Current Systems in the Earth's Magnetosphere

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Outline

Introduction

Electric Currents

An Electric Current is the flux of charge from one place to another (dominated by the motion of electrons).

Density of electric current: is the electric current per unit area of cross section,

$$\boldsymbol{J}(\boldsymbol{r},t) = \sum_i q_i \int v f_i(\boldsymbol{r},\boldsymbol{v},t) d^3\,\boldsymbol{v}$$

- q_i – particle charge for the i-species
- $\boldsymbol{v}$ – particle velocity
- fi – distribution function

Ampère-Maxwell Law: the magnetic field is produced by electric currents and fields varying in time

$$\nabla \times \boldsymbol{B} = \mu_0(\boldsymbol{J} + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}) \quad \text{(Maxwell's Equation)}$$

- μ_0 – permeability of free space
- ε_0 – permittivity of free space
- $\boldsymbol{E}$ – electric field

Introduction

Electric Currents

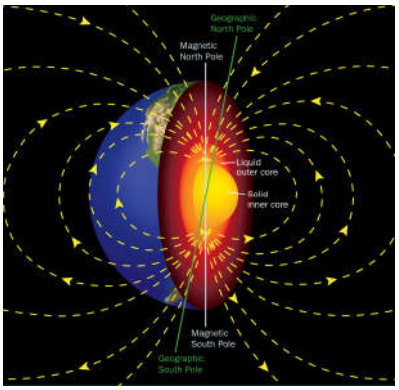
Why do we study electric current systems and their relation with the magnetic field?

- Gauss (1839): possibility of electric currents in space altering the magnetic field observed on the ground.
- Carrington (1860): relation between auroral displays and magnetometer perturbations during the superstorm of that year.
- Stewart (1882): solar radiation ionizes the upper atmosphere to allow for electric currents to flow in this region.
- Birkeland (1908, 1913): field-aligned currents connect the solar wind to the Earth's ionosphere, leading to the aurora.

Introduction

Earth's Magnetic Field and Magnetosphere

Magnetosphere: region of space around a planet where the planetary magnetic field is the main cause for the effects on the charged particles.



The planetary magnetic field is attributed to a dynamo effect of circulating current in its interior

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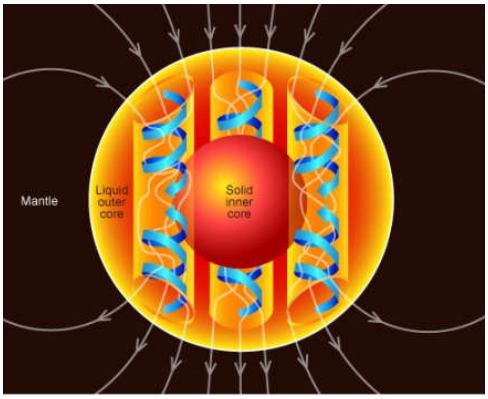
Mechanism by which a celestial body generates a magnetic field
It is thought to be the source of the Earth's Magnetic Field

- outside the Earth's core, it is similar to that of a bar magnet deviated from the spin axis
- the geographic north is the field's magnetic south

Introduction

Earth's Magnetic Field and Magnetosphere



Dynamo theory: describes the process through which a rotating, convecting, and electrically conducting fluid can maintain a magnetic field in astrophysical bodies.

Convection drives the outer-core fluid and it circulates relative to the solid container.

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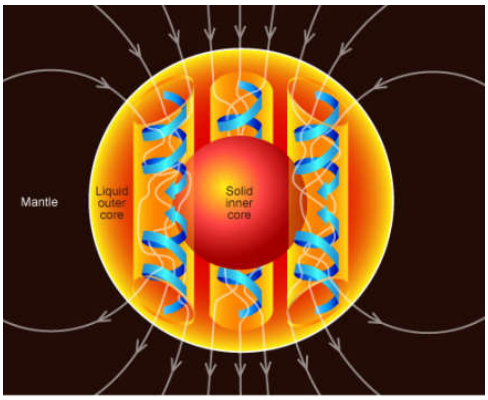
The electrically conducting material moves relative to the earth's magnetic field

A current loop is produced by the interaction between layers. Its magnetic field could sustain a magnetic dipole like the one on Earth.

Introduction

Earth's Magnetic Field and Magnetosphere



Dynamo theory requirements:

- an electrically conductive fluid medium (liquid iron in the outer core);
- kinetic energy provided by planetary rotation (Coriolis Effect) and also by magnetic forces acting on the fluid;
- an internal energy source to drive convective motions within the fluid.

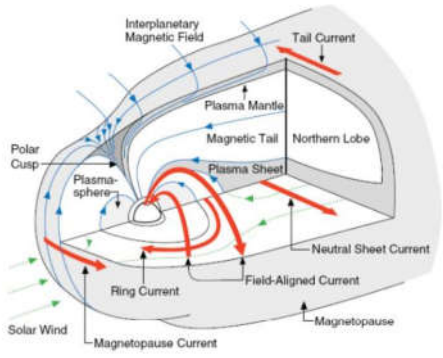
Induction Equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \eta \nabla^2 \boldsymbol{B} + \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

- $\eta = {}^{1}/_{\sigma\mu}$ - magnetic diffusivity

Introduction

Earth's Magnetic Field and Magnetosphere



C. Russell, The solar wind interaction with the Earth's magnetosphere: Tutorial

Sources for the Earth's magnetic field:

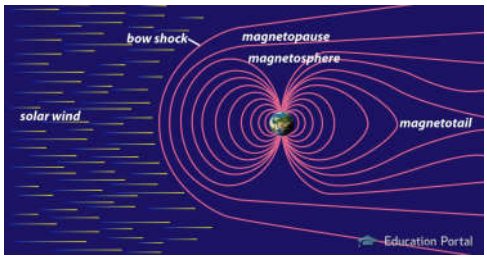
- Internal (dynamo effect and remnant magnetization in the crust)
- External (currents in the magnetosphere and ionosphere)
- Induced (currents in the crust, induced by the external magnetic fields)

Magnetospheric current systems:

- results from particle motion in already existing fields
- contribute for the shape the magnetic field
- connect different regions

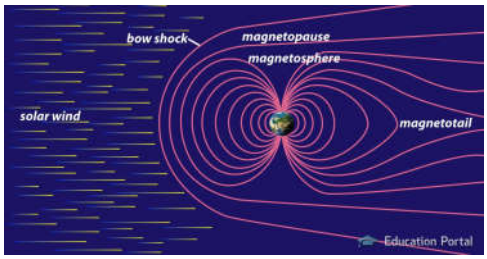
Magnetopause Current

Magnetopause:



- it's a surface boundary between the magnetosphere (planet's magnetic field) and the surrounding plasma (solar wind).
- moves inward and outward as the solar wind intensity increases and decreases, i.e. compressed on the dayside and elongated on the nightside
- its location depends on the balance between solar wind particle pressure and Earth's magnetic field pressure.

Magnetopause Current



This hydrostatic equilibrium can be defined by:

$$\begin{cases} P_{SW} = \rho_{SW} v_{SW}^2 \\ P_{Earth} = \dfrac{B^2}{2\mu_0} \end{cases} \Rightarrow \rho_{SW} v_{SW}^2 = \frac{B^2}{2\mu_0}$$

- P_{SW} - pressure inside the magnetopause
- ρ_{SW} - mass density of the solar wind
- v_{SW} - solar wind flow speed upstream of the bow shock
- B – Magnetic field at the magnetopause

Bow Shock: slows down, compresses and heats the solar wind plasma.

Magnetosheath: region between the magnetosphere and the shock front.

Magnetopause Current

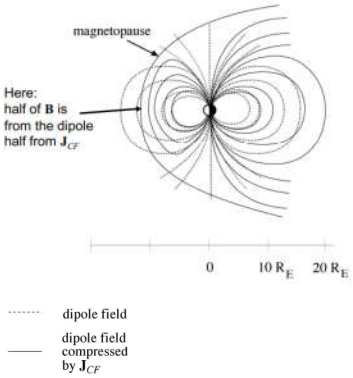
Chapman-Ferrero Magnetopause Current

Chapman-Ferraro distance: distance at which the magnetosphere can withstand the solar wind pressure,

$$R_{CF} = R_P \left(\frac{B_{surf}^2}{\mu_0 \rho V_{SW}^2} \right)^{1/6}$$

- $R_{CF} \gg R_P$ *intrinsic* magnetosphere
- $R_{CF} \ll R_P$ *induced* magnetosphere
- $R_{CF} \approx R_P$

- R_P: radius of the planet
- B_{surf}: magnetic field on the surface of the planet at the equator
- ρ: mass density of solar wind flow
- V_{SW}: velocity of the solar wind



Magnetopause Current

Chapman-Ferrero Magnetopause Current

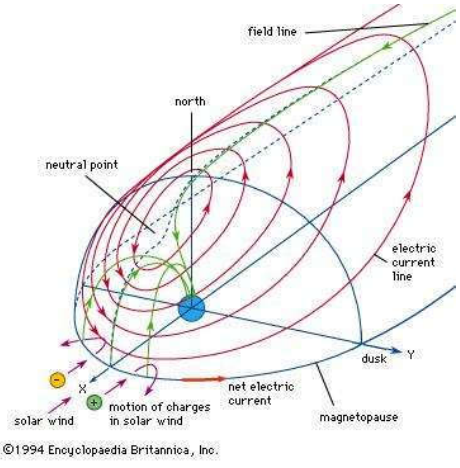
Chapman-Ferraro Current:

- It shapes and limits the magnetosphere
- must provide the force to balance the solar wind dynamic pressure

$$\nabla(2\rho_{SW} v_{SW}^2) = |\boldsymbol{J} \times \boldsymbol{B}| = \nabla\left(\frac{B^2}{\mu_0}\right)$$

Protons and electrons gyrate in opposite directions around the magnetopause

Current flowing from dawn to dusk (equatorial plane)
Current from dusk to dawn (high-latitude)

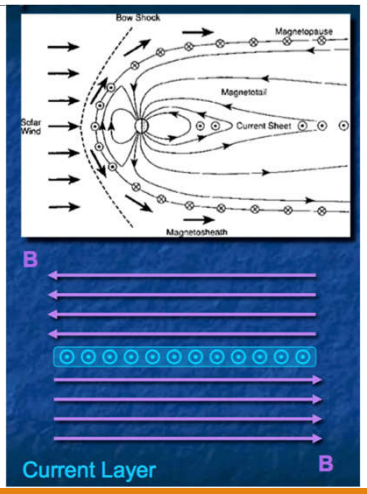


Magnetotail Current

Magnetotail: elongated region of the magnetosphere that extends in the opposite direction from the sun.

Magnetotail current: nightside equatorial current, from dusk to dawn, that divides the magnetotail into two regions with almost uniform magnetic field of opposite direction.

Cusps: marks the separation between the magnetic field lines going to the magnetopause and to the magnetotail.

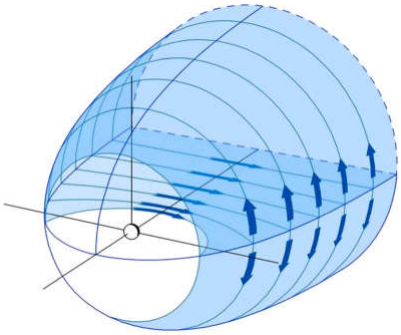


Magnetotail Current

- After flowing through the magnetopause, this current closes above and below the magnetic field regions of the tail

Mid-tail: $B_T \approx 20$ nT $\longrightarrow$ $R_T \approx 20R_E$

Far-tail: $B_T \approx 10$ nT $\longrightarrow$ $R_T \approx 28R_E$

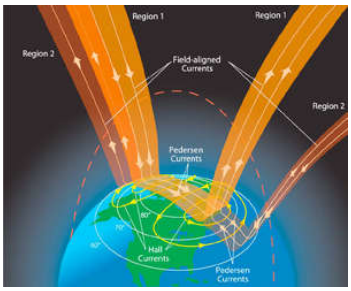


Field-Aligned currents

Field-aligned currents (or Birkeland currents): electric currents that flow along geomagnetic field lines, caused by the spiraling of electric charges around magnetic field lines. They connect the magnetosphere currents with ionosphere currents.

There are two types:

- Region 1 Field-aligned Currents: poleward currents
- Region 2 Field-aligned Currents: equatorward currents

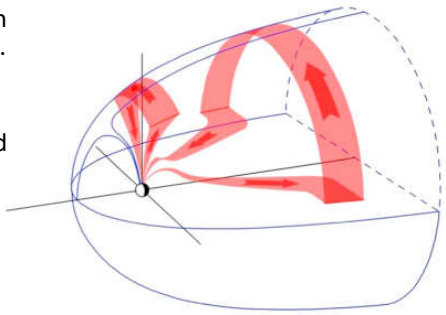


Field-aligned Current

Region 1 Field-aligned currents

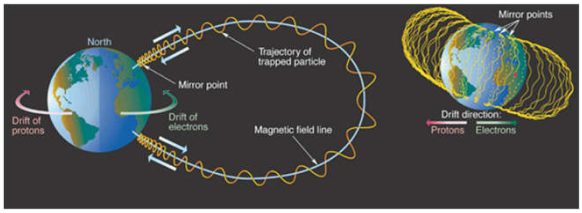
They can be divided in two components, both connecting the magnetosphere and the magnetopause.

They move in the ionosphere from dawn to dusk and are responsible for the convection pattern found in it.



Ring Current

Ring Current: current flowing around the Earth due to the drift of positive ions (westward) and electrons (eastward), with the shape of a ring. It is at a distance of $\sim 3 - 8\ R_E$ and lies on the equatorial plane.

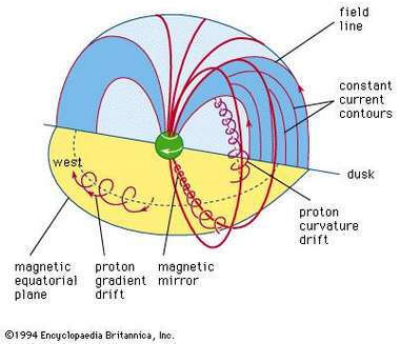


Has a magnetic field opposite to the Earth's internal one → Depress the magnetic field at the Earth's surface

Increase and decrease of the intensity → disturbances of the ground magnetic field during geomagnetic storms

Ring Current

Symmetric Ring current



- It flows westward (clockwise)

$I \sim 1 - 4\ \mathrm{nA/m^2}$ (quite times)

$I \sim 7 - 50\ \mathrm{nA/m^2}$ (during storms)

It is "symmetric" because all the current goes around the Earth in a closed system.

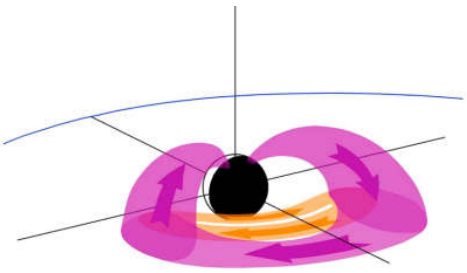
During quiet magnetic activity, this current is symmetric around the magnetic axis.

Ring Current

Partial Ring current

Partial Ring Current: is part of the westward ring current and its due to interactions between the solar wind and the magnetosphere, that results in an asymmetry of the plasma pressure distribution in the inner magnetosphere during disturbed times.

It stands on the night side and closes via Field-Aligned Currents, creating the Region 2 Field-aligned Currents

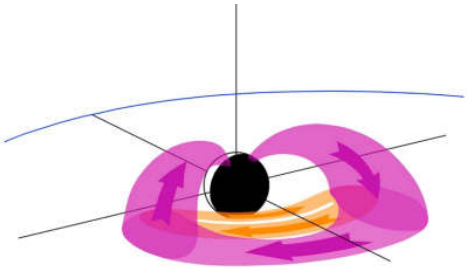


Field-aligned Current

Region 2 Field-aligned currents

While Region 1 currents closes far at the tail, Region 2 Field-aligned Current closes closer to the Earth, in the partial ring current on the nightside.

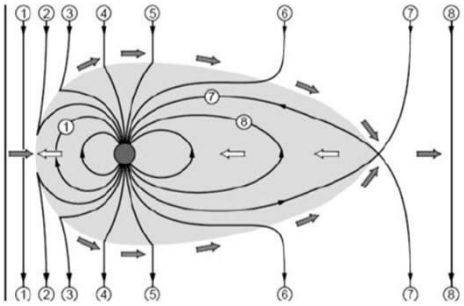
$|I_{R2}|$~MA $< |I_{R1}|$ ⟹ $\frac{|I_{R1}|}{|I_{R2}|}$~1,15



Dynamics between current systems

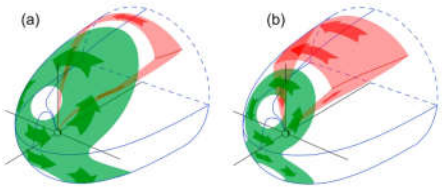
Changes in the solar wind conditions have a large effect on the magnetosphere.

Dungey Cycle: Is a sunward return flow, driven by the magnetic imbalance initially caused by the dayside reconnection with the IMF that turns southward.



Dynamics between current systems

- dayside magnetopause eroded
- magnetopause comes closer to the Earth
- cusps shifted to more equatorward latitudes
- increase in the transport of magnetic flux from the dayside to the nightside

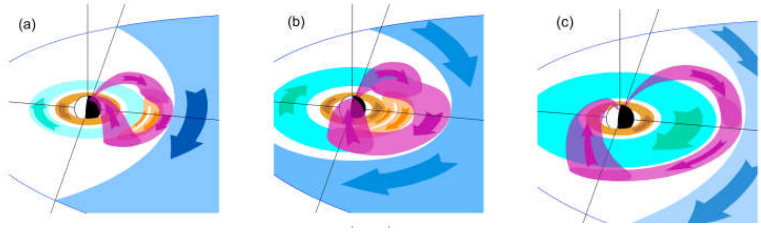


Increase in the size of Region 1 Field-Aligned current system and decrease of the Chapman-Ferraro current system

Dynamics between current systems

During magnetic storms:

- Current systems go through a systematic progression of intensity and location changes



(a) typical main phase configuration

(b) current system locations near storm peak

(c) typical recovery phase current system formation

Summary - Conclusions

General

- The magnetopause protects the Earth from the solar wind.
- The Earth's magnetosphere is dominated by three elements: the internal dipolar magnetic field, the IMF from the Sun and the solar wind properties.
- Where the IMF distorts the Earth's dipole, there is an electric current flowing.
- Each current system has a magnetic field topology associated with it, contributing to the shape of the magnetosphere.
- Understanding the relative strength and location of each electric current system is helpful to accurately predicting the variations of the magnetic field near the Earth's surface.
- There are several current systems that flow through the ionosphere, influencing the electrostatic potential distribution in it.

Summary - Conclusions

Current Systems

- The Chapman-Ferraro current system is directly connected to the dayside magnetospheric topology and completely separates Earth's magnetic field from the solar wind plasma.
- The Magnetotail current divides the magnetotail into two regions with almost uniform magnetic field of opposite direction.
- The Field-Aligned currents flow along geomagnetic field lines, connecting the magnetosphere currents with ionosphere currents. There are two types:
  - Region 1: requires the existence of a plasma pressure gradient and flows from dawn to dusk;
  - Region 2: is created by the partial ring current on the nightside and flows from dusk to dawn.
- The Ring Current is generated by the charges trapped in Van Allen rings
- The Partial Ring Current is part of the ring current on the nightside and it's the result of an asymmetry of the plasma pressure distribution in the inner magnetosphere during disturbed times.
- As the IMF and the solar wind changes, the current systems in the magnetosphere changes their geometry.

Summary - Conclusions

The study of the magnetospheric current systems and their evolution is crucial to understand the potentially hazardous effects of space storms and help to prevent their consequences on space satellites and on the ground!

Thank you!