Earth’s and Planetary Magnetospheres

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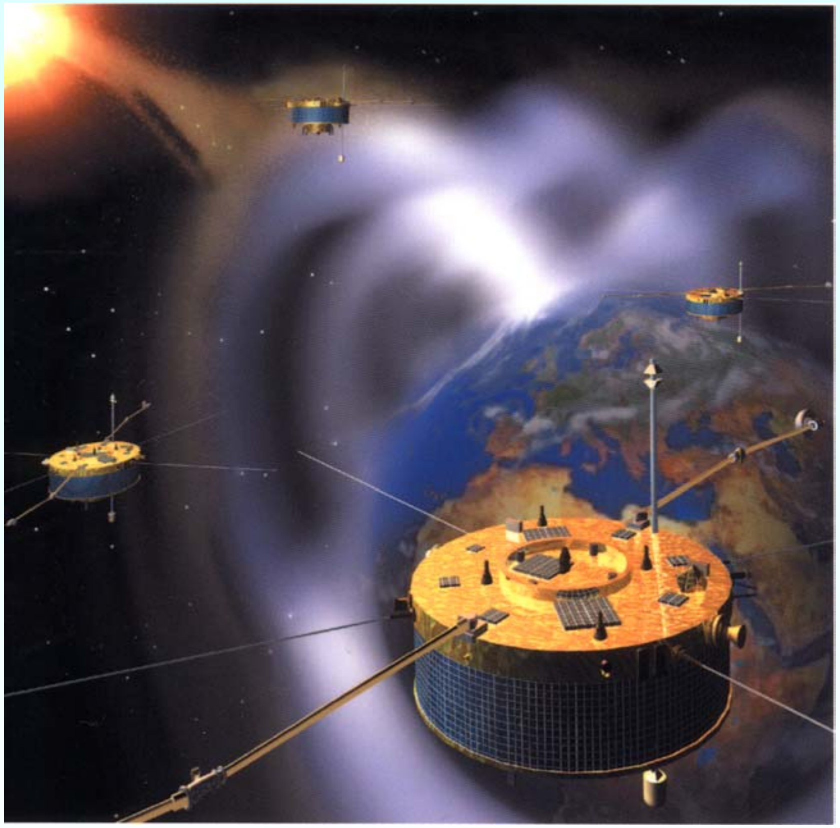


My presentation will be on:

- Definitions and history
- Magnetospheric structure
- Magnetospheric dynamics
- Magnetospheric eigenoscillations
- Comparing magnetospheres
- Mercury
- Jupiter
- Saturn
- Uranus
- Neptun

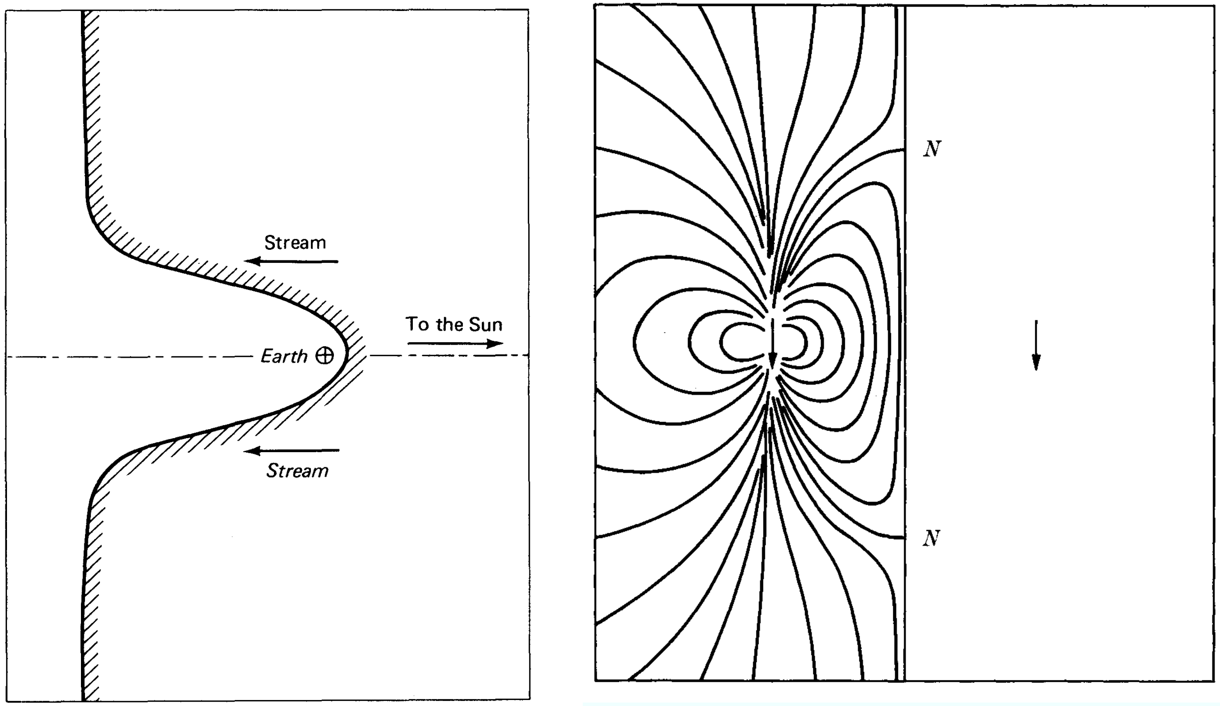
What is a magnetosphere ?

A magnetosphere in its wider sense is the interaction region between the solar wind and a planetary body.

A magnetosphere in its classical sense is the region bounded by the magnetopause and the ionosphere.

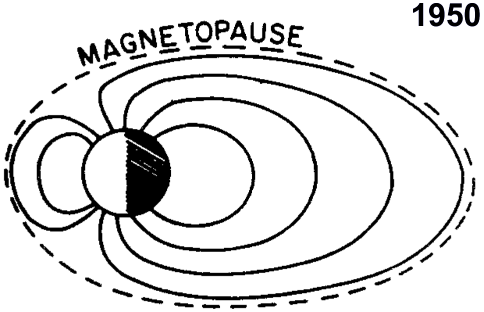
This magnetosphere proper is part of the magnetosphere in its wider sense

Evolution of the Concept „Magnetosphere“

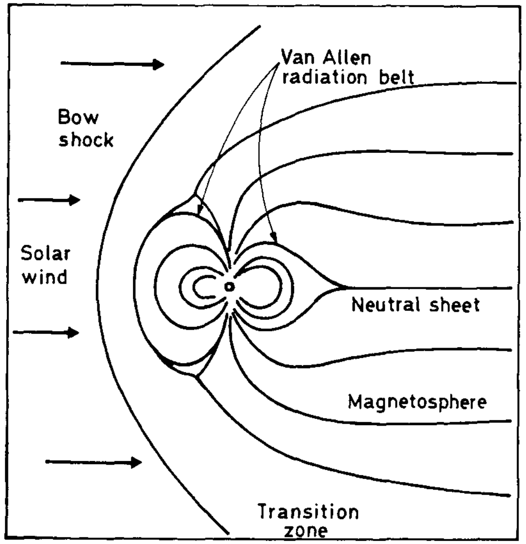


Chapman and Ferraro, in the 30ties

1950

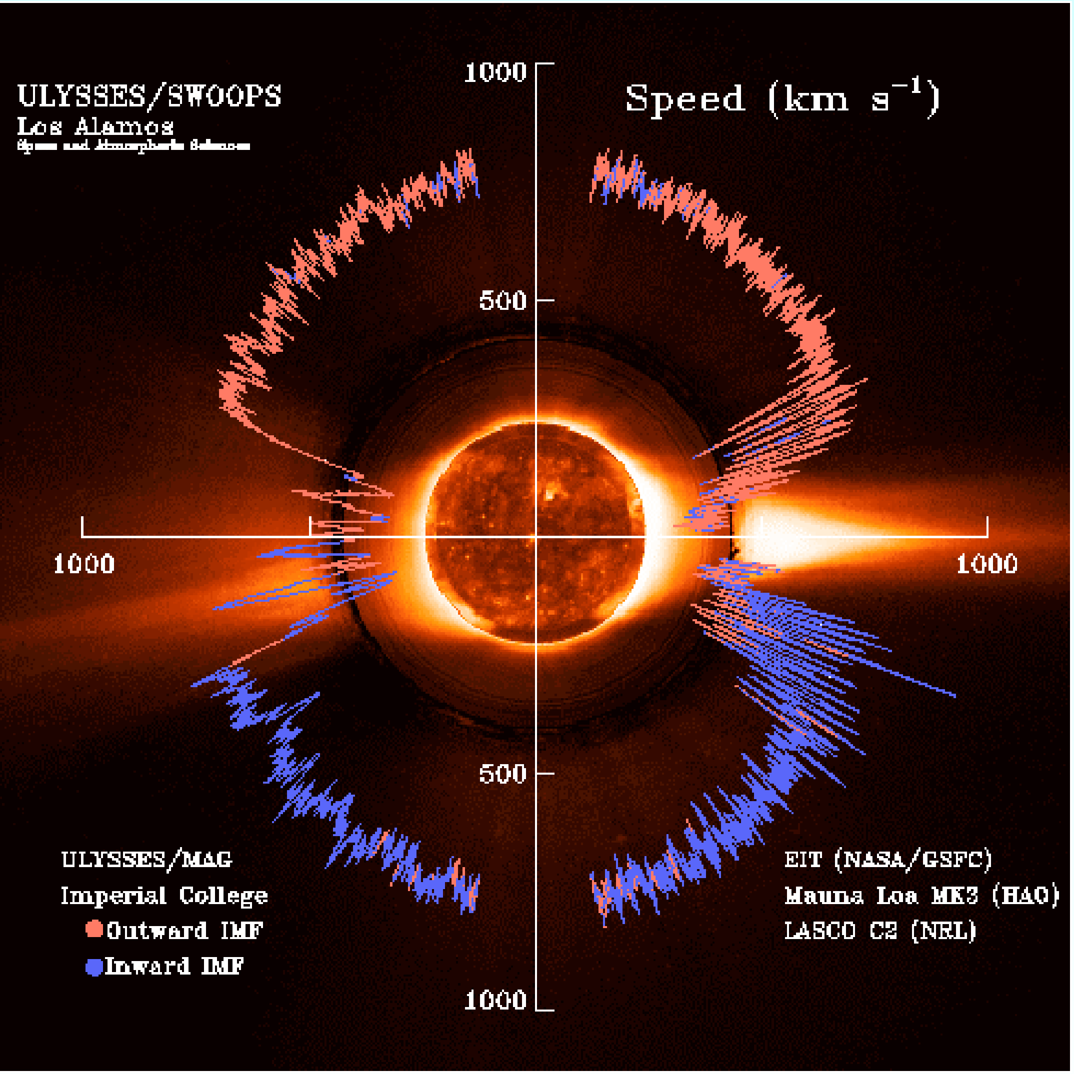


1960's



Reference: Akasofu, S.I., Evolution of ideas in solar-terrestrial physics, Geophys. J. R. astr. Soc., 74, 257-299, 1983.

Solar Wind: The Embedding Medium

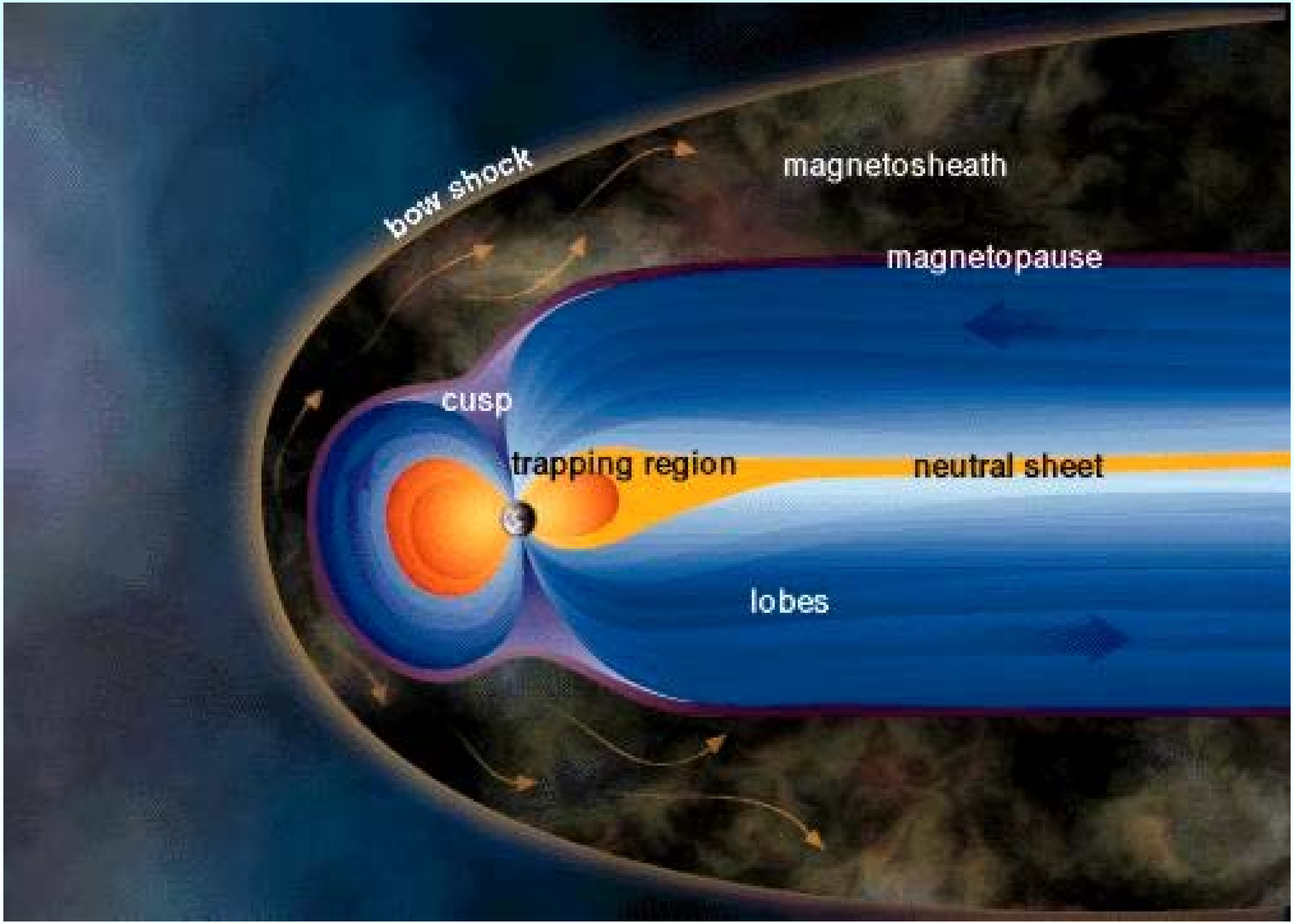


Magnetic field and plasma density

Mercury:	**39 nT**	**33 cm^{-1}**
Earth:	**8 nT**	**5 cm^{-1}**
Jupiter:	**1 nT**	**0.2 cm^{-1}**
Saturn:	**0.6 nT**	**0.06 cm^{-1}**
Uranus:	**0.3 nT**	**0.01 cm^{-1}**
Neptun:	**0.005 nT**	**0.005 cm^{-1}**

The velocity is almost constant in the inner part of the heliosphere

Structure of the Terrestrial Magnetosphere



Key Regions and Associated Physical Processe

Bow shock:	**collisionless shock waves**
Magnetosheath:	**mirror modes,.......**
Magnetopause:	**pressure balance, magnetic reconnection, Kelvin-Helmholtz instability**
Trapping regions:	**particle trapping, wave-particle interaction, drift motions/current**
Neutral sheet:	**magnetic reconnection, current instabilities**
Cusp region:	**turbulence, edge flows,....**
Magnetosphere:	**eigenoscillations**

Magnetospheric Configuration I

The magnetospheric magnetic field is the result of the superposition of three contributions

$$\vec{B}_{Total} = \vec{B}_{Int} + \vec{B}_{CF} + \vec{B}_{IMF}$$

where the Chapman-Ferraro currents at the magnetopause cause the Contribution $\mathbf{B_{CF}}$.

With the boundary condition

$$\vec{n} \cdot \vec{B}_{Total} = f(x_{MP})$$

Reference: G.H. Voigt, in: H. Volland, Handbook of Atmospheric Electrodynamics, Vol. II, chapter 11, CRC Press, 1995

Magnetospheric Configuration II

and

$$\vec{B}_{CF} = -\nabla\Phi_{CF}$$

one has a Neumann boundary value problem for the CF-contribution

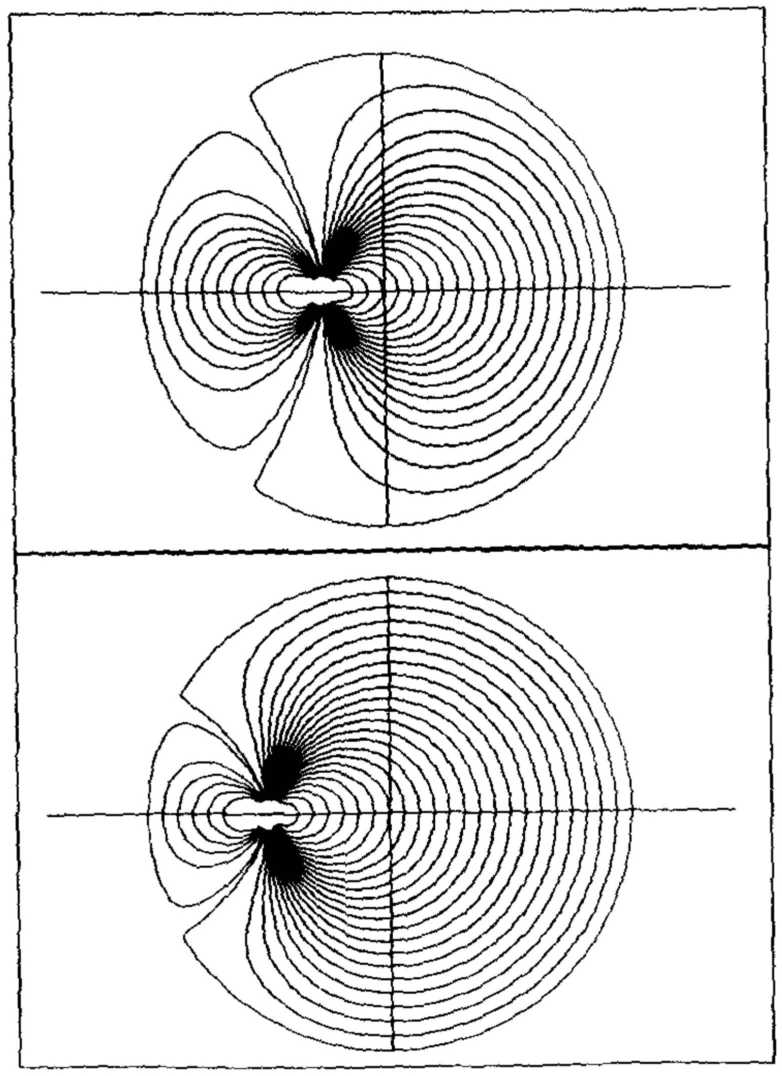
$$\frac{\partial\Phi_{CF}}{\partial n} = \vec{n}\cdot\vec{B}_{Int} - f(x_{MP})$$

$$\nabla^2\Phi_{CF} = 0$$

With the boundary condition $\vec{n}\cdot\vec{B}_{Total} = 0$,which specifies a closed magnetosphere, and prescribing the magnetopause shape allows one to determine the field topology as well as the CF-current density

$$\vec{j}_{CF} = -\frac{1}{\mu_0}\vec{n}\times(\vec{B}_{Int} + \vec{B}_{CF})$$

Magnetospheric Configuration: Dipole in a Sphere



Internal field due to dipole

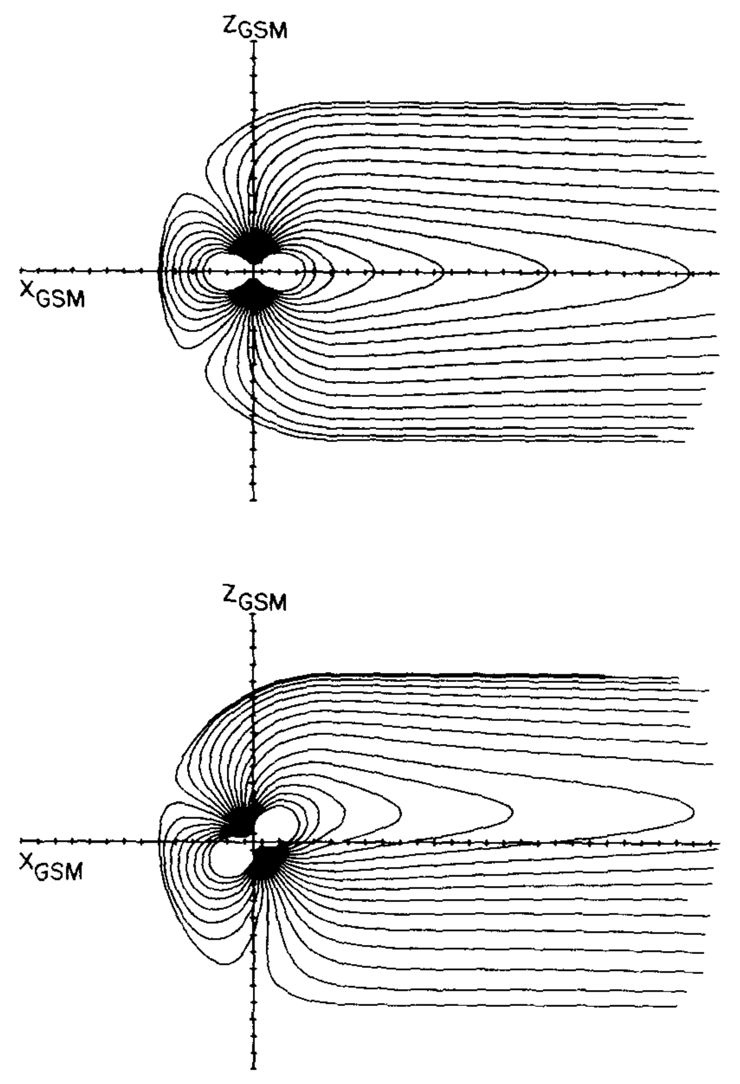
Magnetopause is a sphere

Shift of dipole from center simulates decreasing magnetopause distance

Cusp region moves to lower latitudes for decreasing mp position

Compare Mercury (later)

Magnetospheric configuration: Half-sphere cylinder



Dayside half-sphere; nightside cylinder; closed magnetosphere

Noon-midnight meridian plane

Tilt angle 0° and 35°

Two neutral points with zero magnetic field occur at the magnetopause at the cusps

Magnetopause: Self-Consistent Boundary Shape

The magnetopause shape is the result of momentum conservation across the boundary; its normal is given by the equation

$$k \cdot m_p \cdot n_p (\vec{n} \cdot \vec{v}_x)^2 = \frac{1}{2\mu_0} [\vec{n} \times (\vec{B}_{Int} - \nabla \Phi_{CF})]^2$$

and the shape calculated by an iterative numerical procedure between the Neumann boundary value problem and the above equation

Magnetopause: Stand-off Distance

The magnetopause stand-off distance along the Sun-Earth line is given by

$$r_{MP} = \left(\frac{4B_{Surface}^2}{2\mu_0 k n_p m_p v_x^2}\right)^{1/6}$$

where k = 0.88 is a correction factor resulting from gasdynamic approximations to the magnetosheath flow

Magnetospheric Convection: Corotation I

The atmosphere is corotating with the planet due to frictional coupling to the surface and turbulent transport of angular momentum to the upper atmosphere.

The ionosphere is corotating due to collisional coupling between the ionospheric plasma and the neutral gas of the atmosphere.

Corotation of the magnetospheric plasma requires large ionospheric electric conductivity to allow closure of magnetospheric currents via field-aligned currents in the ionosphere.

Angular momentum transport is via Alfvén waves between the ionosphere and the magnetospheric plasma

Magnetospheric Convection: Corotation II

Corotation implies plasma motion and via the frozen-in theorem

$$\vec{E} + \vec{v} \times \vec{B} = 0$$

electric fields, that is the corotational electric field is given as

$$\vec{E}_{cor} = -\frac{\Omega_{Earth} B_{surface} R_E^3}{r^2} \vec{e}_r$$

and corotation driven plasma motion is ExB-drift convection

$$\vec{v}_{cor} = \frac{\vec{E}_{cor} \times \vec{B}}{B^2}$$

The Open Magnetosphere and the Interplanetary Electric Field

Most space plasmas are ideal magnetohydrodynamic plasmas, that is there are no magnetic field-aligned electric fields, or magnetic field lines are on constant electric potential.

Thus, two points in the solar wind plasma are on different potentials if they are not magnetically connected, that is the electric potential difference is given by the interplanetary electric field

$$\vec{E}_{IEF} = -\vec{v}_{sw} \times \vec{B}_{IMF}$$

This electric field may drive plasma convection in the magnetosphere proper, if and only if two points in the magnetosphere are magnetically connected to two points in the solar wind. In such an open magnetosphere

$$\vec{v}_{con} = \alpha \vec{E}_{IEF} \times \vec{B}_{IMF} / B^2_{IMF}$$

Magnetic Reconnection I

Magnetic reconnection is a plasma process which converts magnetic into kinetic energy. Thus, reconnection may be regarded as anti-dynamo action.

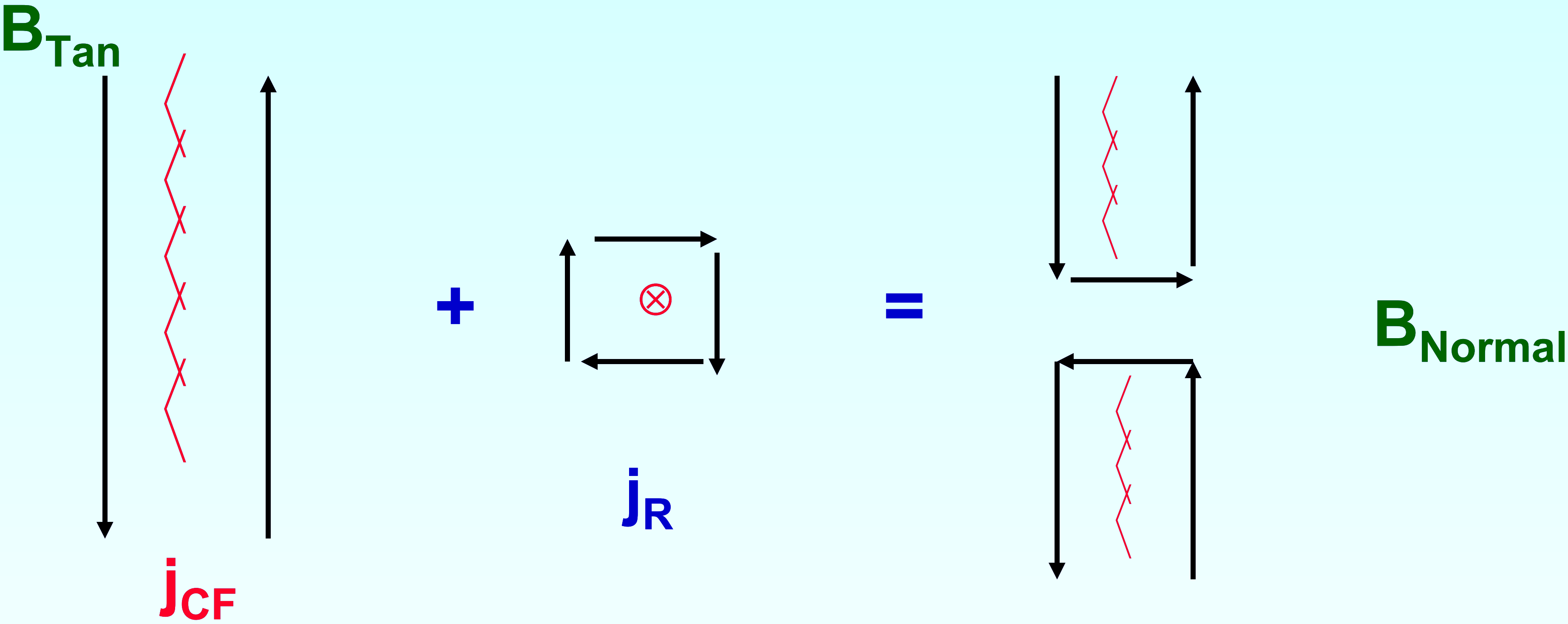
Magnetic reconnection occurs where large electric current flow densities in a plasma are inhibited due to various plasma instabilities and non-ideal plasma conditions.

A generalized Ohm‘s law must be used:

$$\vec{E}+\vec{v}\times\vec{B}=\eta\,\vec{j}+\frac{1}{ne}\,\vec{j}\times\vec{B}-\frac{\nabla p_e}{ne}+\frac{m_e}{ne^2}\frac{\partial\vec{j}}{\partial t}$$

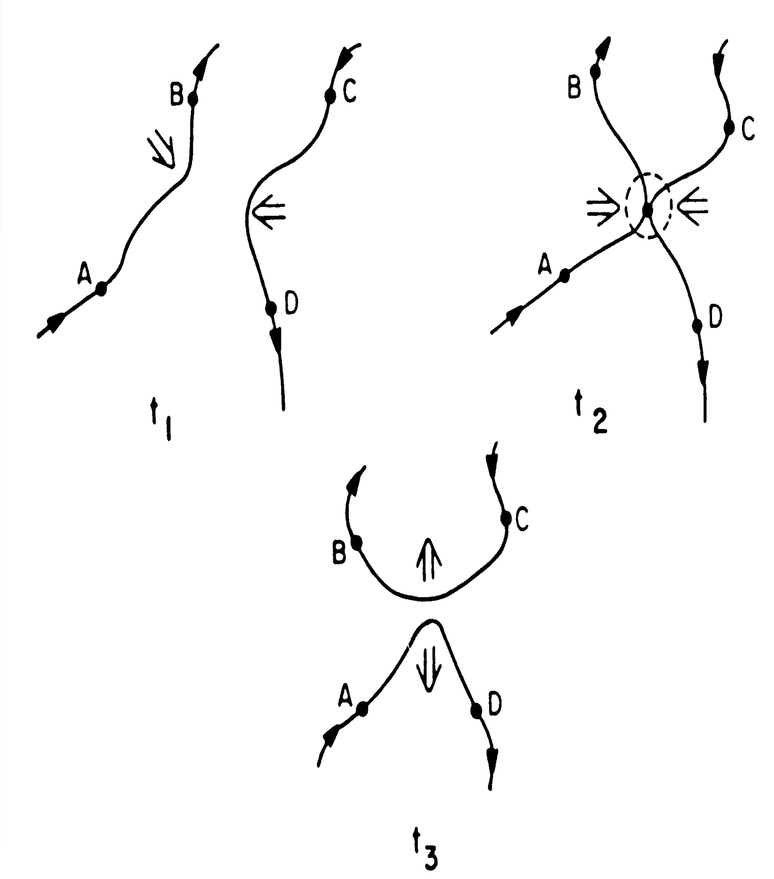
Inhibiting electric current flow is equivalent to switching on ananomalous conductivity resulting in a counter current flow.The concept of a counter-current j_R being switched-on leads to this scenario:

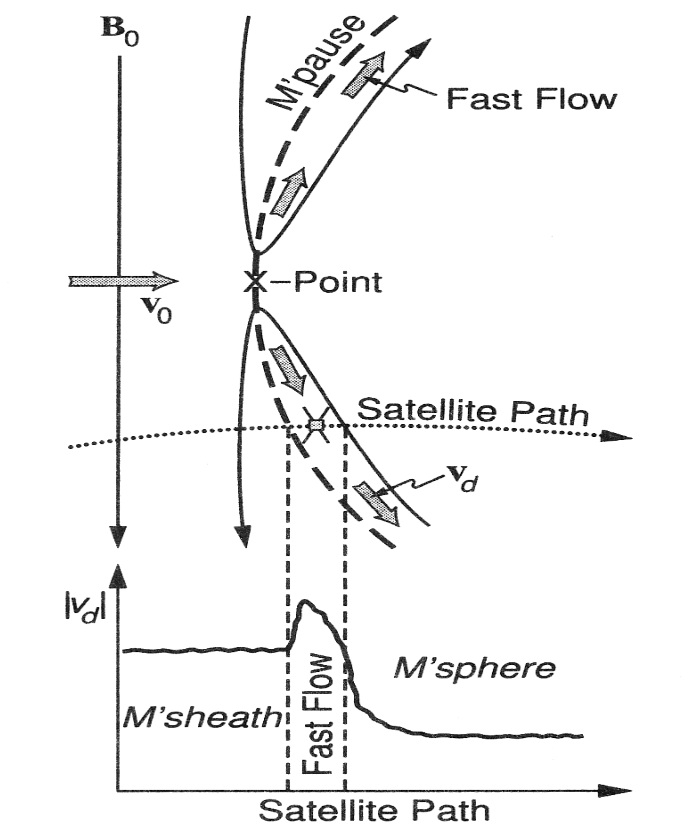
Magnetic Reconnection II



The counter current j_R leads to a reconfiguration of the fieldlines

Magnetic Reconnection III

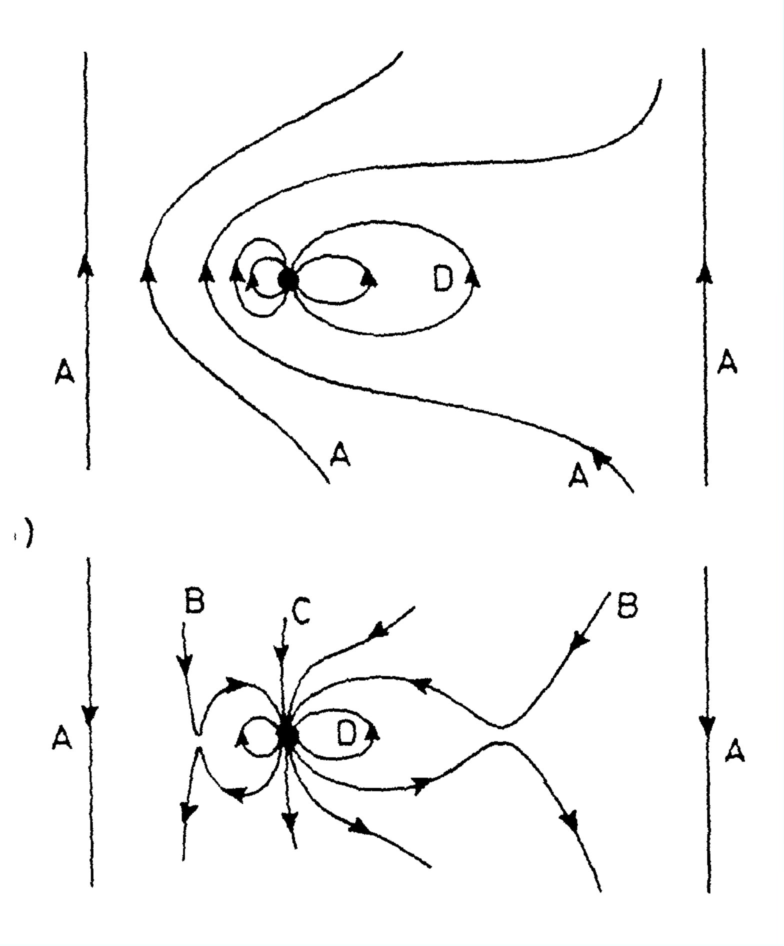




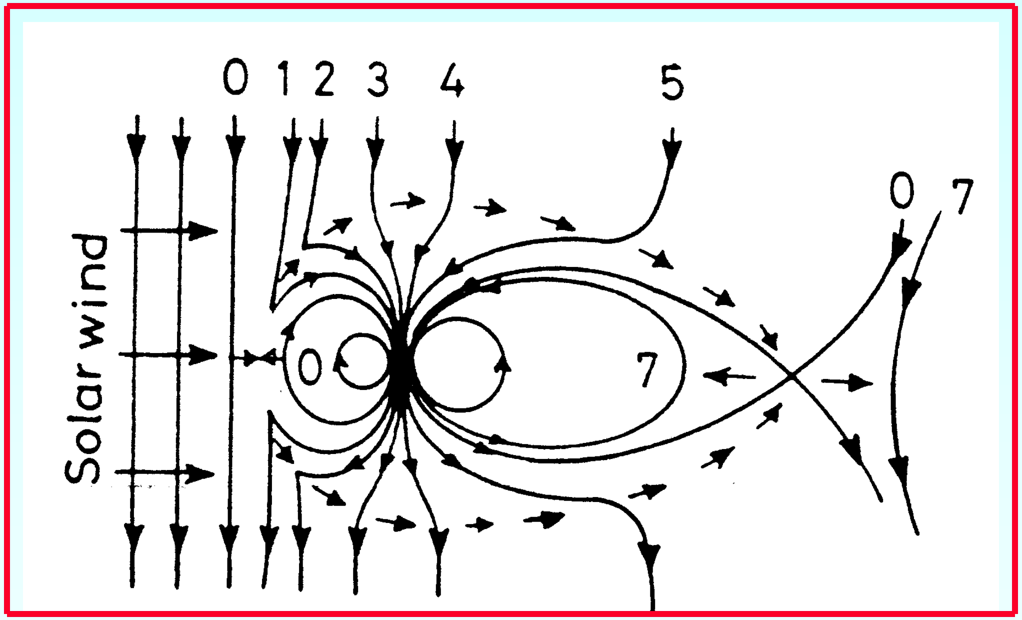
Reference: W.I. Axford, Magnetic field reconnection, in: E.W. Hones (Ed.), Magnetic reconnection in space and laboratory plasmas, AGU, 1984.

R. Treumann & W. Baumjohann, Advanced space plasma physics, CUP, 1998.

Flux Transport in the Open Magnetosphere

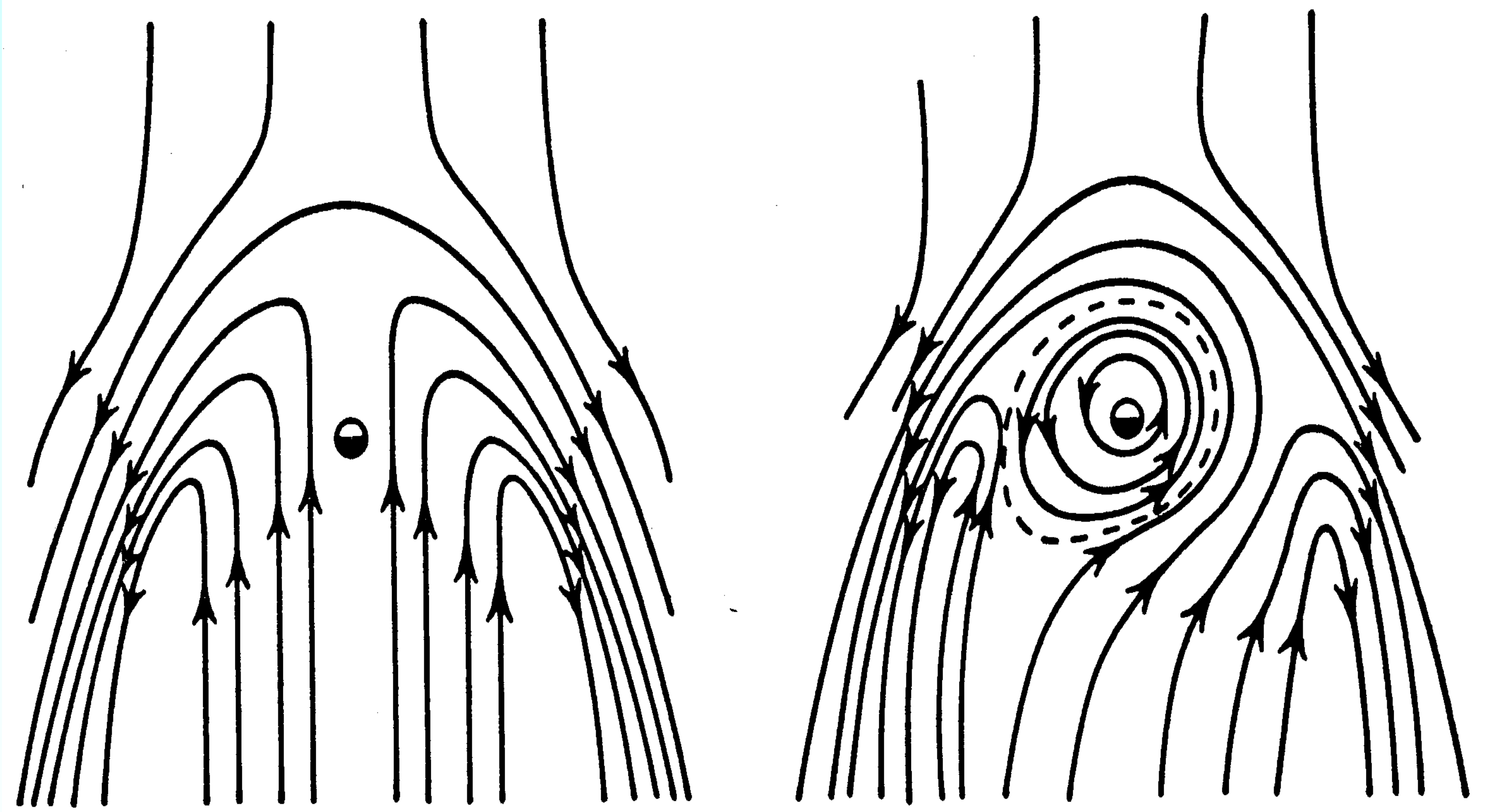


Dungey's model of the closed and
open magnetosphere



Dayside reconnection transports plasma and magnetic flux towards the nightside tail where return flux is initiated by reconnection again.

Corotation and Reconnection Induced Convection



Plasmasphere formation !

The Polar Cap and Open, Tail Forming Field Lines

Geomagnetic field lines, opened by dayside reconnection

Leave the geomagnetic pole regions, i.e. the polar cap

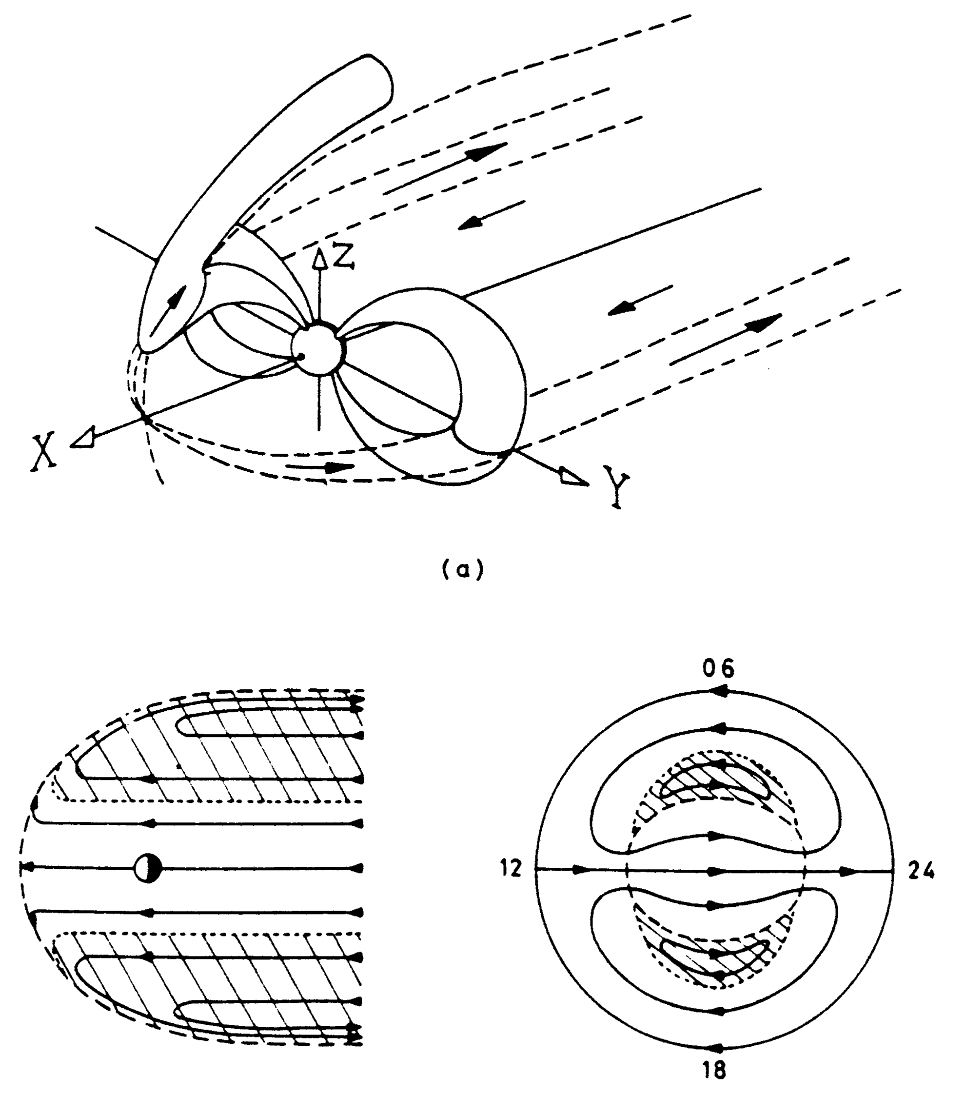
And form the nightside magnetoail regime.

The polar cap is the region above about ± 80° latitide.

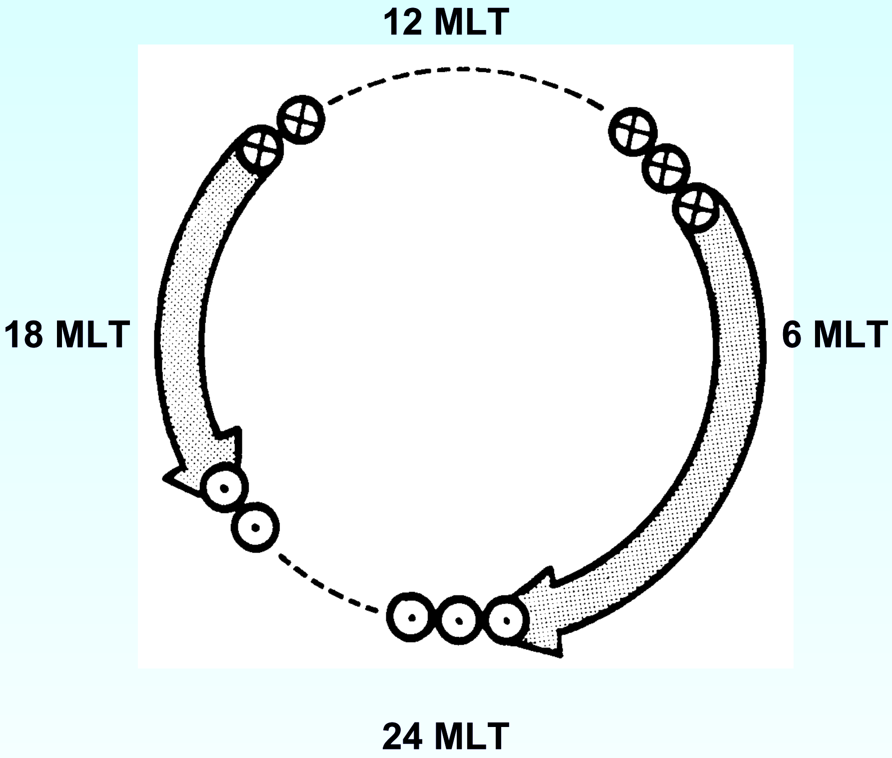
The electric field potential drop across the polar cap is

determined by interplanetary electric field.

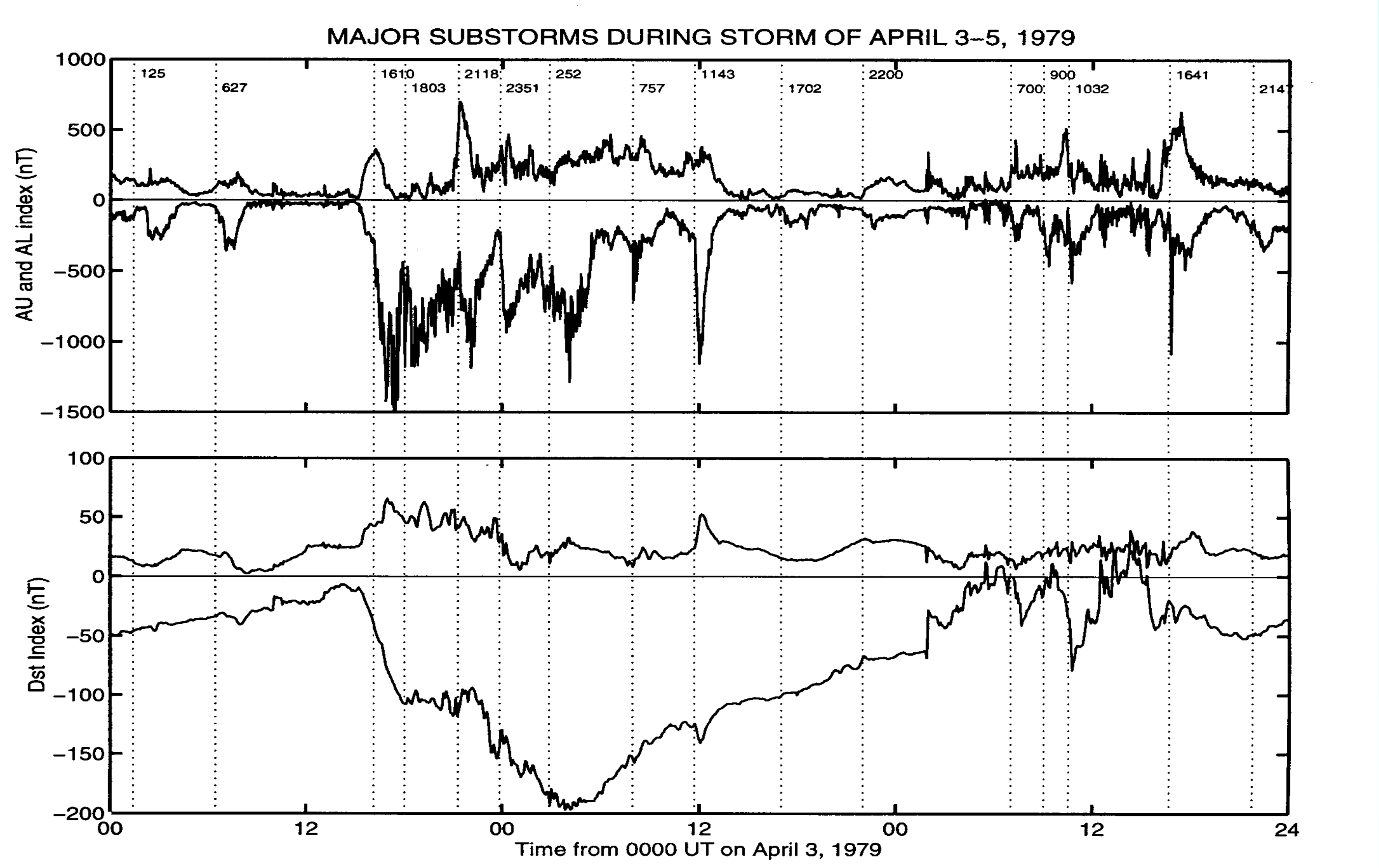
Dawn-Dusk Field, Polar Cap Potential, and Ionospheric Electric Field



Convection driven, polar electrojets in the Ionosphere



Magnetospheric Activity: Magnetic Substorm



MAJOR SUBSTORMS DURING STORM OF APRIL 3–5, 1979

Magnetospheric Activity: Auroral Break-up

The Founder of Magnetospheric Physics

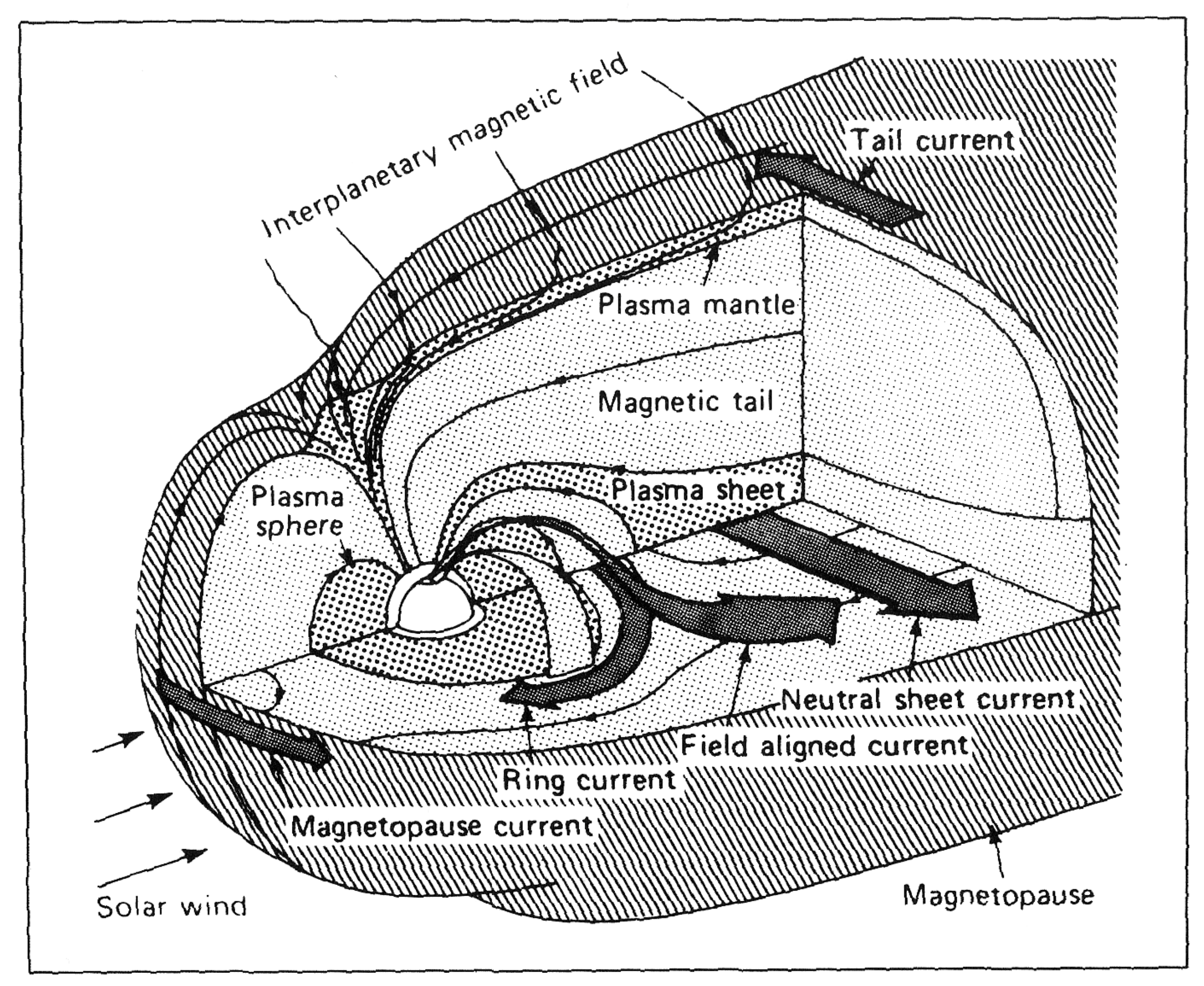
is Olaf Peter Hjorter (1696-1750), assistent to Anders Celsius, who made more than 10.000 concurrent observations of auroral and magnetic activity in the years 1741 and 1742, i.e. in 17.520 hours !

This most careful work proofed the anticipated connection between these two phenomena.

The credit for this seminal discovery was later given to his supervisor Anders Celsius.

Watch out !

Electric Currents in the Magnetosphere



Magnetopause currents

Ring current

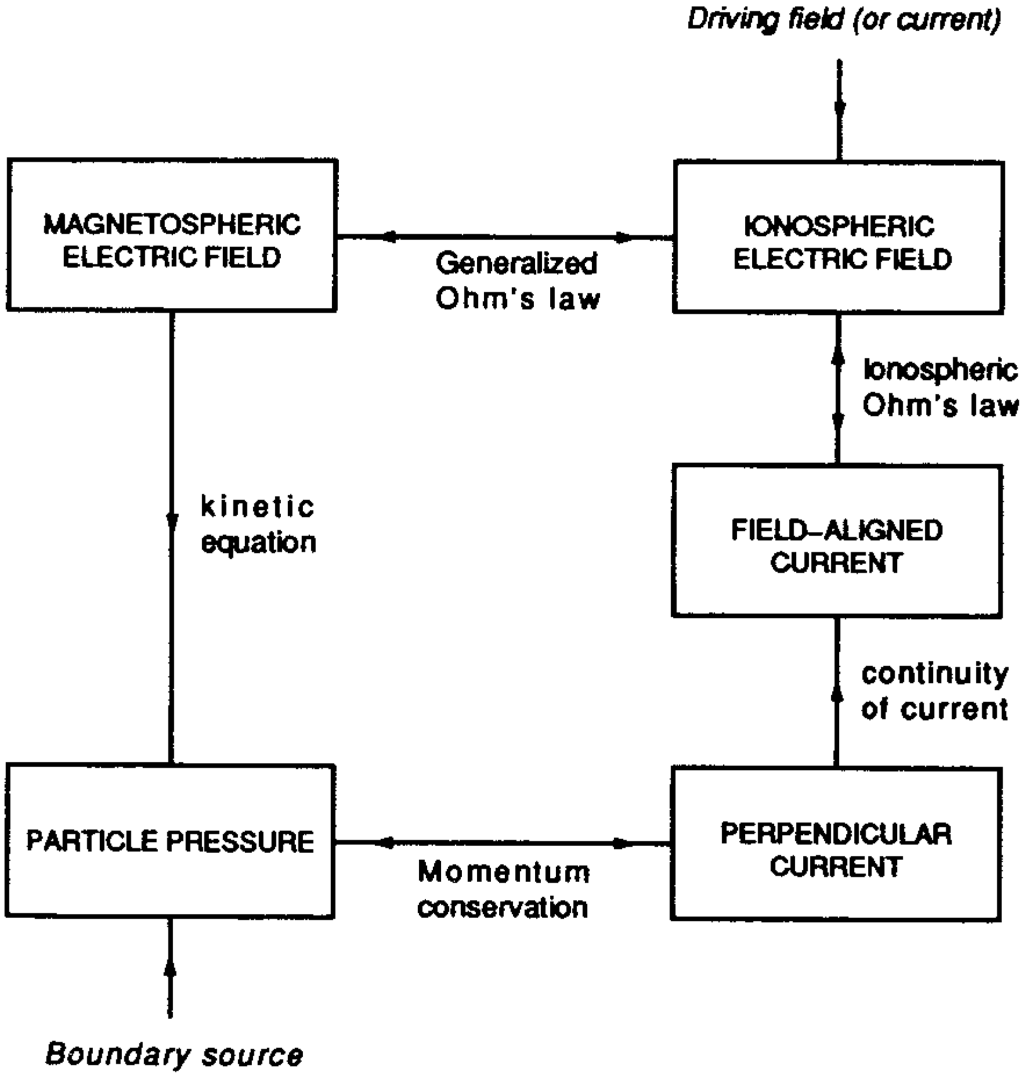
Neutral sheet current

Tail current

Field-aligned currents

Polar electrojet currents

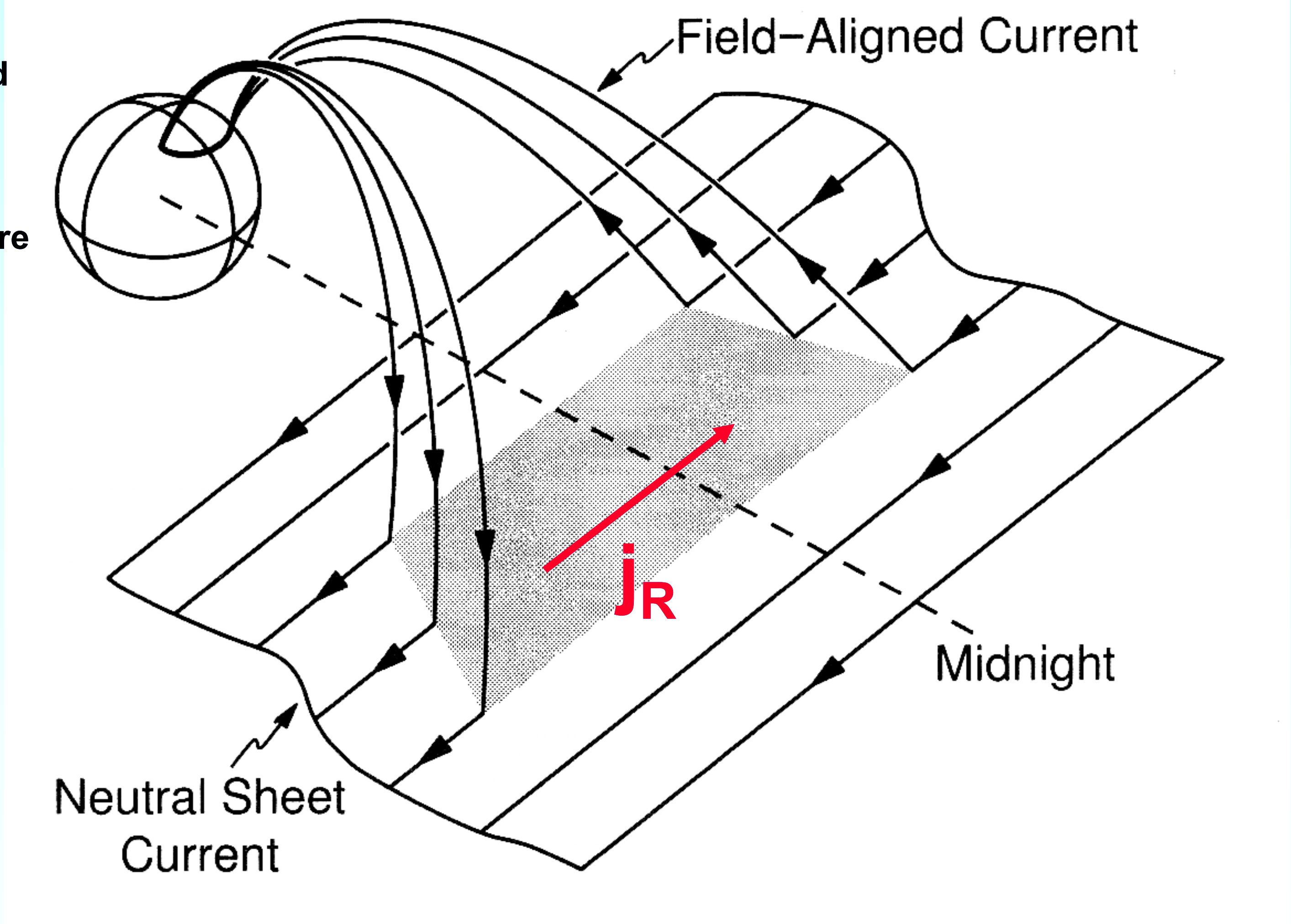
Magnetosphere-Ionosphere Coupling



Field-aligned currents are a major agent for the coupling of the magnetospheric plasma and the ionosphere electro-mechanically

Reference: V. M. Vasyliunas, in: B. M. McCormack, Particles and fields in the magnetosphere, Reidel, Dordrecht, 1970

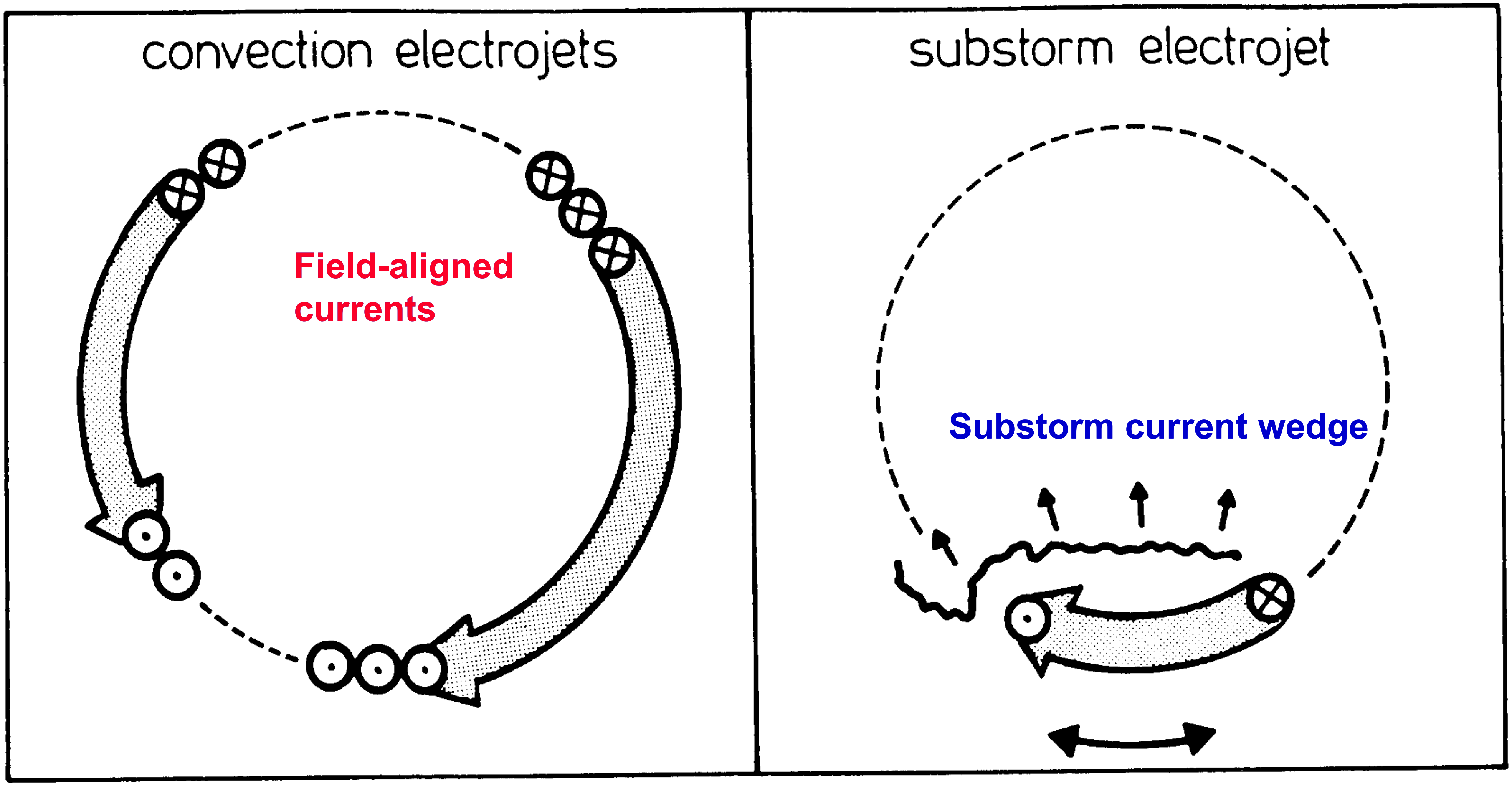
The Substorm Current Wedge



Enhanced westward electrojet in the ionosphere

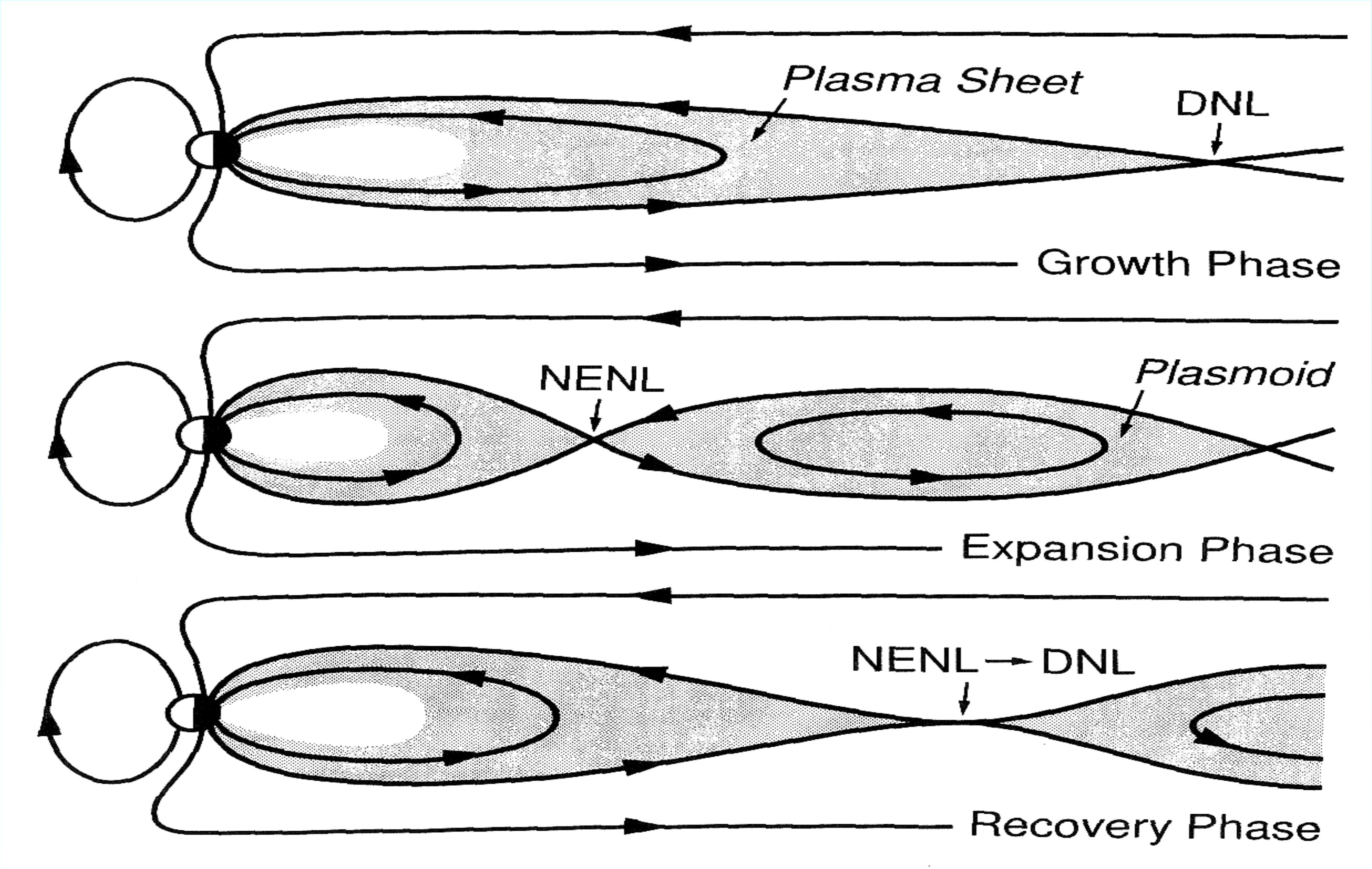
Reference: R. L. McPherron, Magnetospheric substorms, Rev. Geophys. Space Phys., 17, 657-681, 1979.

Electric Currents Systems in the Ionosphere



Reference: Baumjohann, W. and R. Treumann, Basic space plasma physics, CUP, 1997

A Substorm Scenario



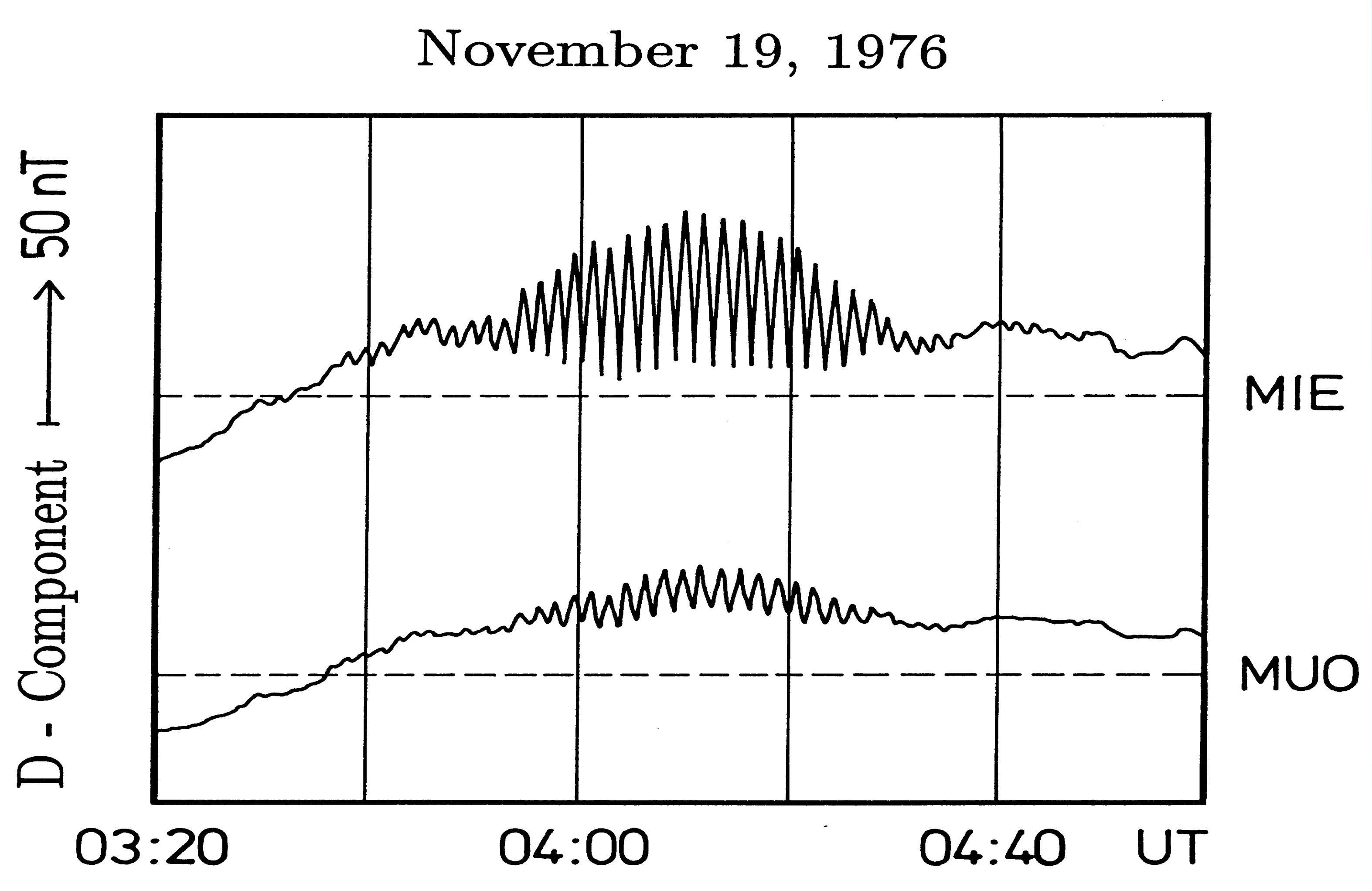
Cometary Tail Disruptions – Substorms ?

p/Halley

January 10,

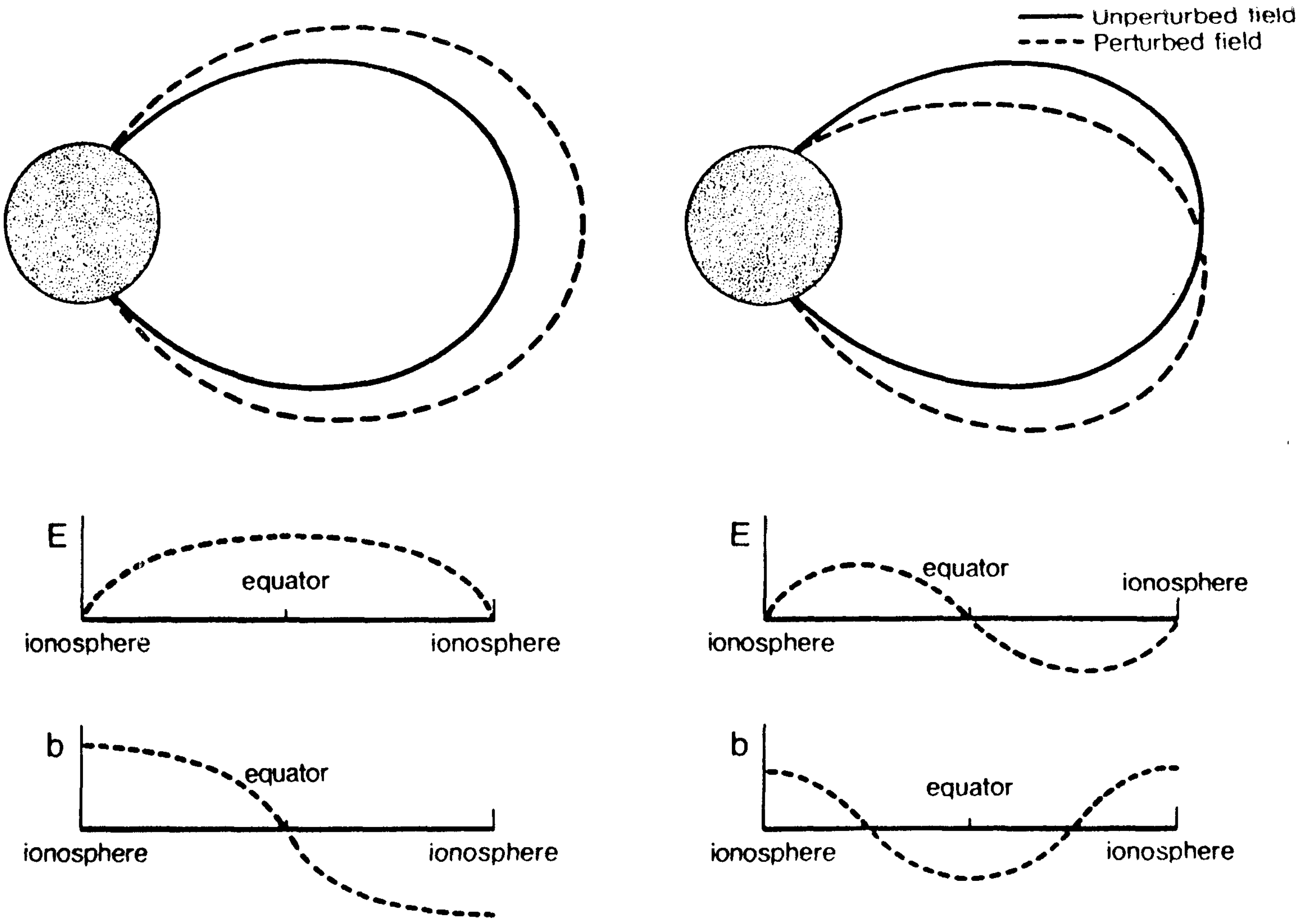
1986

Ultra-low Frequency Pulsations - Magnetospheric Eigenoscillations



Reference: K.H. Glassmeier, ULF pulsations, in: H. Volland, Handbook of atmospheric electrodynamics, CRC, 1995.

Ultra-low Frequency Pulsations – Standing MHD Waves in the Magnetosphere



a) ODD MODE (fundamental)

b) EVEN MODE (second harmonic)

STANDING OSCILLATIONS IN A DIPOLE FIELD

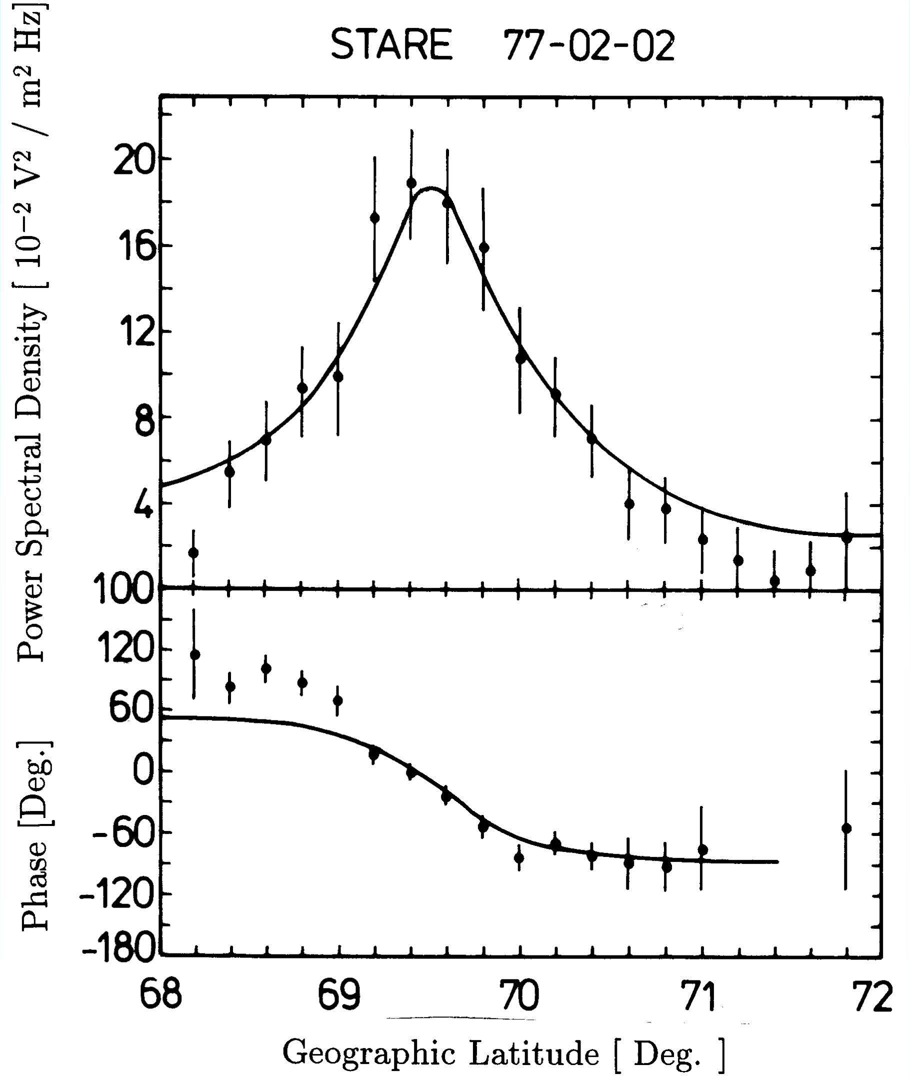
Field-Line Resonances: The Problem

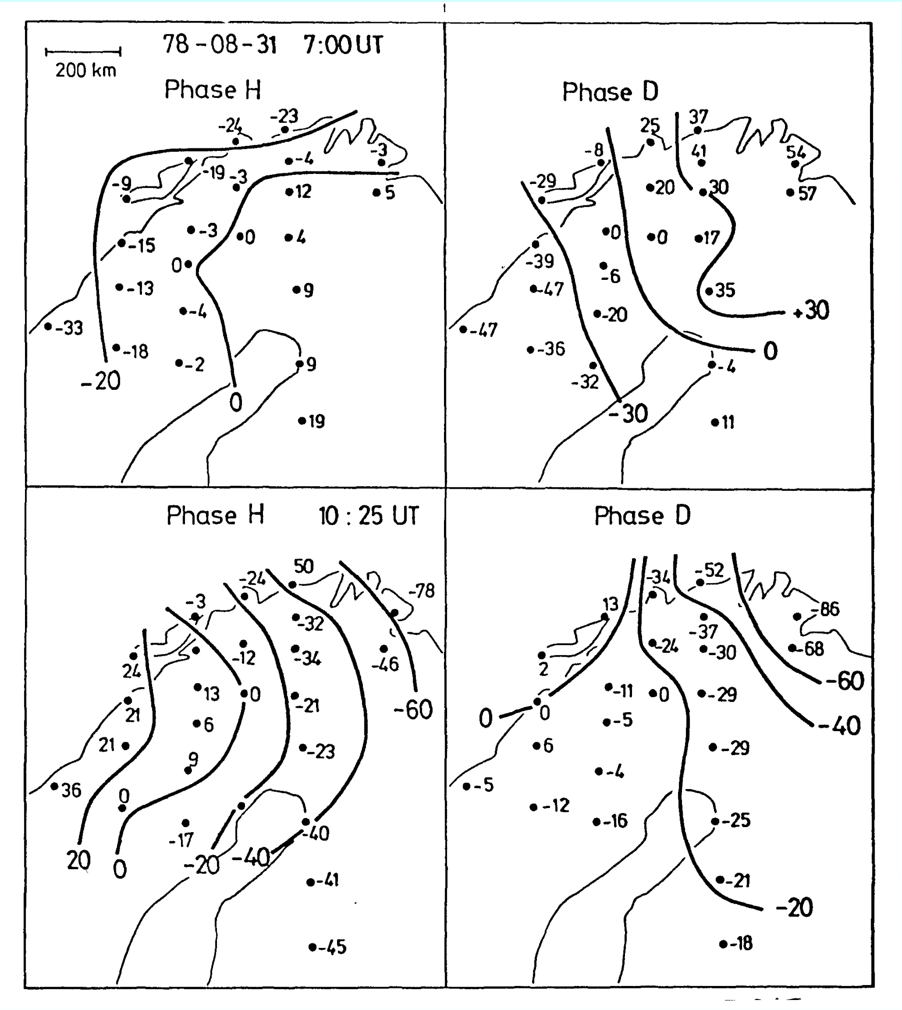
Alfvén and Fast modes are the eigenmodes of a uniform and homogeneous plasma

However, the magnetospheric magnetic field and the plasma density are strongly non-uniform and inhomogeneous.

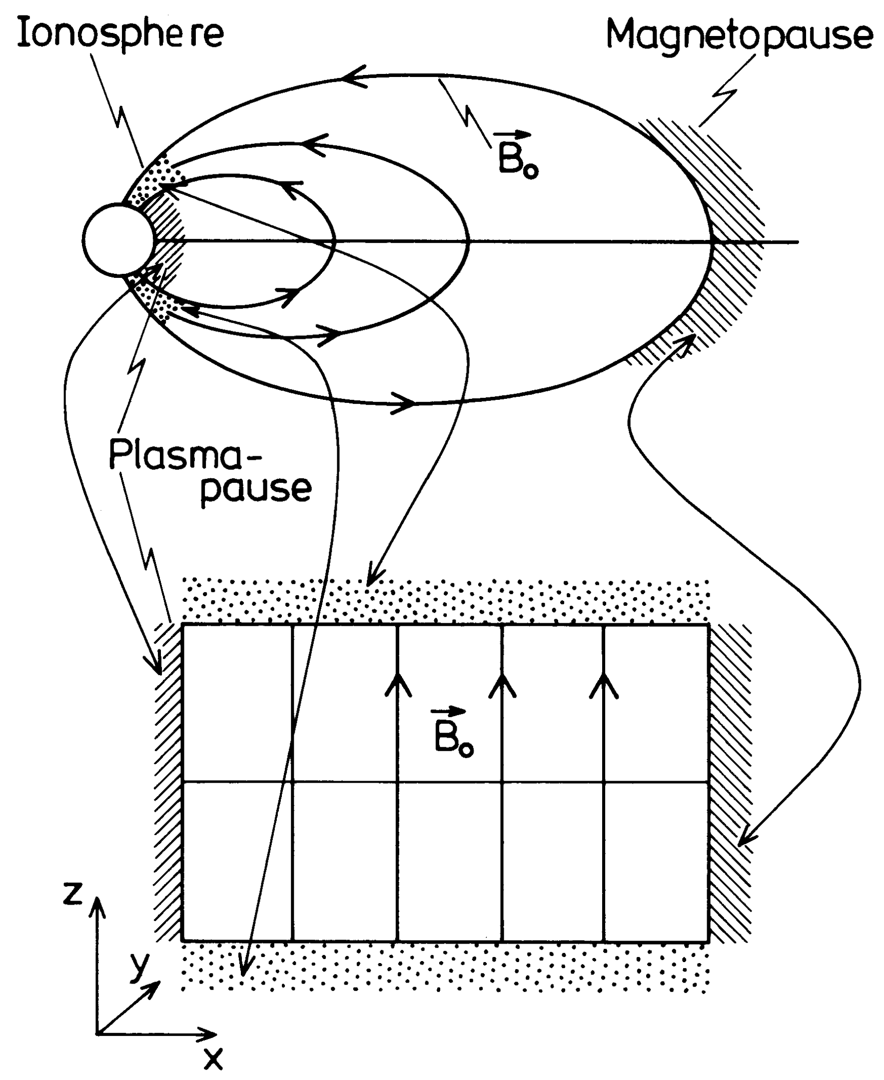
Thus, propagation of MHD waves in magnetospheric plasmas needs to be studied.

Field-Line Resonances: Observational Facts





Field-Line Resonances: The Model



Magnetic field topology uniform

Inhomogeneity introduced by plasma density variation in x-direction

Ionosphere, plasmapause, and magnetopause as boundaries

Field-Line Resonances: The Theory I

Ansatz: $\vec{E}(x,y,z) = (E_x(x), E_y(x))\exp(imy + ikz - i\omega t)$

$\vec{b}(x,y,z) = (b_x(x), b_y(x), b_z(x))\exp(imy + ikz - i\omega t)$

Thus, with Ampere-Maxwell‘s law:

$$-\frac{\mu_0 i\omega\rho}{B_0^2}E_x = imb_z - ikb_y$$

$$-\frac{\mu_0 i\omega\rho}{B_0^2}E_y = ikb_x - \frac{\partial b_z}{\partial x}$$

Field-Line Resonances: The Theory II

and applying Faraday-Henry:

$$(\frac{\mu_0 \rho}{B_0^2}\omega^2 - k^2)E_x = im\,(\frac{\partial E_y}{\partial x} - imE_x)$$

$$(\frac{\mu_0 \rho}{B_0^2}\omega^2 - k^2)E_y = -\frac{\partial}{\partial x}(\frac{\partial E_y}{\partial x} - imE_x)$$

If the plasma is uniform, i.e. no gradient in x-direction, or if the perturbation is axisymmetric (m = 0), then both electric field components are decoupled and correspond to the Alfvén and fast modes.

Field-Line Resonances: The Coupling Equatio

$$\frac{\partial^2 E_y}{\partial x^2} - m^2 \frac{\partial R^2 / \partial x}{(R^2 - k^2)(R^2 - k^2 - m^2)} \frac{\partial E_y}{\partial x} + (R^2 - k^2 - m^2)\, E_y = 0$$

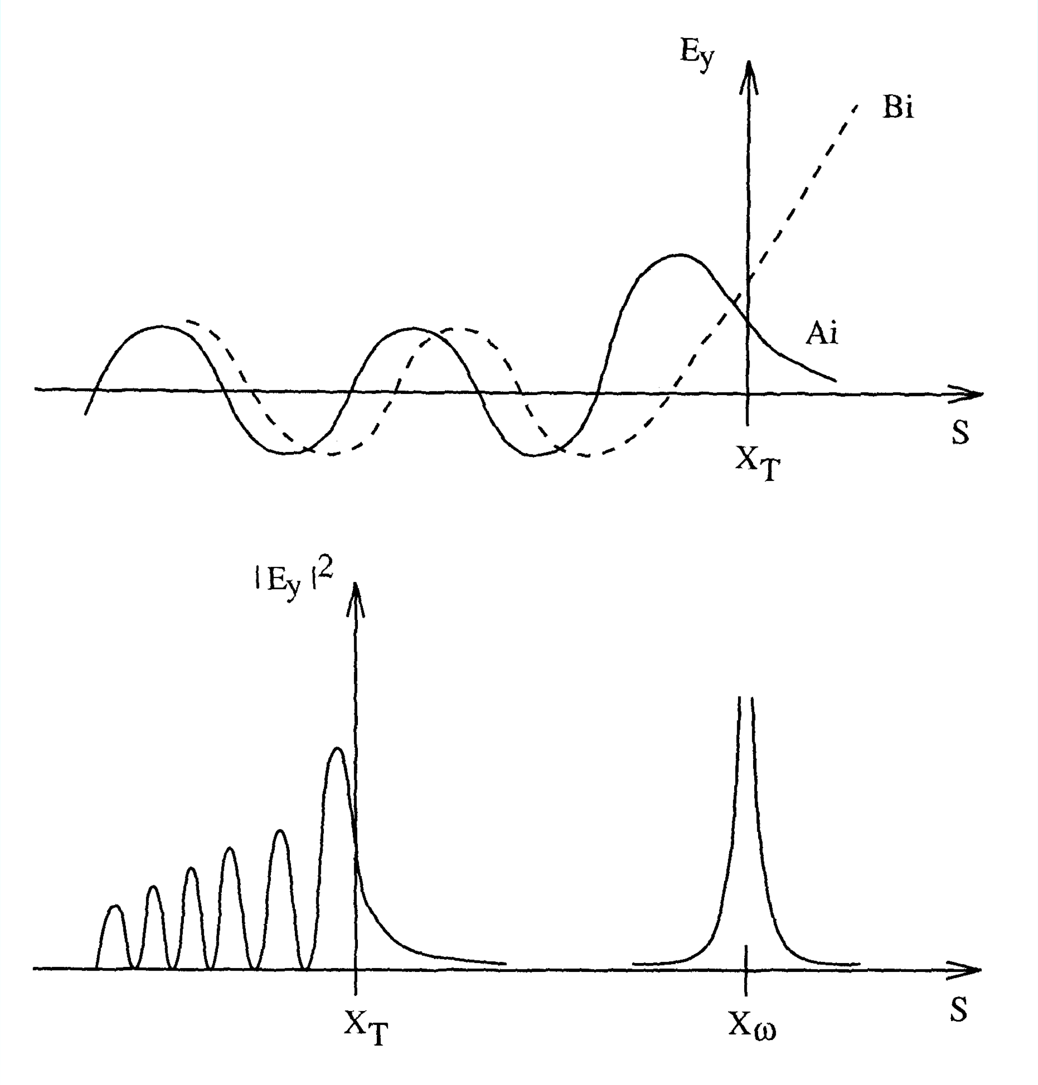
$$R^2 = \frac{\omega^2}{v_A^2(x)} = \frac{\mu_0 \rho \omega^2}{B_0^2}$$

Logarithmic singularity at resonance point: $R^2 = k^2$

that is, where the eigenfrequency of the local Alfvén

wave equals the frequency of the source wave

Field-Line Resonances: The solution



Wave cut-off point at x_T

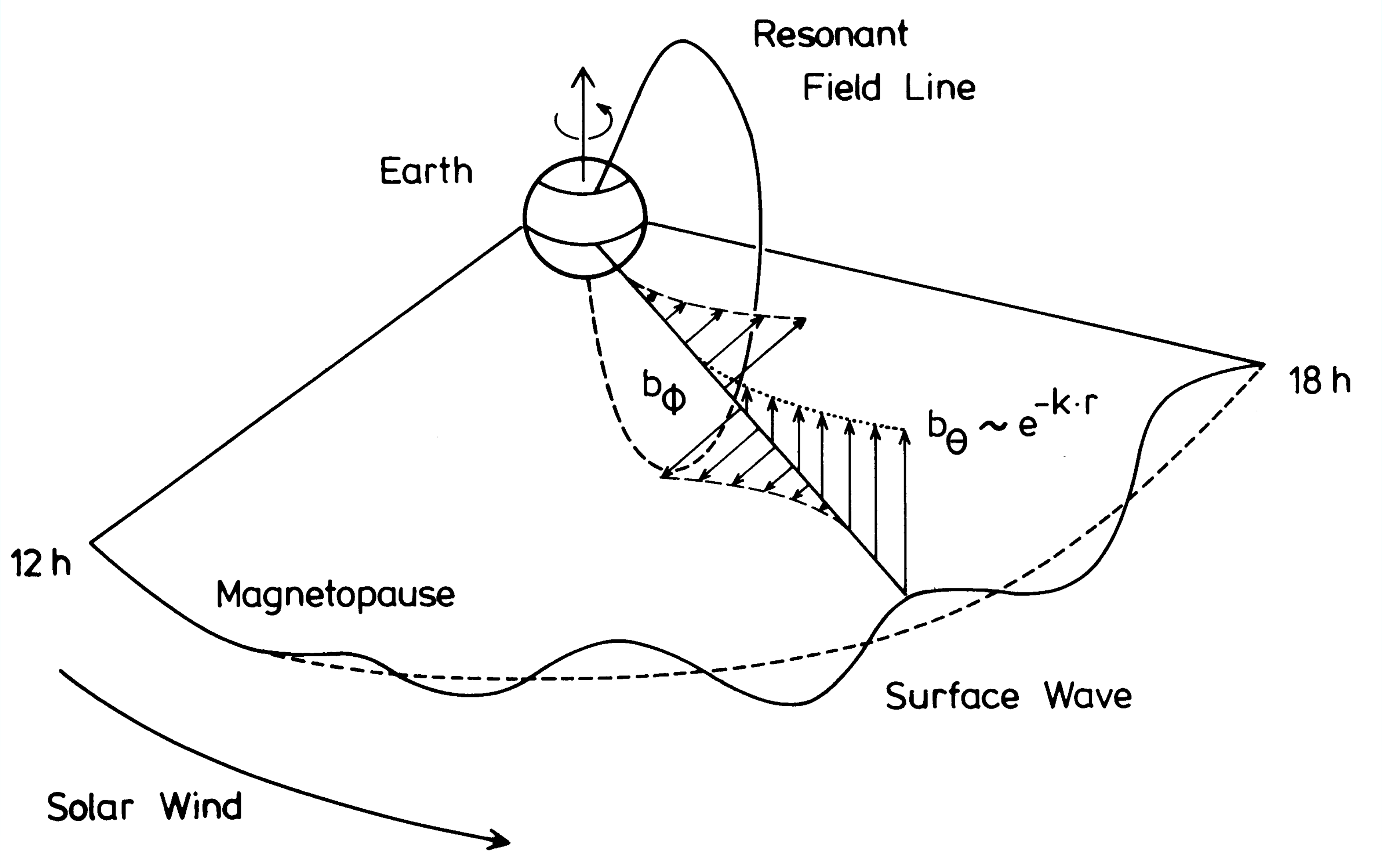
(remember Dieter's presentation on solar eigenmodes !!!!)

and tunneling of the

wave to the resonance

point

Field-Line Resonances: A Picture

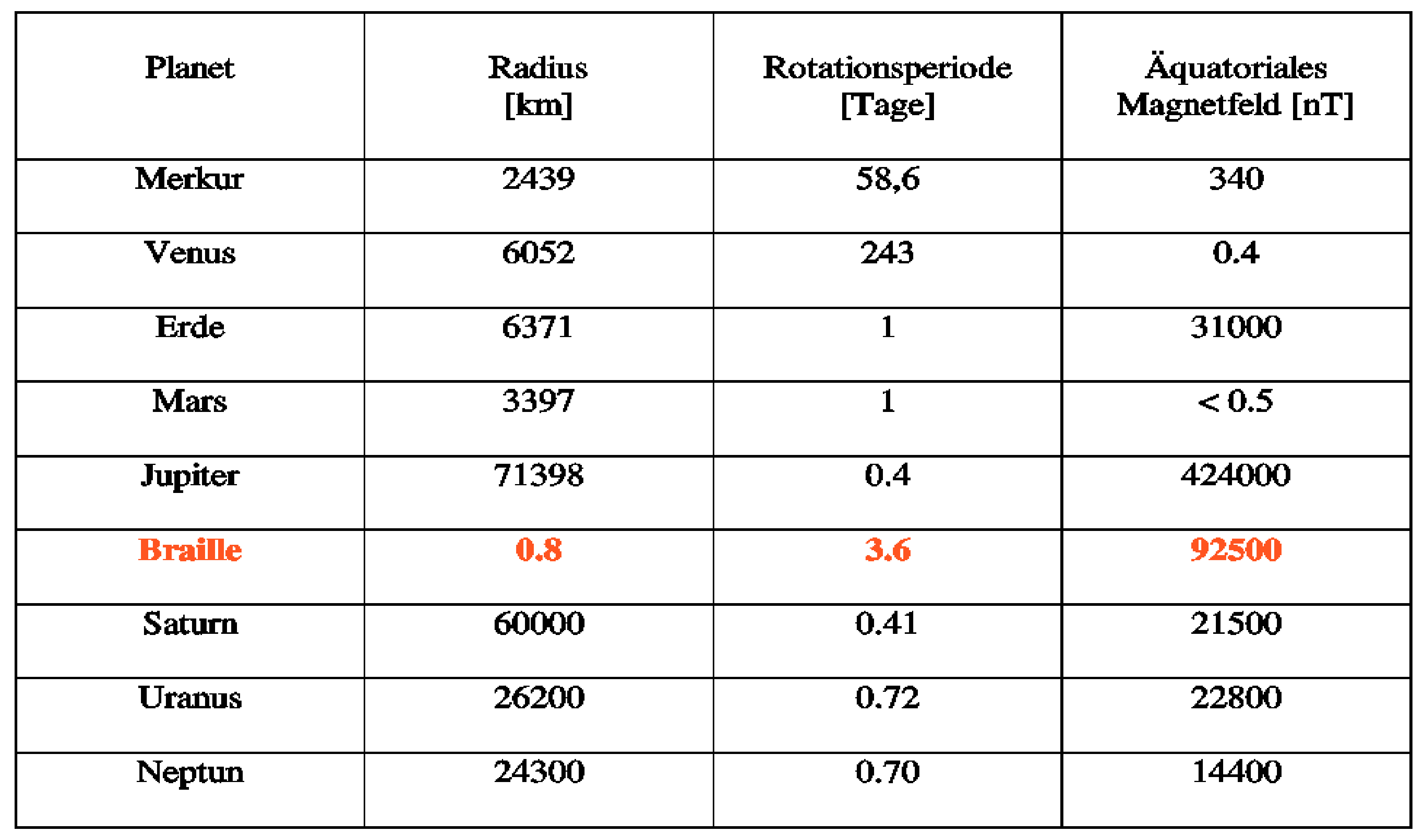


Magnetospheric Control Parameters

- Solar wind dynamic pressure
- B_Z component of the interplanetary magnetic field
- Planatery magnetic field
- Planetary rotation
- Plasma sources and mass density
- Ionospheric conductivity
- Magnetospheric scale

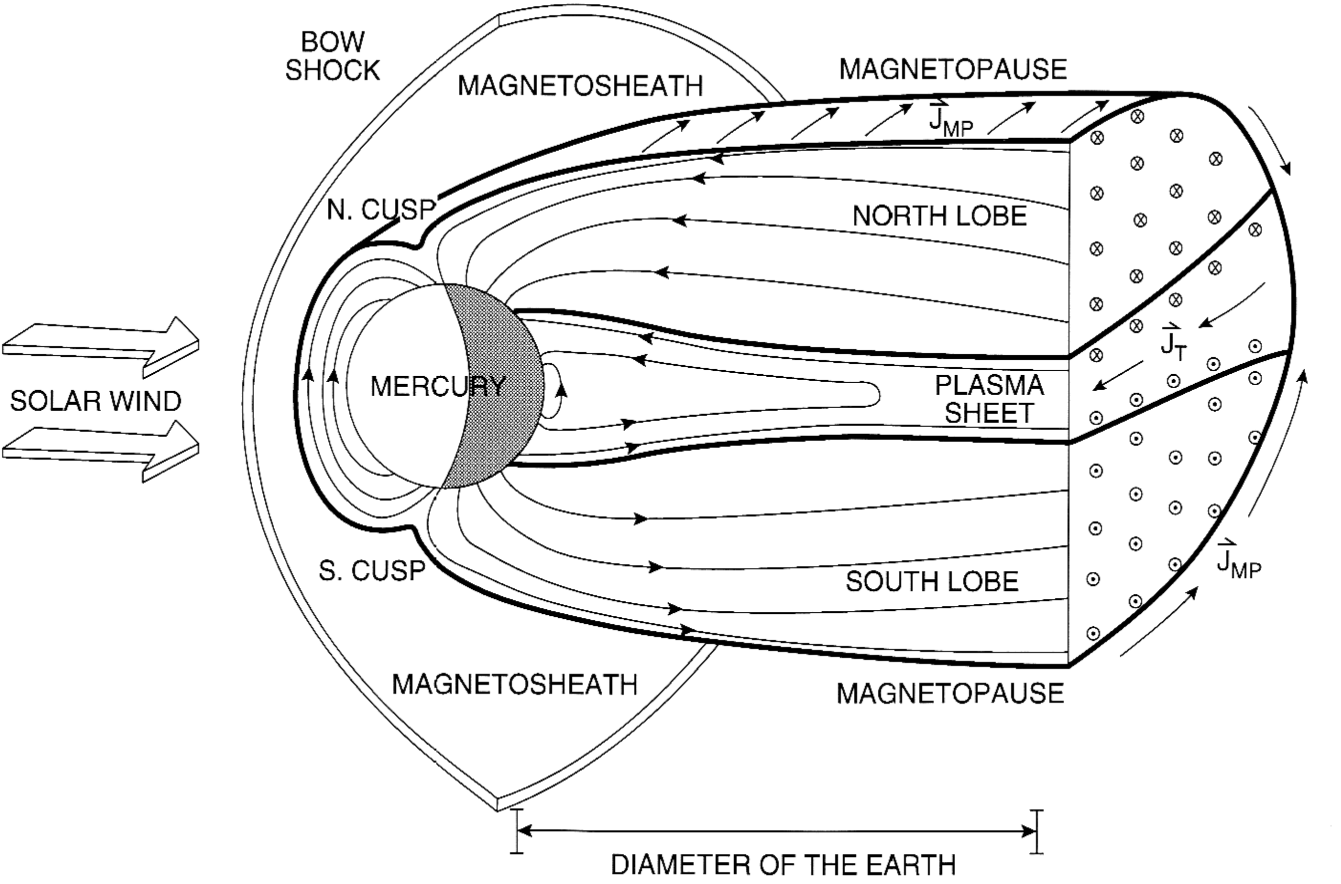
Thus, each magnetosphere is a point in a multi-dimensional control space

Magnetospheric Control Parameters: Realizations



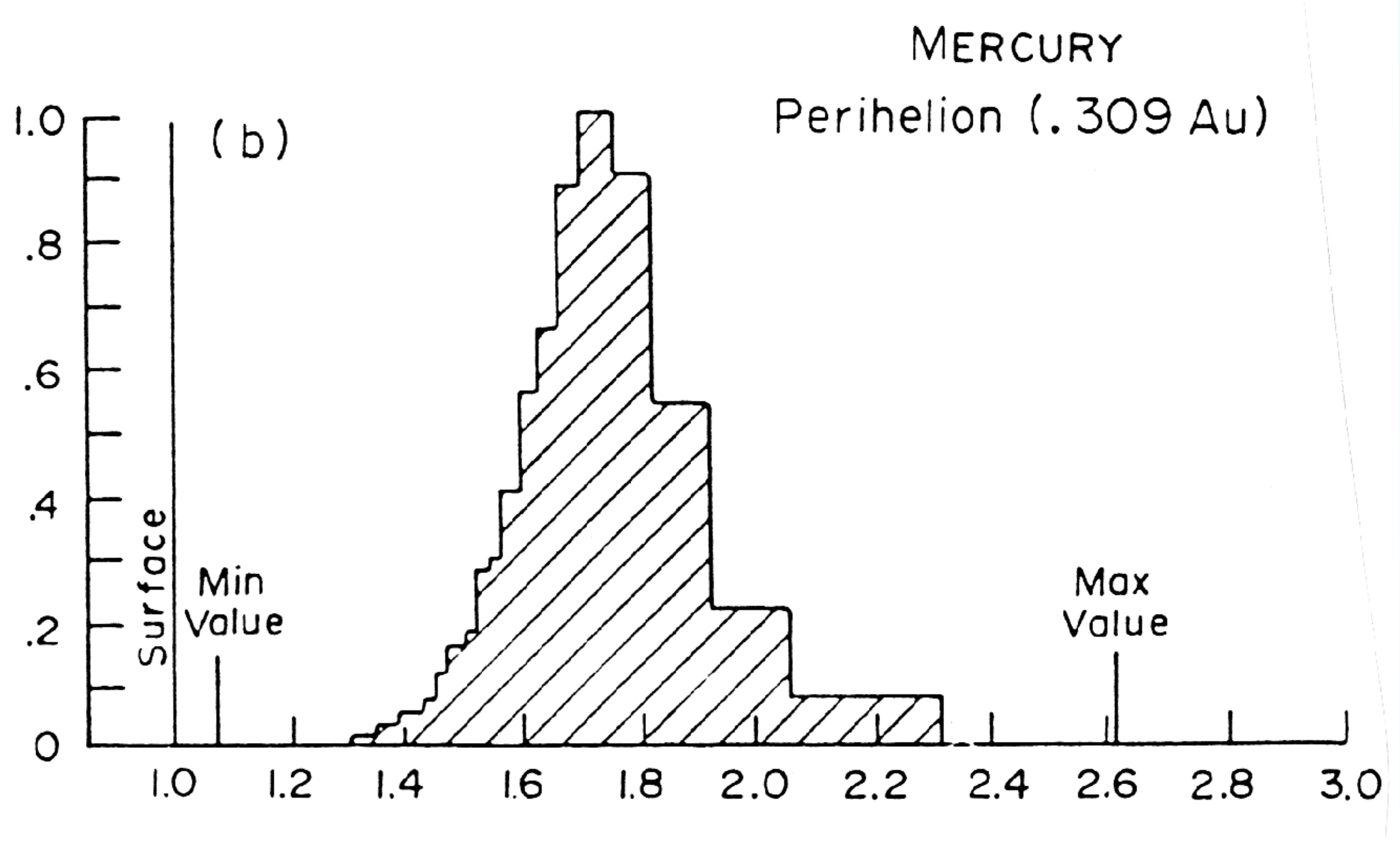
Planet	Radius [km]	Rotationsperiode [Tage]	Äquatoriales Magnetfeld [nT]
Merkur	2439	58,6	340
Venus	6052	243	0.4
Erde	6371	1	31000
Mars	3397	1	< 0.5
Jupiter	71398	0.4	424000
Braille	**0.8**	**3.6**	**92500**
Saturn	60000	0.41	21500
Uranus	26200	0.72	22800
Neptun	24300	0.70	14400

The Magnetosphere of Mercury: Facts



- **No atmosphere**
- **No ionosphere**
- **Exosphere**
- **No plasmasphere**
- **Weak magnetic field**
- **Multi-ion plasma**
- **Small magnetosphere**

Mercury - An Externally Driven Magnetosphere ?



Magnetospheric Plasma Sources

Mercury: solar wind and sputtering of surface material, e.g. sodium

Earth: solar wind and ionosphere

Jupiter: solar wind and volcanic activity of the moon Io

Saturn: solar wind, atmosphere of moon Titan, sputtering at surfaces of icy moons and rings

Uranus: polar ionosphere, minor solar wind contribution

Neptun: ionosphere, moon Triton

Plasma Distribution

Along filed lines balance between pressure and gravitational/centrifugal forces

with

$$\frac{dp_{//}}{ds} \approx \rho \frac{d\Phi}{ds}$$

$$\Phi = \Phi_G + \Phi_C = -\frac{\gamma M_p}{r} + \frac{1}{2}\Omega^2 r^2 \sin^2 \vartheta$$

Close to planet: Φ_G **dominates, pressure minimizes at field line vertex**

Far from planet: Φ_C**dominates, pressure maximizes at field line vertex**

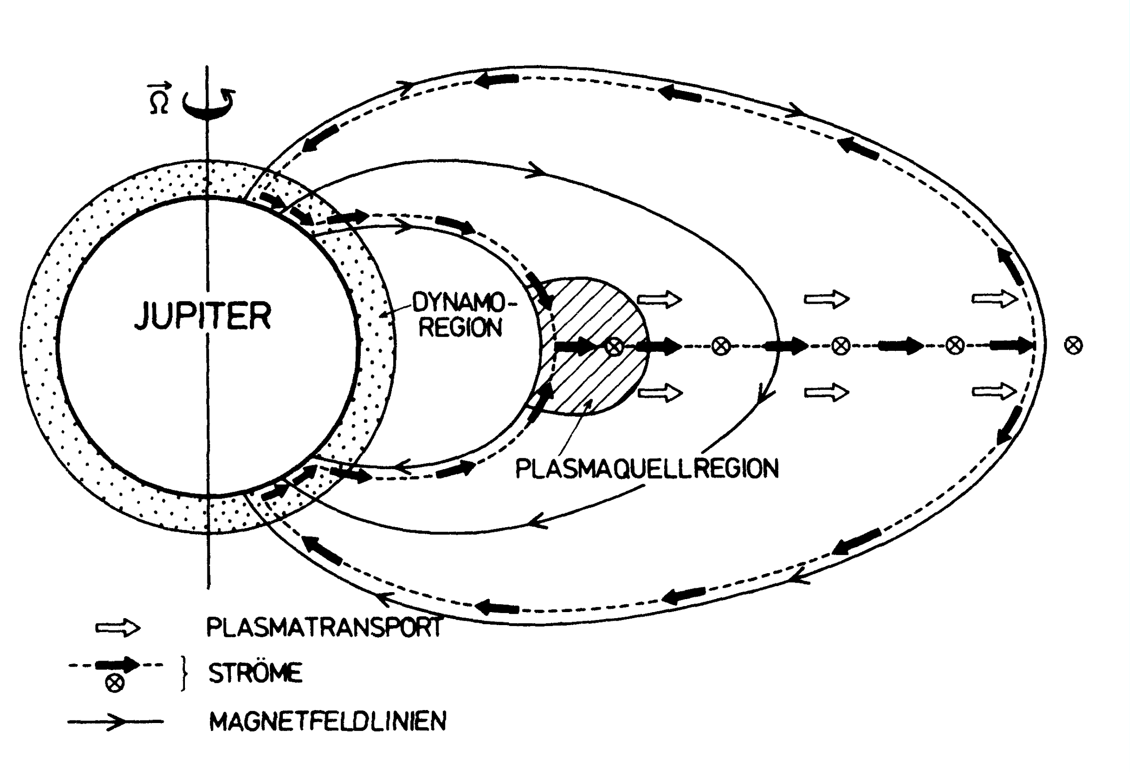
Transition at

$$L_T = \left(\frac{2}{3} \frac{\gamma M_p}{\Omega^2 R_P^3} \right)^{1/3}$$

$L_{Mercury}$ = 87.6; L_{Earth} = 5.7; $L_{Jupiter}$ = 1.9; L_{Uranus} = 1.6

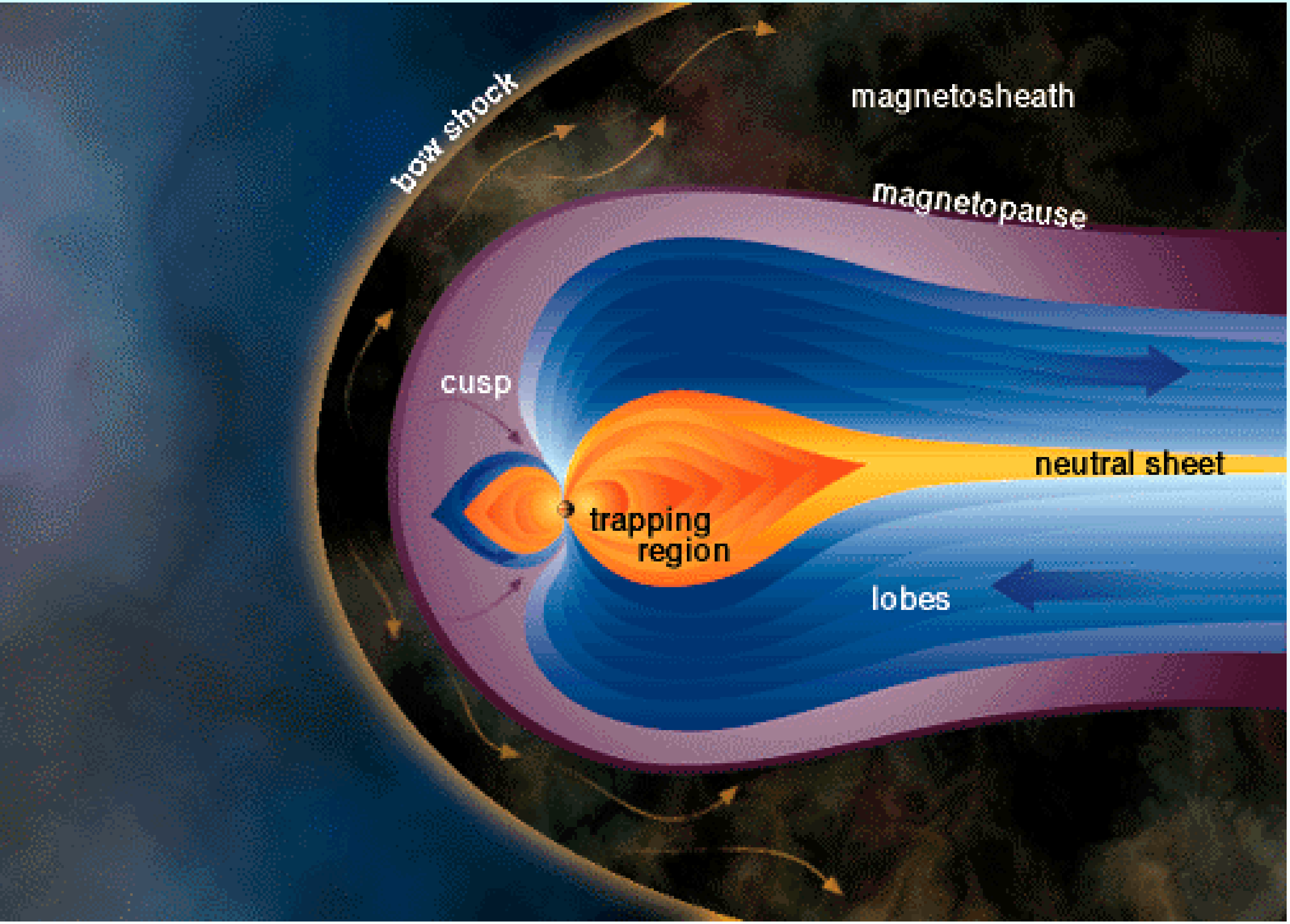
Radial Transport and Magnetospheric Currents

Perpendicular to $\vec{B}$ pressure gradients and centrifugal forces are balanced by azimuthal $\vec{j} \times \vec{B}$ forces:



F. M. Neubauer, in: K.H. Glassmeier, M. Scholer, Plasmaphysik im Sonnensystem, Mannhein, 1991

The Jovian Magnetosphere



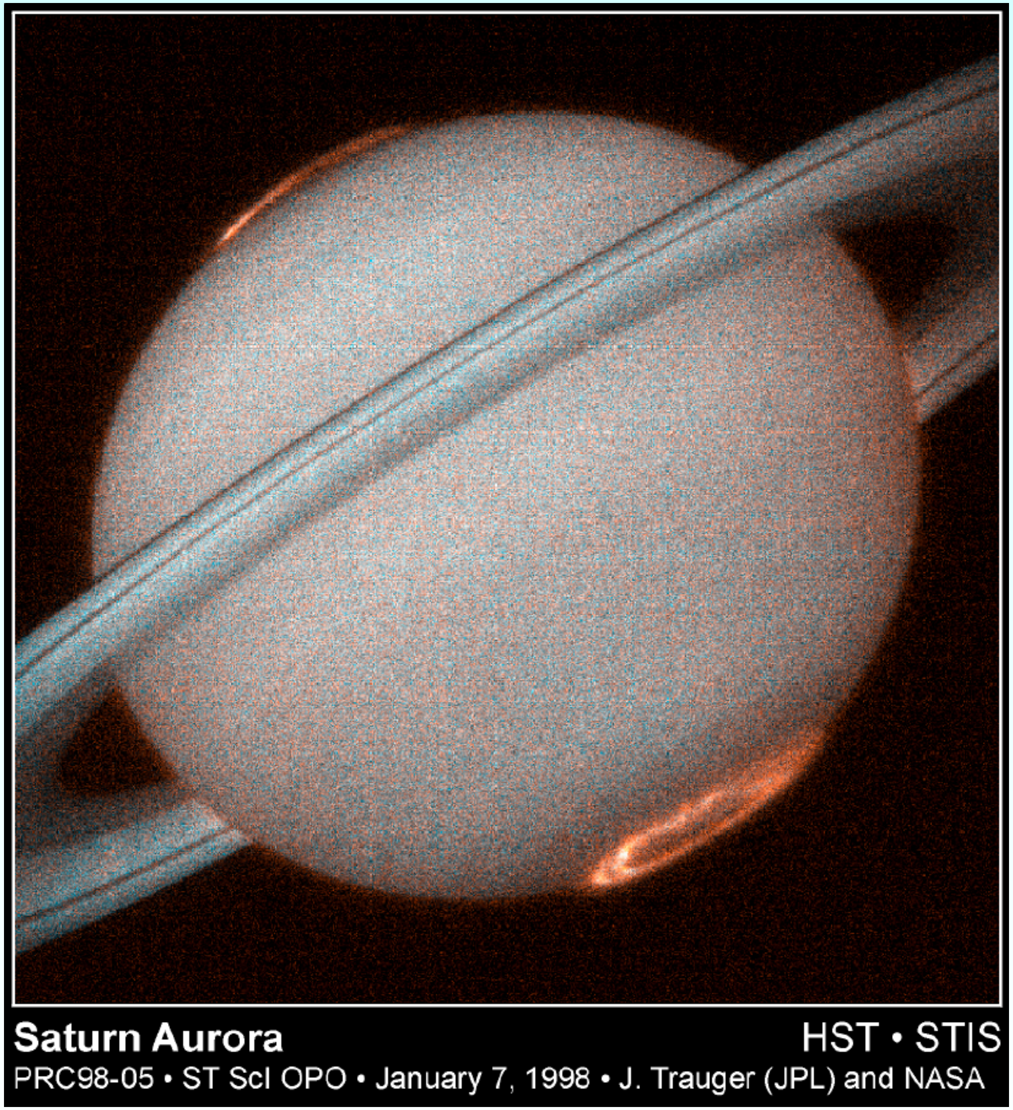
Reference:

Dessler, A. J. (Ed.),

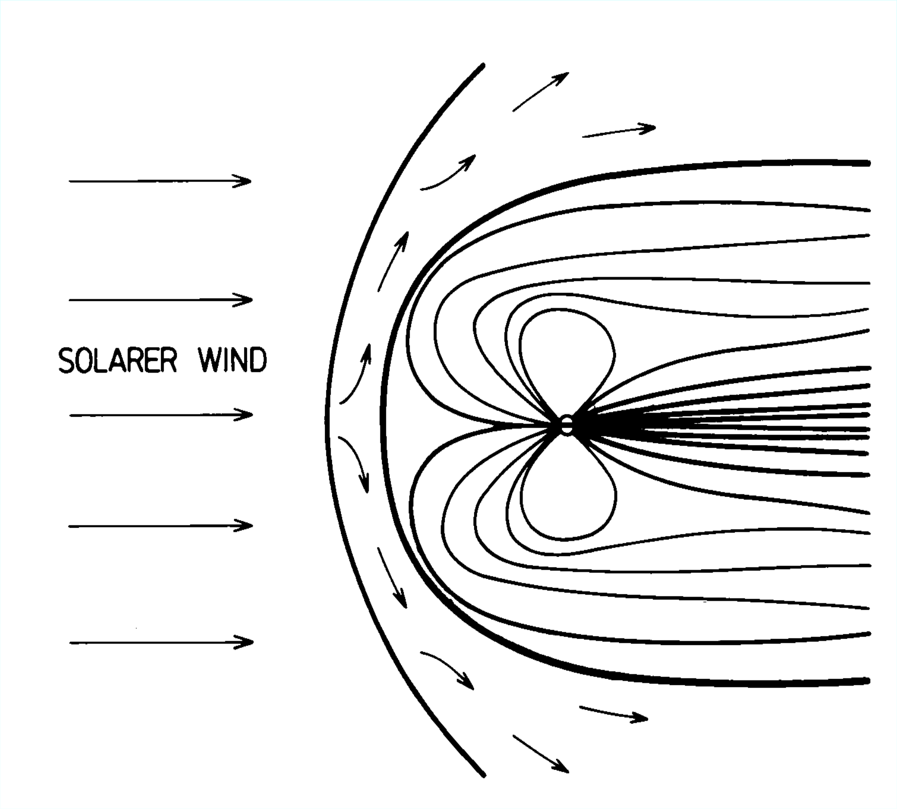
Physics of the Jovian Magnetosphere,

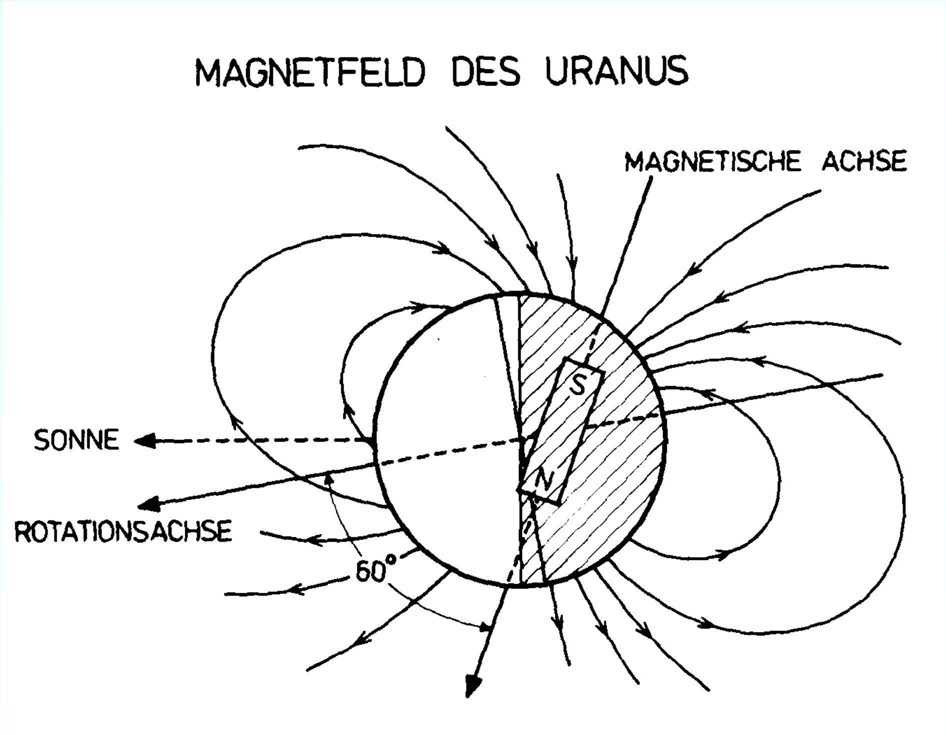
Cambridge, 1983.

Saturn and its Aurora



The Magnetosphere of Uranus

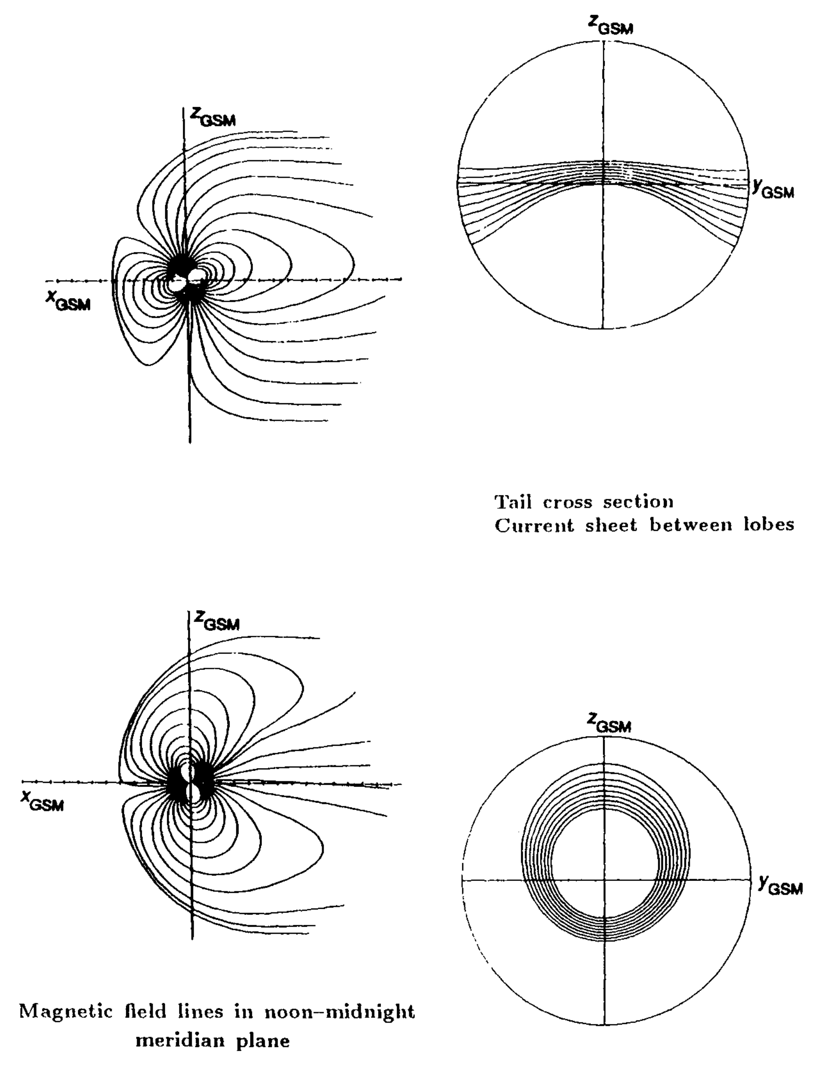




Pre flyby in January 1986

Post flyby

The Magnetosphere of Neptun



Tail cross section
Current sheet between lobes

Magnetic field lines in noon–midnight meridian plane

Neptun exhibits Earth´s-like and pole-on type magnetospheric configuration

Magnetospheres such as.....

- planetary magnetospheres

- the heliosphere

- galactic interaction regions

- neutron star magnetospheres

are cellular structures in the universe

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Suggested Reading

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