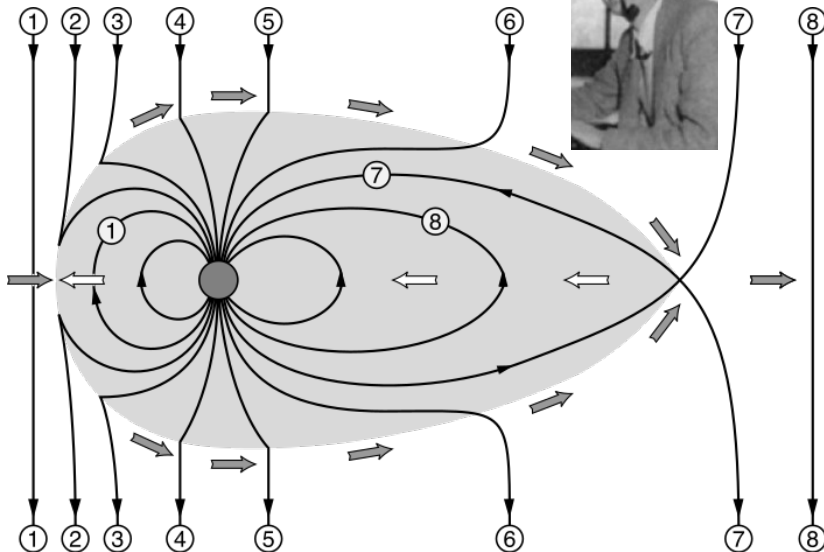


Elena Kronberg (Room 442)  
elena.kronberg@lmu.de

# IMF southward: Dungey Cycle

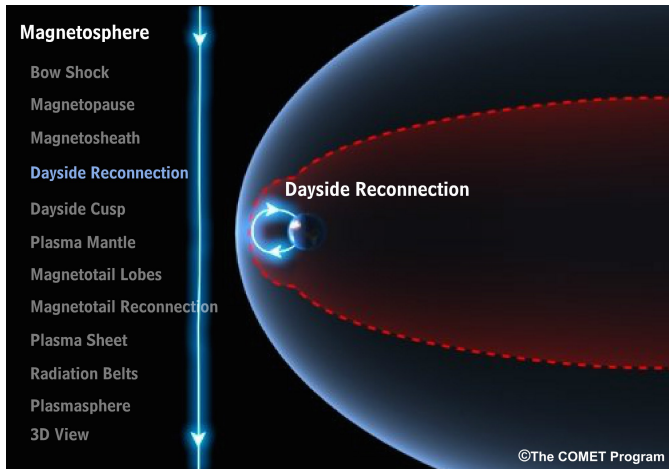


James Dungey, British physicist, 1923–2015 proposed the theory in 1961



Baumjohann & Treumann

- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms

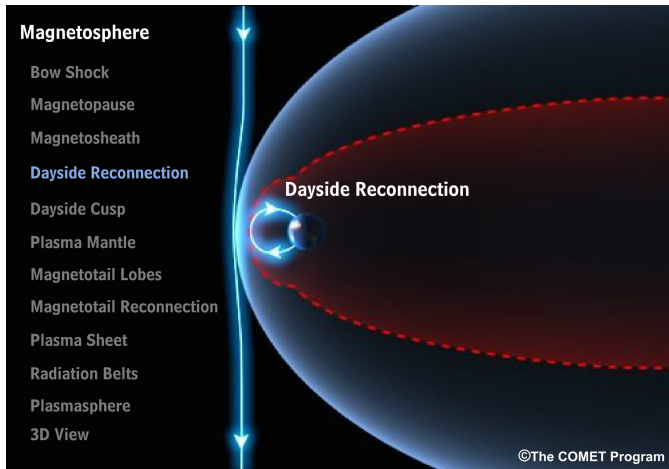


- 
- The diagram illustrates the structure of Earth's magnetosphere. On the left, a vertical blue line with arrows at both ends represents the solar wind flow. The magnetosphere is shown as a blue, teardrop-shaped region on the right. A red dashed line outlines the boundary between the magnetosphere and the solar wind. Key features labeled include:
- Bow Shock**: The point where the solar wind is first deflected by the magnetosphere.
  - Magnetopause**: The boundary between the magnetosphere and the solar wind.
  - Magnetosheath**: The region of solar wind plasma between the bow shock and the magnetopause.
  - Dayside Reconnection**: The process where magnetic field lines from the solar wind and Earth's magnetosphere connect on the dayside.
  - Dayside Cusp**: The region where the magnetopause is closest to Earth due to reconnection.
  - Plasma Mantle**: The region of plasma between the magnetopause and the ionosphere.
  - Magnetotail Lobes**: The regions of low plasma density in the magnetotail.
  - Magnetotail Reconnection**: The process where magnetic field lines reconnect in the magnetotail.
  - Plasma Sheet**: The region of high plasma density in the magnetotail.
  - Radiation Belts**: The regions of high-energy particles trapped in the magnetosphere.
  - Plasmasphere**: The region of low-energy plasma in the inner magnetosphere.
  - 3D View**: A perspective view of the magnetosphere.
- ©The COMET Program

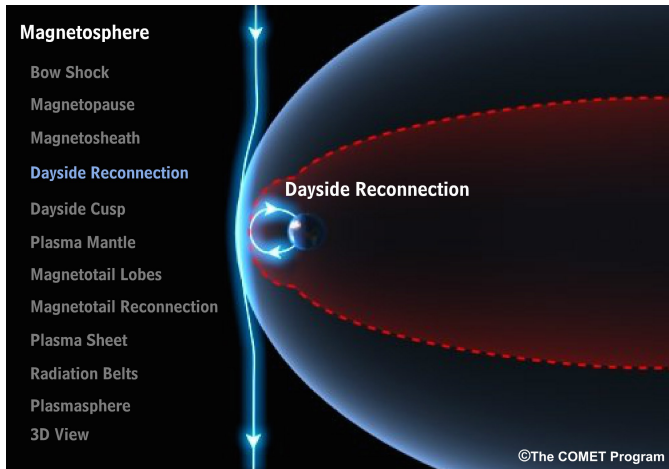


- 
- The diagram illustrates the structure of Earth's magnetosphere. A vertical blue line with arrows at both ends represents the solar wind flow. The magnetosphere is shown as a blue, teardrop-shaped region on the right. A red dashed line outlines the magnetopause. A small blue sphere represents Earth. A red dashed line outlines the magnetotail. A blue arrow points from the magnetopause towards Earth, labeled 'Dayside Reconnection'. A blue arrow points from the magnetotail towards Earth, labeled 'Magnetotail Reconnection'. A blue arrow points from the magnetopause towards the magnetotail, labeled 'Plasma Sheet'. A blue arrow points from the magnetotail towards the magnetopause, labeled 'Radiation Belts'. A blue arrow points from the magnetopause towards the magnetotail, labeled 'Plasmasphere'. A blue arrow points from the magnetotail towards the magnetopause, labeled '3D View'.
- Magnetosphere**
- Bow Shock
  - Magnetopause
  - Magnetosheath
  - Dayside Reconnection**
  - Dayside Cusp
  - Plasma Mantle
  - Magnetotail Lobes
  - Magnetotail Reconnection
  - Plasma Sheet
  - Radiation Belts
  - Plasmasphere
  - 3D View
- Dayside Reconnection**
- ©The COMET Program

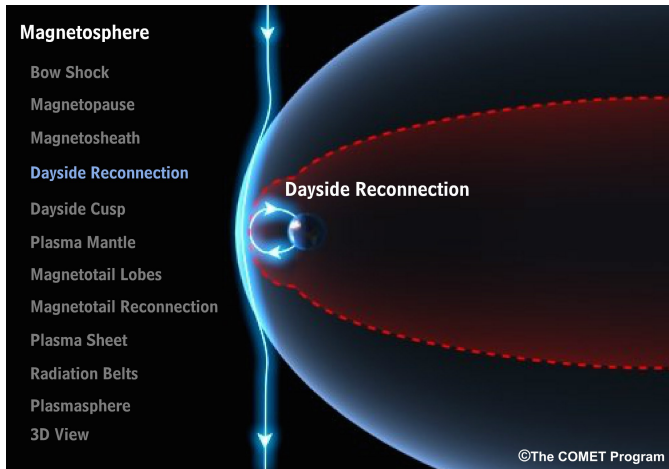
- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms

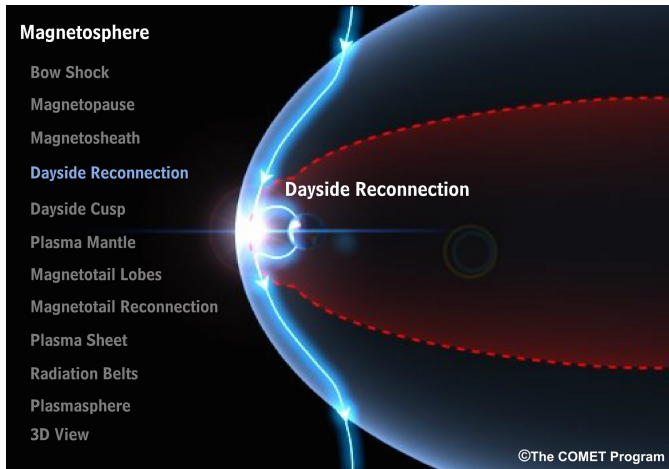


- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms

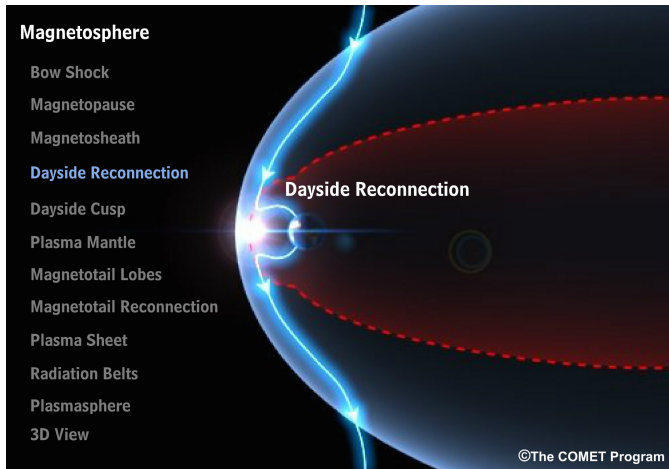


- 
- Magnetosphere**
- Bow Shock
  - Magnetopause
  - Magnetosheath
  - Dayside Reconnection**
  - Dayside Cusp
  - Plasma Mantle
  - Magnetotail Lobes
  - Magnetotail Reconnection
  - Plasma Sheet
  - Radiation Belts
  - Plasmasphere
  - 3D View
- ©The COMET Program

- 



- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



- The diagram illustrates the structure of Earth's magnetosphere. On the left, a list of components is provided: Magnetosphere, Bow Shock, Magnetopause, Magnetosheath, Dayside Reconnection, Dayside Cusp, Plasma Mantle, Magnetotail Lobes, Magnetotail Reconnection, Plasma Sheet, Radiation Belts, Plasmasphere, and 3D View. The main image shows a cross-section of the magnetosphere. The Earth is at the center, with the magnetopause boundary on the left. The magnetosheath is the region between the bow shock and the magnetopause. The dayside cusp is where the solar wind enters the magnetosphere. The plasma mantle is the region between the cusp and the magnetopause. The magnetotail lobes are the regions of low plasma density in the tail. The magnetotail reconnection is the process where magnetic field lines reconnect in the tail. The plasma sheet is the region of high plasma density in the tail. The radiation belts are the regions of high-energy particles. The plasmasphere is the region of low-energy plasma. The 3D view shows the magnetosphere as a whole.

**Magnetosphere**

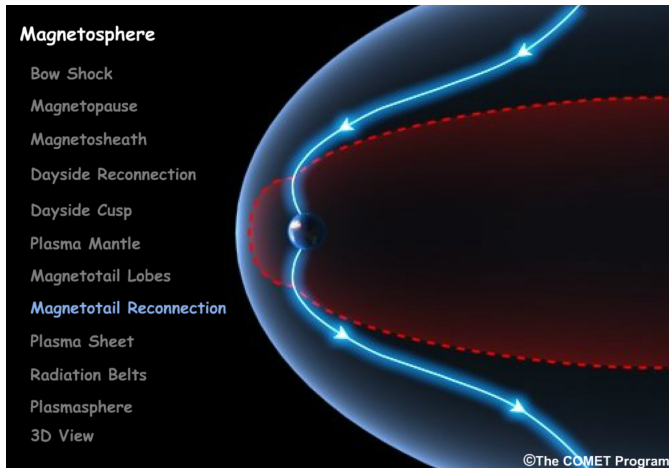
  - Bow Shock
  - Magnetopause
  - Magnetosheath
  - Dayside Reconnection**
  - Dayside Cusp
  - Plasma Mantle
  - Magnetotail Lobes
  - Magnetotail Reconnection
  - Plasma Sheet
  - Radiation Belts
  - Plasmasphere
  - 3D View

**Dayside Reconnection**

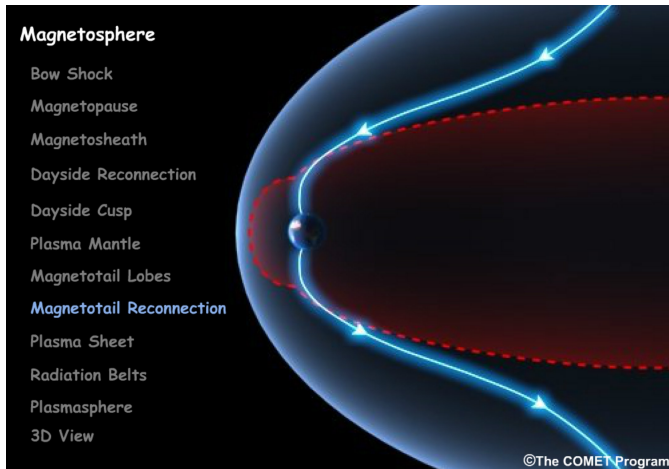
©The COMET Program



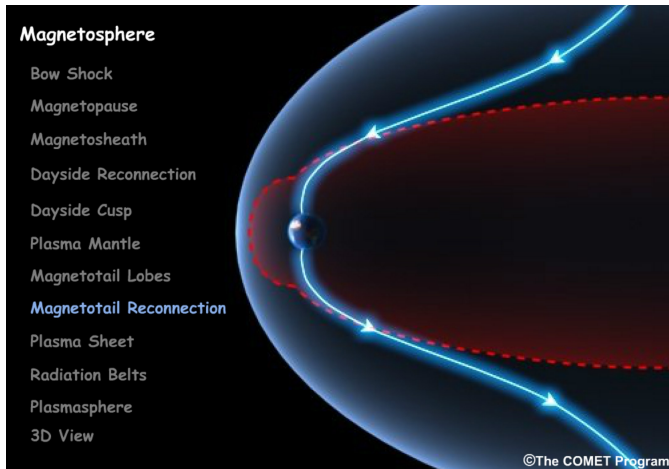
- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



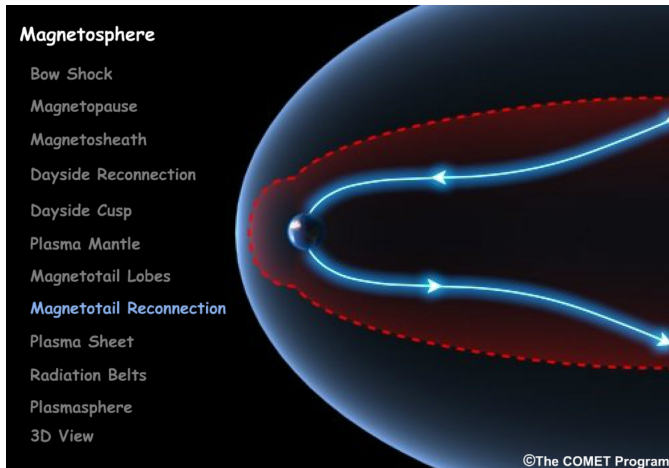
- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



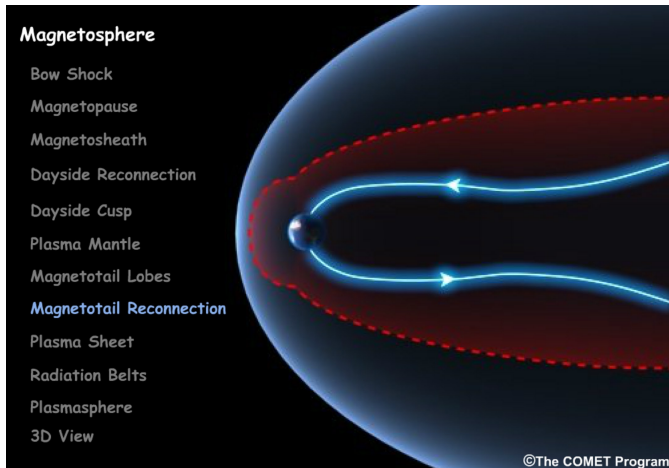
- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



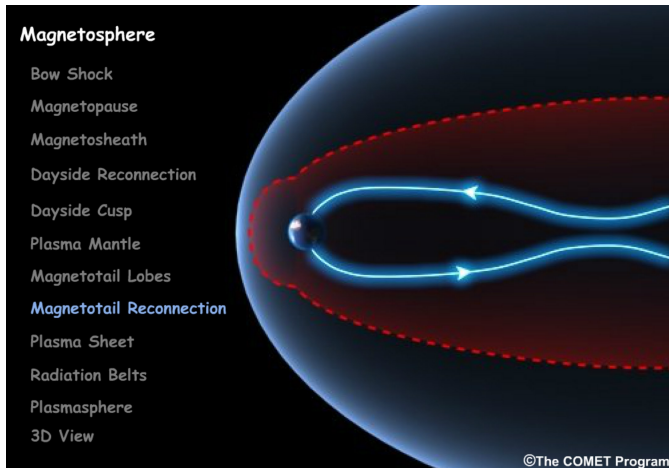
- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



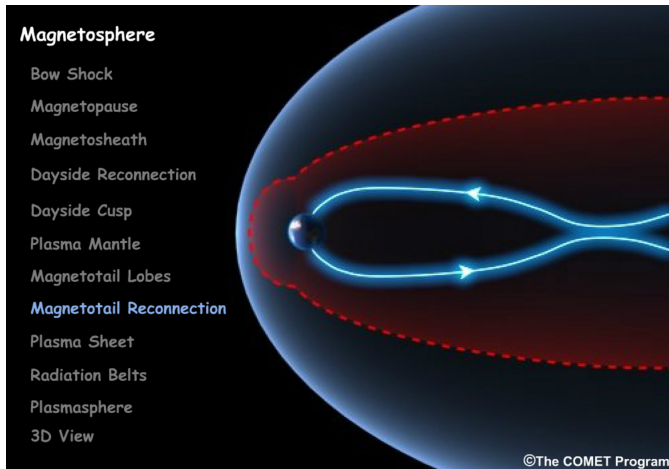
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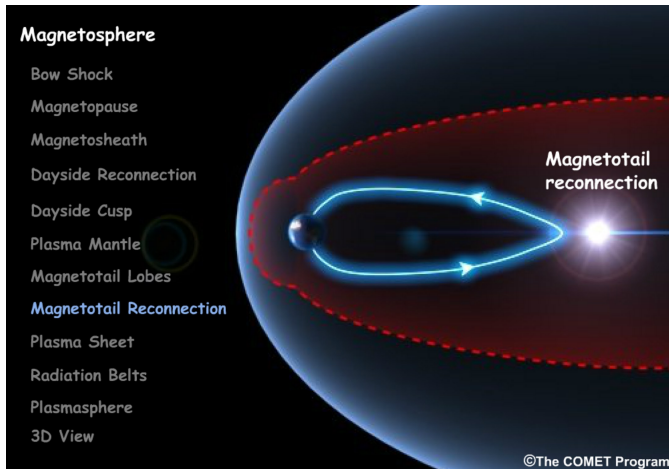
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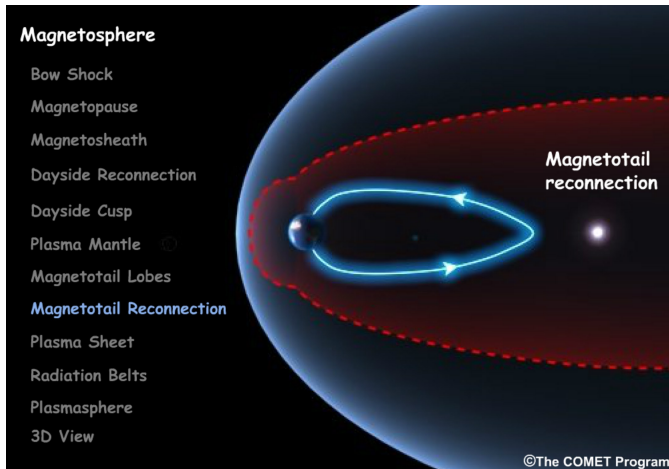
- The diagram illustrates the structure of Earth's magnetosphere. On the left, a list of components is provided: Magnetosphere, Bow Shock, Magnetopause, Magnetosheath, Dayside Reconnection, Dayside Cusp, Plasma Mantle, Magnetotail Lobes, Magnetotail Reconnection, Plasma Sheet, Radiation Belts, Plasmasphere, and 3D View. The main image shows a 3D cross-section of the magnetosphere. The Earth is on the left, with the magnetosphere extending to the right. The Bow Shock is the outermost boundary, followed by the Magnetopause and Magnetosheath. The Dayside Reconnection is shown as a bright point on the left. The Dayside Cusp is a region of open magnetic field lines. The Plasma Mantle is the region of plasma between the cusp and the magnetopause. The Magnetotail Lobes are the two large lobes of the magnetotail. The Magnetotail Reconnection is shown as a bright point on the right. The Plasma Sheet is the region of plasma between the lobes. The Radiation Belts are the two regions of high-energy particles. The Plasmasphere is the region of low-energy plasma. The 3D View is indicated by a small icon.



- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms

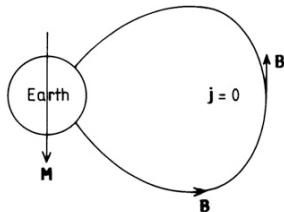


- IMF  $B_z < 0$  drives the magnetospheric convection: storms/substorms



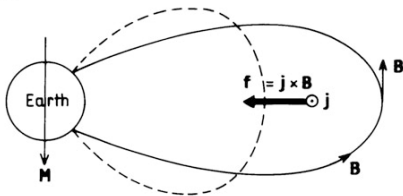
# Reconnection in the magnetotail

a)



DIPOLE MAGNETIC FIELD  $\mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B} = 0$

b)

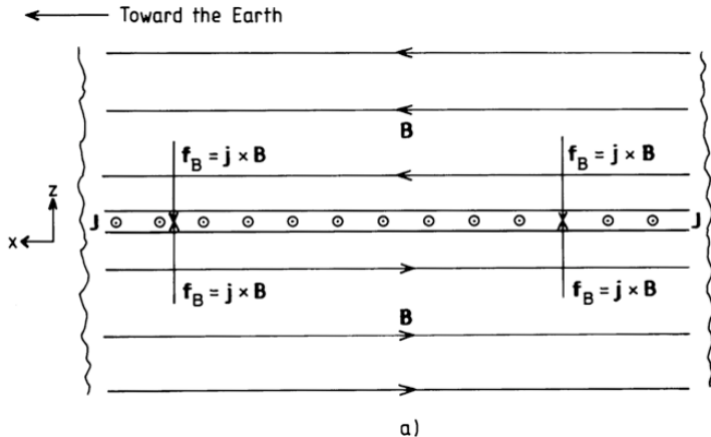


DISTORTED DIPOLE FIELD  $\mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B} \neq 0$

Brekke 2013

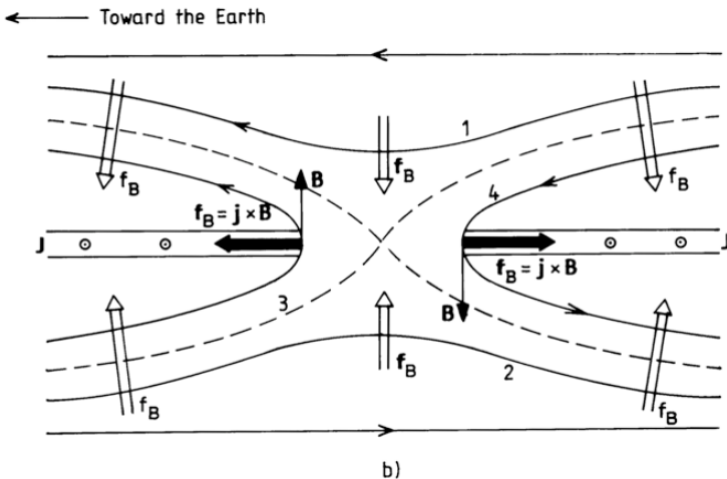
# Reconnection

Brekke 2013



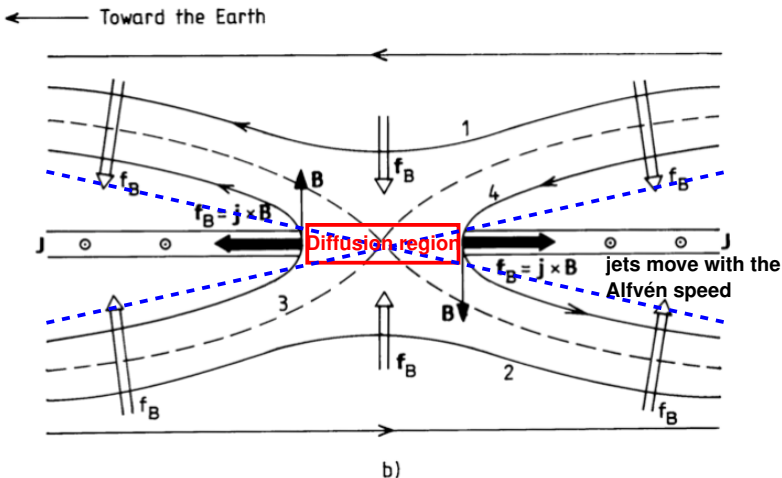
# Reconnection

Brekke 2013



# Reconnection: how to get it fast?

Brekke 2013



Sweet-Parker theory (1956-1958): reconnection occurs in the diffusion region via small-scale physics (resistive 2D MHD), slower than in space plasmas

Petschek theory (1964): diffusion region has been shrunk to a dot, nobody managed to simulate

# Challenge: What physics can produce necessary electric fields to accelerate plasma?

Vasyliunas 1975

## Generalized Ohm's law

$$\vec{E} = -\vec{v}_e \times \vec{B} - \frac{1}{en_e} \nabla \cdot \vec{P}_e - \frac{m_e}{e} \left( \frac{\partial \vec{v}_e}{\partial t} + \vec{v}_e \cdot \nabla \vec{v}_e \right)$$

convection  
term

vanishes  
because

$B \sim 0$

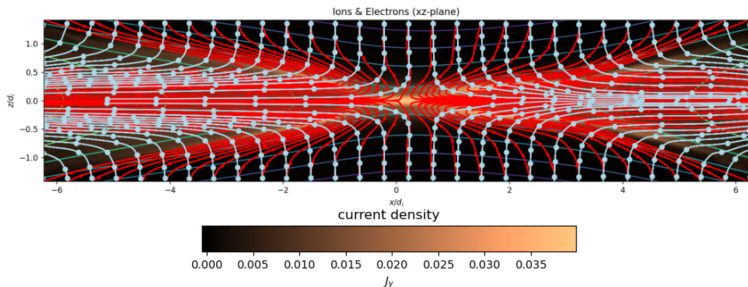
divergence  
of the  $e$

pressure  
tensor

electron  
inertia term

# Challenge: What physics can produce necessary electric fields to accelerate plasma?

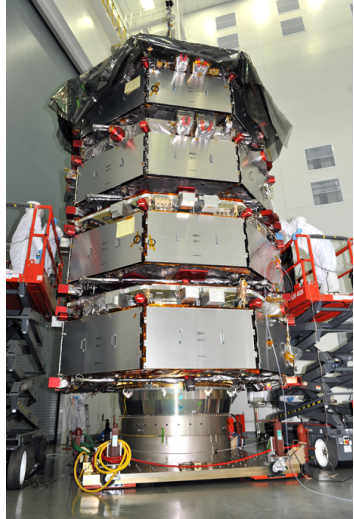
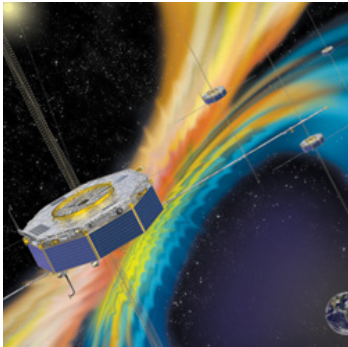
Visualizations by Tom Bridgman



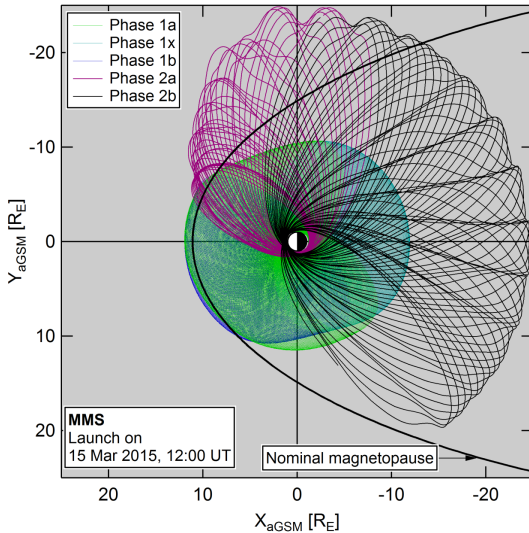
- Sonnerup (1979) has proposed generation of the out-of-plane magnetic field with quadrupolar structure
- This is due to the difference in  $e$  and ion behavior (Hall effect)
- Leads to generation of the Hall electric field,  $\mathbf{E} = \frac{1}{ne} \mathbf{j} \times \mathbf{B}$ .



# Observations by Magnetospheric Multiscale (MMS) mission

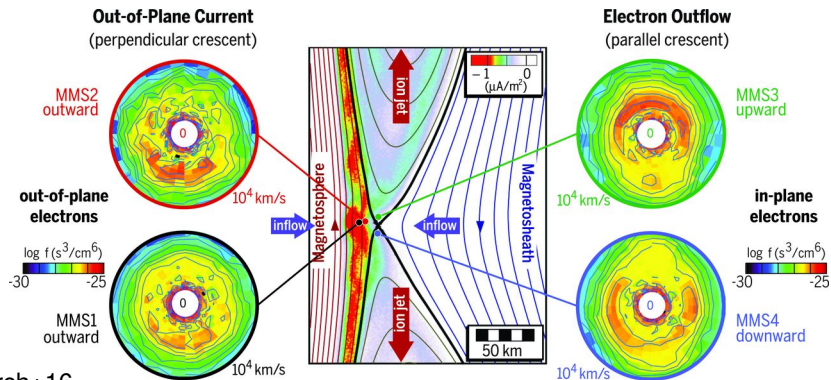


# MMS trajectories: separation between spacecraft 10 km



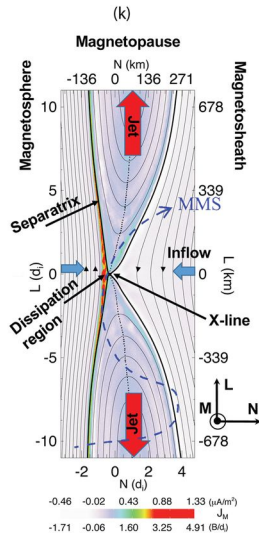
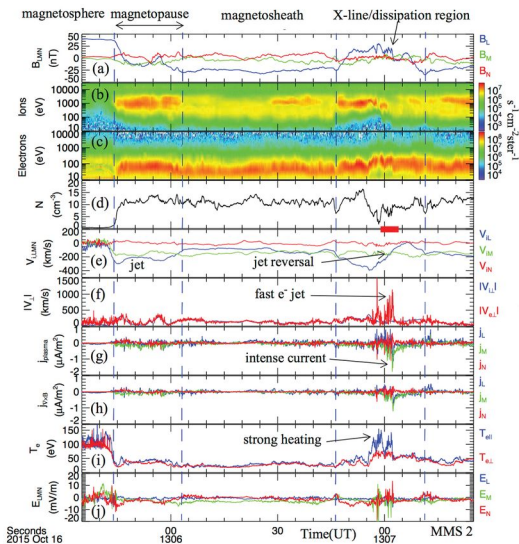
# Electron-scale measurements of magnetic reconnection

- Left side: electrons with velocities from 0 to  $10^4$  km/s carrying current out of the drawing plane
- Right side: electrons flowing upward and downward along the reconnected magnetic field



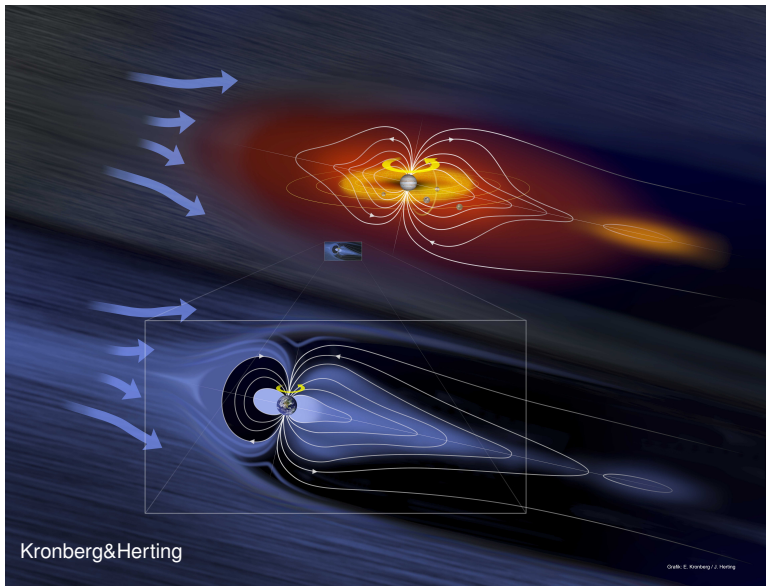
Burch+16

# Two magnetopause crossings of MMS2

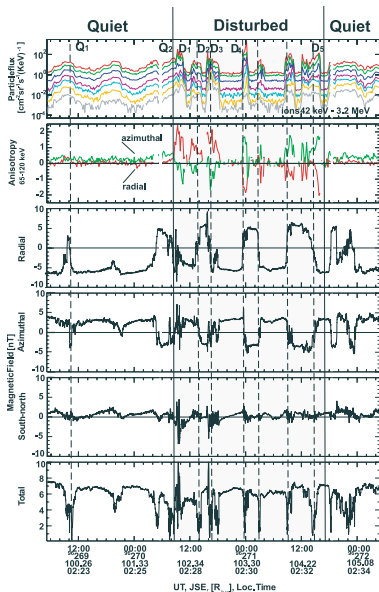


Burch+16

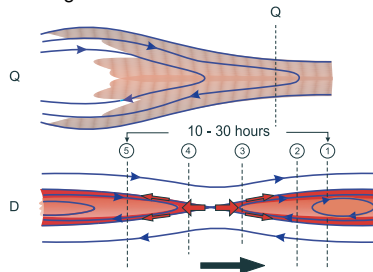
# Reconnection in the magnetotail: Earth and Jupiter



# X-line formation

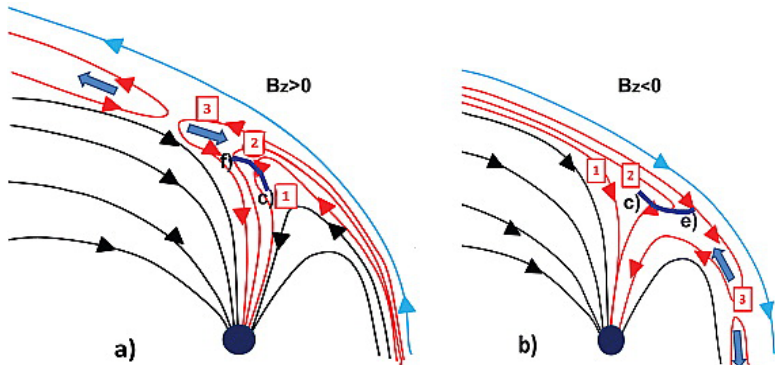


Kronberg+05



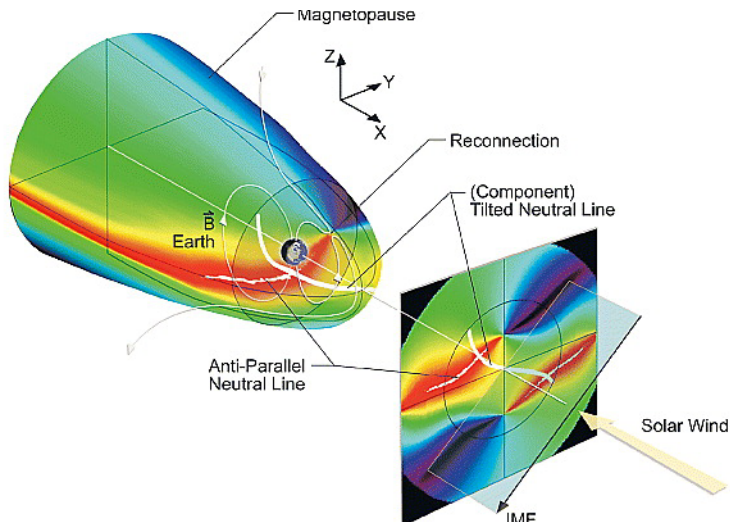
- X-line formation is one of the key signatures of the reconnection
- A change of the flow direction is often observed during the energy release phase

# IMF northward: Reconnection at high latitudes



Nykyri+11

# Reconnection: IMF with dawn-dusk component

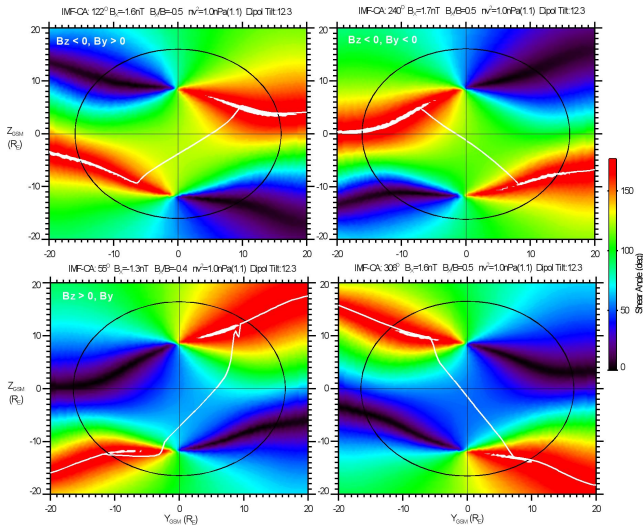


Trattner+07



# Reconnection: IMF with dawn-dusk component

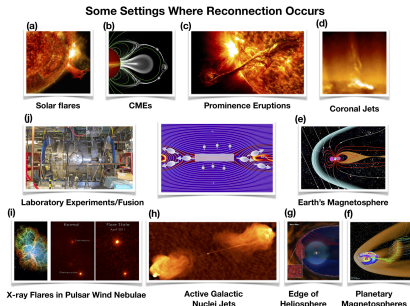
## Location of the reconnection at different IMF directions



Luo+2017

# Summary

- The IMF strongly influences the dynamics of the magnetosphere.
- Reconnection is a commonplace transformation process of magnetic energy to particle energy in plasmas.
- It changes the magnetic field topology and accelerates particles.
- It can be observed at the Sun, in the solar wind, in the magnetospheres of various planets, in Tokamaks. . .
- It leads to spectacular phenomena such as solar flares, CMEs, auroras. . .



Hesse&Cassak, 2019

- M. Hesse and P. Cassak, Magnetic Reconnection in the Space Sciences: Past, Present, and Future, JGR, 2019
- W. Baumjohann and R. Treumann, Basic Space Plasma Physics, 1996
- A. Brekke, Physics of the Upper Polar Atmosphere, 2013
- K. Nykyri, et al., Cluster observations of a cusp diamagnetic cavity: Structure, size, and dynamics, JGR, 2011
- J. Burch, Electron-scale measurements of magnetic reconnection, Science, 2016
- E. Kronberg, Mass release at Jupiter: Substorm-like processes in the Jovian magnetotail. JGR, 2005