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# *The Formation of the Earth's Magnetosphere:*
## *Basic physical principles and steady-state configuration*

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# The Formation of the Earth's Magnetosphere:

## Basic physical principles and steady-state configuration

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*May 2006*

*The support provided by COST, COST Action 724 and the Abdus Salam ICTP is gratefully acknowledged*

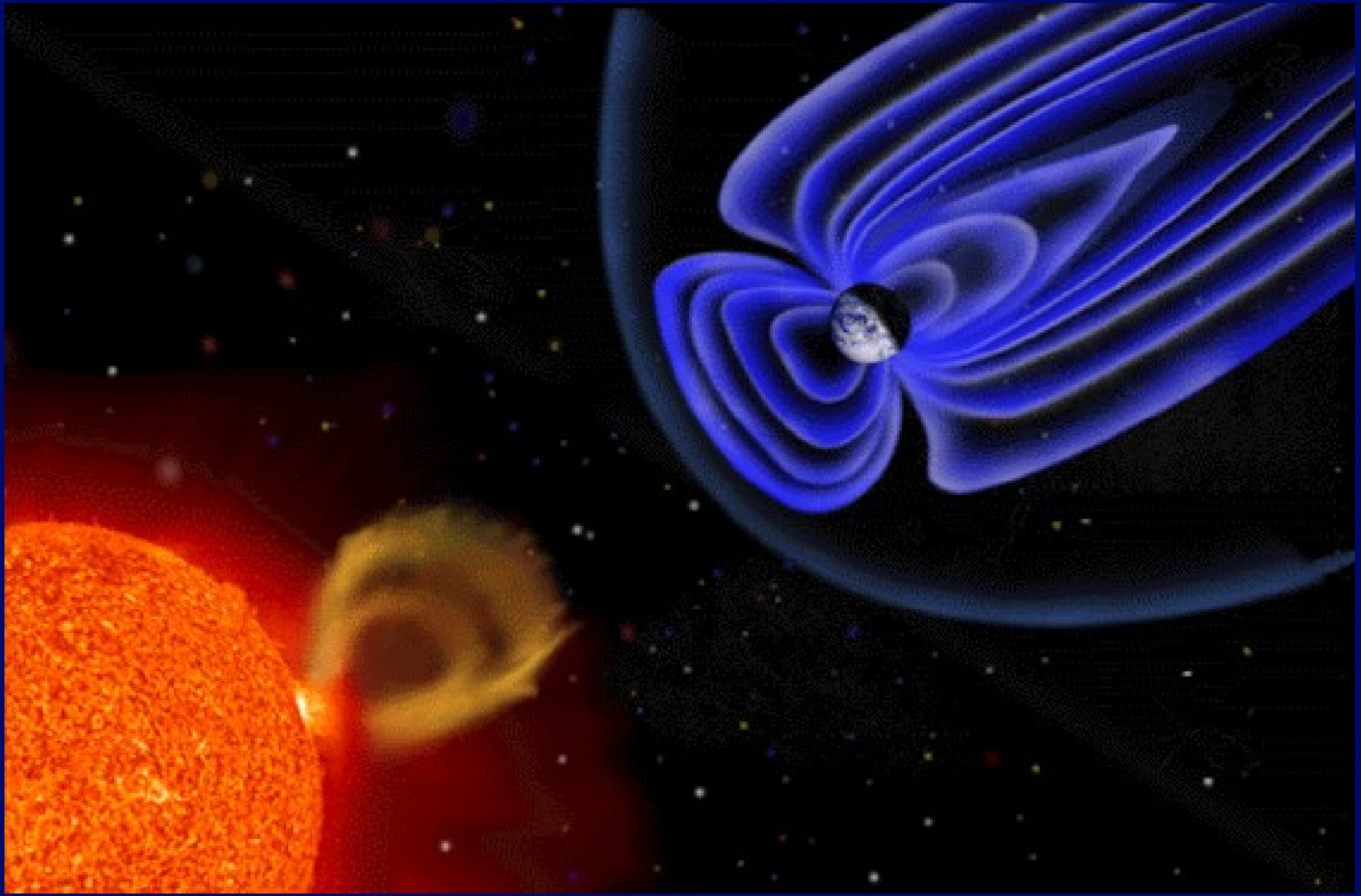


*Figure by Steele Hill (from D. Stern "The exploration of the Earth's magnetosphere")*

The formation of a planetary magnetosphere requires:

- a quasi-permanent magnetic field of the planet
- an ionized plasma stream which interacts with the planetary magnetic field and thereby shapes its "magnetosphere"

## What is a plasma ?

Matter which is ionized to such an extent that the electromagnetically dominated collective behavior of the electrons and ions governs the dynamics of the medium. The solar wind, the ionized upper atmosphere and the fluid outer core of the Earth are examples of matter in the plasma state.

The troposphere contains ions (produced by cosmic rays, UV radiation, candle light, ... ) but the charged particle density is too small compared to the neutral air to enable collective behavior. The relatively low charged particle density allows only single particle behavior dominated by mechanical forces (gravity, collisions).

- Planet Earth has a quasi-static magnetic field of internal origin (30 - 60 μT at the Earth's surface)

- Mercury has a (weak) magnetic field

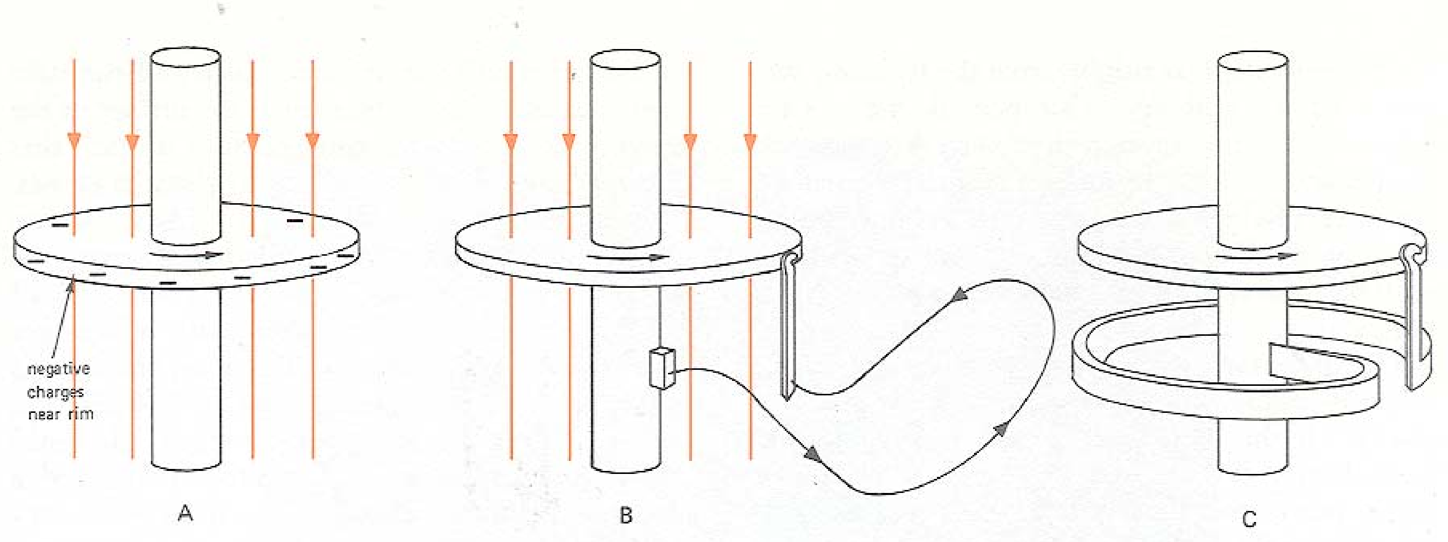
- Mars and Venus have at present time no measurable magnetic field (Mars has some remnants), consequently they do not possess a magnetosphere

- The giant gas planets and the outer planets are known to have a magnetic field

The magnetic field measured at the surface of the Earth is too strong to be generated solely by (crustal) permanent magnetization.

It must have a different source

## The geodynamo




4. 7 (a) Disc rotating in magnetic field, no current flows.

(b) External circuit enables current to flow.

(c) Current provides a field and gives a self-exciting dynamo.

electrically conducting disc:
$\mathbf{v}\times\mathbf{B}$ force drives positively charged particles toward the center

*Figure from E. Bullard, "The Earth's magnetic field and its origin"*

# Cowling theorem (1933):

An axisymmetric magnetic field generated by currents at finite distance cannot be maintained by a plasma velocity field of finite magnitude

The way out: Three-dimensional "mean field" electrodynamics

$$\mathbf{v} = \overline{\mathbf{v}} + \mathbf{v}'$$

$$\mathbf{B} = \overline{\mathbf{B}} + \mathbf{B}'$$

$$\mathbf{j} = \overline{\mathbf{j}} + \mathbf{j}' = \sigma \left\{ \overline{\mathbf{E}} + \mathbf{E}' + ( \overline{\mathbf{v}} + \mathbf{v}' ) \times ( \overline{\mathbf{B}} + \mathbf{B}' ) \right\}$$

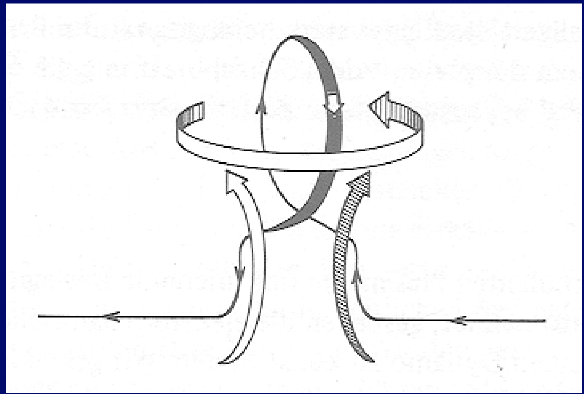
$$\overline{\mathbf{j}} = \sigma \left\{ \overline{\mathbf{E}} + \overline{\mathbf{v}} \times \overline{\mathbf{B}} + ( \overline{\mathbf{v}' \times \mathbf{B}'} ) \right\}$$

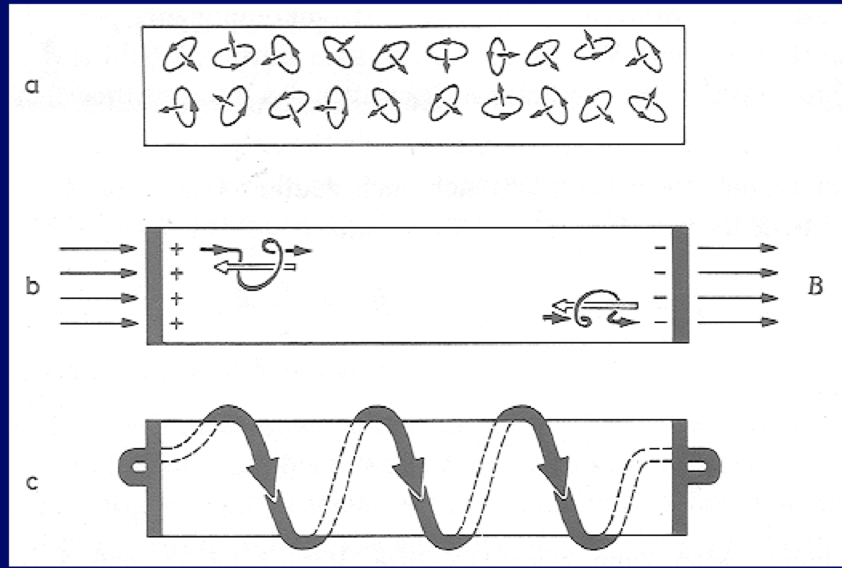
**v'** and **B'** assumed to be correlated (and a few further assumptions) lead to

$$( \overline{\mathbf{v}' \times \mathbf{B}'} ) = \alpha \, \overline{\mathbf{B}} - \beta \, \nabla \times \overline{\mathbf{B}}$$

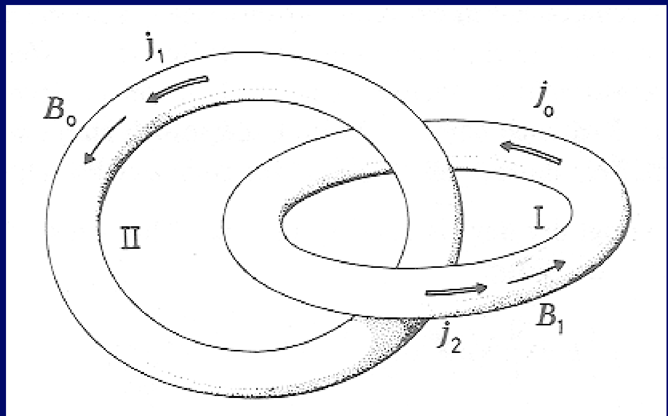
If turbulence has a preference rotation then

$$\alpha \neq \mathbf{0} \quad \Rightarrow \quad \alpha\textbf{-effect}$$






perfectly conducting plasma:
magnetic field is "frozen-in"




*Figures from Kippenhahn/Moellenhoff, "Elementary plasma physics" (1975)*

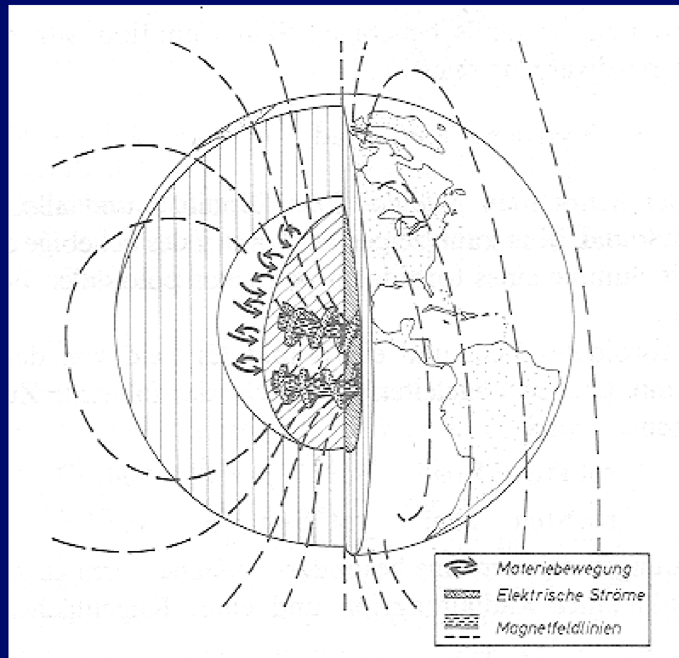



*Figure from Kertz after Elsasser (1958)*

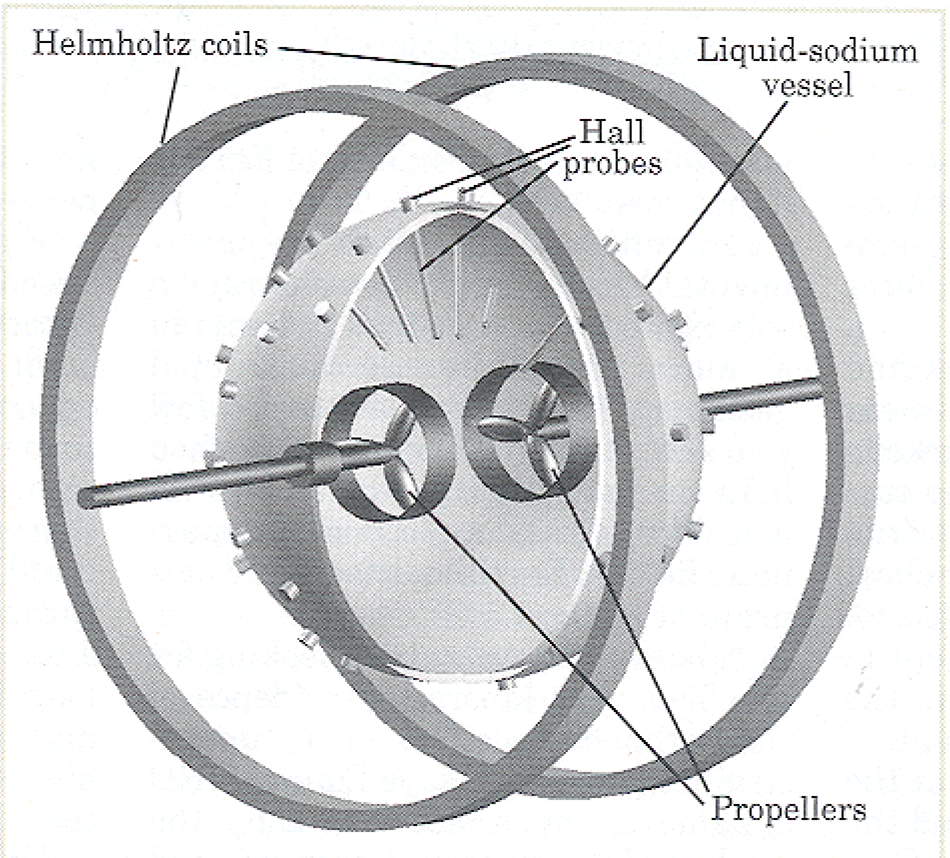



**Figure 1. In the Madison Dynamo Experiment**, liquid sodium filling a 1-meter-diameter spherical vessel is agitated by two counterrotating propellers. Helmholtz coils, coaxial with the propeller shafts, impose an almost uniform axial magnetic field on the vessel. Arrays of Hall probes measure the resultant magnetic field inside the liquid and on the vessel's surface. (Adapted from ref. 2.)

Laboratory dynamo experiment

*Figure from "Physics Today", 2006*

# The solar wind

Flow of mainly protons and electrons

+ a few percent fully ionized Helium

+ a few heavier ions

(almost always supersonic and super-Alfvénic)

dragging along the interplanetary magnetic field

## Solar wind speed derived from isothermal coronal expansion models

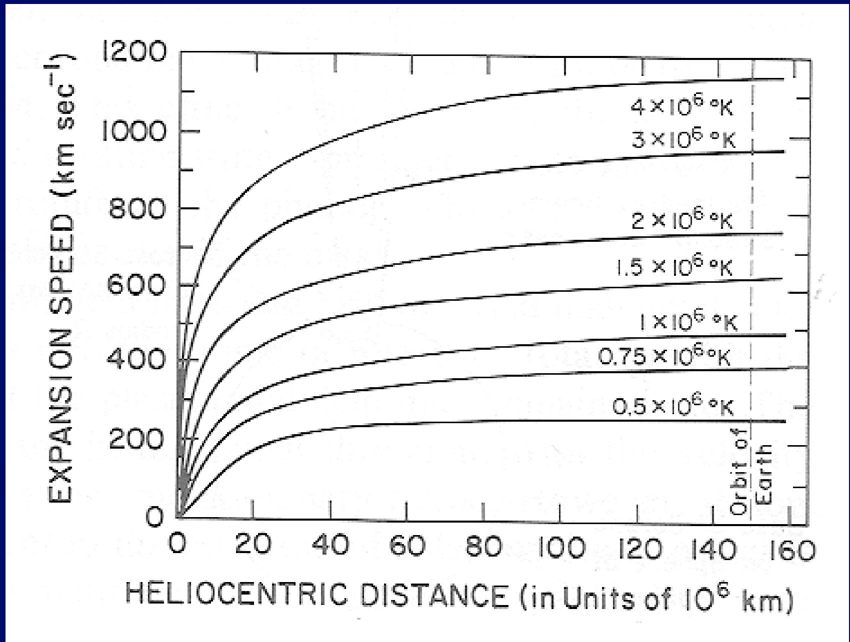



*Figure after Parker (1958)*

## Solar wind speed inferred from radio wave scintillation observations

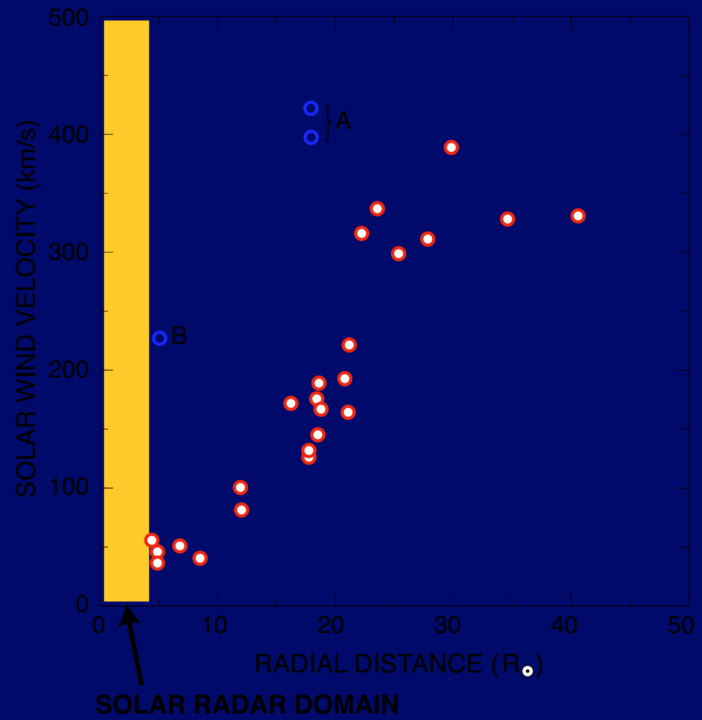



FIGURE 15: The solar wind velocity as a function of radial distance from the Sun obtained from interplanetary scintillation (IPS) measurements made at the Kashima 34-m radio telescope in Japan in 1989. The points indicated by A and B are thought to be related to coronal mass ejection (CME) events. A powerful solar radar would probably allow measurements of the early stages of solar wind acceleration and CME development at low solar altitudes. After *Tokomaru et al.* [108]; see also [109] and [120].

*From "Radio studies of solar-terrestrial relationships"*
*The LOIS Science Team (2002)*

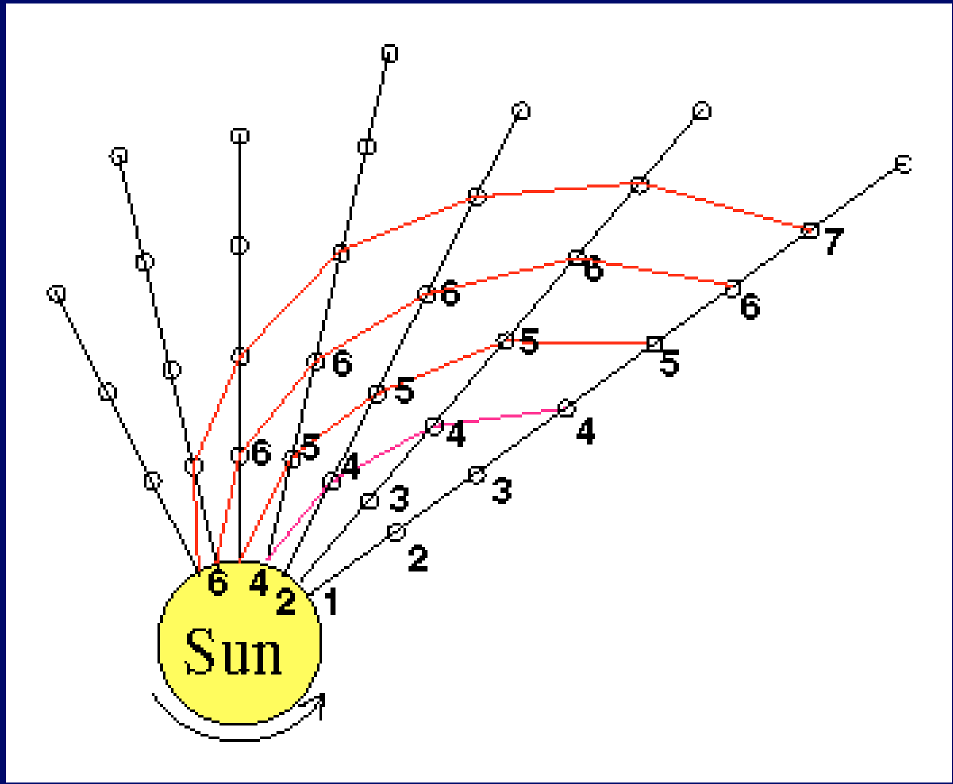


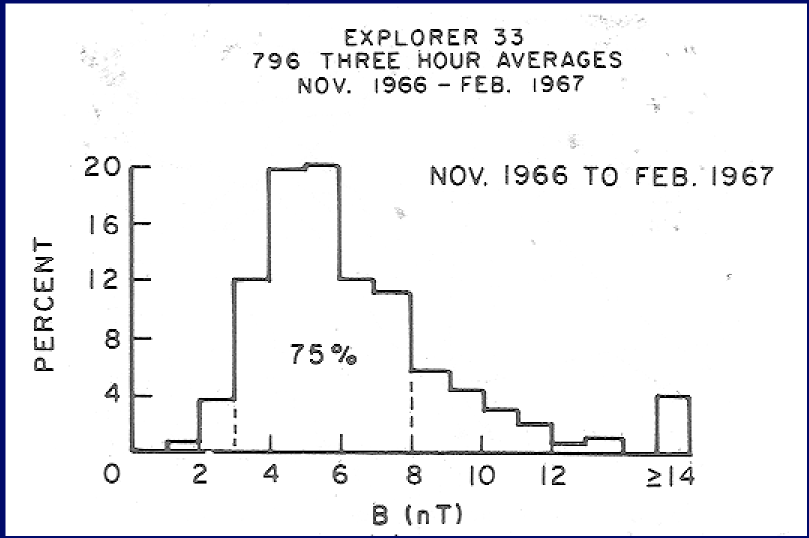

*Figure from D. Stern "The exploration of the Earth's Magnetosphere"*

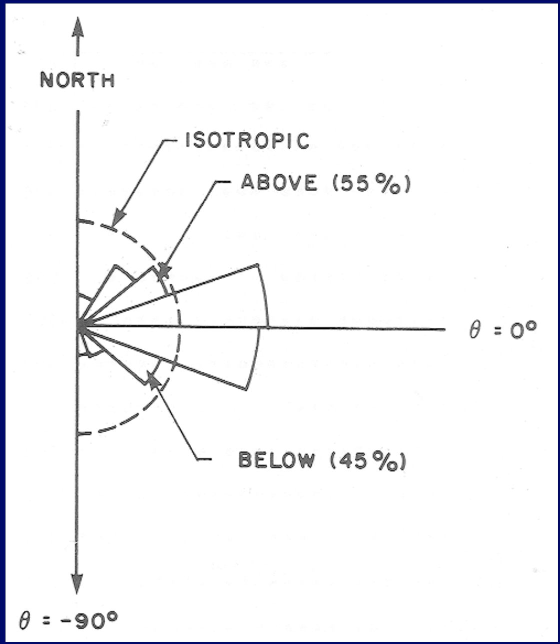
Solar wind plasma expands radially outward

solar magnetic field is carried along ("frozen-in")

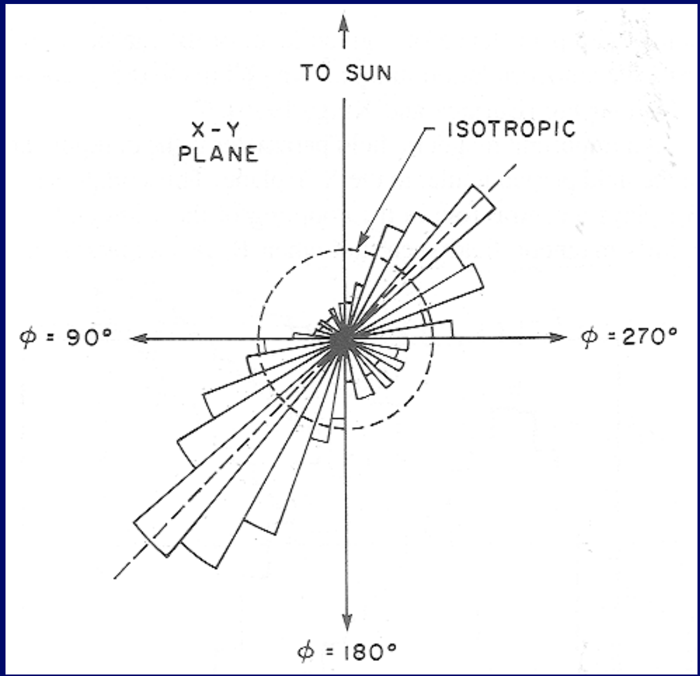
$\Rightarrow$ magnetic field lines form Archimedian spiral (Parker spiral)

at 1 AU (Earth orbit) $\approx 45°$




Amplitude and orientation of the interplanetary magnetic field near 1 AU




*Figures after Hirshberg, 1969*

The current sheet which generates the sector structure observed near Earth

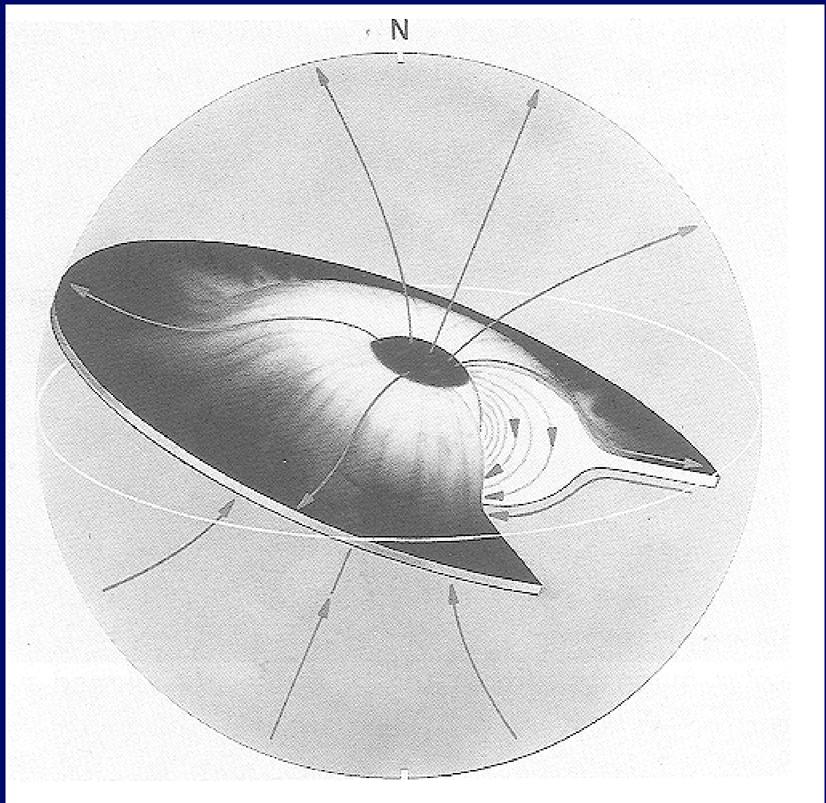



Figure from Hundhausen (1977)

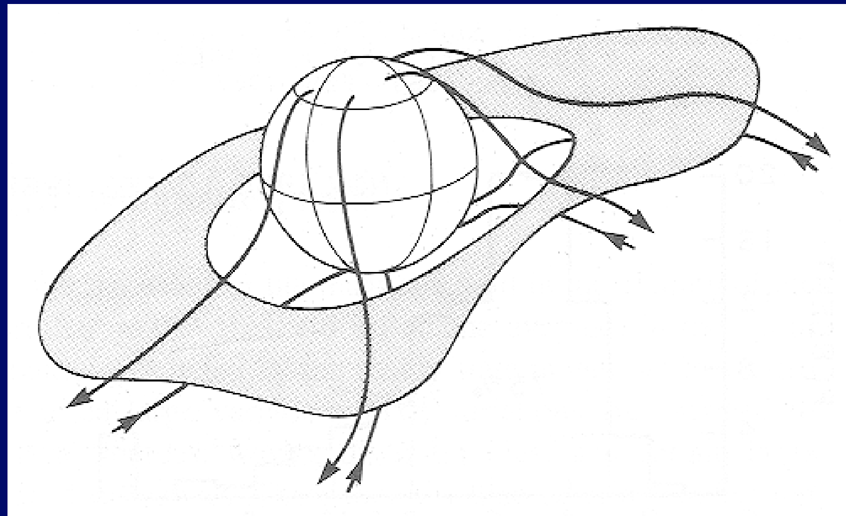


Figure from Smith (1979)

# The solar wind

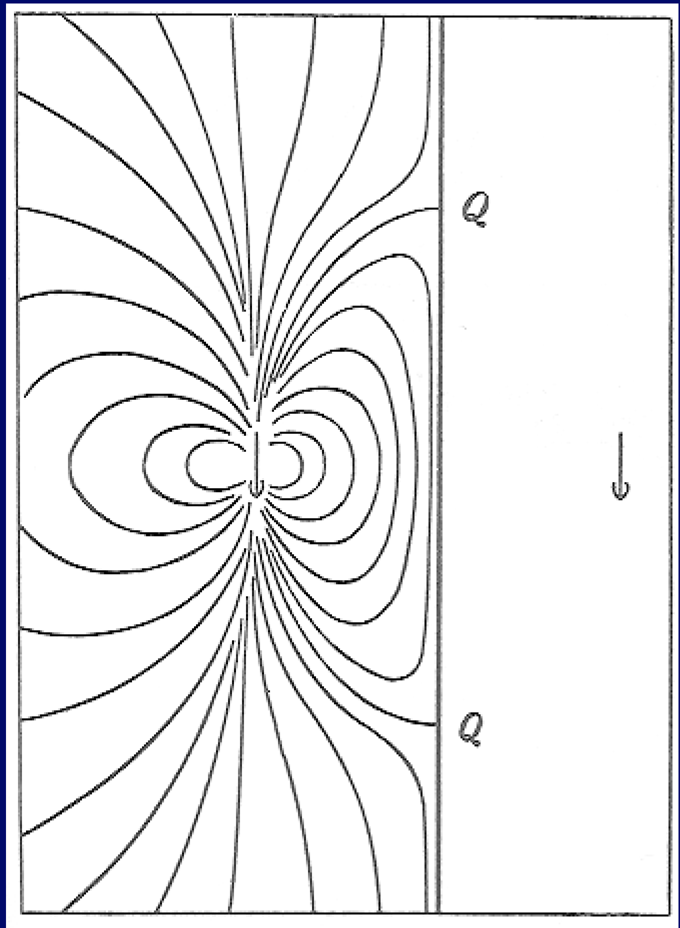
Typical numbers at 1 AU (slow solar wind)

| | |
|---|---|
| plasma density | 5-10 ions / $cm^3$ |
| bulk speed | 350-450 km/s |
| Mach number | 6 |
| $p^+$ and $e^-$ temperatures | $1\text{-}2\times10^5$ K |
| magnetic induction | 5-10 nT |

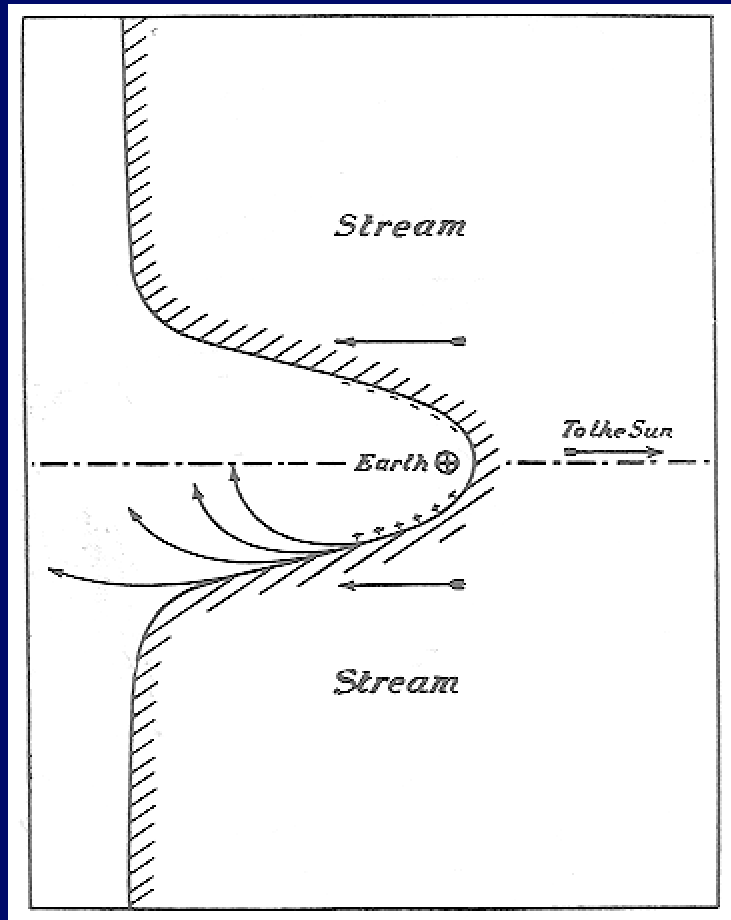
# Interaction of the solar wind with the Earth's dipole field

(1) The Chapman-Ferraro magnetopause
(a closed magnetosphere)

Compression of a dipole field being approached by a rigid superconducting slab




Cavity formation and charge separation through the interaction between a highly conducting medium and a dipole field




*Figures from Chapman and Bartels, "Geomagnetism", 1940*

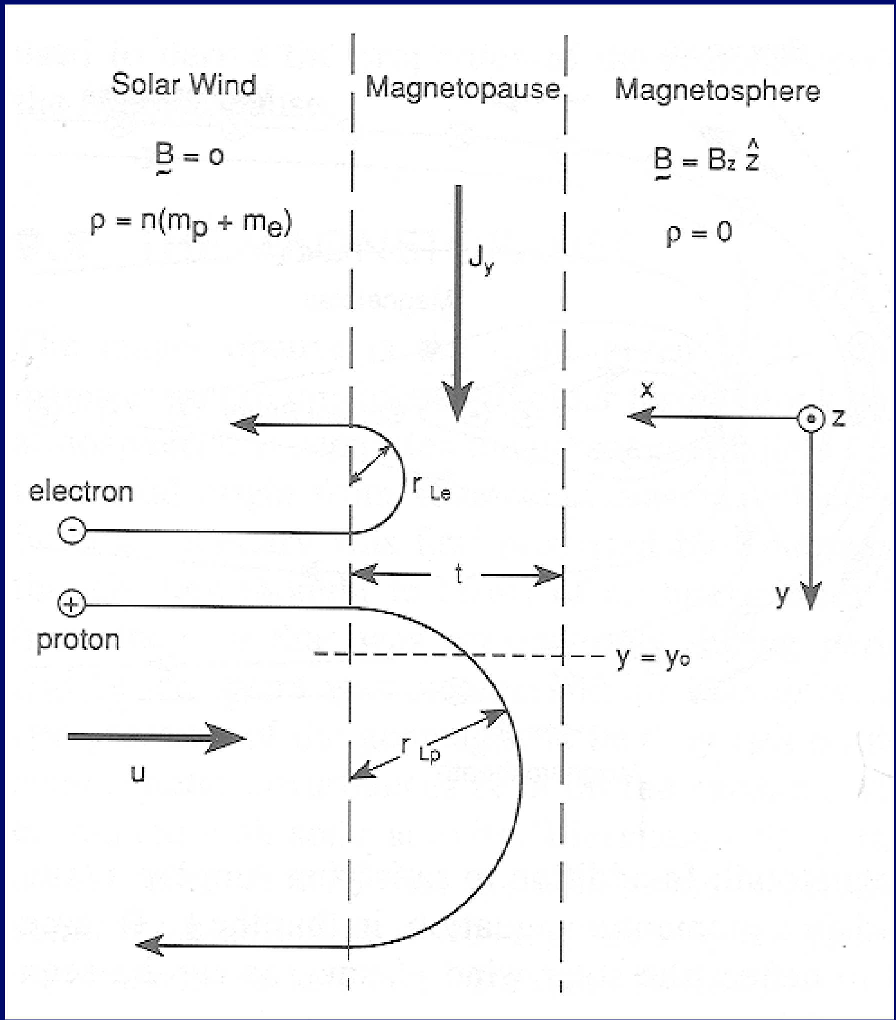



*Figure from Hughes, "Magnetopause, magnetotail, reconnection"*
*Chapter 9 in "Introduction to Space Physics"*

Larmour radius of protons and electrons

$$r_{Lp,e} = v\, m_{p,e} / (e\, B_z)$$

Protons (electrons) crossing $y=y_0$ per time unit are all those which arrive between $y_0$ and $y_0$-2 $r_{Lp}$ ($y_0$+2 $r_{Le}$)

$$N_{p,e} = 2\, r_{Lp,e}\, n\, v$$

Current crossing $y=y_0$ per time unit

$$J = (N_p+N_e)\, e = 2\, (r_{Lp}+r_{Le})\, n\, v\, e$$

$$= 2\, \{v\, (m_p+m_e) / (e\, B_z)\}\, n\, v\, e$$

For full repulsion the current cancels the magnetic field outside the magnetopause

$$J = B_z / \mu_0$$

$$\rho_{SW} = n\, (m_p+m_e)$$

Combing all yields the balance between solar wind dynamic pressure and magnetospheric magnetic pressure

$$\rho_{SW}\, v_{SW}^2 = B_{MS}^2 / (2\, \mu_0)$$

| | |
|---|---|
| solar wind dynamic pressure | $\rho\ v^2$ |
| solar wind magnetic and thermal pressure | $p$ |
| momentum conservation (integration over stream tube) | $(\rho\ v^2 + p)\ S = \text{const}$ |
| far away from magnetopause | $p_\propto \ll \rho_\propto v_\propto{}^2$ |
| at magnetopause nose (stagnation point) | $\rho_{stag} v_{stag}{}^2 \ll p_{stag}$ |
| Mach number (standard solar wind) | $M \approx 6$ |
| after some theory | $K = p_{stag}/(\rho_\propto v_\propto{}^2)$ |
| | $= \{½\ (\gamma+1)\}^{(\gamma+1)/(\gamma-1)}\ \{(\gamma - (\gamma-1)/(2M^2)\}^{\gamma-1}$ |
| | $\approx$ 0.9 (typical solar wind conditions) |
| inside magnetopause | $p_{plasma} \ll p_{magnetic}$ |
| pressure balance at magnetopause | $K\ \rho_\propto v_\propto{}^2 = (\alpha\ B_0)^2 / (2\ \mu_0\ L_{mp}{}^6)$ |
| compression factor (accounts for plasma) | $\alpha \approx 2\text{-}3$ |

# Interaction of the solar wind with the Earth's dipole field

(1) The Chapman-Ferraro magnetopause
(a closed magnetosphere)

(2) The magnetospheric cavity

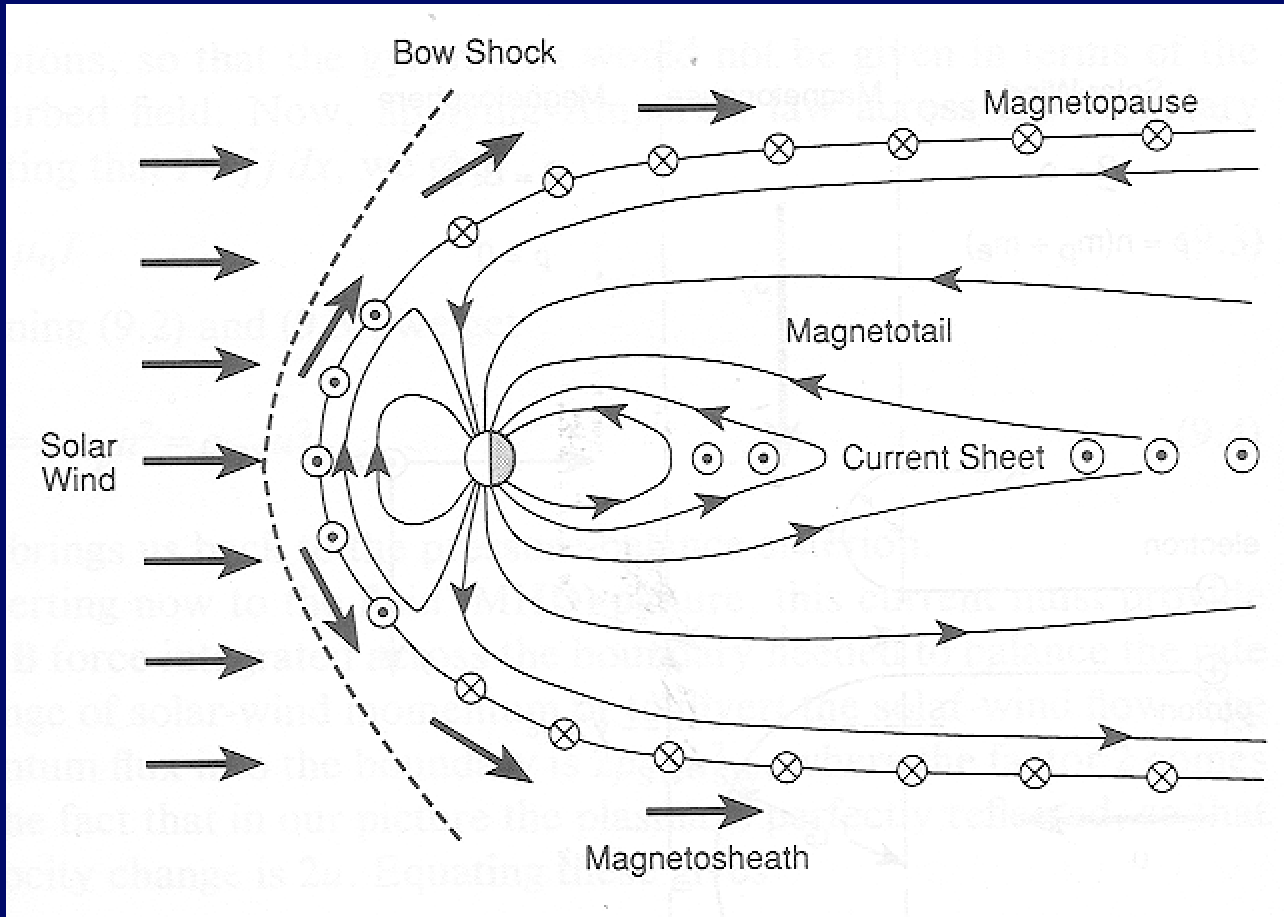
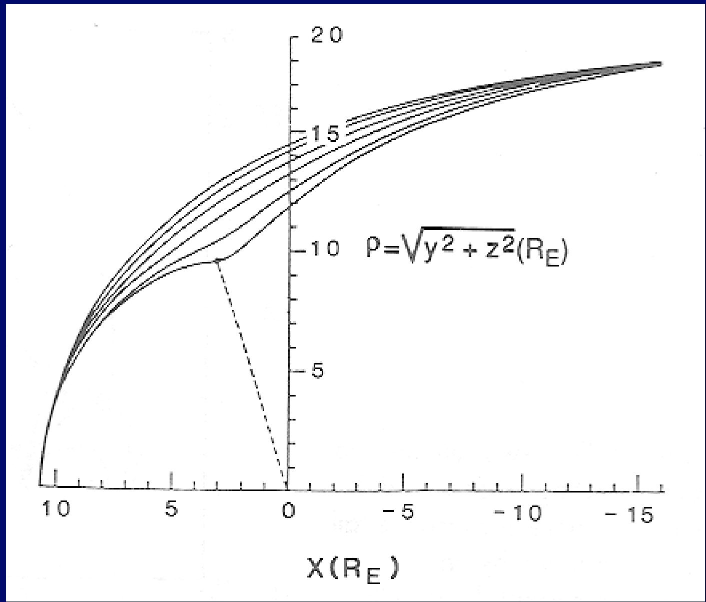


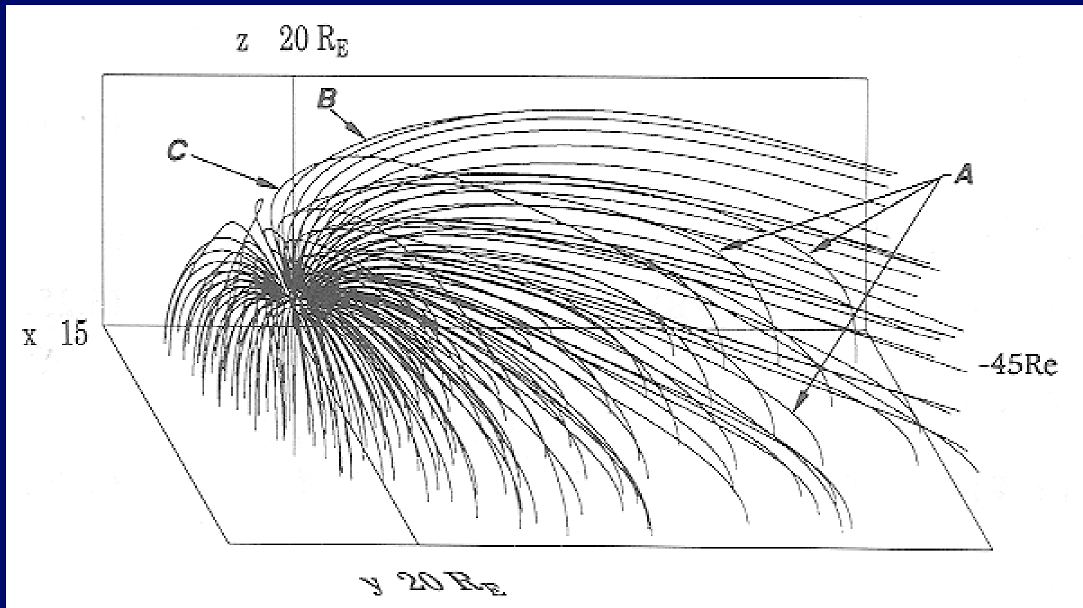

*Figure from Hughes, "Magnetopause, magnetotail, reconnection"*
*Chapter 9 in "Introduction to Space Physics"*

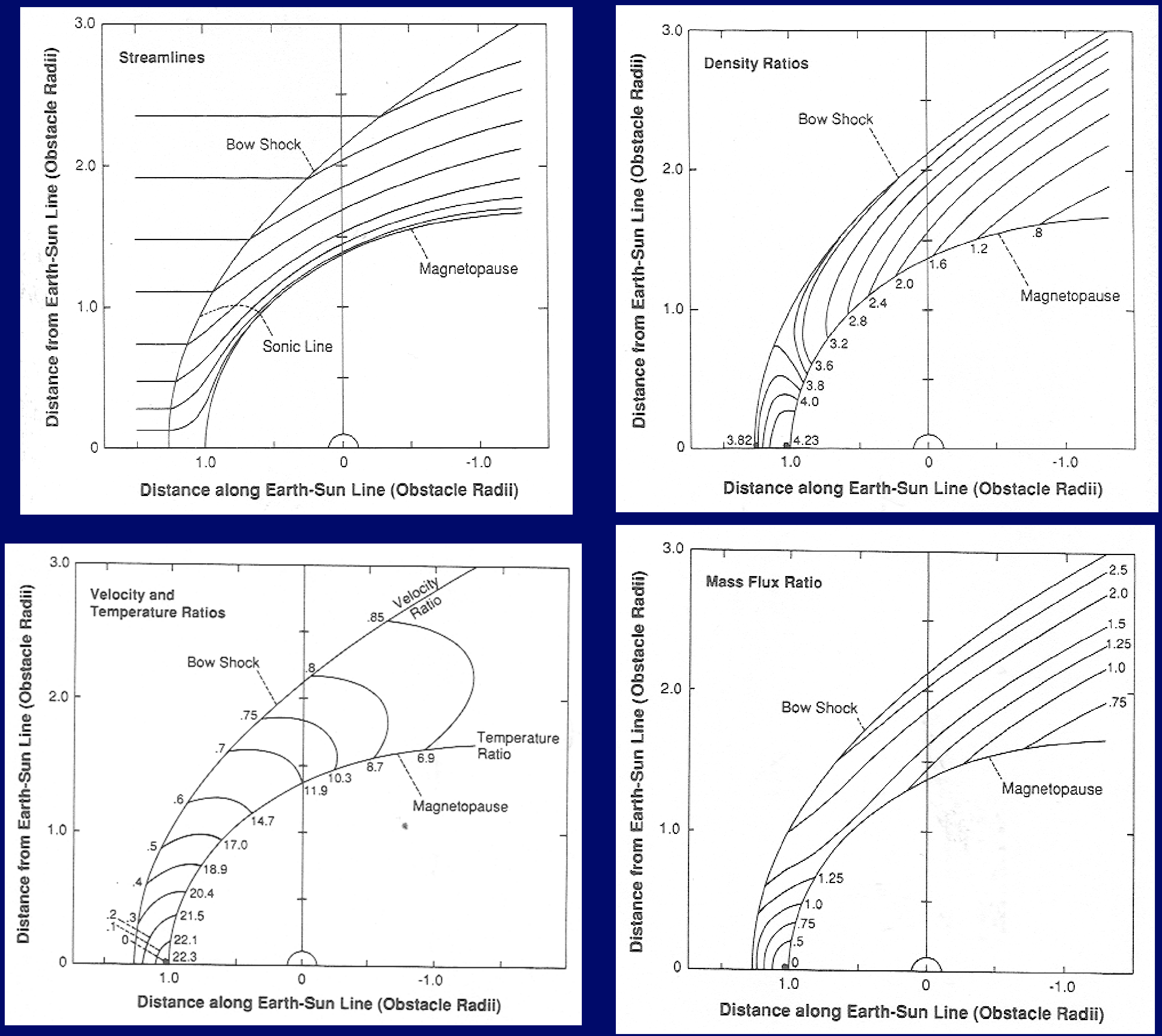



## Numerical models of the magnetosphere

*Top figure after Mead and Beard (1964)*

*Bottom figure from Ogino et al. (1992)*

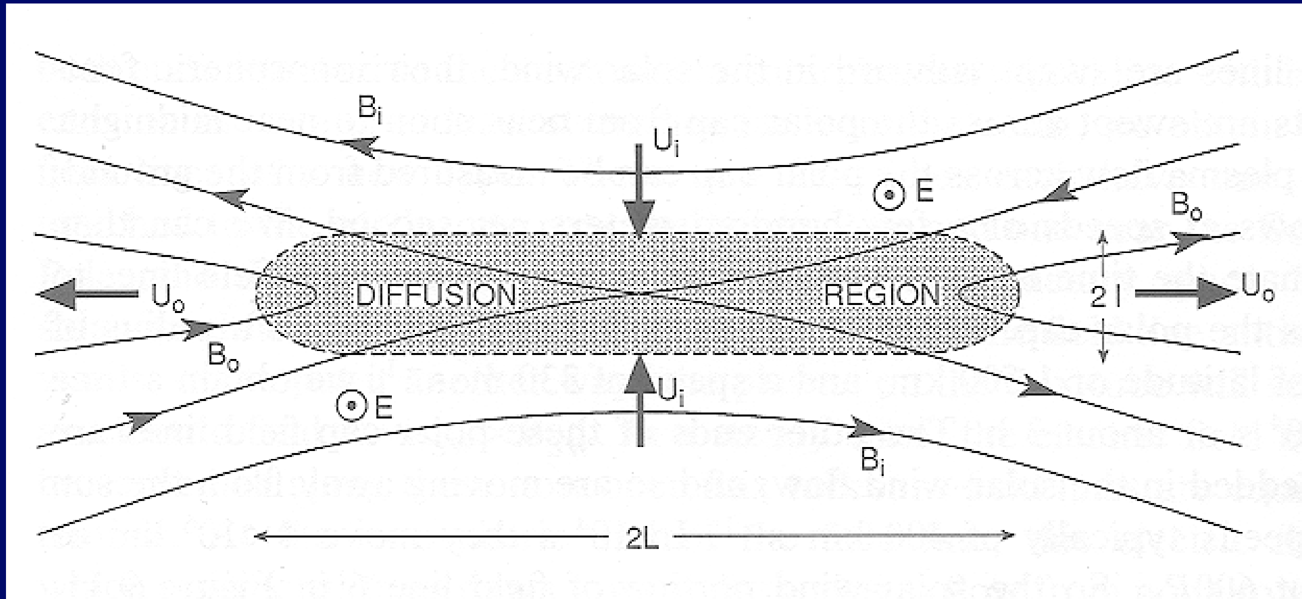





*Figures after Spreiter et al. (1966)*

The concept of field line merging

(magnetic reconnection)




Sweet-Parker reconnection geometry

*Figure from Hughes, "Magnetopause, magnetotail, reconnection" chapter 9 in "Introduction to Space Physics"*

Magnetic Reynolds number $R_m = \mu_0 \sigma v L$ *(L = typical scale size of the system)*

$R_m \gg 1 \Rightarrow$ frozen-in flux condition holds

General magnetospheric flow: $v \approx 100$ km/s, $L \approx R_E \Rightarrow R_m \gg 1$

Neighbouring flux tubes can be significantly different

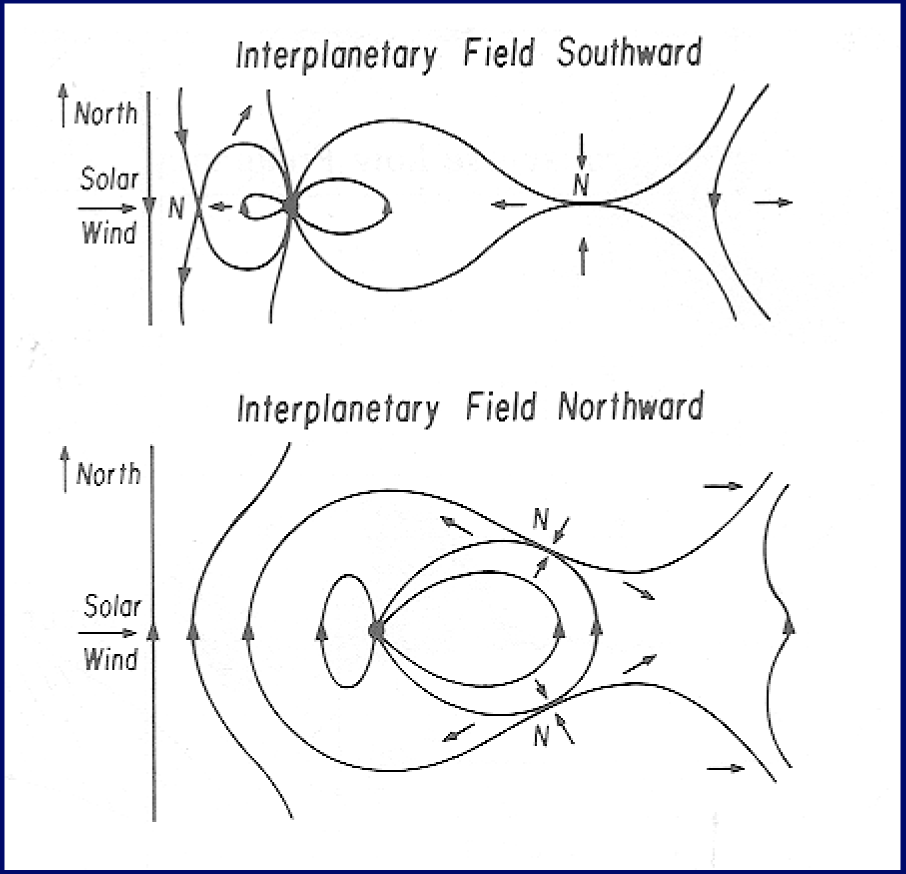
- they are separated by a thin current sheet
  - L can be small here such that $R_m \approx 1$
    - a plasma diffusion region is generated
      - reconnection can occur at a sufficiently fast rate

# Interaction of the solar wind with the Earth's dipole field

(1) The Chapman-Ferraro magnetopause
(a closed magnetosphere)

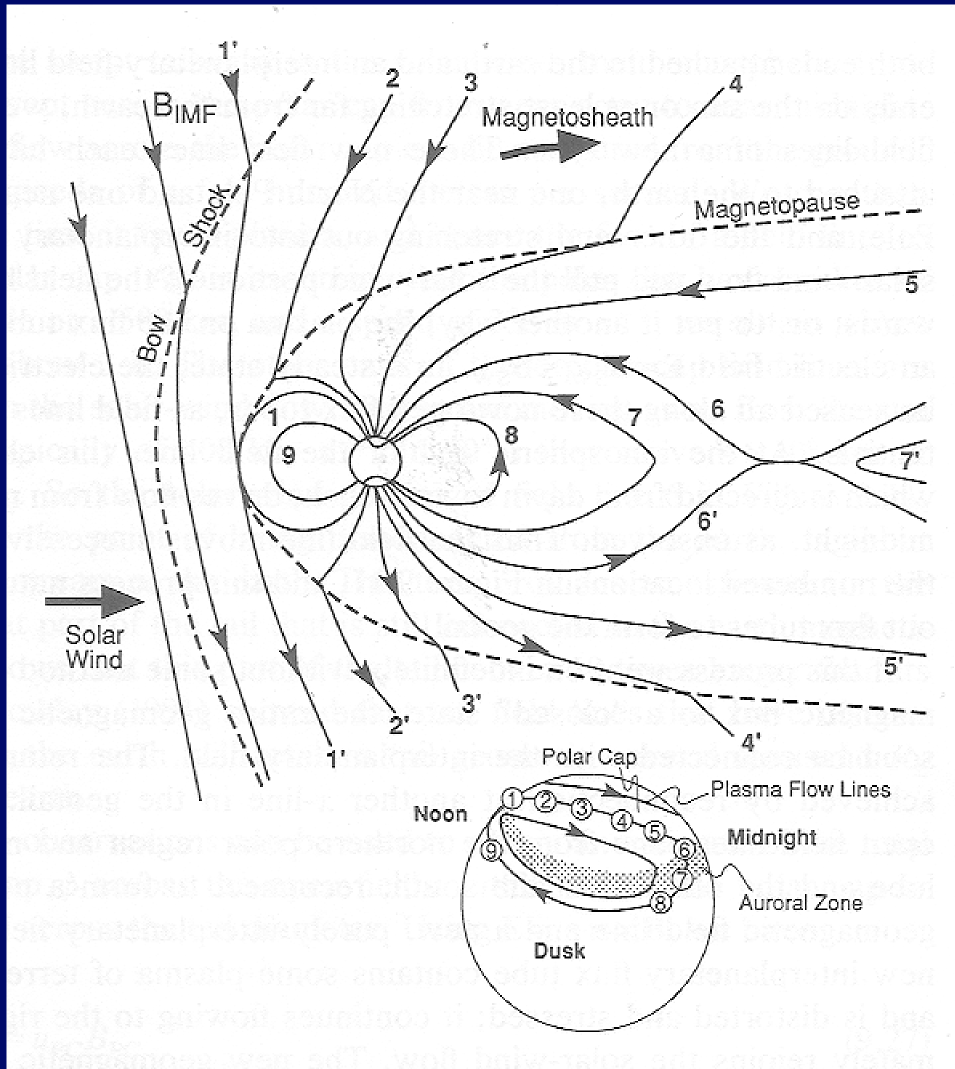
(2) The magnetospheric cavity

(3) Dungey's open magnetosphere




An early model of the open magnetosphere

*Dungey (1963)*




Dungey's open magnetosphere model: "field line dragging"

*Figure from Hughes, "Magnetopause, magnetotail, reconnection", Chapter 9 in "Introduction to Space Physics"*

# Interaction of the solar wind with the Earth's dipole field

(1) The Chapman-Ferraro magnetopause
(a closed magnetosphere)

(2) The magnetospheric cavity

(3) Dungey's open magnetosphere

(4) The geomagnetic tail

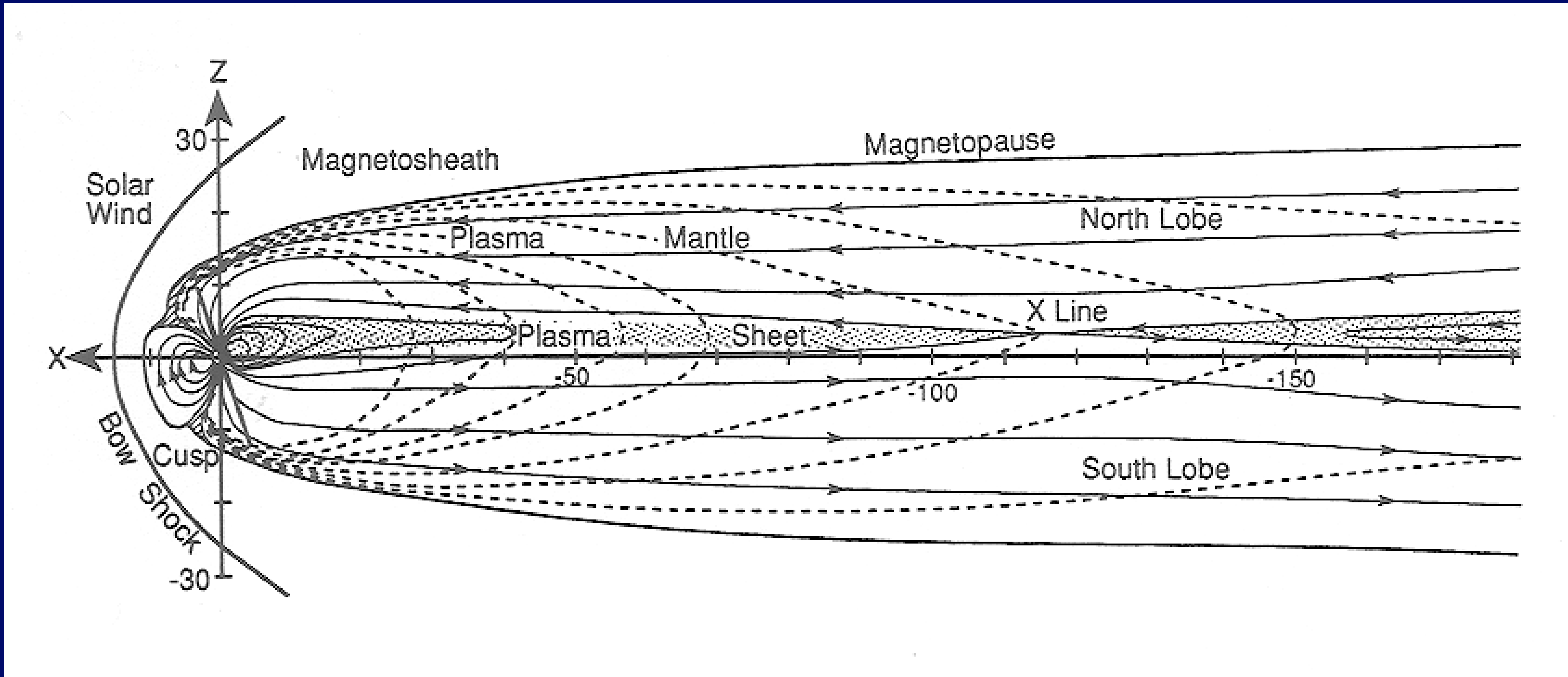



*Figure from Hughes, after Philipp and Morfill (1978)*

# Interaction of the solar wind with the Earth's dipole field

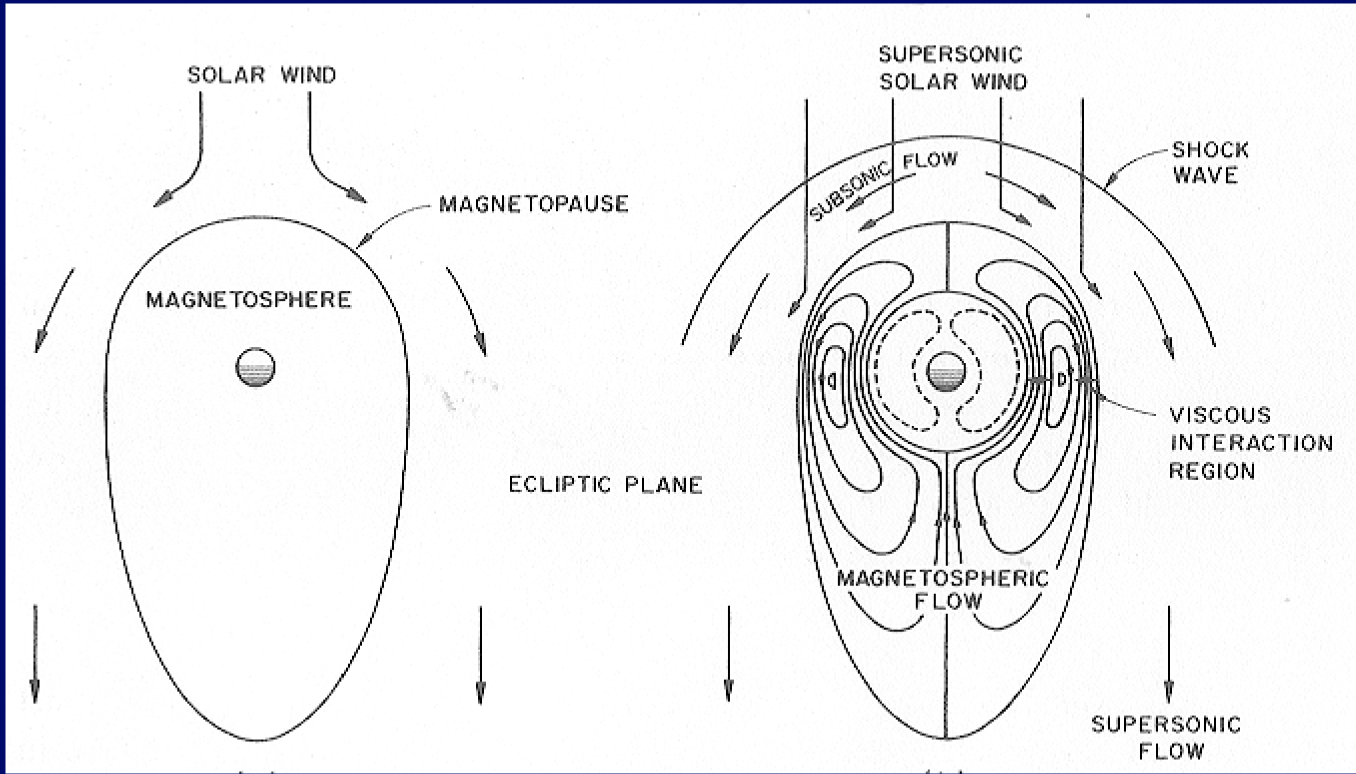
(1) The Chapman-Ferraro magnetopause
(a closed magnetosphere)

(2) The magnetospheric cavity

(3) Dungey's open magnetosphere

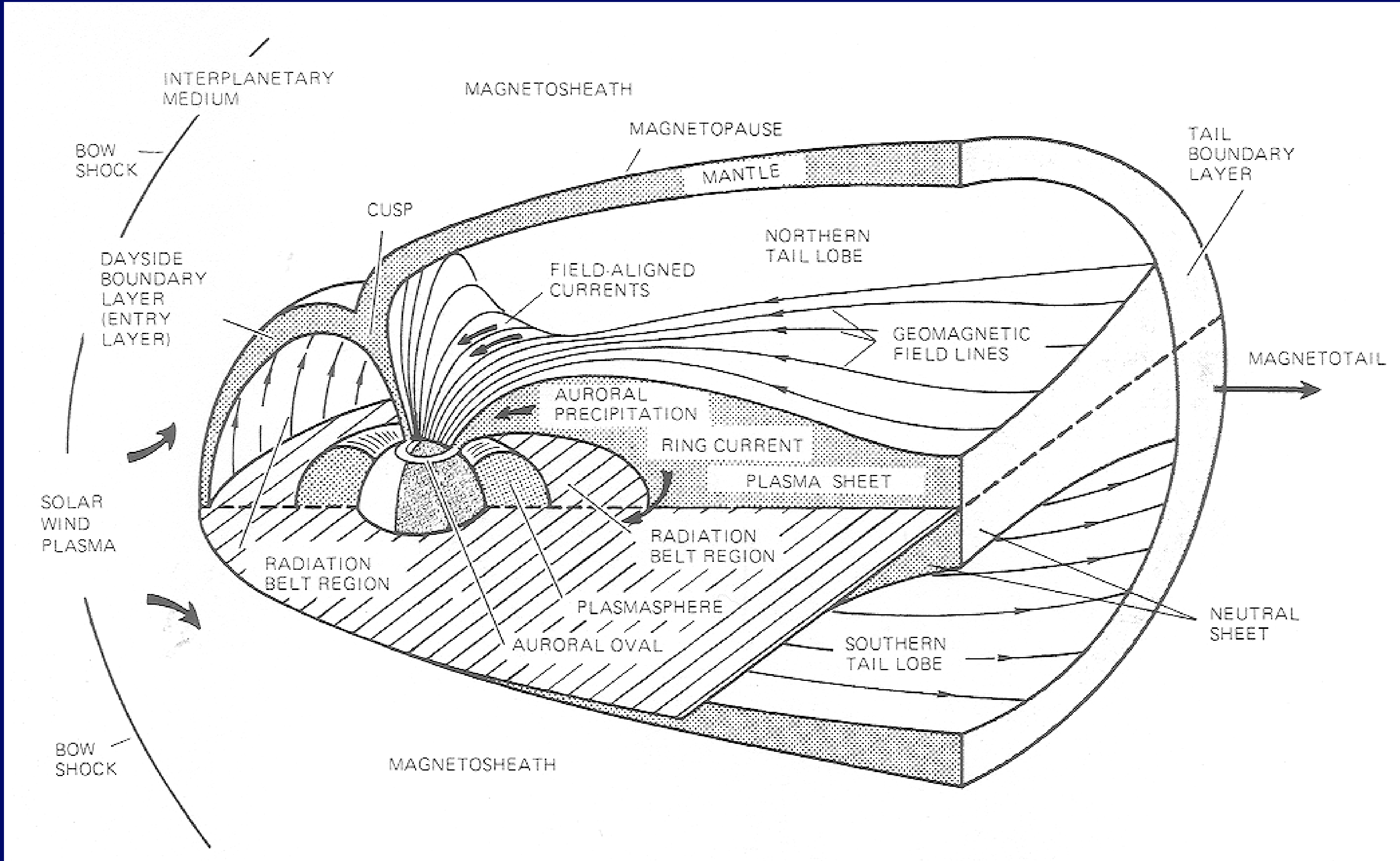
(4) The geomagnetic tail

(5) Viscous interaction




Viscous interaction across the magnetopause leads to magnetospheric convection. The solar wind is the active part, not the interplanetary magnetic field.

*Figure from M.C. Kelley "The Earth's Ionosphere" (1989) after Axford and Hines (1961)*




The whole interaction regime: bow shock, magnetosheath, magnetosphere

*Figure from M.C. Kelley "The Earth's Ionosphere" (1989)*

*So far neglected*

The bow shock

The magnetosheath

# Supersonic shock

airplane: relative air bulk speed exceeds acoustic velocity
mechanical air pressure (collisons) builds up a shock front

solar wind: particle mean free path >> magnetosphere diameter
$\Rightarrow$ shock without collisions

*upstream* $\rho$, $v$, $B$, $p$ | *downstream* $\rho$, $v$, $B$, $p$

MHD theory: mass, momentum, energy are conserved
$\Rightarrow$ several conditions across shock front apply

$\rho\, v_\perp = \text{const}$ (mass stream per unit area)

$\rho\, v_\perp^2 + p + B_\perp^2 / (2\,\mu_0) = \text{const}$ (shock normal momentum)

$\rho\, v_{||} - B_{||} / \mu_0 = \text{const}$ (shock parallel momentum)

$B_\perp = \text{const}$ (e.m. boundary condition)

$v_{||}\, B_\perp = v_\perp\, B_{||}$ (e.m. boundary condition)

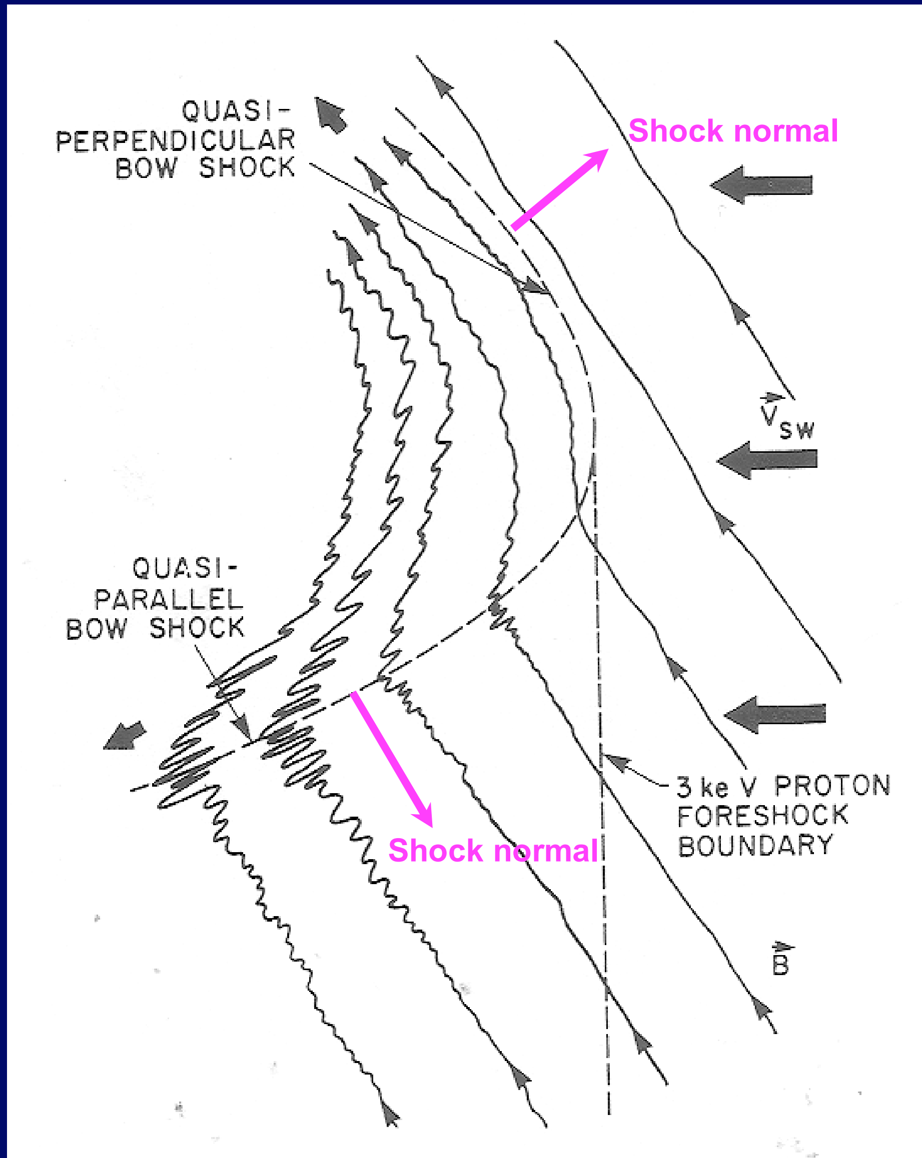



*Figure from J. Feynman "Solar Wind"*
*Chapter 3 in "Handbook of Geophysics and the Space Environment"*

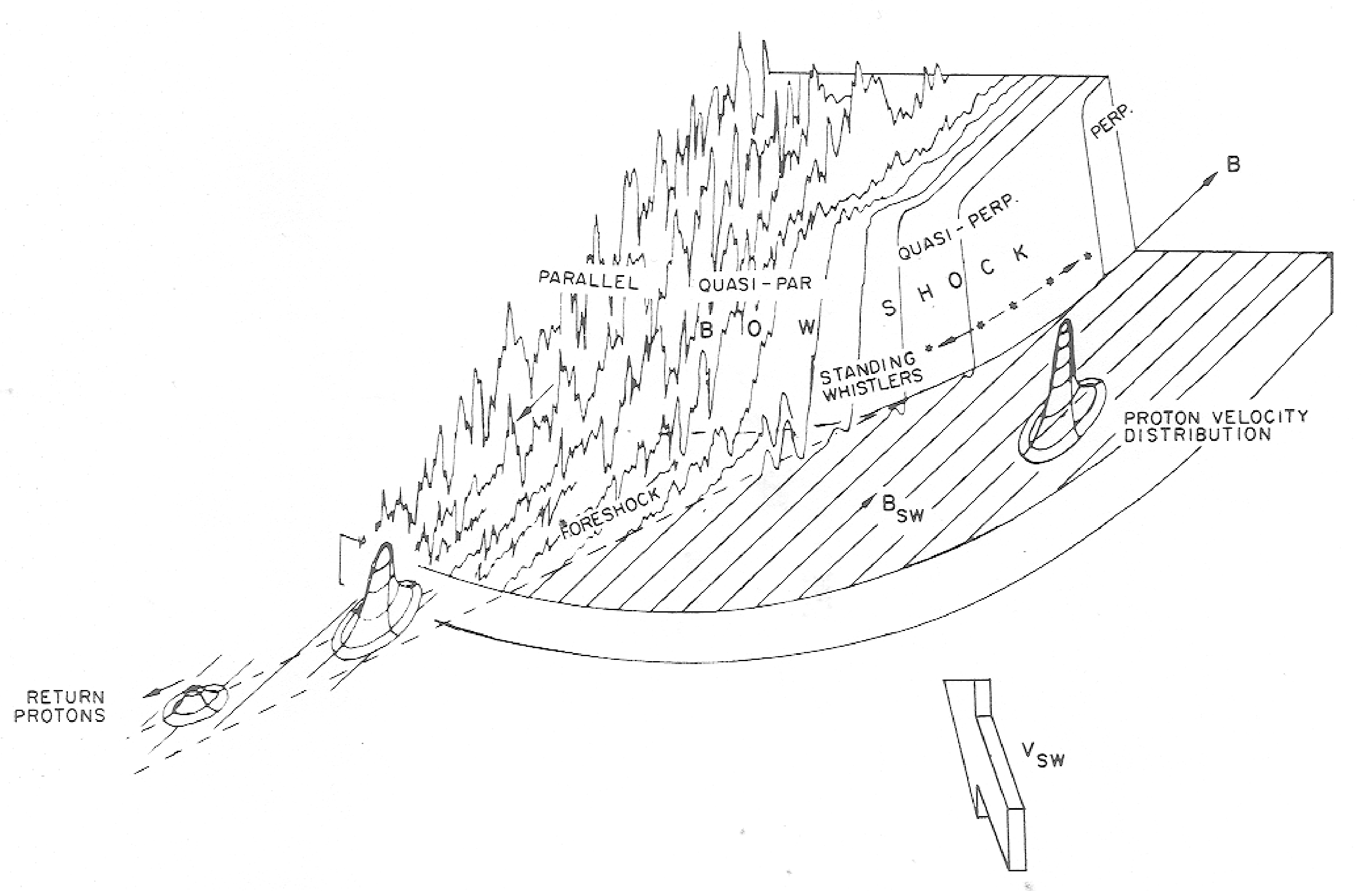



*Figure from J. Feynman "Solar Wind"*
*Chapter 3 in "Handbook of Geophysics and the Space Environment"*

# MHD model of magnetospheric magnetic field lines and electric currents

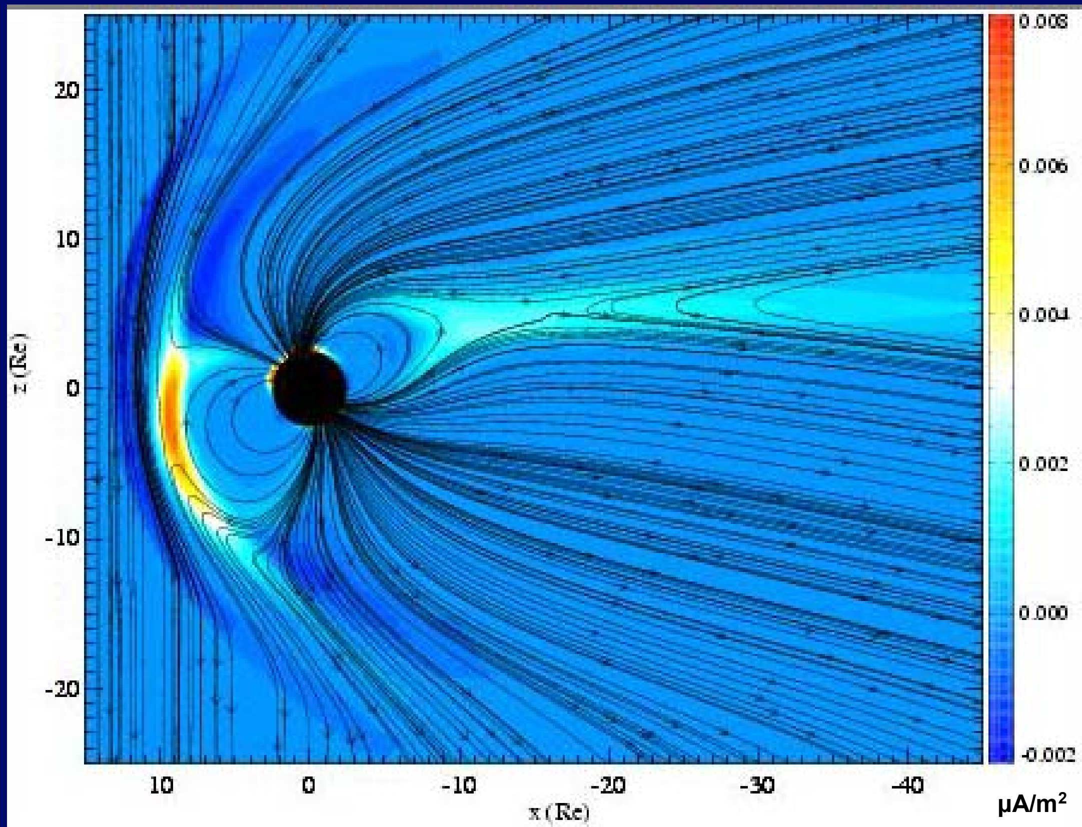
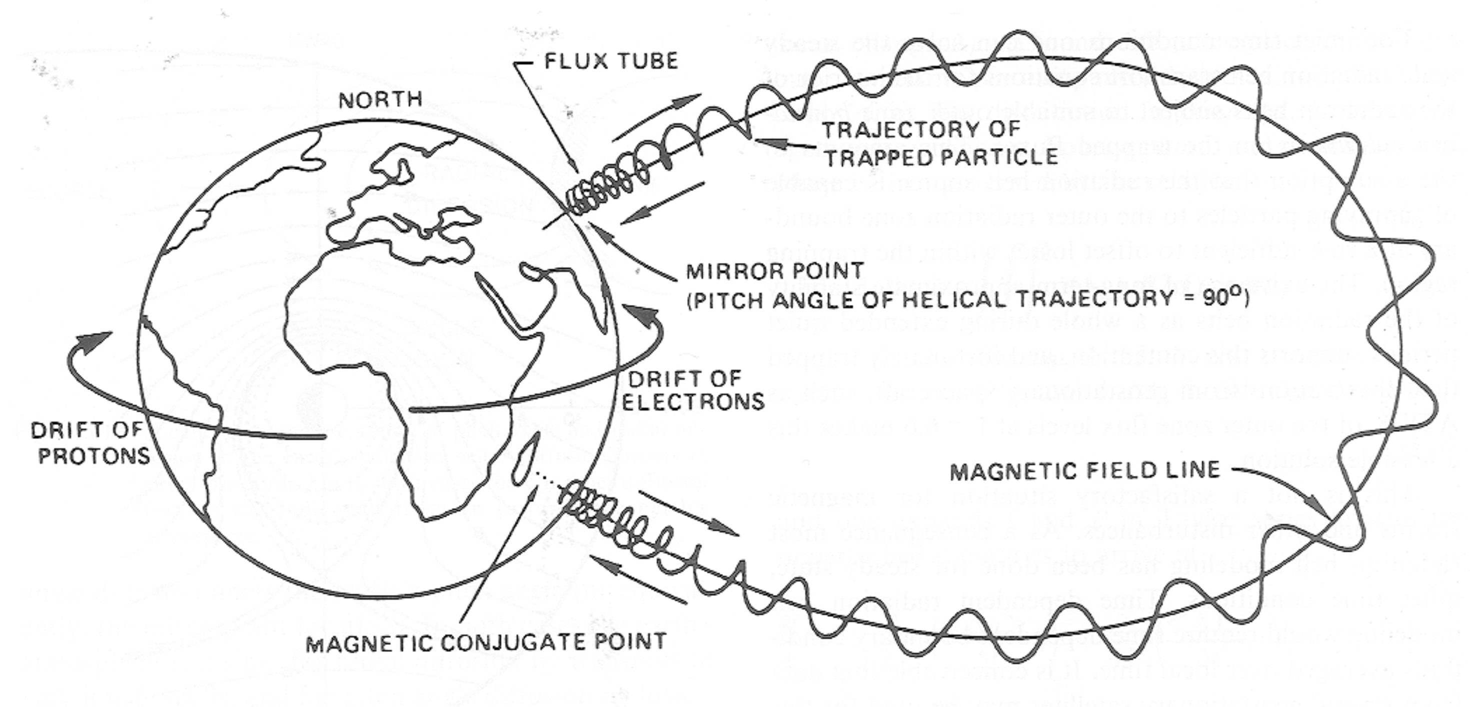



*Figure by the Finnish Meteorological Institute (?)*

Charged particle motion under stationary conditions

3 adiabatic invariants

(quasi-periodic single particle motions)




quasi-periodic motions at three different time scales

$$f_{gyro} \gg f_{bounce} \gg f_{drift}$$

*Figure from Spjeldvik and Rothwell, "The radiation belts"*
*Chapter 5 in "Handbook of Geophysics and the Space Environment"*

Hamilton-Jacobi action integral is constant in periodic motions

$$J = \oint p \, dq = \text{const}$$

Magnetic moment of a particle (first adiabatic invariant)

$$J = \oint m v_\perp r_L d\theta = 2\pi r_L m v_\perp = 2\pi m v_\perp^2 / \omega_c = 4\pi m/|q| \, \mu$$

Conditions: $B / |\nabla B| \gg m v_\perp / (|q|B)$ *(spatial gradient scale >> gyro radius)*

$T_B \gg 2\pi m / (|q|B)$ *(temporal change scale >> gyro period)*

Half-cycle bouncing period between mirror points (second adiabatic invariant)

$$J = \oint v_{||} \, ds$$

Drift period around the globe (third adiabatic invariant)

$$J = q \oint \underline{B} \, d\underline{S} = - 2\pi B_E R_E^2 / L$$

L = McIlwain parameter, defined by

$$L = 1 / \cos^2(\Lambda)$$

with $\Lambda$ being the latitude where the field line intersects the Earth's surface

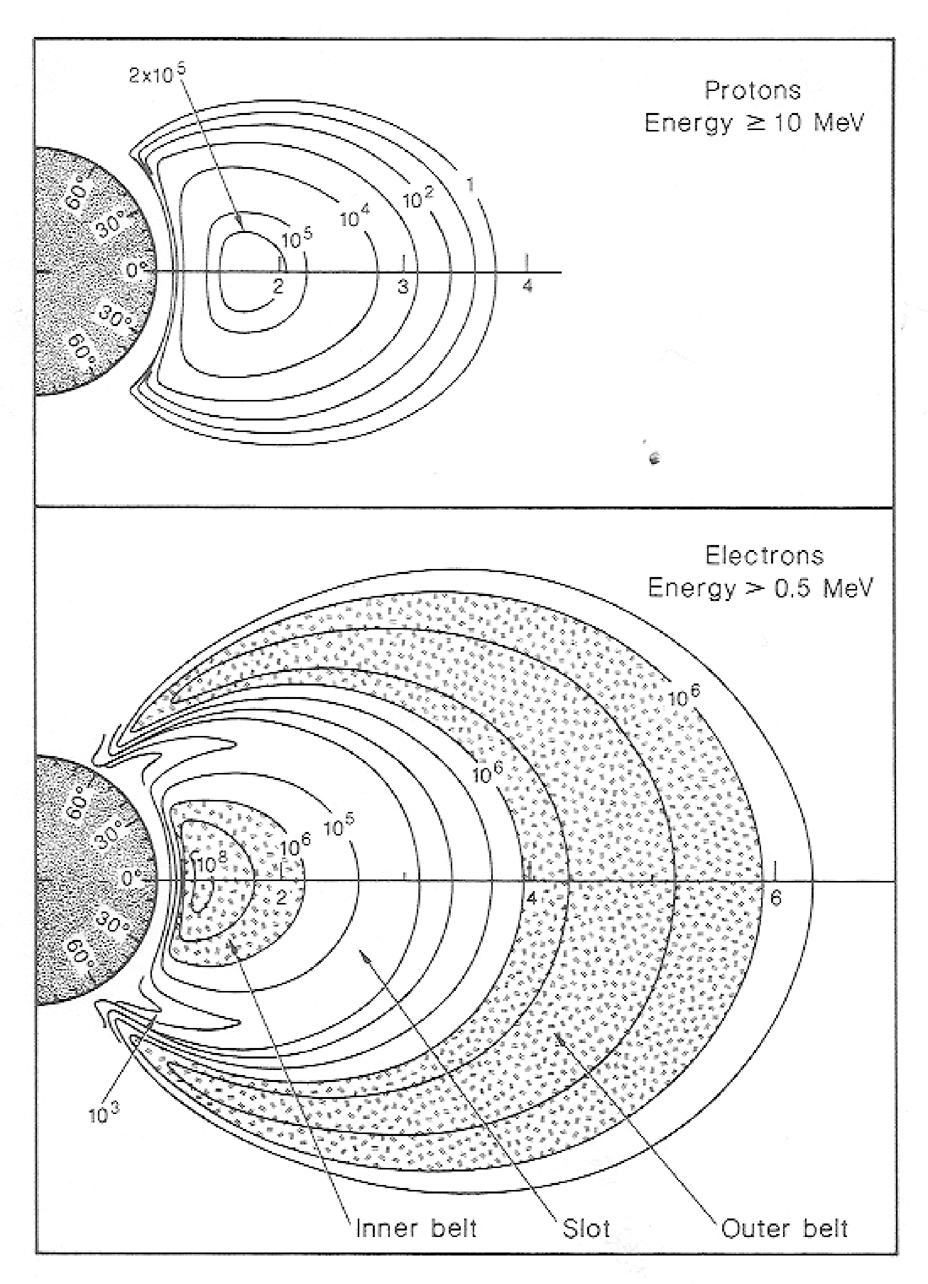
# Net result

Particles can be trapped in their flux tube thereby drifting around the Earth

⇒ high energy particles (several MeV) populate the
Inner Van Allan Belts (also termed trapped radiation belts)

⇒ high energy particles (several MeV) populate the
outer radiation belts

⇒ low energy particles (up to several hundred keV) populate the
ring current (coincides with outer radiation belt)



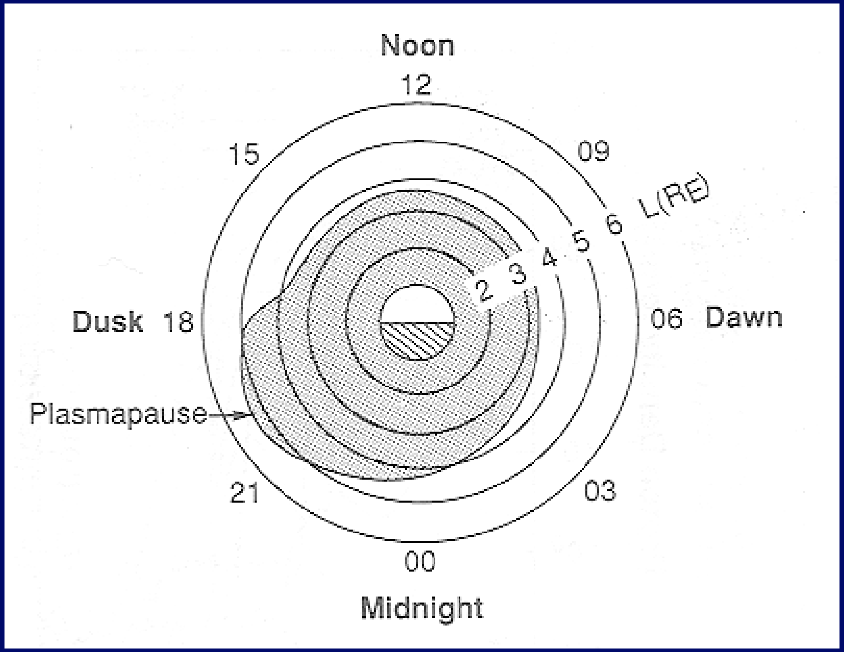

## Ion and electron radiation belts

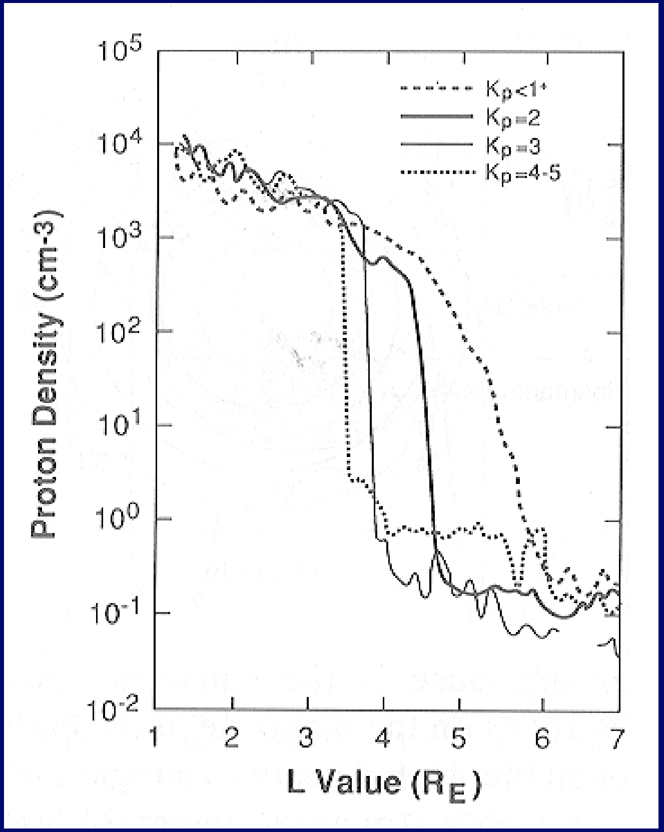
*Figure from Russel, "A brief history of solar-terrestrial physics"*
*Chapter 1 in "Introduction to space physics"*

# The plasmasphere

Cold (1 eV) plasma in the inner magnetosphere

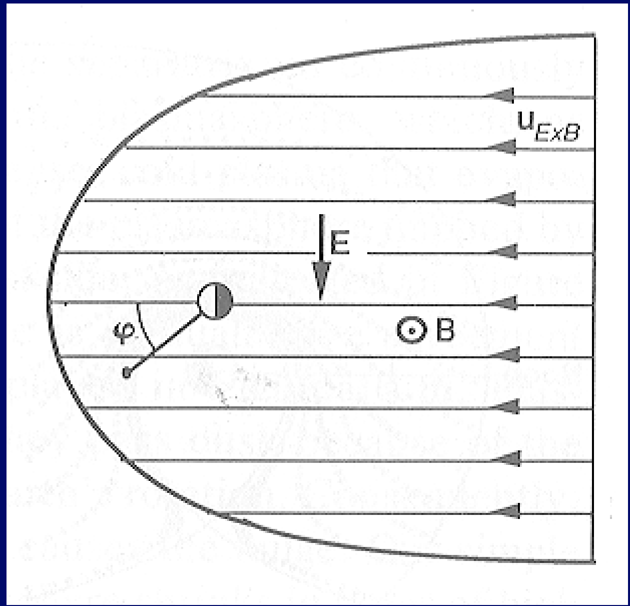
coexisting with the hot radiation belt population

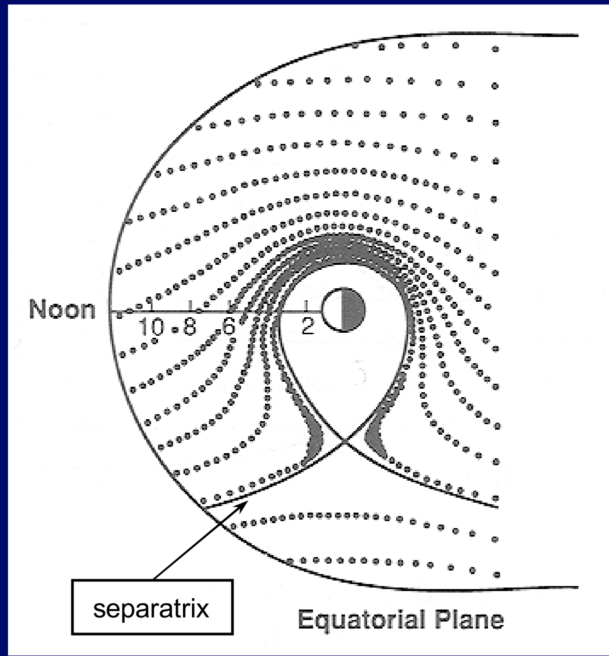



Plasma density in the inner magnetosphere

*Figures from R. Wolf "Magnetospheric Configuration"*
*Chapter 10 in "Introduction to Space Physics"*




*Figures from R.A. Wolf "Magnetospheric configuration"*
*Chapter 10 in "Introduction to Space Physics"*

| | |
|---|---|
| Origin of the plasmasphere: | outflow of plasma from polar regions |
| Far-out plasma drift governed by | $\Phi_{convection} = - E\ r \sin\varphi$ |
| Near-Earth plasma tends to corotate | $\Phi_{corotation} = - \omega\ B_0\ r_E^3 / r$ |
| Dawn side of the Earth | both drive plasma sunward |
| Dusk side of the Earth | they counteract each other |

Separatrix forms a strict boundary which cannot be crossed

# Magnetospheric current system

(magnetosphere-ionosphere coupling currents)

(1) The large-scale current system

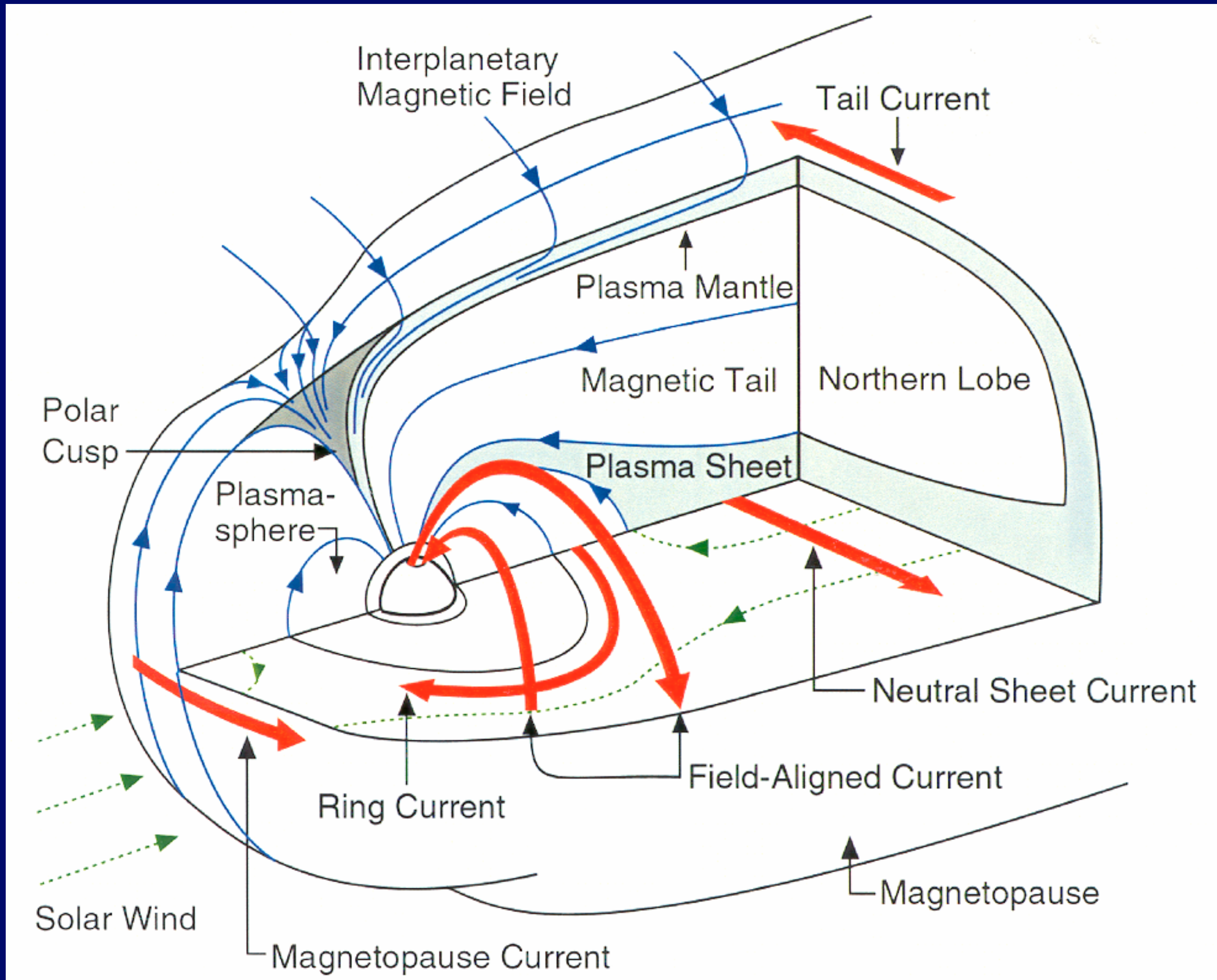


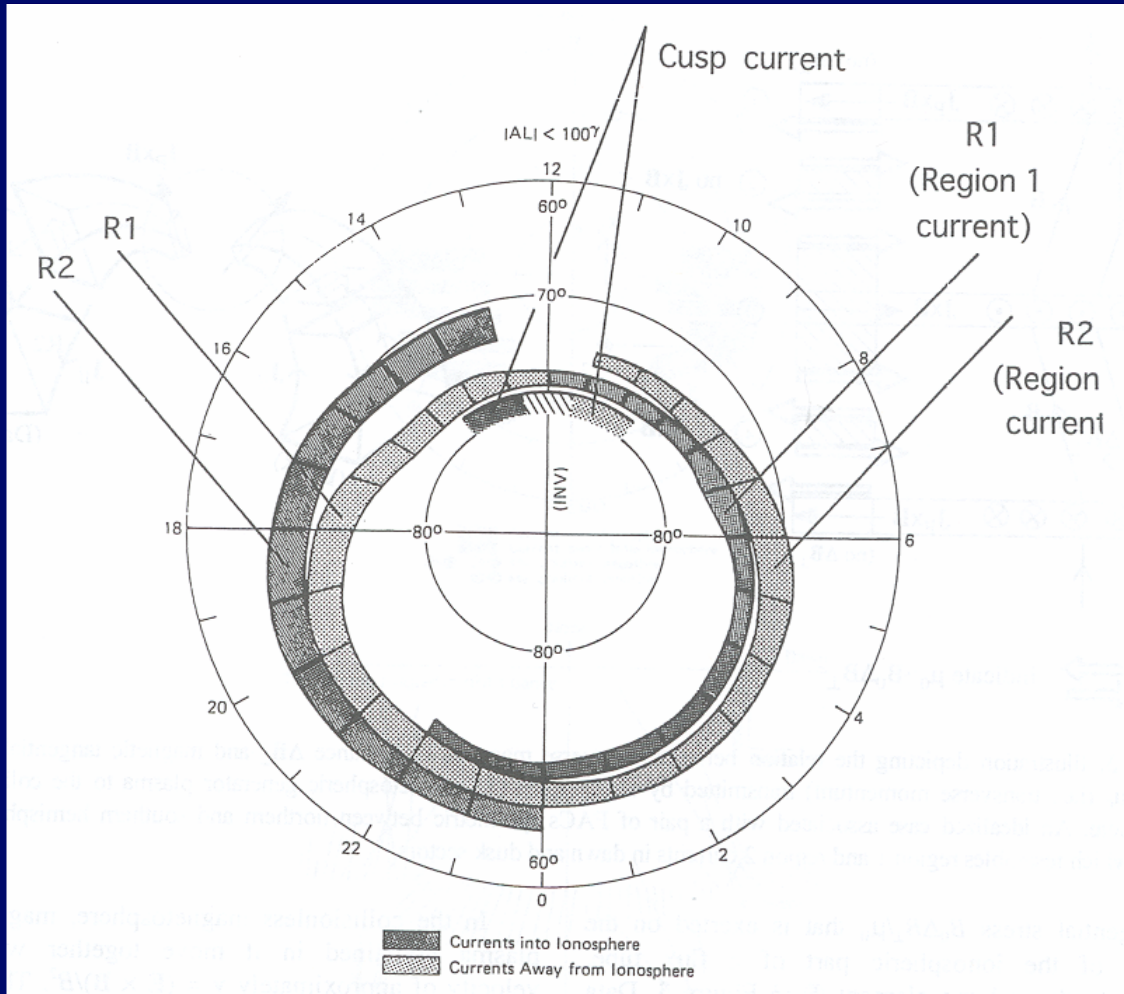

*Figure from “Report from the first Geospace Environment Modeling (GEM) Campaigns: 1991-1997”*

# Magnetospheric current system

(magnetosphere-ionosphere coupling currents)

(1) The large-scale current system

(2) Field-aligned currents (FAC)




Basic system of field-aligned currents
derived from TRIAD satellite measurements

*Iijima and Potemra (1982)*

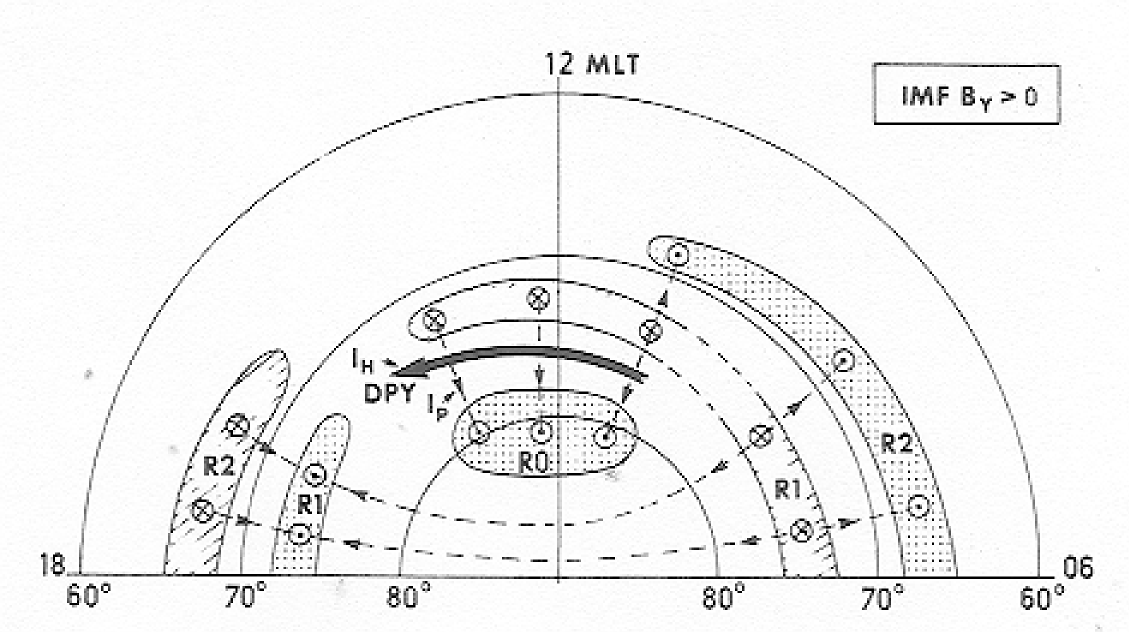
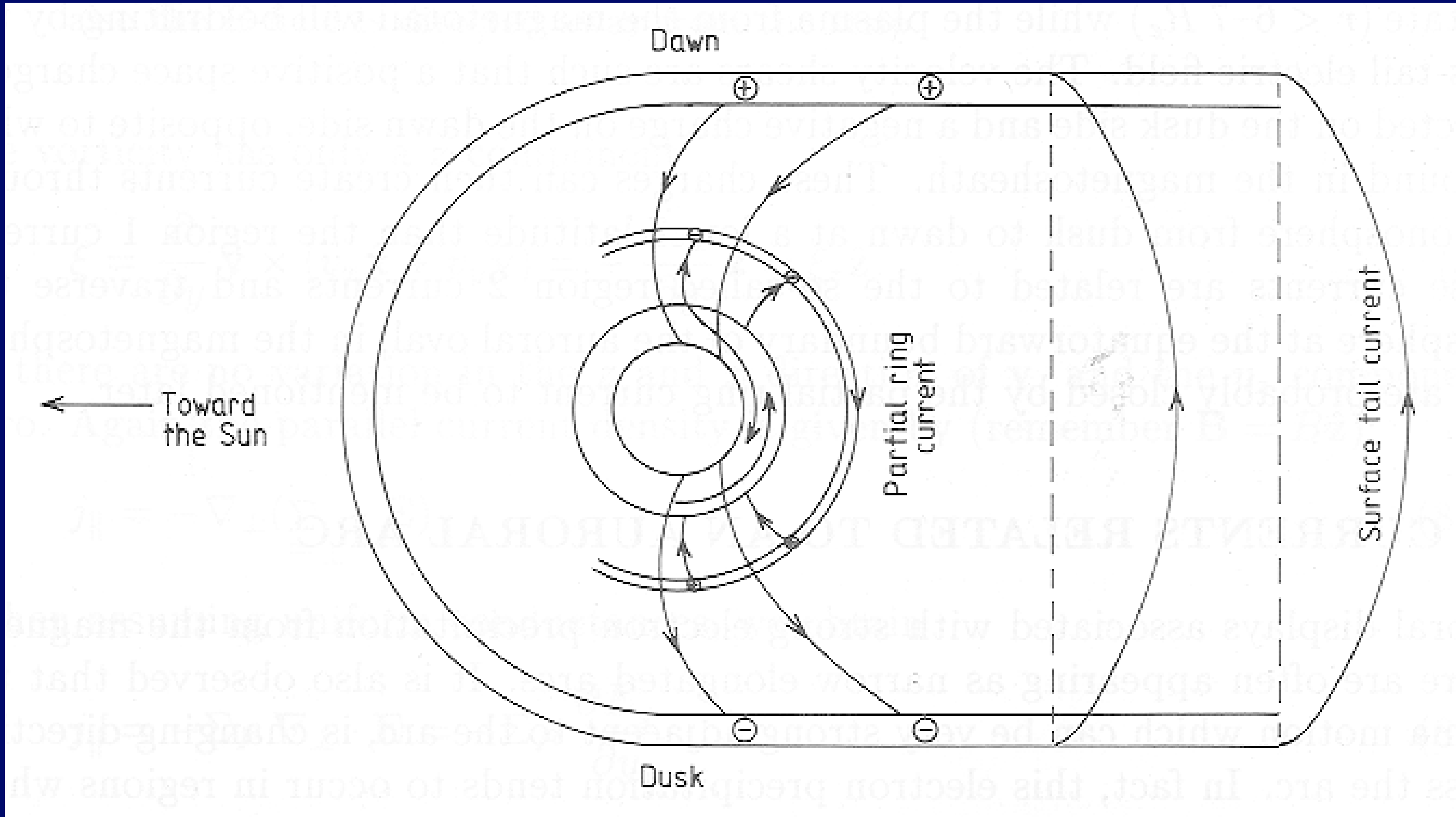



*Figure and list by Stauning, DMI*

Region 1 (R1) FACs
connect to Low-latitude Boundary Layer (LLBL)

- Region 2 (R2) FACs
  connect to Ring Current (RC) Region
- Region 0 (R0) or "Cusp Currents"
  connect to Cusp Region (Ionospheric DPY currents)
- Northward IMF Bz (NBZ) FACs
  connect to High-latitude Boundary Layer (HLBL)
- Substorm FACs
  connect to Tail Region (Plasma Sheet)

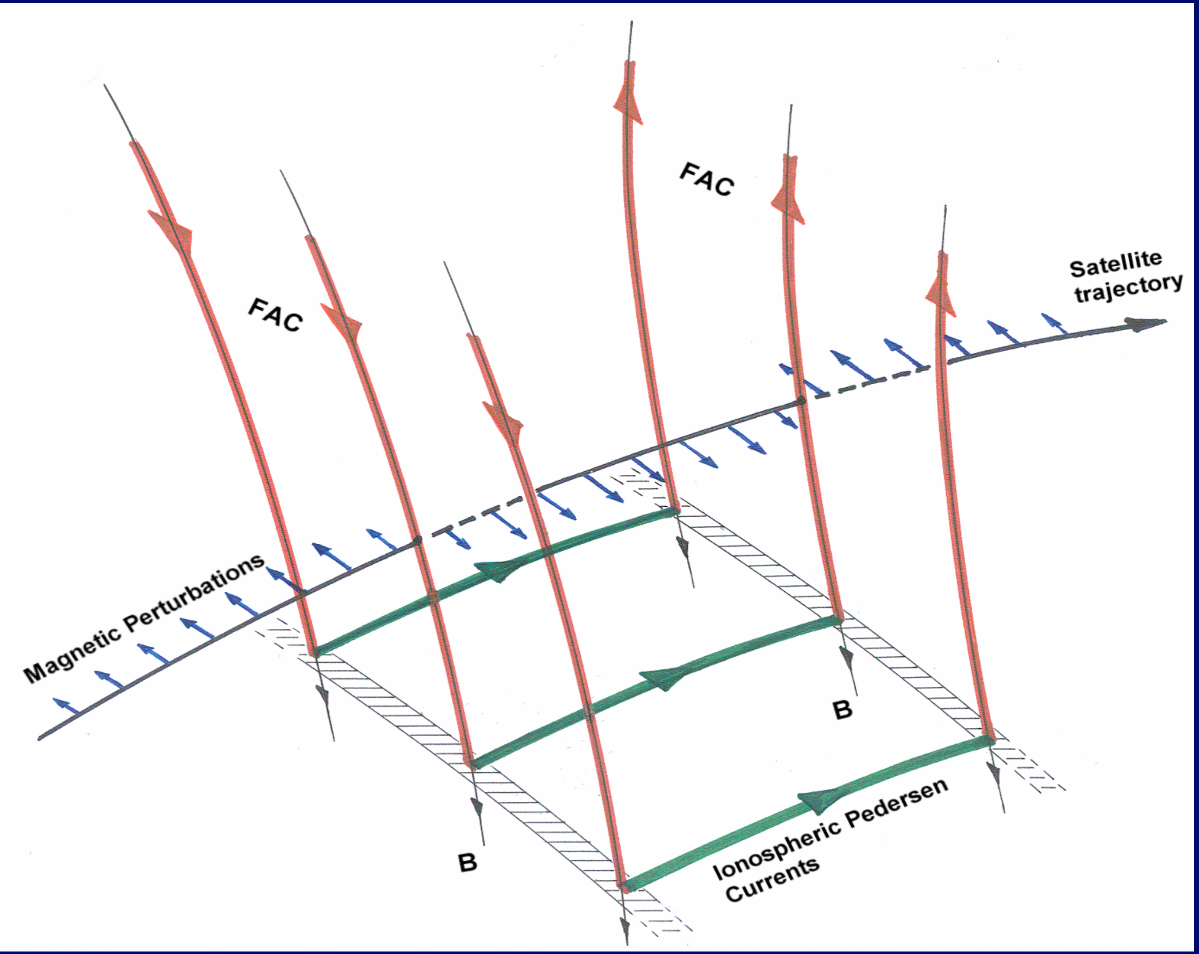



Closure of near-Earth magnetospheric current system

*Figure from Brekke "Physics of the Upper Atmosphere" (1997)*

How to determine FAC from satellite magnetometer measurements?

(a) Inference from a single satellite pass




Low-altitude satellite pass crossing field-aligned current sheets

*Figure prepared by P. Stauning, DMI*

# FAC inferred from a single satellite pass

Right-handed orthogonal system:

$x$ along satellite trajectory

$y$ perpendicular to satellite trajectory

$z$ along field line (south $\rightarrow$ north)

$\Rightarrow$ $B_z = 0$

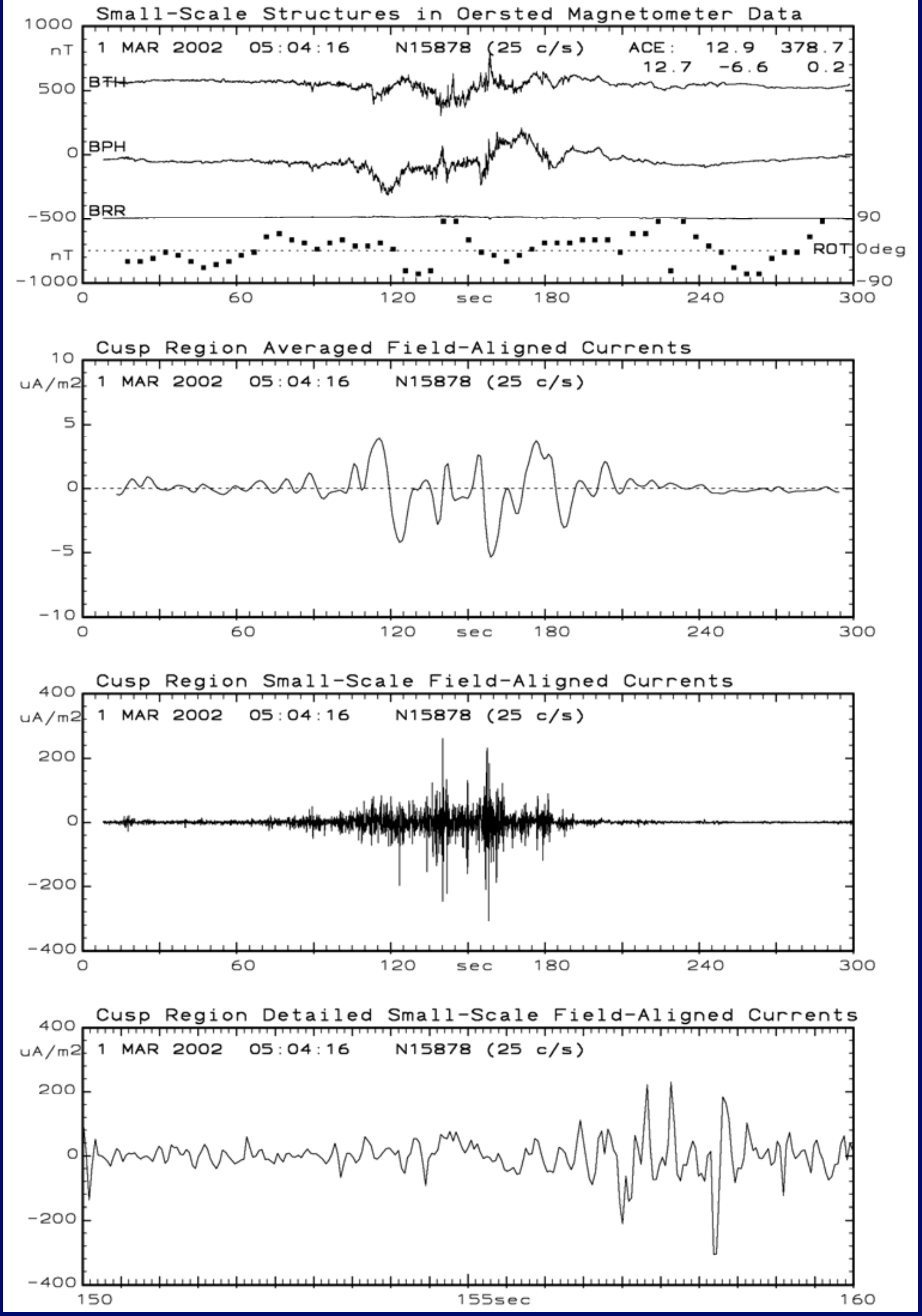
Ampère's law:

$\mu_0 \, j_{||} = \nabla \times B = \partial B_y / \partial_x - \partial B_x / \partial_y$

Assume FAC in parallel sheets

$\varphi$ = angle between trajectory and FAC sheets

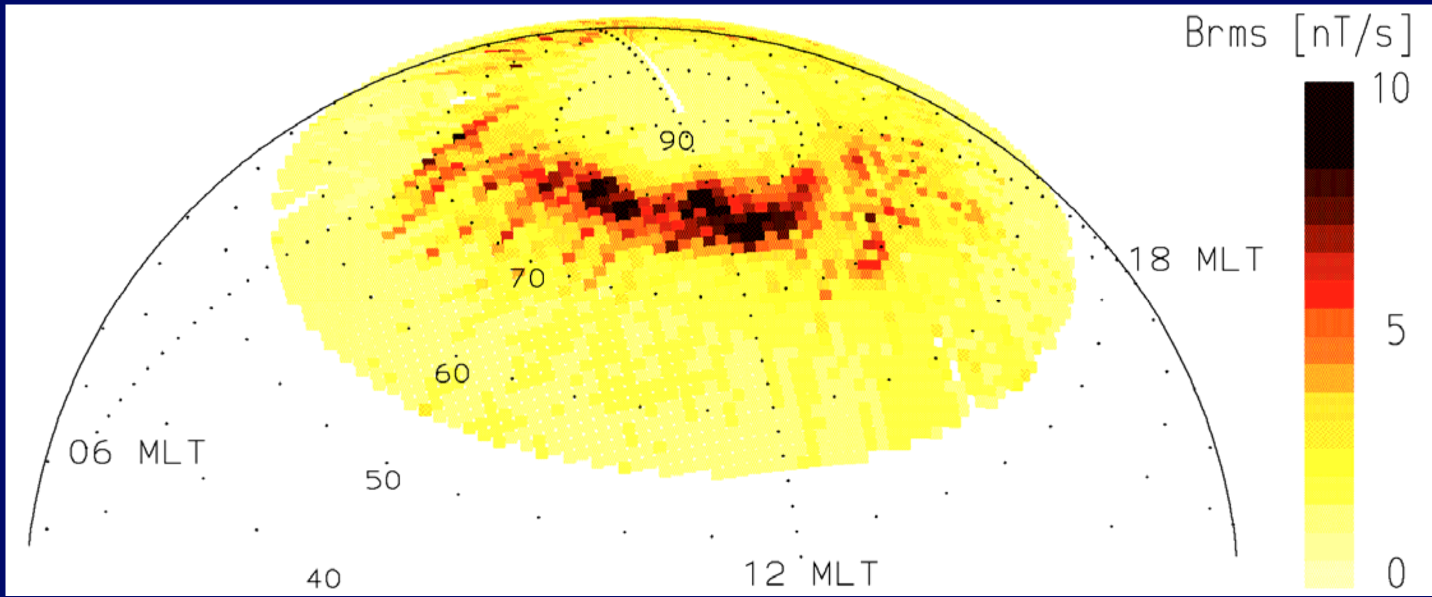
$\mu_0 \, j_{||} = 1/\sin\varphi \; \partial B_y / \partial_x$ (discard data if $\varphi < 45°$)




Large-scale and small-scale field-aligned currents

*Figure by P. Stauning, DMI*

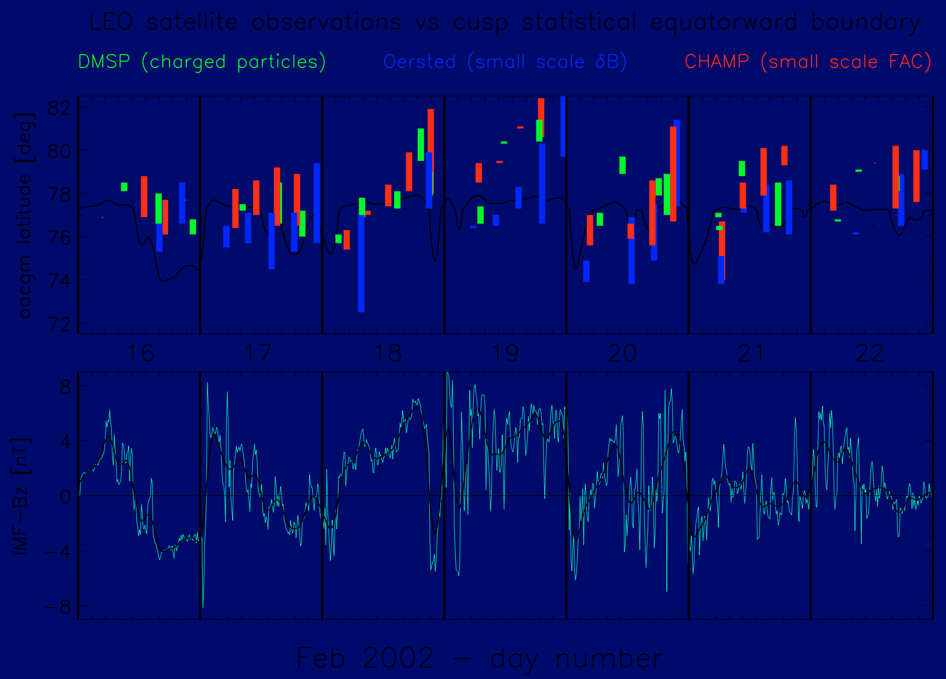
# Occurrence of fine-scale field-aligned currents

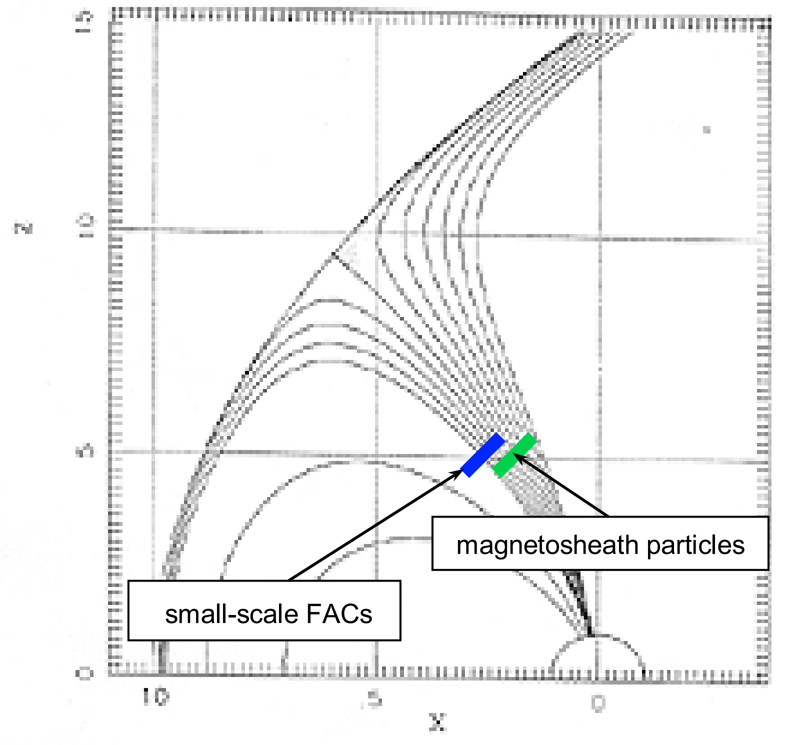



Distribution of fine-scale FAC intensities over the polar cap
mapped in magnetic latitude – local time coordinates

*Figure from Stauning et al., "Earth Observations with CHAMP", Springer, Berlin - Heidelberg - New York, 2005*

# Results from a DMSP – Ørsted – CHAMP joint data analysis



How to determine FAC from satellite magnetometer measurements?

(a) Inference from a single satellite pass

(b) Spatial interpolation of data accumulated over many orbits

# FAC inferred from a multitude of satellite passes

Right-handed orthogonal system:

x along satellite trajectory

y perpendicular to satellite trajectory

z along field line (south → north)

$\Rightarrow B_z = 0$

Ampère's law:

$\mu_0 j_{||} = \nabla \times B = \partial B_y/\partial_x - \partial B_x/\partial_y$

Bin data from many satellite passes according to certain criteria in order to fill a latitude-longitude grid *(in the hope that very similar magnetospheric conditions prevailed during the observations for each bin)*

- solar wind mass density and velocvity
- IMF magnitude and orientation *(determines field line merging)*
- season *(influences critically ionospheric conductivity)*

Interpolate between grid points (e.g., fit $2^{nd}$ order polynomial to each cell)

Apply Ampère's law on the two-dmensional grid (now full curl)

# Steady-state FAC Distributions ($V_{sw}$~400, $D_{sw}$~5, summer conditions)

*Figure by P. Stauning, DMI*

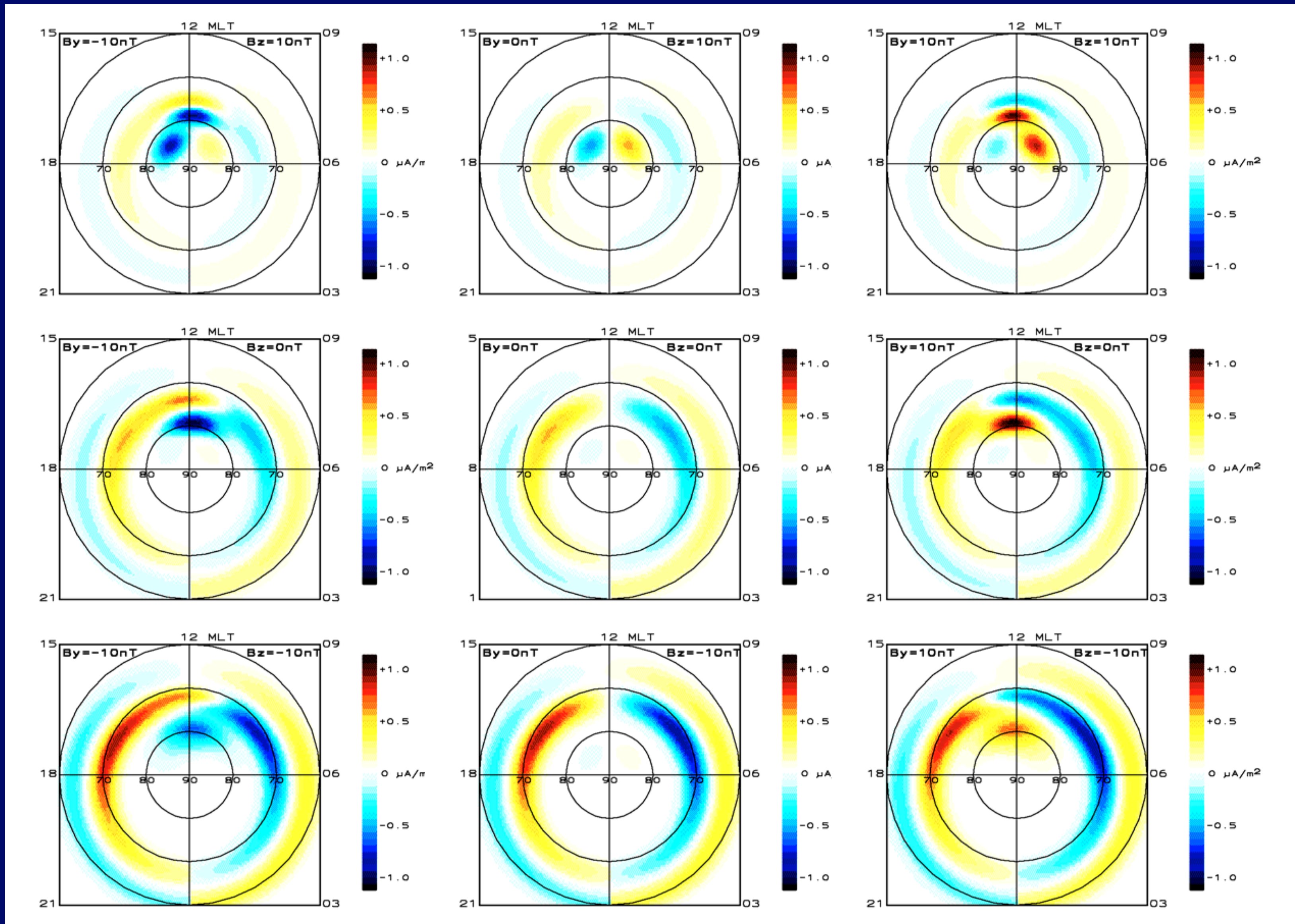
red : outward
blue : inward

By = -10 nT | By = 0 nT | By = +10 nT

Bz = +10 nT

Bz = 0 nT

Bz = -10 nT



How to determine FAC from satellite magnetometer measurements?

(a) Inference from a single satellite pass

(b) Spatial interpolation of data accumulated over many orbits

(c) Other methods for smoothing 2-D data collections

- Spherical Cap Harmonic Analysis
- Spherical harmonic expansion of certain suitable potentials (e.g., magnetic Euler potential)

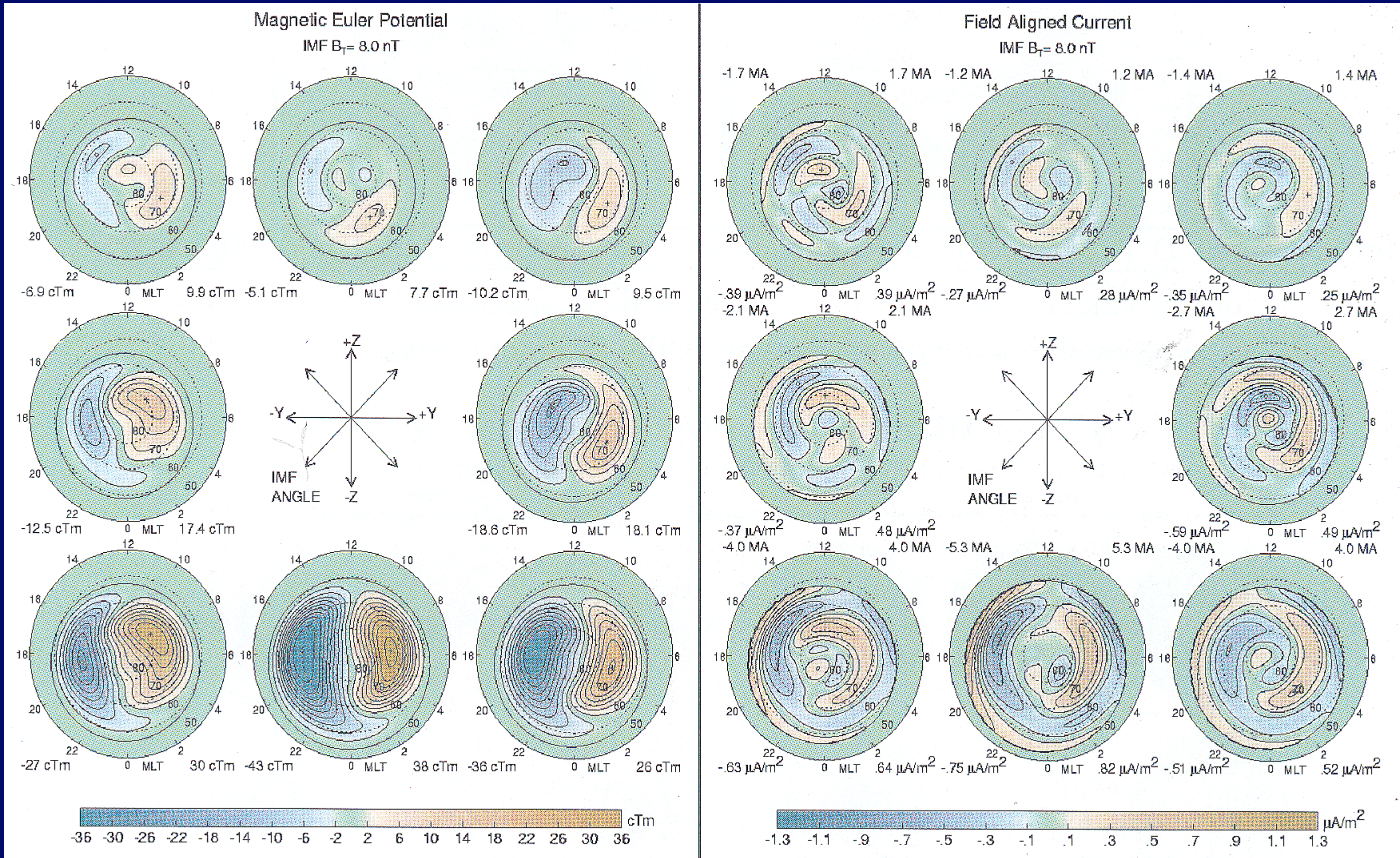



*Figure from Weimer, OIST-4 Proceedings (Copenhagen 2003)*

## How to determine FAC from satellite magnetometer measurements?

(a) Inference from a single satellite pass

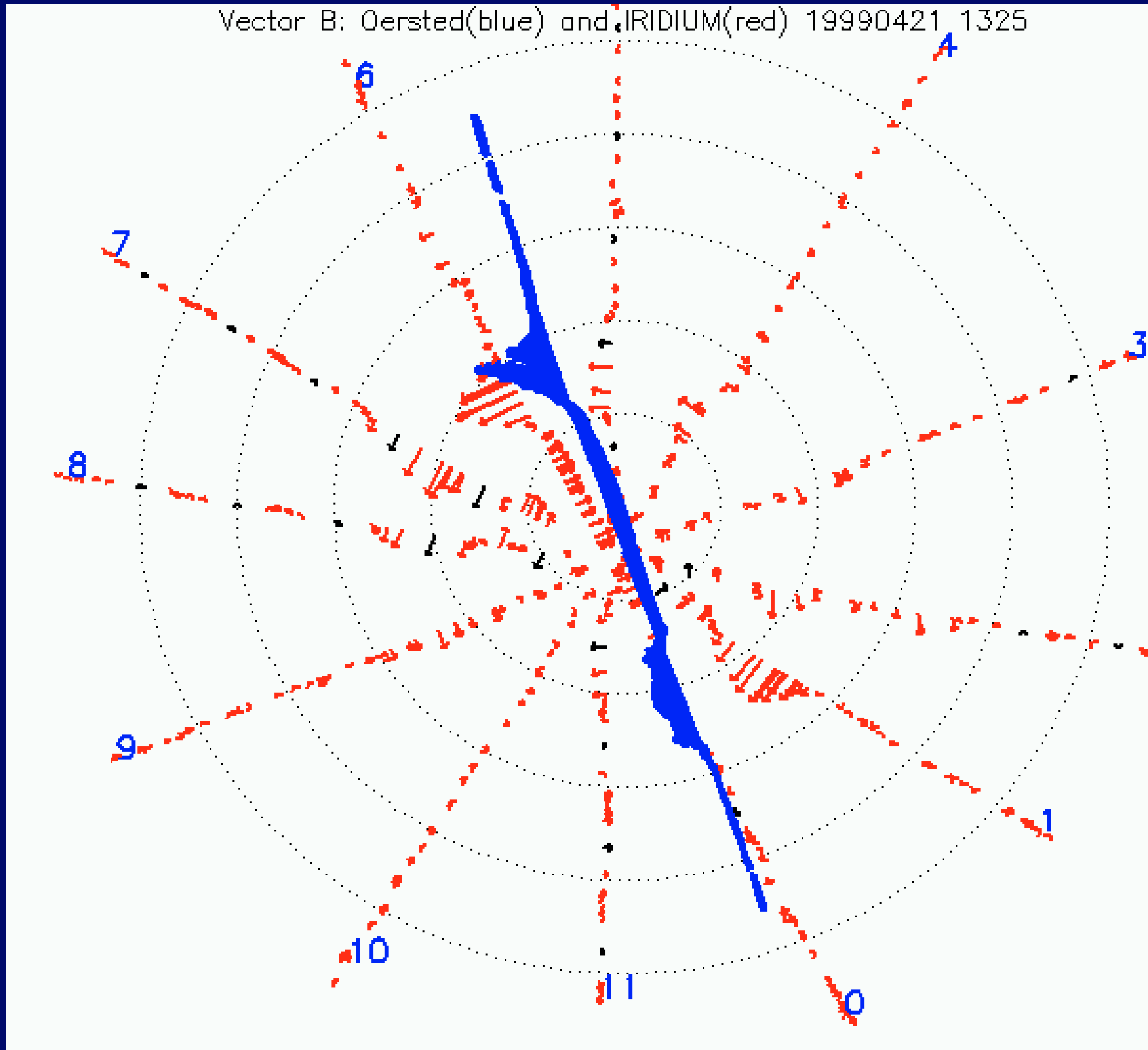
(b) Spatial interpolation of data accumulated over many orbits

(c) Other methods for smoothing 2-D data collections

- Spherical Cap Harmonic Analysis
- Spherical harmonic expansion of certain suitable potentials (e.g., magnetic Euler potential)

(d) Taking advantage of a multi-satellite constellation

Coincident magnetic field observations from 6 Iridium and the Ørsted satellite



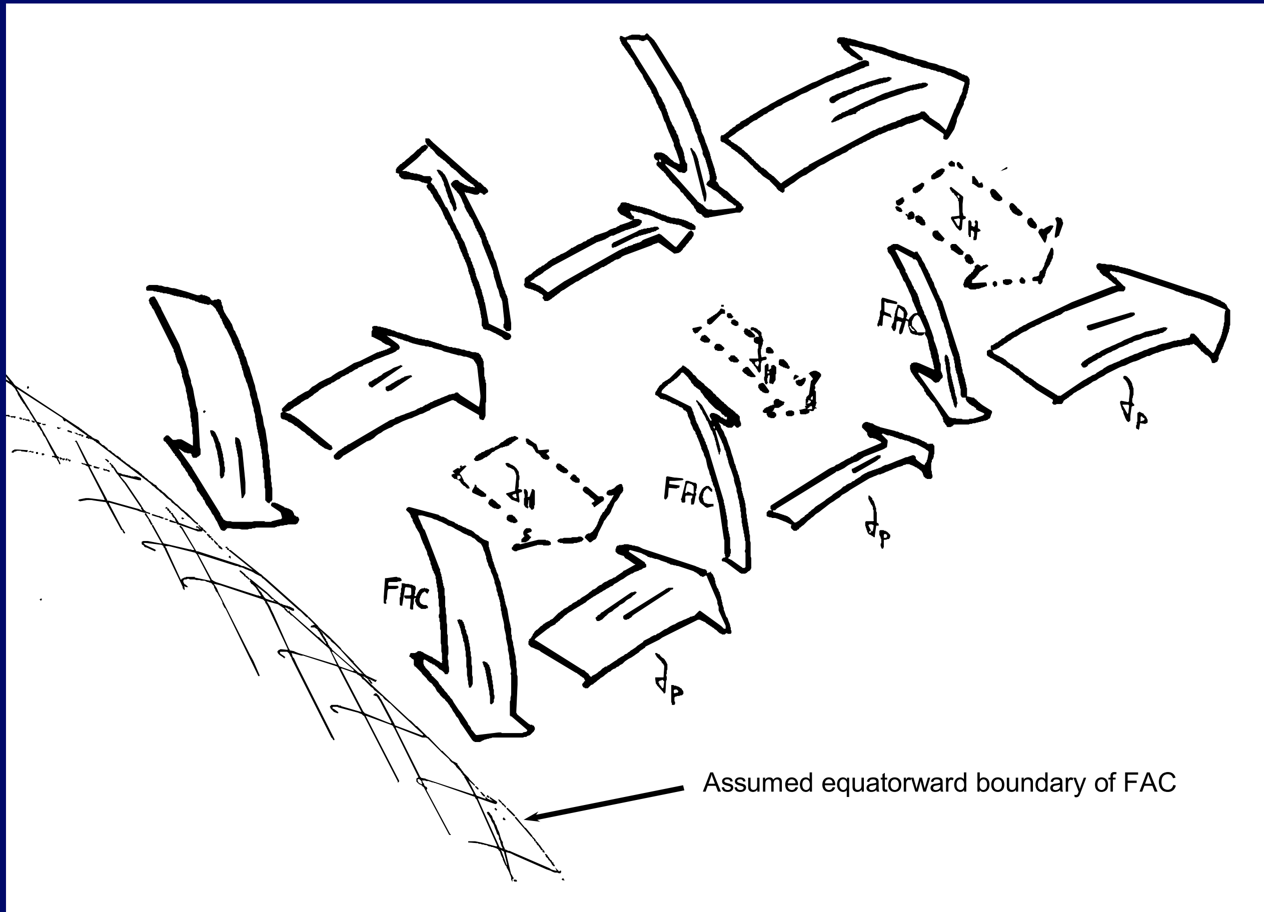
# Magnetospheric current system

(magnetosphere-ionosphere coupling currents)

(1) The large-scale current system

(2) Field-aligned currents (FAC)

(3) Ionospheric currents and convection



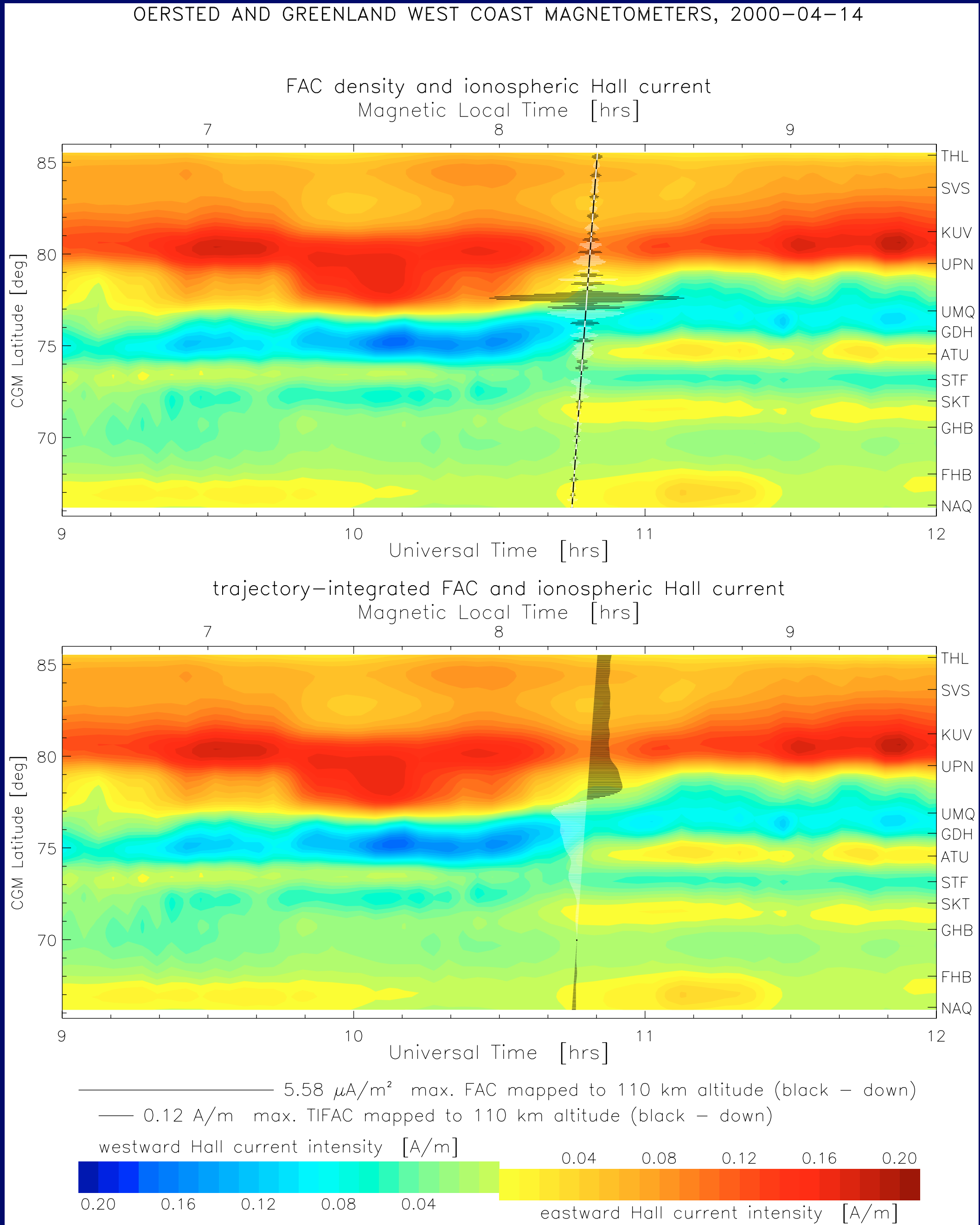

Sequence of uniform, infinitely extended high-latitude sheet currents

field-aligned currents (FAC)

ionospheric Pedersen currents ($J_P$)

ionospheric Hall currents ($J_H$)

*Trajectory-integrated FAC (TIFAC)* $\approx$ *Pedersen current*




# Synoptic view of FAC and ionospheric equivalent current

Ionospheric equivalent current across the magnetometer chain

*vs*

CGML and time (color-coded)

Ørsted trajectory with FAC density (top panel)

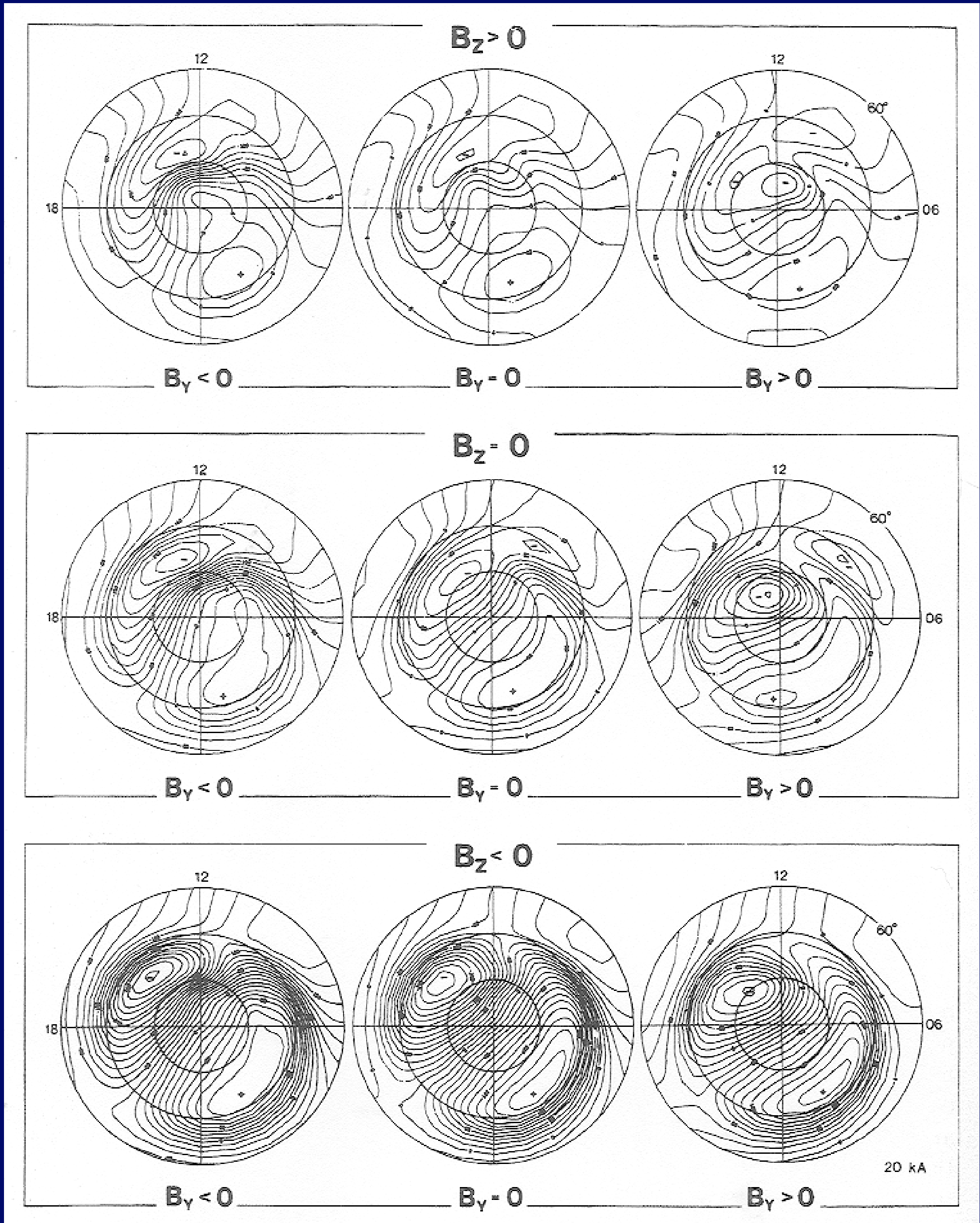
and trajectory integrated FAC (bottom panel)

white -- upward

black – downward

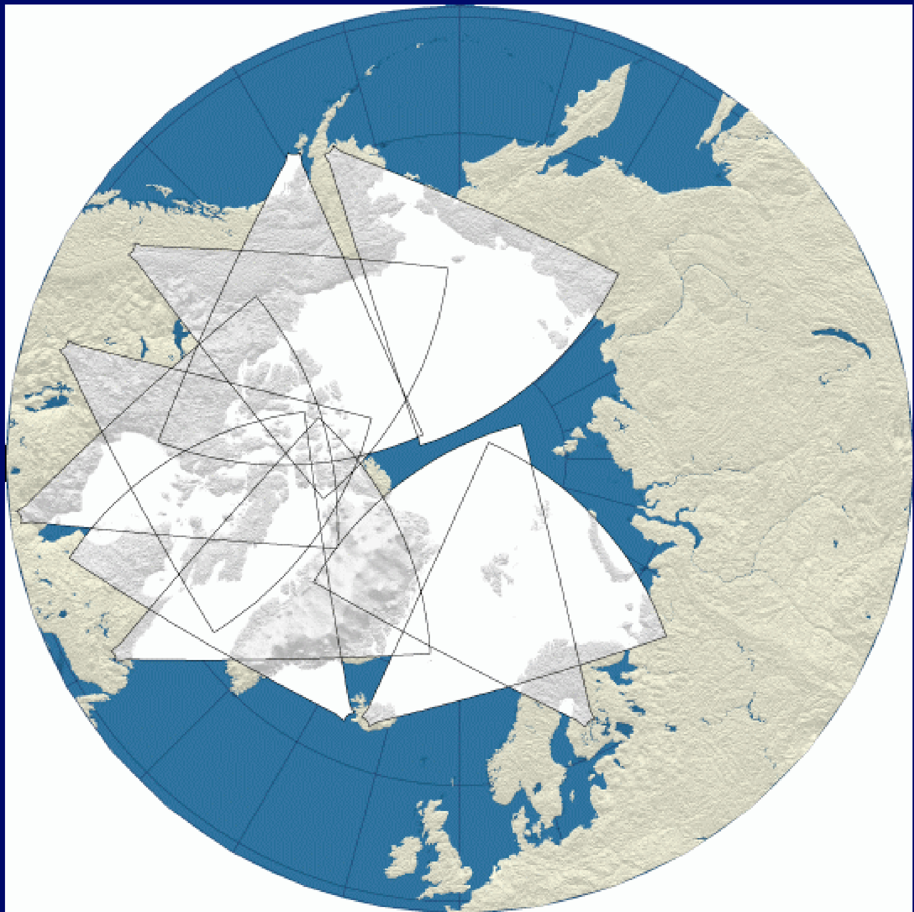
| Input | Assumptions | Output | Name of method | Remarks |
| --- | --- | --- | --- | --- |
| $\vec{B}_G$ | - | $\vec{J}_{eq,Ion}$, $\vec{J}_{eq,Int}$ | field continuation, field separation | forward method<br>no true currents, no FACs |
| $\vec{B}_G$ | $\Sigma_H$, $\Sigma_P$ | $\vec{E}\ (\Phi_E)$, $\vec{J}$, $j_\parallel$ | KRM | forward method<br>boundary conditions critical if non-global |
| $\vec{B}_G$,<br>$\{\vec{E}\ (\Phi_E)$,<br>satellite data$\}$ | $\Sigma_H$, $\Sigma_P$ | $\{\vec{E}\ (\Phi_E)\}$, $\vec{J}$, $j_\parallel$ | AMIE,<br>“three-dimensional modeling” | optimisation method (least square or “trial and error”);<br>data need not to cover whole analysis area |
| $\vec{B}_G$, $\vec{E}$<br>- - - - -<br>$j_\parallel$, $\vec{E}$ | $\alpha = \Sigma_H / \Sigma_P$ | $\Sigma_H$, $\Sigma_P$, $\vec{J}$, $j_\parallel$ | method of characteristics (JEQ-based)<br>- - - - -<br>(FAC-based) | forward method<br>$\alpha$ assessible from ASC or $\vec{B}_G$ |
| $j_\parallel$ | $\Sigma_H$, $\Sigma_P$ | $\vec{E}\ (\Phi_E)$, $\vec{J}$ | - | forward method<br>boundary conditions critical if non-global |
| $\vec{B}_G$, $j_\parallel$, $\{\vec{E}\}$ | - | $\vec{J}$, $\{\Sigma_H$, $\Sigma_P\}$ | elementary current method | forward method |

*Table from Amm et al., OIST-4 Proceedings (Copenhagen 2003)*




Equivalent ionospheric currents for various combinations of the interplanetary magnetic field components $B_z$ and $B_y$

*Figure from Friis-Christensen (1985)*

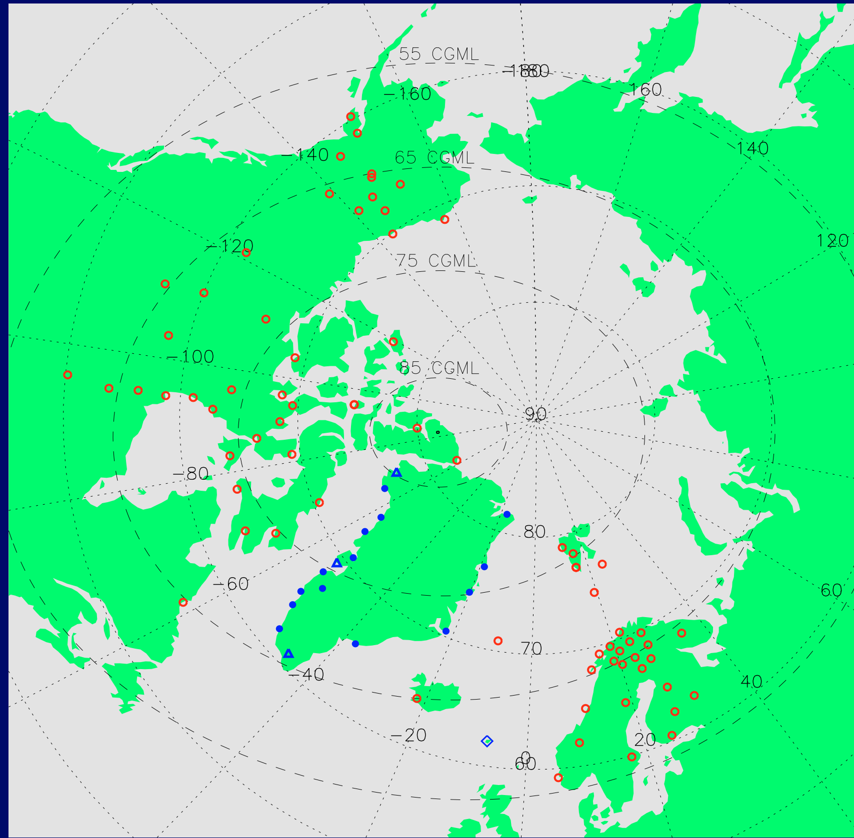


SuperDARN

Super Dual Auroral Radar Network

**HF coherent scatter radar coverage of the northern hemispheric ionosphere**

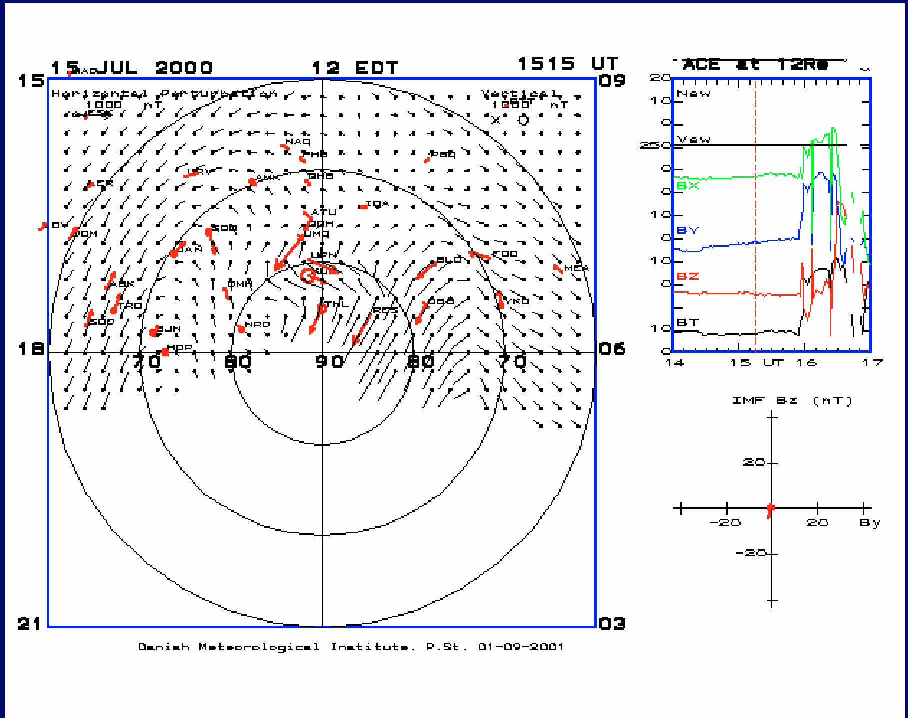
*figure by JHU / APL*

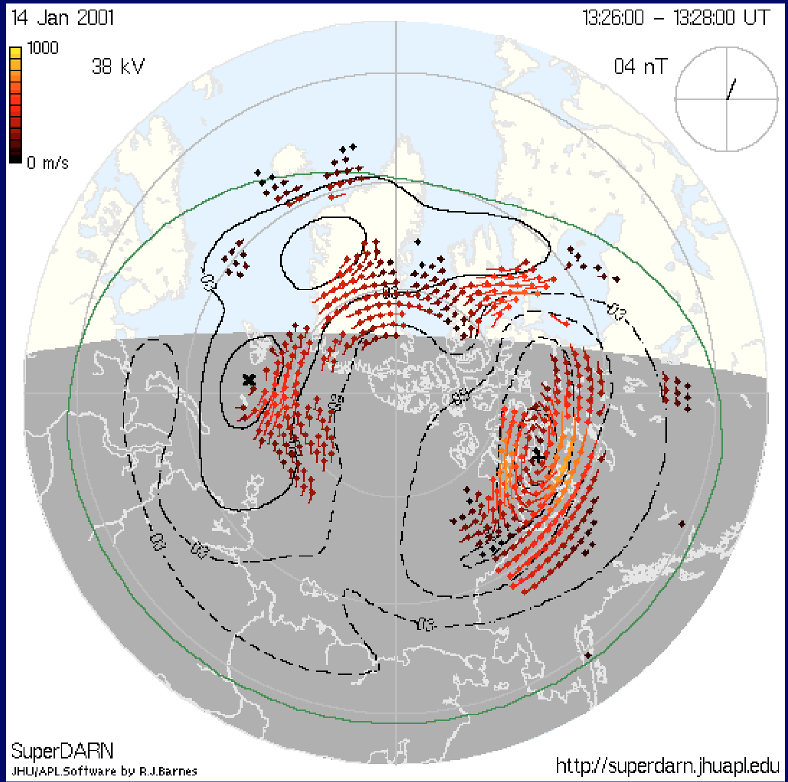



**Magnetometer sites**

blue – DMI stations

red – other institutions




Ionospheric convection inferred from northern hemisphere ground-based magnetometers

SuperDARN sample convection pattern

*Frame from a convection movie, Peter Stauning, DMI*

*Figure from Opgenoorth et al., 2001*

# Geomagnetic field models and indices

Jurgen Watermann

Geomagnetism and Space Physics Program

Danish Meteorological Institute

*May 2006*

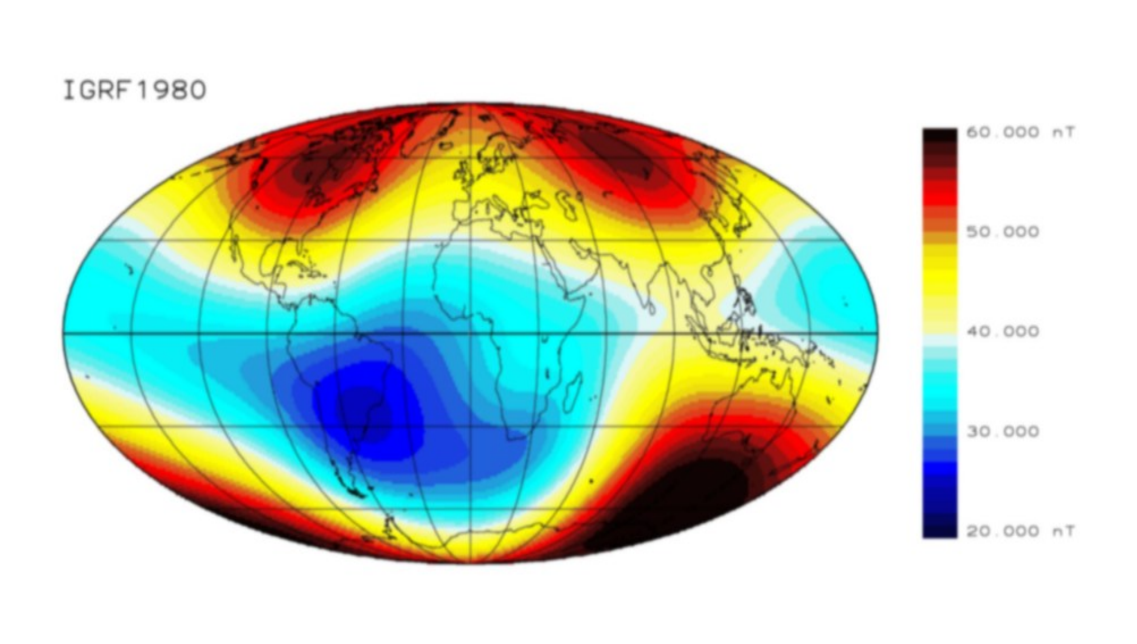
*The support provided by COST, COST Action 724*
*and the Abdus Salam ICTP is gratefully acknowledged*

# Geomagnetic and magnetospheric field models

(1) IGRF geomagnetic model

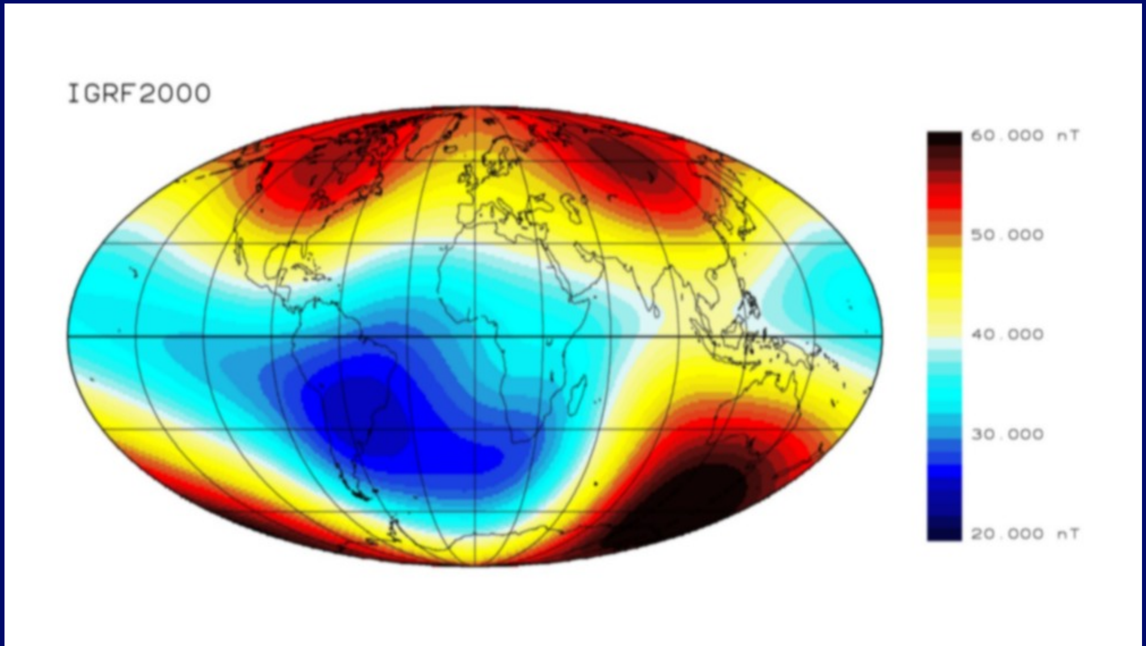
# IGRF – a model of the geomagnetic main field

- only quiet days are considered
- external contributions are removed to the most possible extent
- sources are considered solely internal
  $\Rightarrow$ magnetic field at and above the Earth's surface is a potential field
- the magnetic field potential is expanded in spherical harmonics
  up to year 2000 with order and degree 10
  after year 2000 with order and degree 13
- the coefficients of the expansion are updated every 5 years
  in order to account for the secular variation




IGRF 1980 based on MAGSAT data

total field strength




IGRF 2000 based on Ørsted data

total field strength

# Geomagnetic and magnetospheric field models

(1) IGRF geomagnetic model

(2) Tsyganenko magnetospheric model

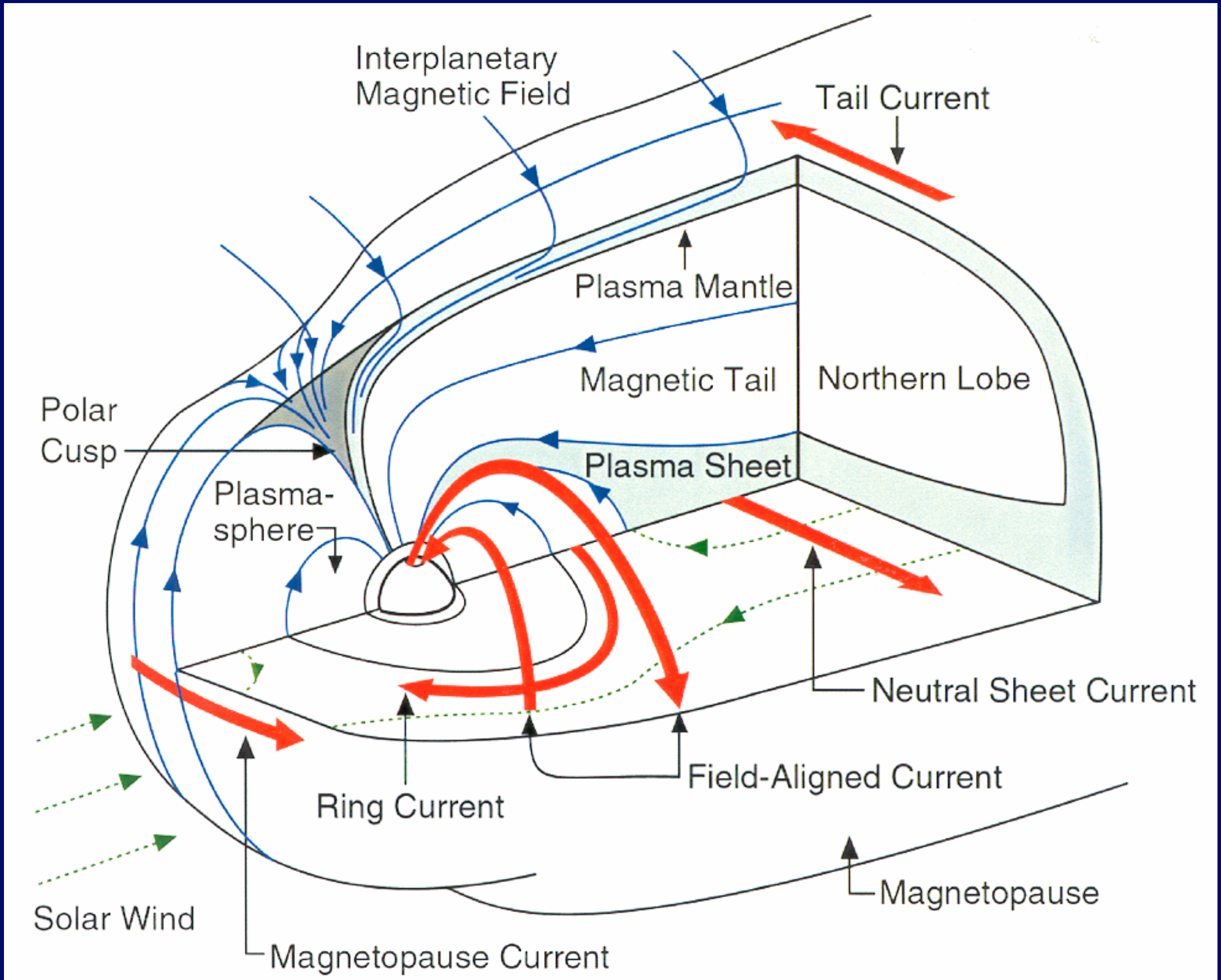
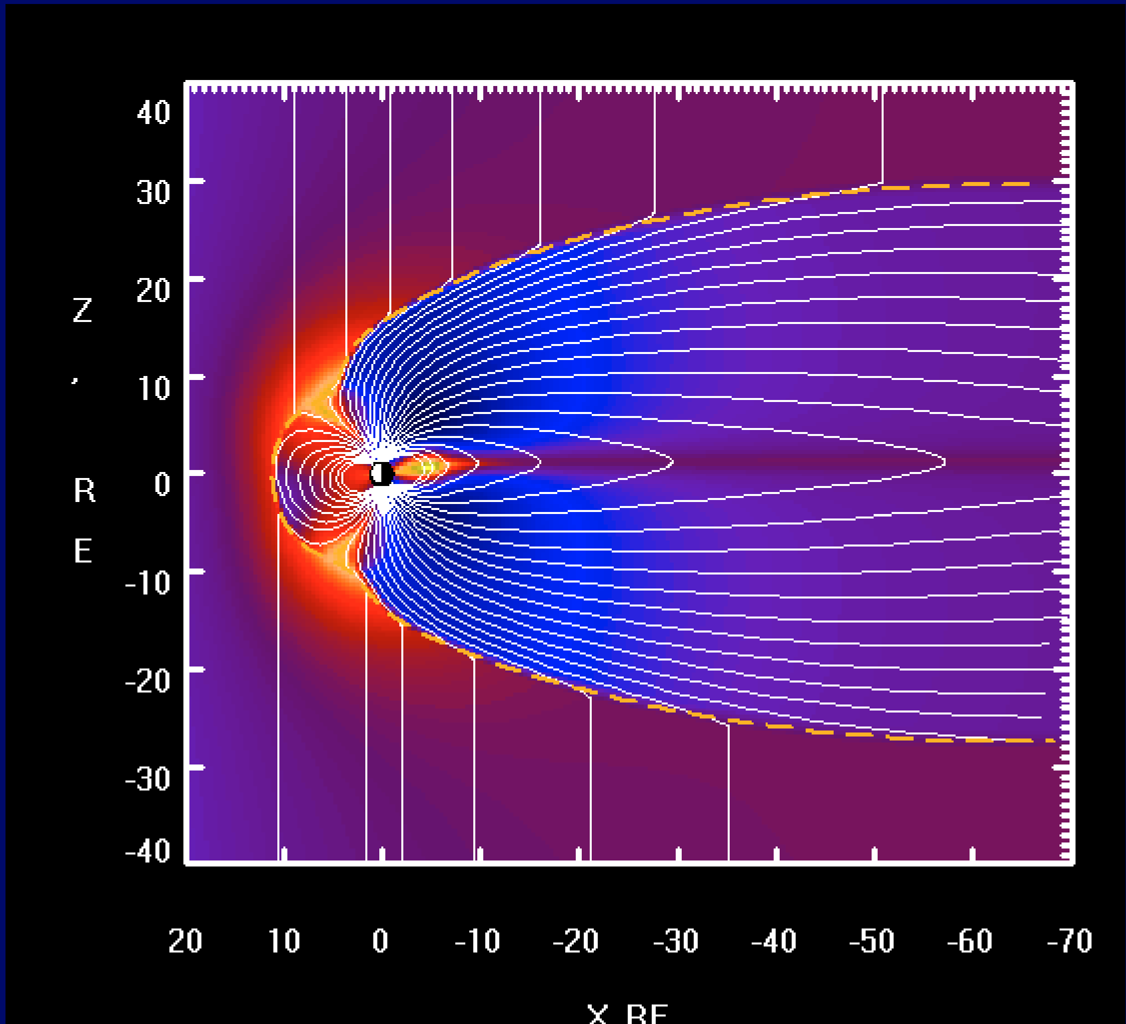


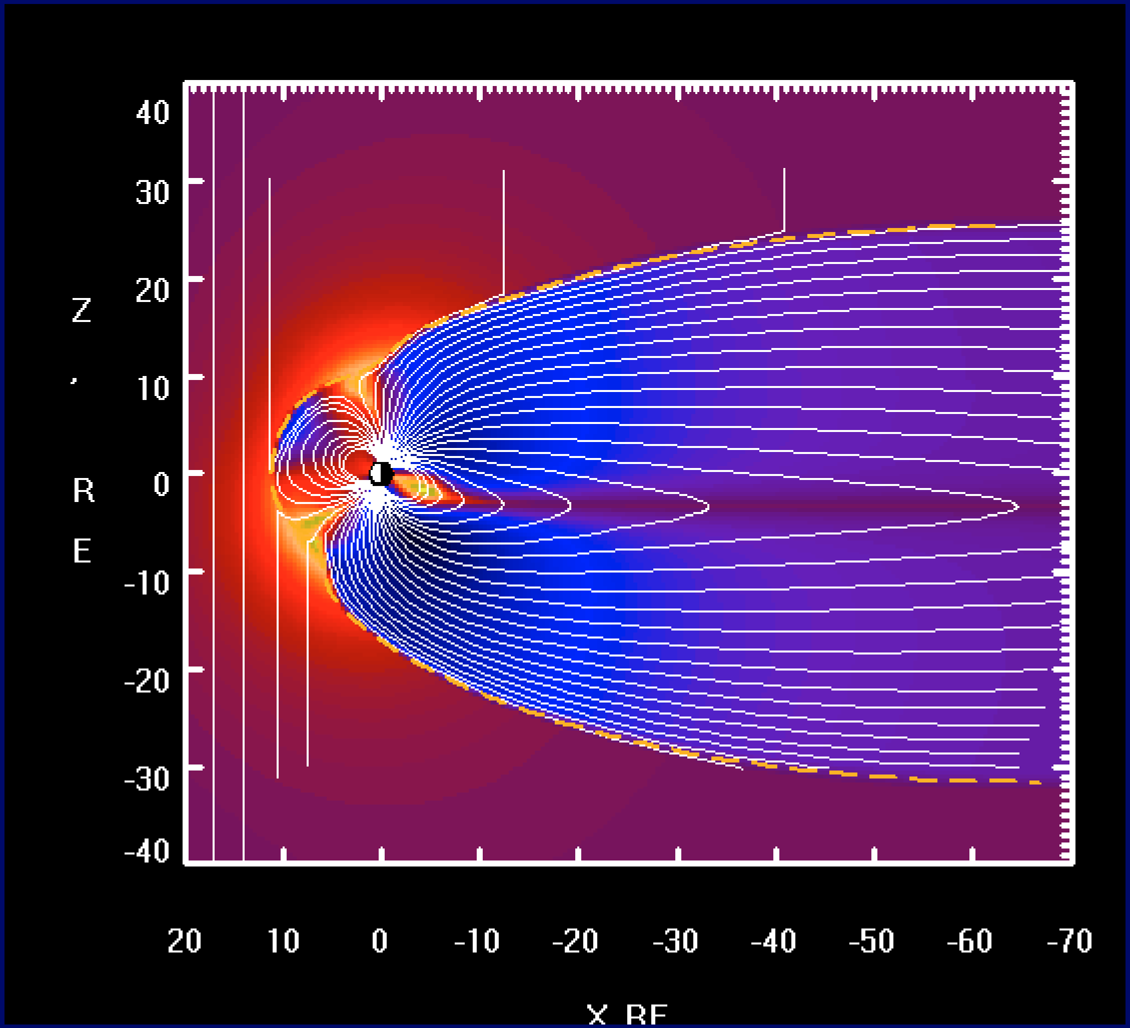

*Figure from "Report from the first Geospace Environment Modeling (GEM) Campaigns: 1991-1997"*

# Tsyganenko 95 model




*Animation by N. Tsyganenko*

# Tsyganenko 95 model




*Animation by N. Tsyganenko*

## IAGA approved magnetic indices

for monitoring magnetospheric and ionospheric electric currents

description available at the ISGI home page

http://www.cetp.ipsl.fr/~isgi/homepage1.htm

# Dst

## quantitative magnetic storm index (physical unit nT)

« Storm is an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere system, to an intensified ring current strong enough to exceed some key threshold of the quantifying storm time index Dst. »

*Gonzalez et al., 1994*

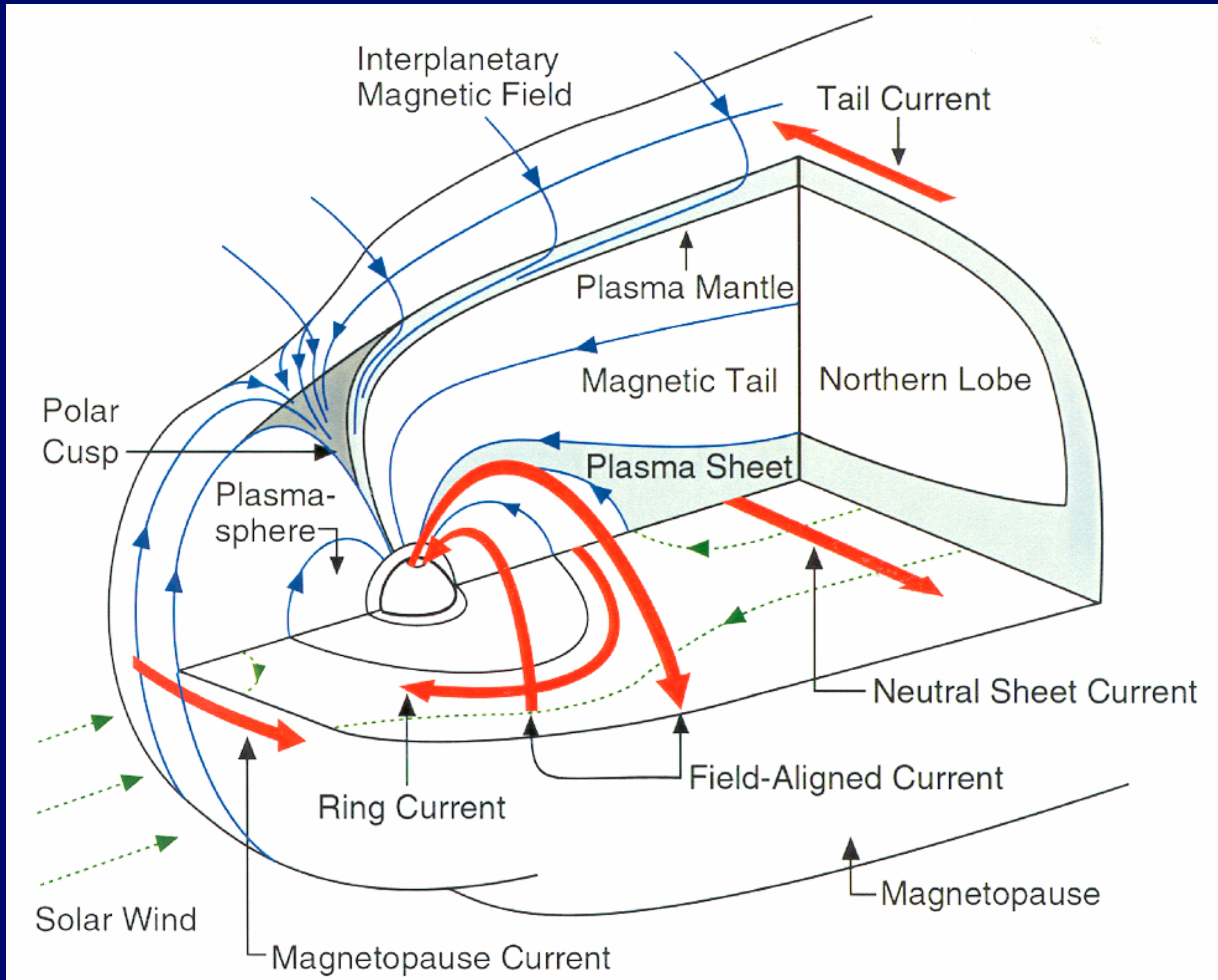



*Figure from "Report from the first Geospace Environment Modeling (GEM) Campaigns: 1991-1997"*

# Details of the Dst index

Objective:

quantify the axisymmetric magnetic field of magnetospheric currents (primarily the ring current, secondarily magnetopause currents)

Contributors:

four low-latitude (but not equatorial) observatories

Physical quantity:

deviation of the horizontal magnetic field component from reference level

Reference level:

quasi-static internal geomagnetic field plus Sq (solar quiet) variation

Method of derivation:

(1) at each station: $D_k$ = hourly mean of $\Delta H_k$

(2) Dst = {mean of $D_k$ (k=1,...,4)} / {mean of $\cos(dip_k)$}

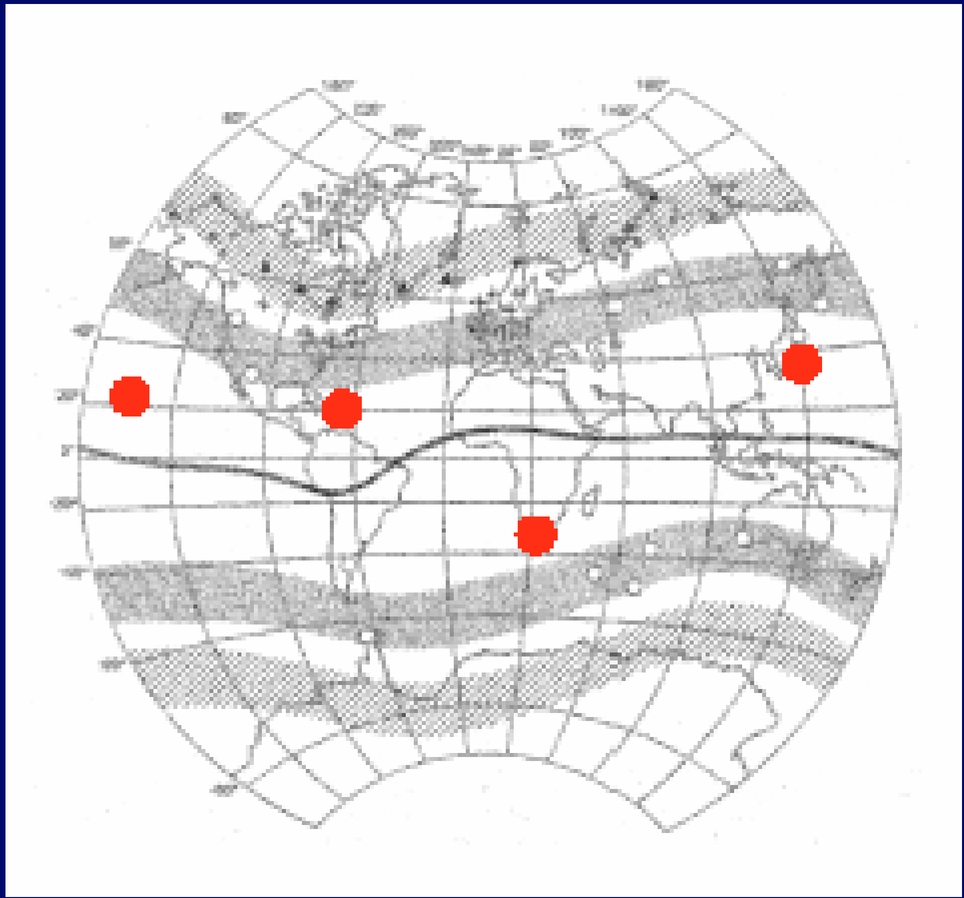
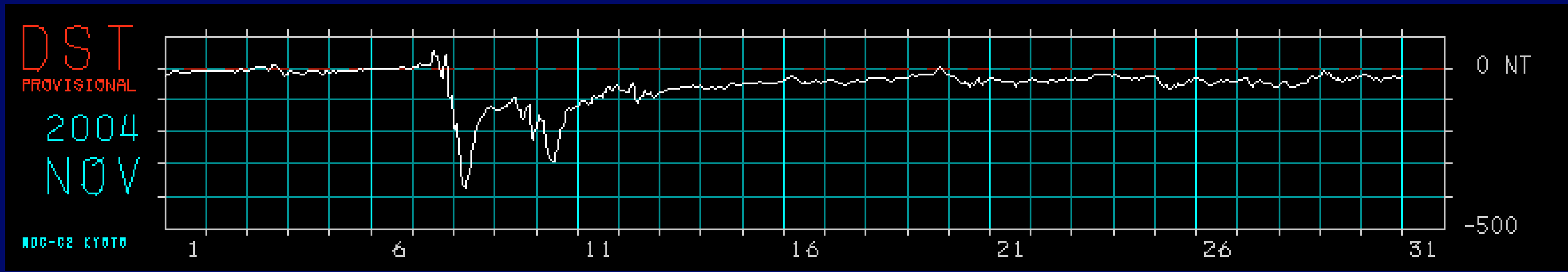


*Figure from Menvielle and Marchaudon (2006)*
*"Geomagnetic Indices in Solar-Terrestrial Physics and Space Weather"*

# Provisional Dst

*provided by the World Data Center for Geomagnetism Kyoto (courtesy of T. Kamei)*

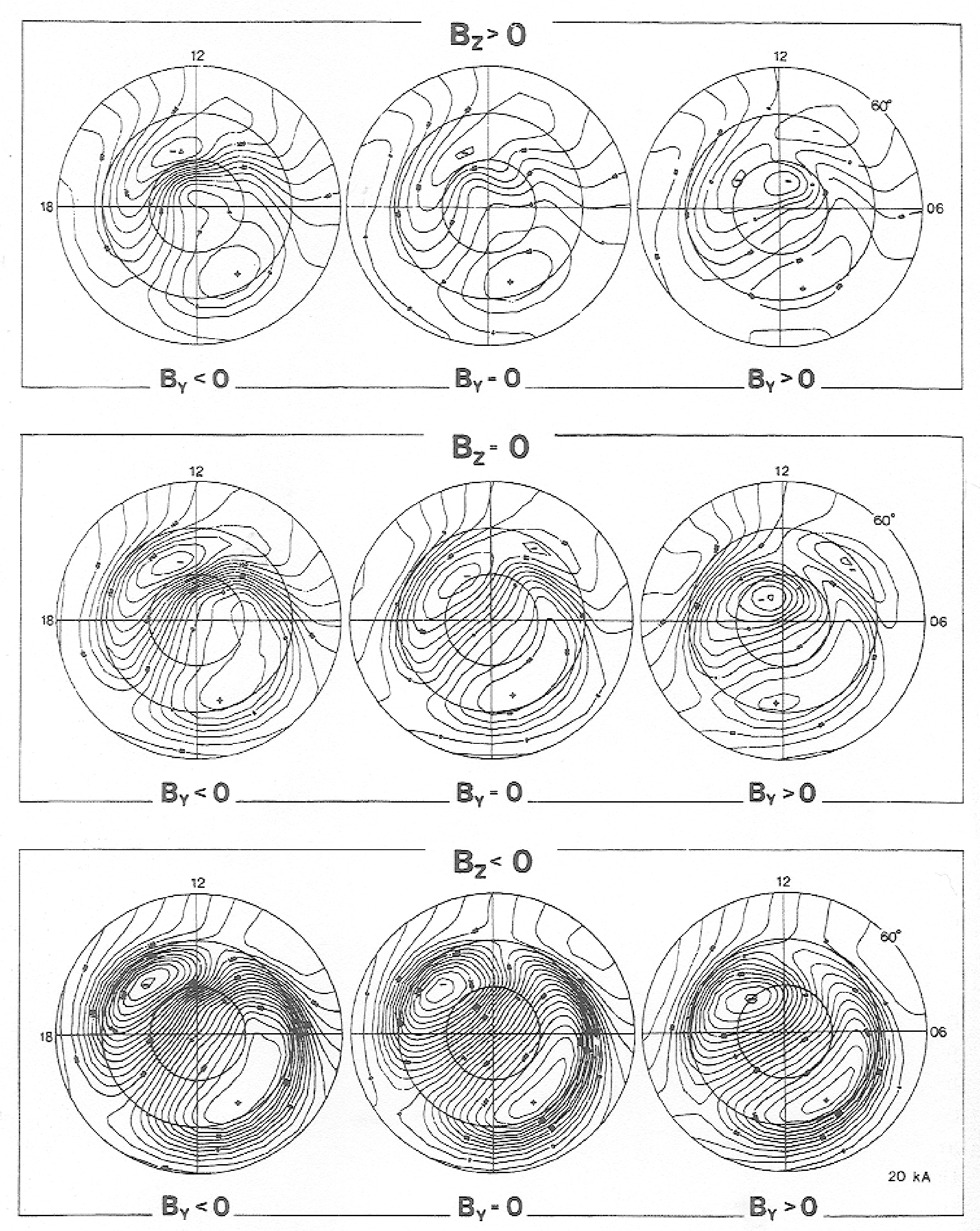



| Storm strength | Dst exceeds |
|---|---|
| severe (super storm) | -200 nT / -250 nT |
| intense (strong) | -100 nT |
| moderate | -50 nT |

# AE (AU, AL, A0)

## quantitative auroral activity index (physical unit nT)

The AE group of indices monitors the enhancement of the global auroral ionospheric currents (electrojets) which are mostly associated with magnetosphere-ionosphere coupling through field-aligned currents (R1 and R2 currents).




Equivalent ionospheric currents for various combinations of the interplanetary magnetic field components $B_z$ and $B_y$

*Figure from Friis-Christensen (1985)*

# Details of the auroral activity indices

**Objective:**

quantify the magnetic field of the auroral electrojets
(AU signifies the eastward and AL the westward current)

**Contributors:**

11 observatories in the nominal northern auroral zone

**Physical quantity:**

deviation of the horizontal magnetic field component from reference level

**Reference level:**

quasi-static internal geomagnetic field plus Sq (solar quiet) variation

**Method of derivation:**

AU = largest ΔH recorded at the contributing stations (1-min mean)
AL = smallest ΔH recorded at the contributing stations (1-min mean)
AE = AU – AL
A0 = (Au + AL) / 2

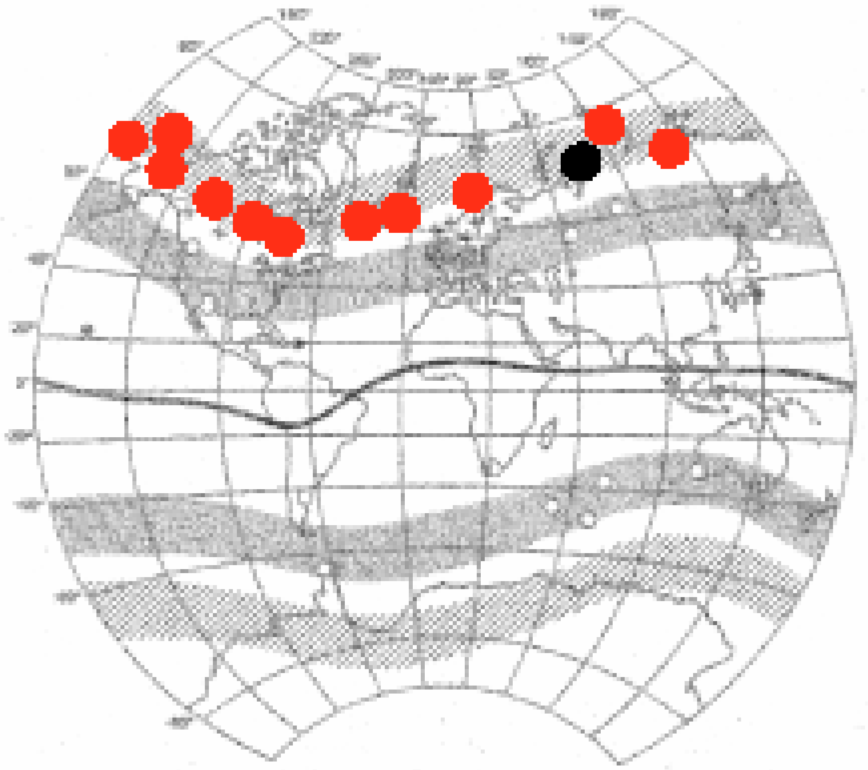
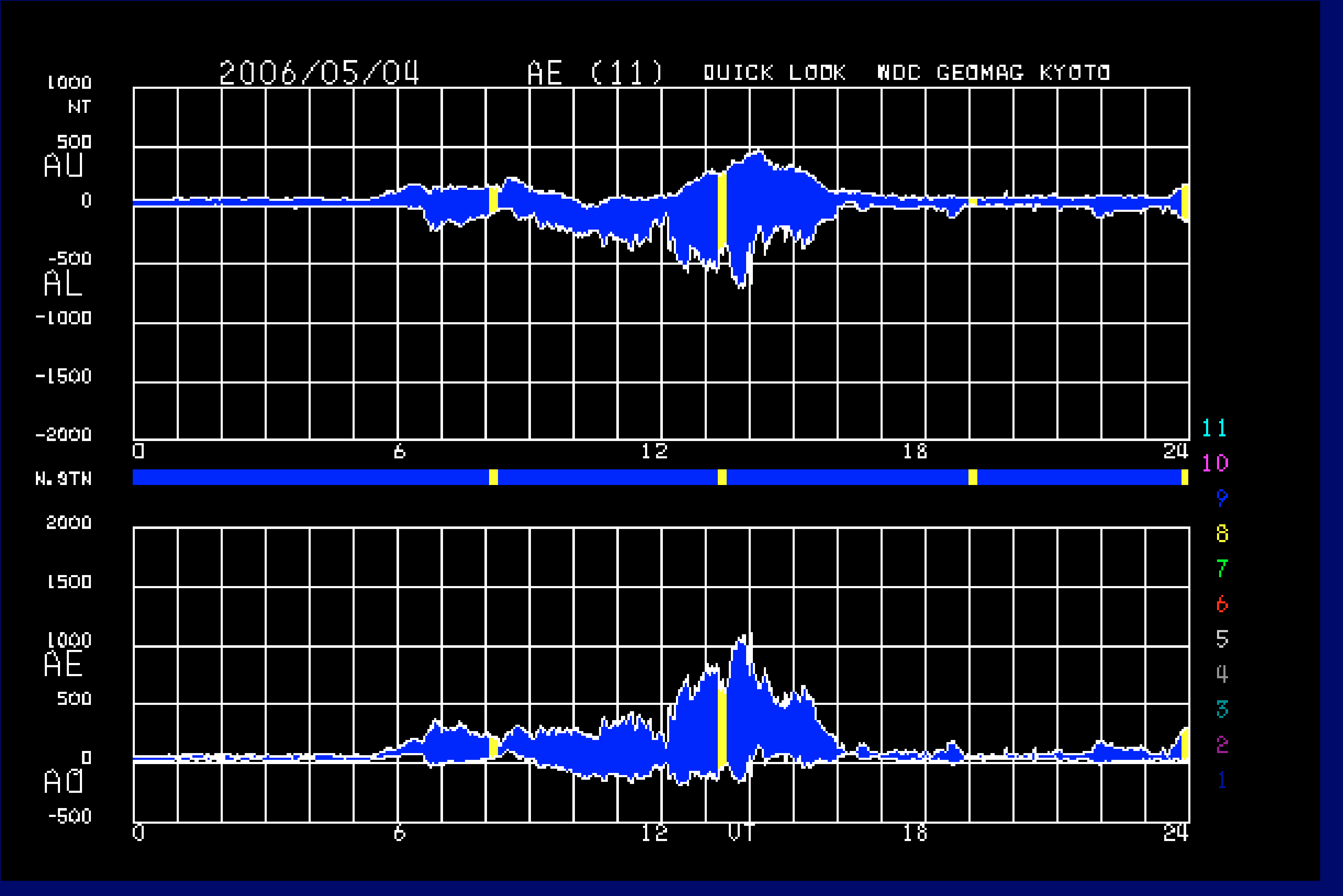


*Figure from Menvielle and Marchaudon (2006)*
*"Geomagnetic Indices in Solar-Terrestrial Physics and Space Weather"*




Real-time (quicklook) Auroral Activity indices

*provided by the World Data Center for Geomagnetism Kyoto (courtesy of T. Kamei)*

# Potential problem

## (in fact, real problem)

When the cross polar cap electric potential is high the auroral oval expands and the centers of the electrojets move equatorward. The AE stations, per definition located in the nominal auroral oval, may in fact be found poleward of the actual auroral oval.

# Kp and related indices

## semi-quantitative global general activity indices

## (K* dimensionless, a* in nT scale)

The Kp group of indices monitors to some extent the overall magnetospheric activity (energy content of the magnetosphere)

# Details of the Kp and related indices

**Objective:**

quantify the overall geomagnetic activity

**Contributors:**

13 observatories at subauroral latitudes (Kp and ap)
23 observatories at subauroral latitudes (Km and related)

**Physical quantity:**

range value of the horizontal magnetic field component

**Reference level:**

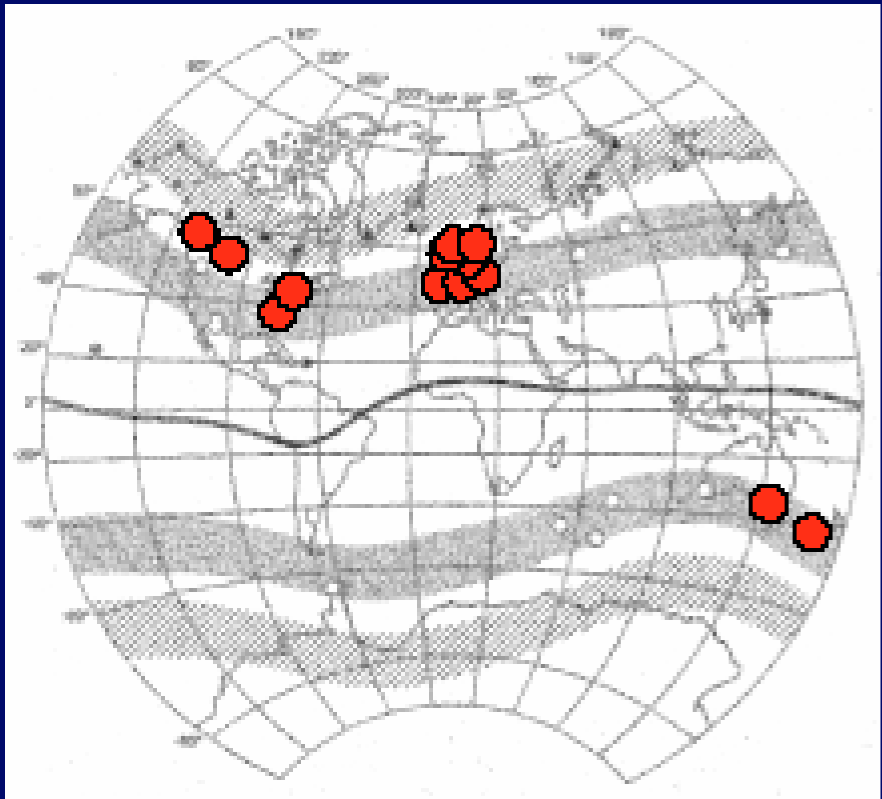
not required but Sq (solar quiet) variation is subtracted

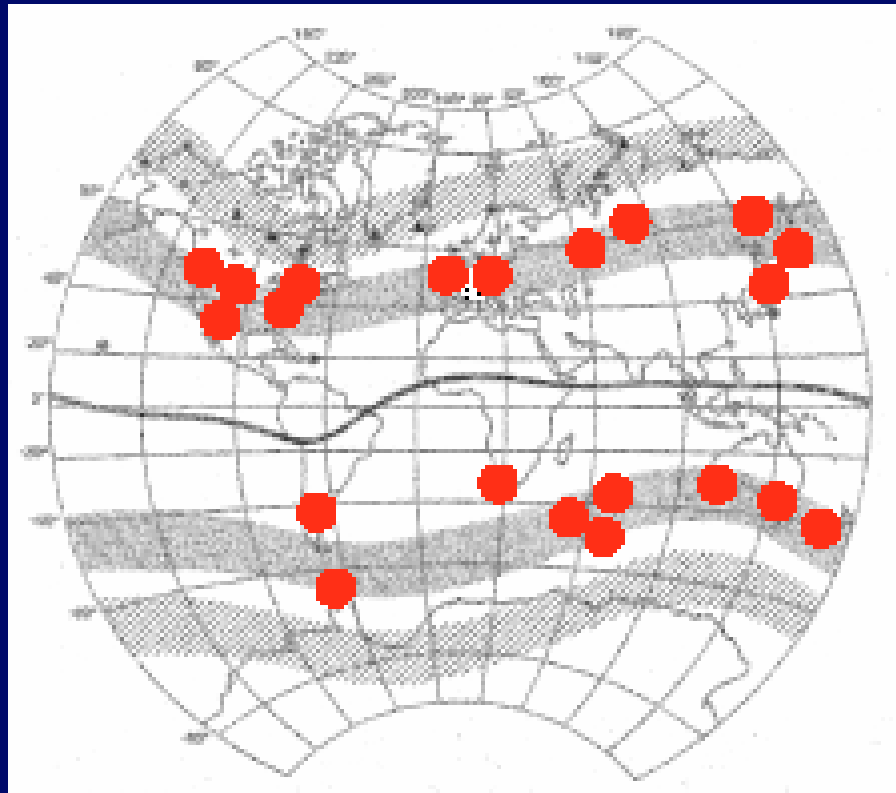
**Method of derivation:**

3-hour range (max–min) of the horizontal magnetic field
a bit awkward since it involves empirical scaling

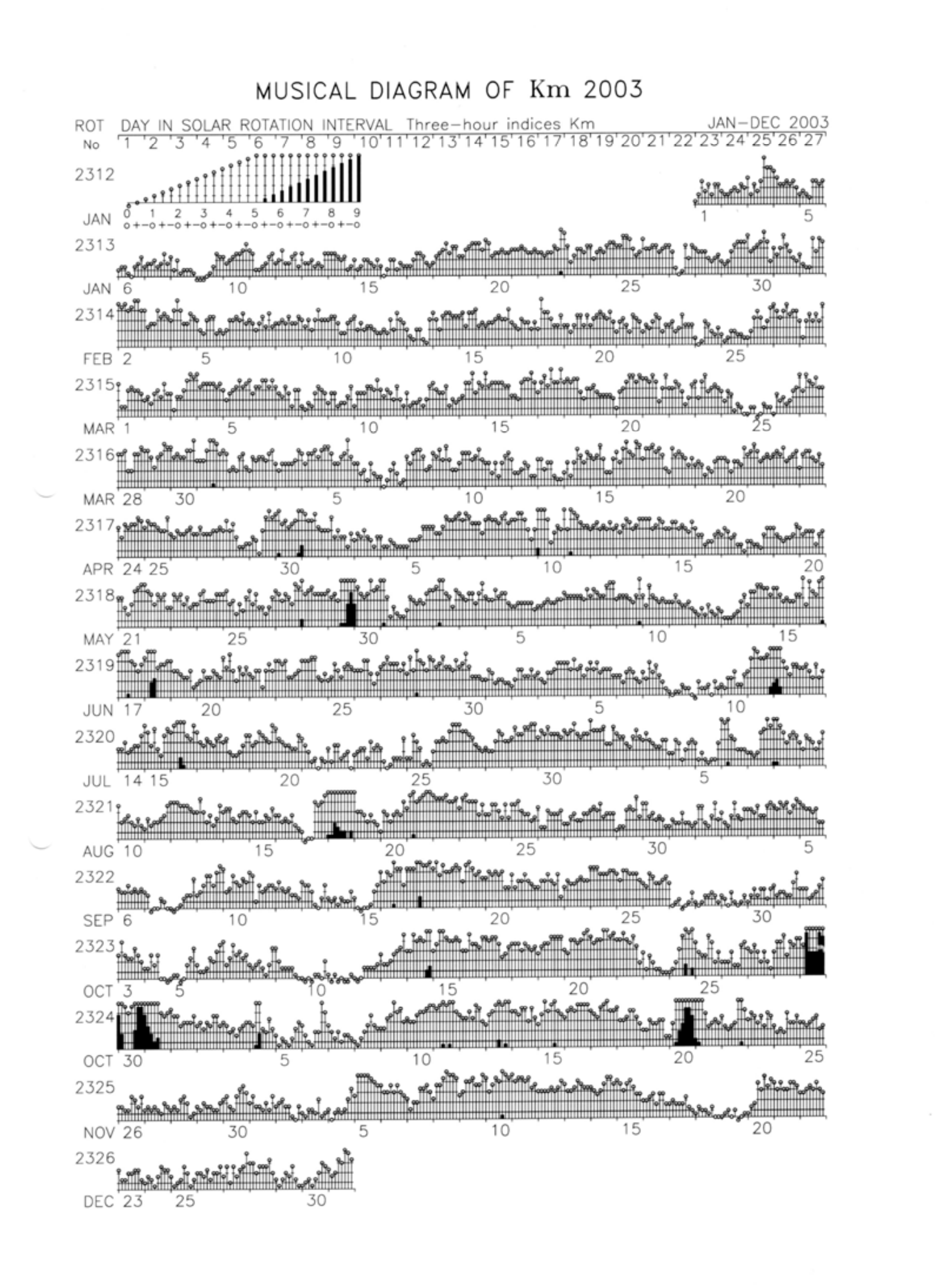
Kp (ap) observatories

Km (an, as, am) observatories





*Figures from Menvielle and Marchaudon (2006)*
*"Geomagnetic Indices in Solar-Terrestrial Physics and Space Weather"*




Km "musical diagram"

*provided by the GFZ Potsdam*

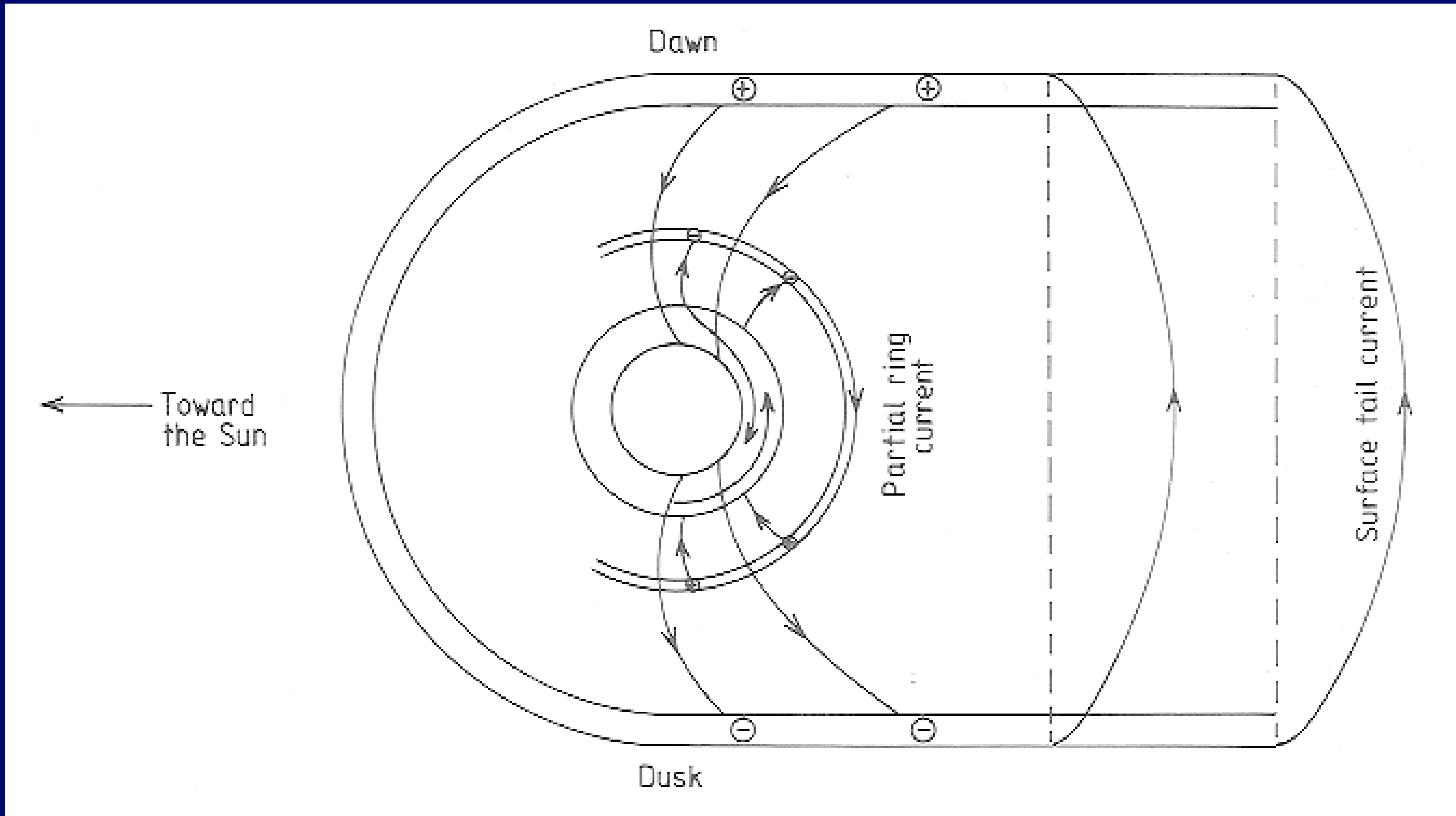
## The Kp group is not well suited for space weather applications

- the indices represent a three-hour interval
- they are range values rather than absolute values
- they possess a maximum class which cannot properly account for extreme events
- the Kp (and ap) indices stem from a very unevenly distributed sites

# Magnetic indices not (yet) IAGA approved

# SYM and ASY

quantitative Dst related indices




Closure of near-Earth magnetospheric current system

*Figure from Brekke "Physics of the Upper Atmosphere" (1997)*

# Details of the SYM-H and ASY-H indices

**Objective:**

improve upon the Dst index through
- increasing the number of stations
- monitoring the symmetric and asymmetric part of the ring current
- increasing te time resolution from 1 hour to 1 minute

**Contributors:**

six low- and mid-latitude observatories resp. observatory pairs

**Physical quantity:**

deviation of the horizontal magnetic field component from reference level

**Reference level:**

quasi-static internal geomagnetic field plus Sq (solar quiet) variation

**Method of derivation:**

as for Dst computation but based on 1-min averages

**Characteristics:**

SYM-H is essentially Dst on a 1-min basis
ASY-H is sensitive to substorms (like AE)

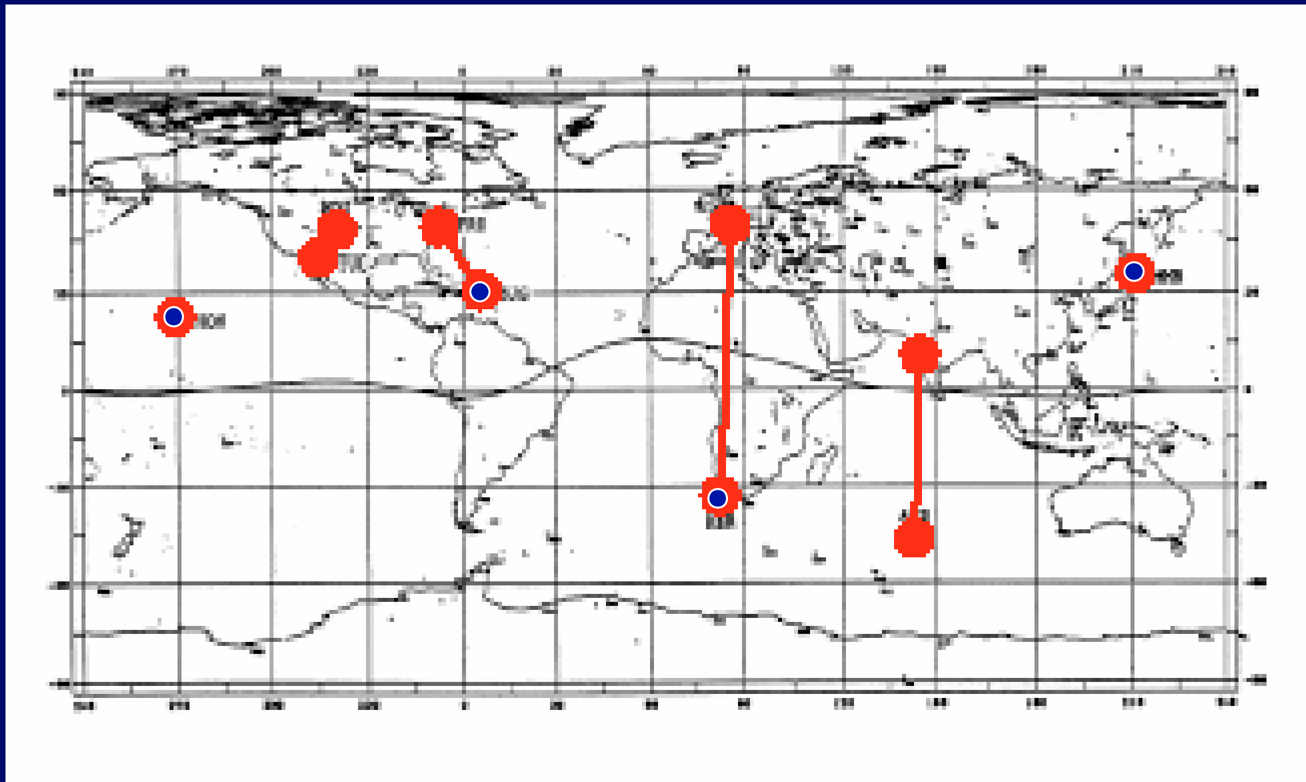
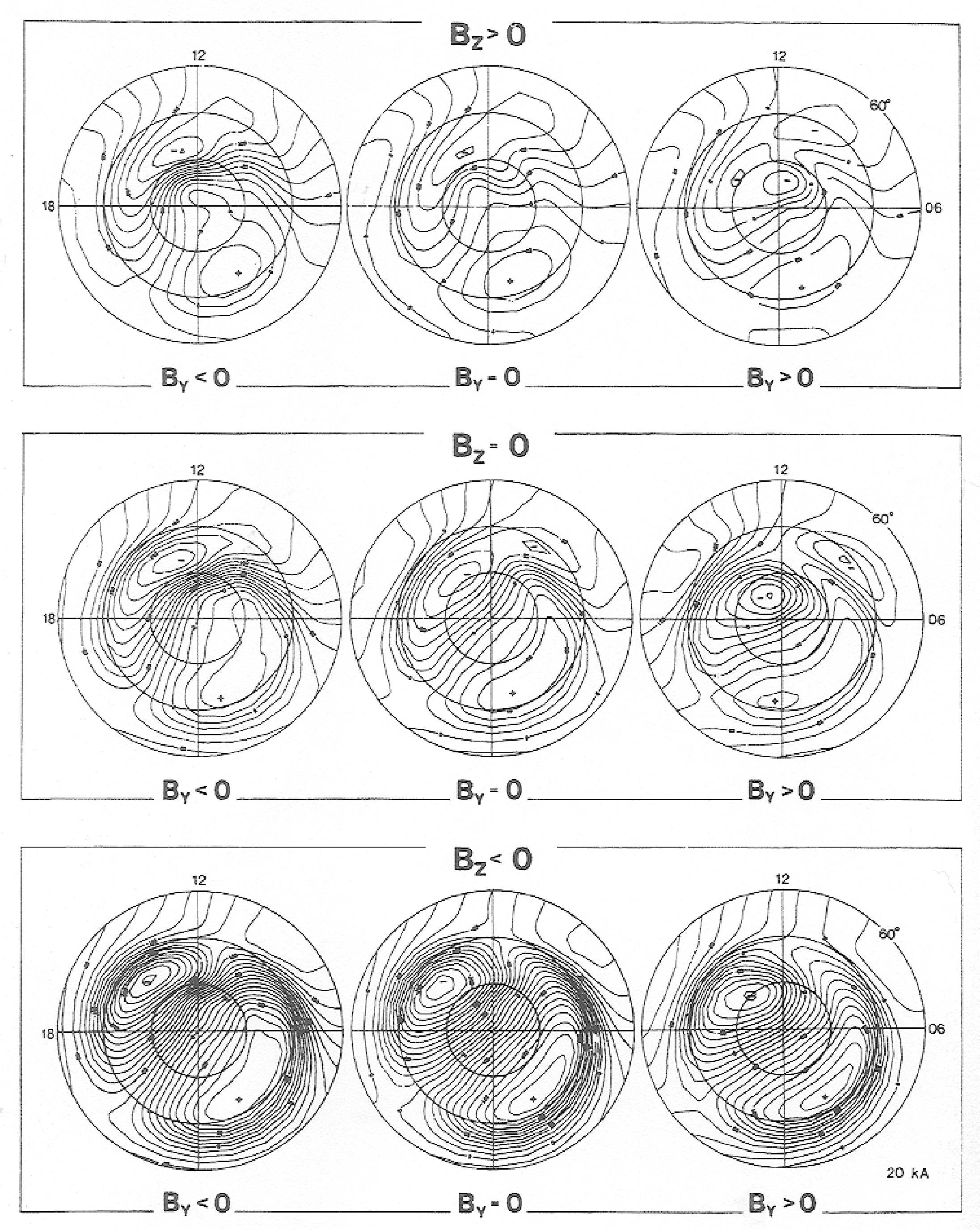


*Figure from Menvielle and Marchaudon (2006)*

*"Geomagnetic Indices in Solar-Terrestrial Physics and Space Weather"*

# PC-North and PC-South

quantitative dimensionless indices




Equivalent ionospheric currents for various combinations of the interplanetary magnetic field components $B_z$ and $B_y$

*Figure from Friis-Christensen (1985)*

# Details of the PC indices

**Objective:**

monitor the cross polar cap ionospheric current

**Contributors:**

two observatories near the geomagnetic north and south poles

**Physical quantity:**

deviation of the horizontal magnetic field component from reference level

**Reference level:**

has been defined in various ways – unified definition under development

**Method of derivation:**

more complicated, several times revised – unified method in preparation

solar wind merging electric field $E_m = v_{sw} (B_y^2+B_z^2)^{½} \sin^2(\theta/2)$

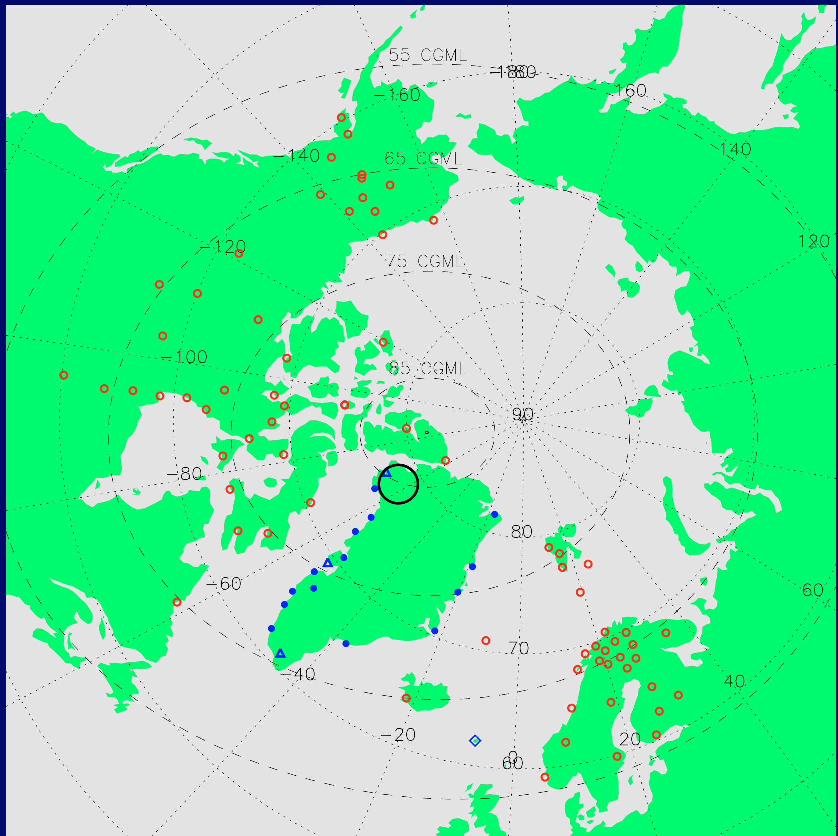
transpolar current magnetic field $\Delta F_{PC} = \Delta H \sin \gamma \pm \Delta D \cos \gamma$

good correlation ($r > 0.8$) $\Delta F_{PC} = \alpha E_m + \beta$

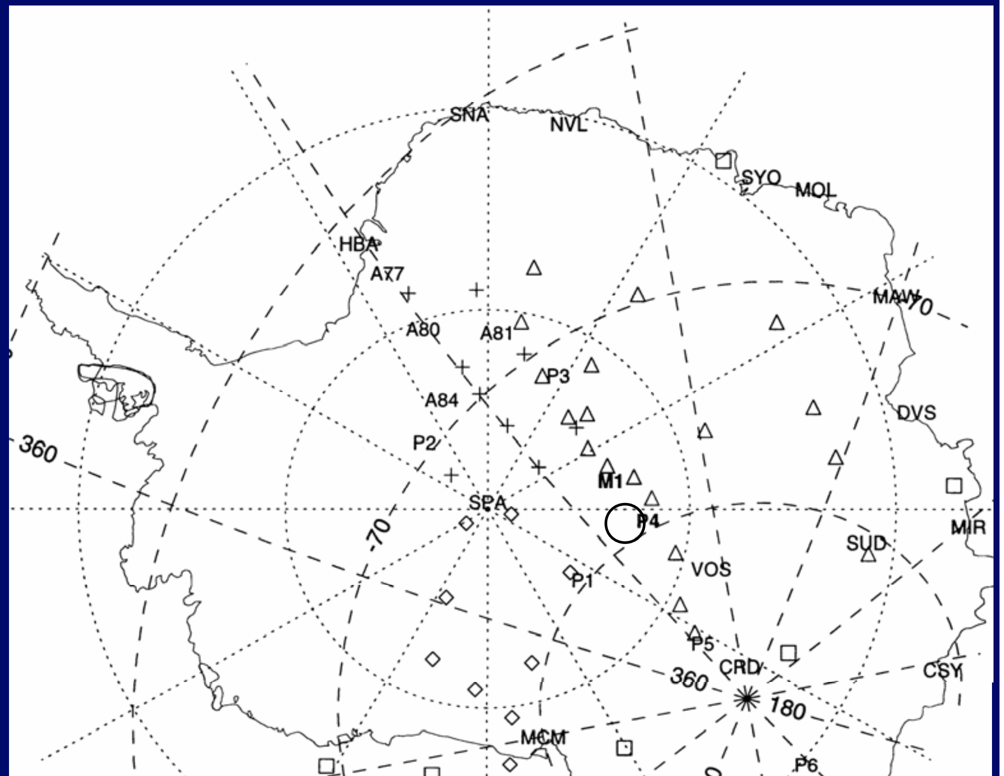
**Characteristics:**

represents in a statistically optimal way the solar wind merging electric field

## Qaanaaq observatory (PC North)




## Vostok observatory (PC South)



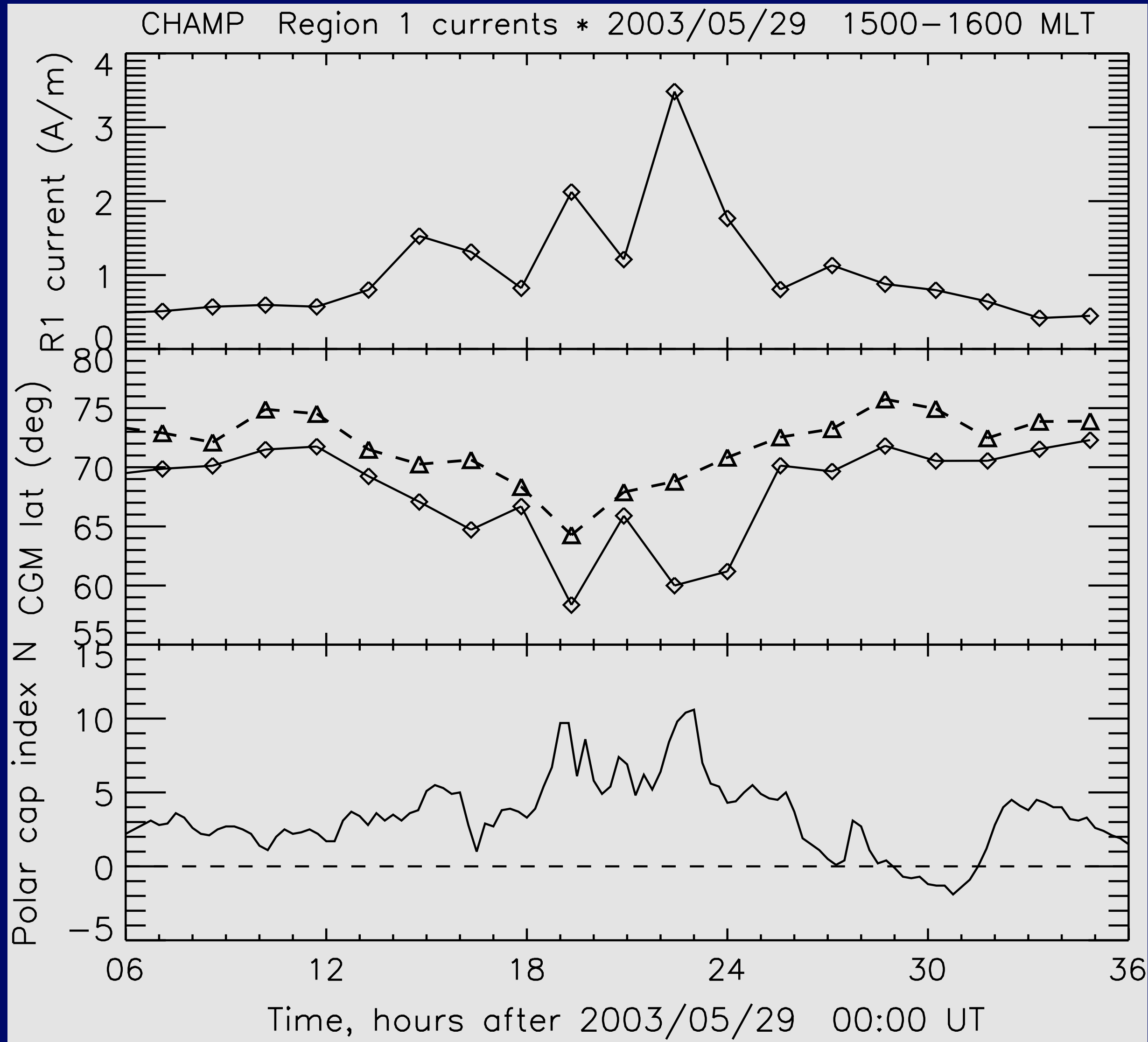



*Figure from Hanuise et al. (2006)*

# Indices: Summary

(1) SYM-H and ASY-H are possibly the most appropriate storm indices for space weather applications. Being relatively recent they are less suitable for long-term studies.

(2) The Kp group of indices is generally not very suitable for space weather purposes although Kp is used a lot – unfortunately.

(3) The high-latitude indices (AE group and PC group) are useful for both space weather research and operational applications