The magnetosphere

- Overview:
  - Geomagnetic field,
  - Geomagnetic dynamo,
  - Topology of the magnetosphere,
  - Plasmas and currents,
  - The open magnetosphere and reconnection,
  - Geomagnetic disturbances,
  - Aurora,
  - Energetic particles in the magnetosphere.

- Pre-requisites:
  - Basics of MHD (dynamo, reconnection, frozen-in fields),
  - Plasma waves.

The terrestrial magnetic field

- The inner field:
  - Originates in a dynamo process inside the outer core,
  - Close to the surface described by as a dipole or a multipole,
  - Variable in magnitude and direction (even on historical time scales),
  - Polarity reversals approximately all 500 000 years.

- The outer field:
  - Originates in current systems in the ionosphere and magnetosphere,
  - Daily variations due to the asymmetry of the magnetosphere are superposed on variations on time scales from seconds to solar cycles and even longer.

Geomagnetic coordinates I

- Inclination between dipole axis and axis of rotations,
  - Geomagnetic coordinates Λ and Φ,
  - Geographic coordinates λ and φ,
  - Magnetic south pole: φo = 78.3°N, λo = 291°E

$$\sin\Phi = \sin\varphi\,\sin\varphi_{\mathrm{o}} + \cos\varphi\cos\varphi_{\mathrm{o}}\cos(\lambda-\lambda_{\mathrm{o}}) \qquad \sin\Lambda = \frac{\cos\varphi\sin(\lambda-\lambda_{\mathrm{o}})}{\cos\Phi}$$

- Geomagnetic potential $V = \frac{\mu_{\mathrm{o}}}{4\pi}\frac{\vec{M}_{\mathrm{E}}\cdot\vec{r}}{r^3} = -\frac{\mu_{\mathrm{o}}}{4\pi}\frac{M_{\mathrm{E}}\sin\varphi}{r^2}$

- Gives magnetic field $\vec{B} = \frac{\mu_{\mathrm{o}}}{4\pi}\frac{M_{\mathrm{E}}}{r^3}\left(-2\sin\Phi\,\vec{e}_{\mathrm{r}} + \cos\Phi\,\vec{e}_{\Phi}\right)$

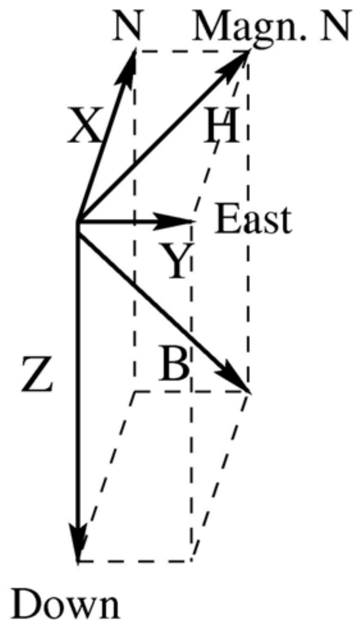
- And flux density: $B = \sqrt{B_{\mathrm{r}}^2 + B_{\Phi}^2} = \frac{\mu_{\mathrm{o}}}{4\pi}\frac{M_{\mathrm{E}}}{r^3}\sqrt{1+3\sin^2\Phi}$

- Field at the surface:

$$B_{\Phi} = B_{\mathrm{E}}\cos\Phi \qquad \text{and} \qquad B_{\mathrm{r}} = 2B_{\mathrm{E}}\sin\Phi \qquad B_{\mathrm{E}} = \frac{m_{\mathrm{o}}M_{\mathrm{E}}}{(4\pi R_{\mathrm{E}})^3} = 3.11\times10^{-5}\ \mathrm{T}$$

Geomagnetic coordinates II

- Cartesian coordinates XYZ:
  - x points towards the north,
  - y points towards the east,
  - z points vertically.
- Cylindrical coordinates DHZ:
  - Z vertical intensity (Br),
  - H horizontal intensity (Bφ),
  - D declinations.
- Spherical coordinates BID:
  - B total intensity,
  - D declination,
  - I inclination.



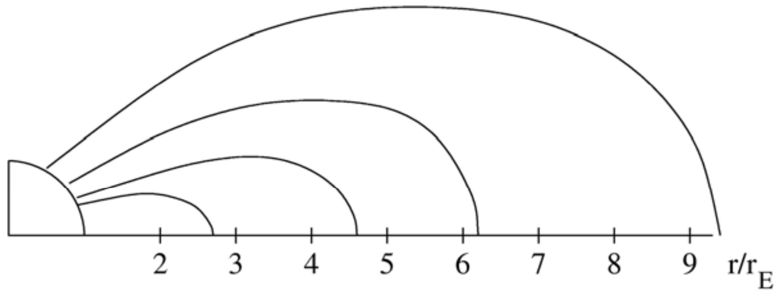
Dipole field line

- Last equation on slide 3 yields $\frac{B_\Phi}{B_r} = \frac{r d\Phi}{dr} = \frac{1}{2\tan\Phi}$ and thus for the field line

$$\frac{dr}{r} = 2d\Phi \tan\Phi = \frac{2\sin\Phi}{\cos\Phi} d\Phi = 2\frac{d(\cos\Phi)}{\cos\Phi}$$

Integration

$$r = r_{eq} \cos^2\Phi$$



- Definition L-shell: distance of the field line t the equator from the center of the Earth in units of earth radii:

$$B(L_o, \Phi) = \frac{B_E}{L_o^3} \frac{\sqrt{1+3\sin^2\Phi}}{\cos^6\Phi}$$

Physics: during its motion the guiding center of a particle stays on a fixed L-shell

Multipole expansion

- More adequate description of the field close to the surface due to multipole expansion

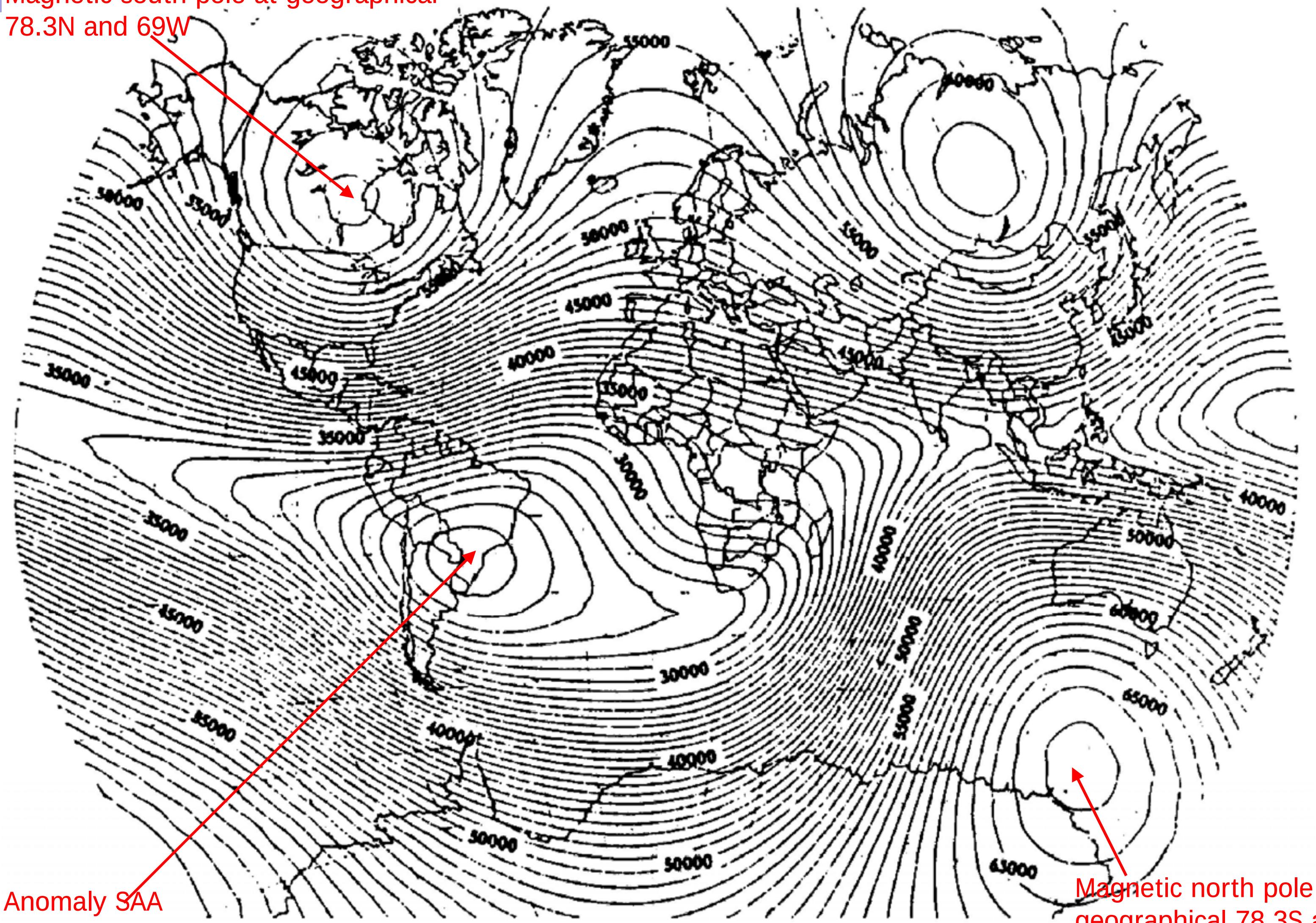
$$V(r) = \sum_{n=1}^{\infty} \frac{r_{\mathrm{E}}}{r^{n+1}} \sum_{m=0}^{n} \{g_n^m \cos(m\varphi) + h_n^m \sin(m\varphi)\} P_n^m(\cos\theta)$$

with

  - g, h for normalization and
  - P as Legendre coefficients.

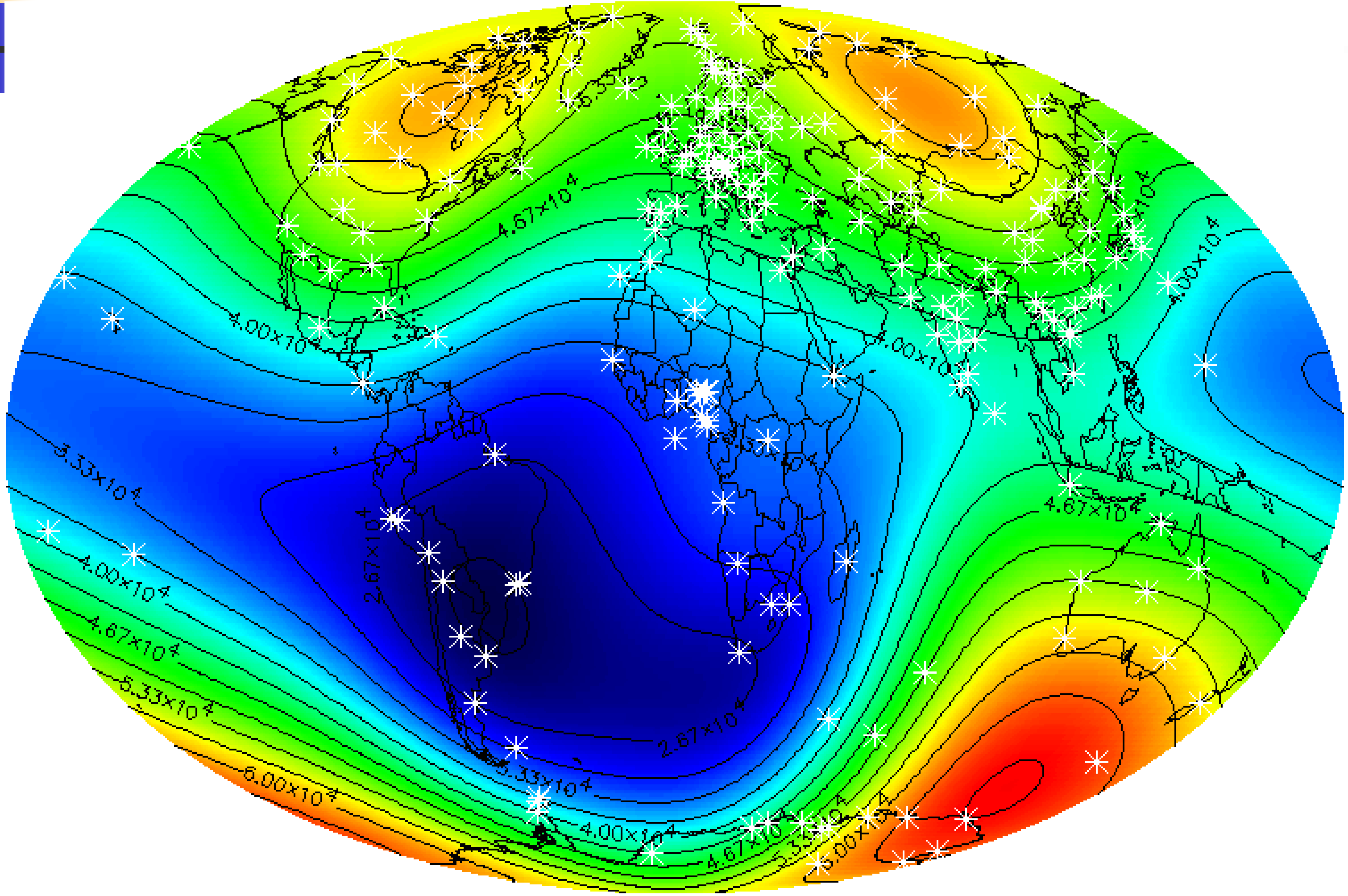
- Accuracy close to the surface better than 0.5%.

Geomagnetic reference field



IAGA, 1985, EOS 67, see als www.agu.org/eos_elec/000441e.html

IGRF Observatories

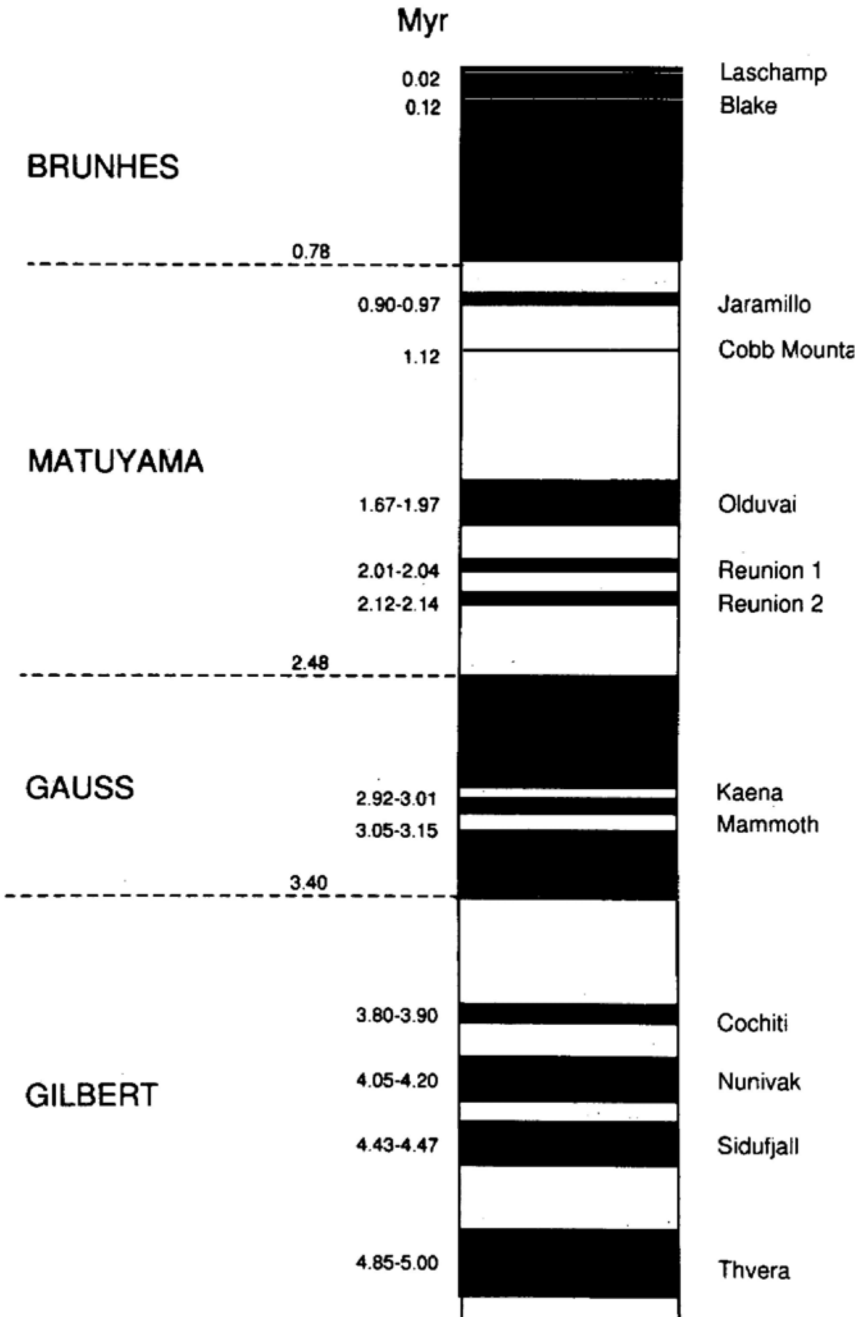


http://www.ngdc.noaa.gov/seg/geomag/icons/Obs1999_lg.gif

- For models see: http://www.ngdc.noaa.gov/seg/geomag/models.shtml

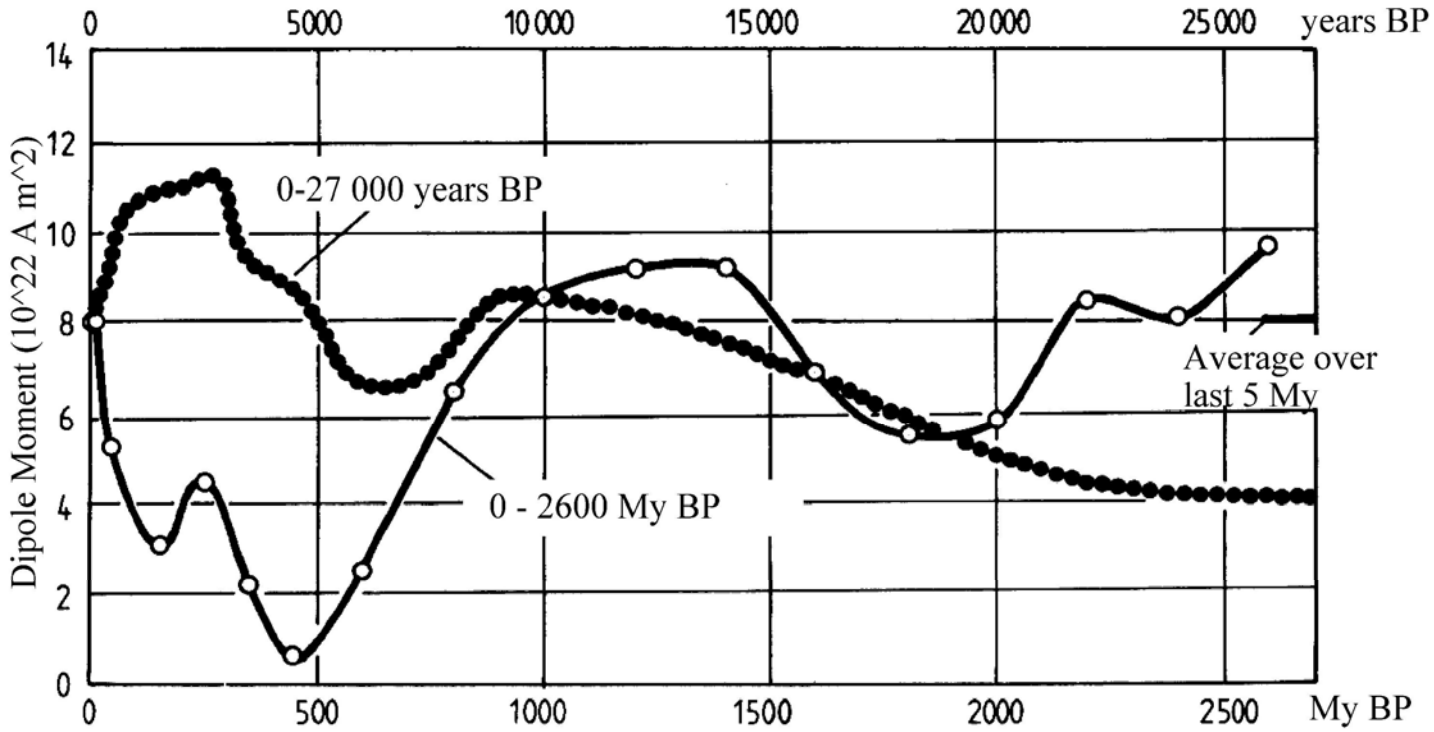
Polarity reversals

- Polarity reversals with highly variable temporal spacing.
- Average duration between two reversals 500 000 years.
- Last reversal about 30000 a ago.
- Additional short episodes of reversed fields (magnetic events) on time scales of a few 1000 years.
- Reversals accompanied by mass extinction and climate change.



Gubbins, 1994, Rev. Geophys. 32, 61

"Short-term" variations



Strohbach,1991, Unser Planet Erde, Borntraeger

- Magnitude of the field variable even at times of constant polarity.
- 2000 years ago: dipole moment 50% larger than present.
- 500 000 years ago: dipole moment less than 10% of the present.

Secular variations

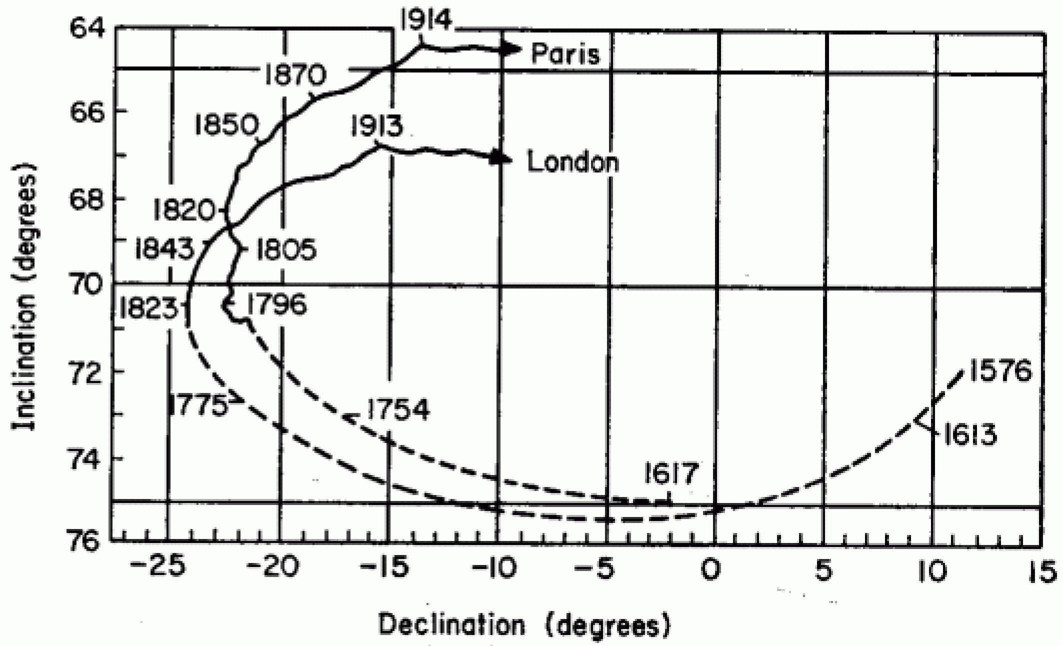


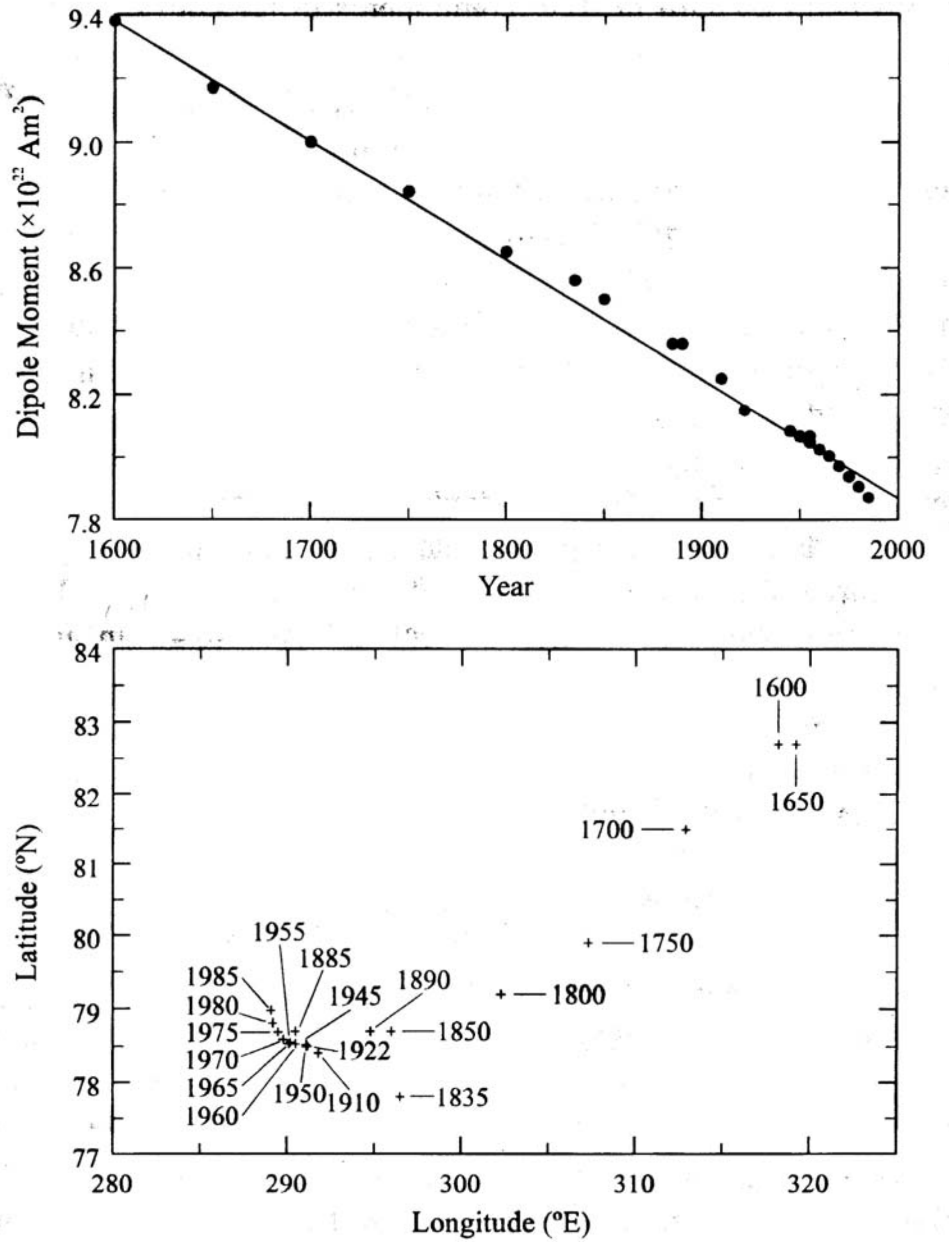
FIGURE 4 Variation of declination and inclination at London and Paris from observatory measurements. After Gaiber-Puertas (1953), *Observ. del. Elso*, Memo. No. 11.

http://geophysics.ou.edu/solid_earth/notes/mag_earth/earth.htm

- Variations in magnitude, declination and inclination at a fixed position.
- Time scales: decades
- Variations can be very different at different positions.

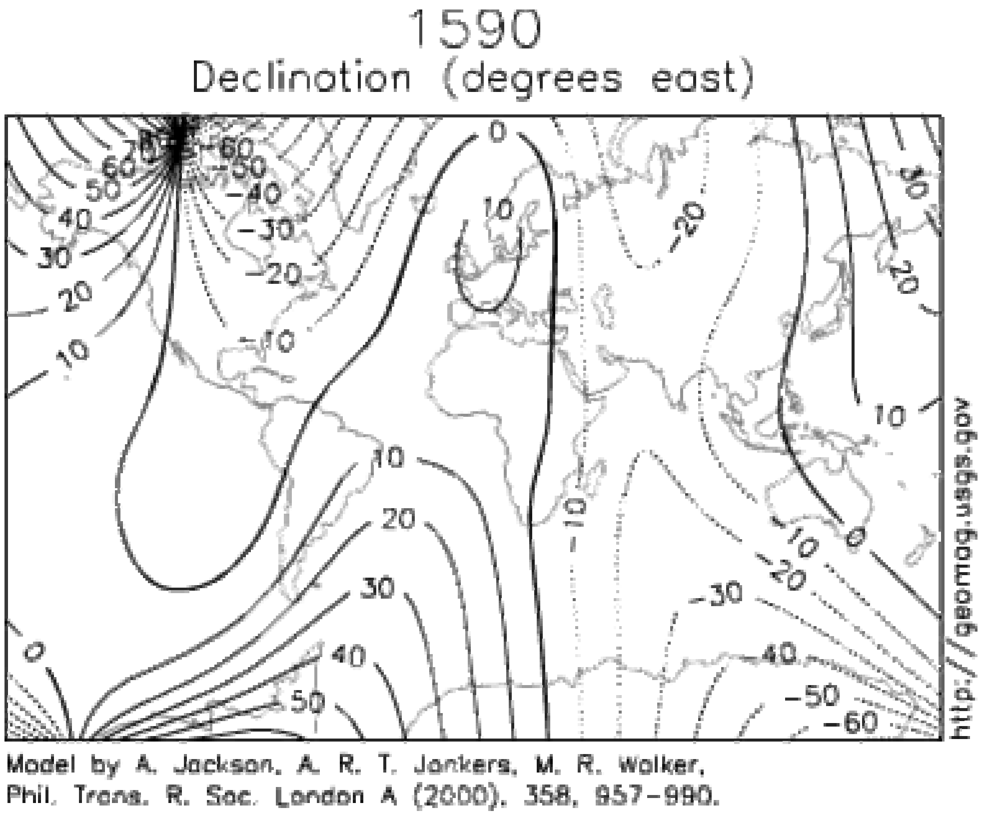
Magnetic field since 1600

- Dipole moment decreases by about 5% per century.
- Decrease since about 1950 faster ($4x10E19\ Am^2/a$, dipole contributions would vanish within 2000 a).
- Between 1600 and 1850 the northern pole has wandered by about 0.08°/a westwards and 0.01°/a southwards.
- Afterwards position of the northern pole relatively stable.



Fraser-Smith, 1987, Rev. Geophys. 25, 1

Evolution of the field declination

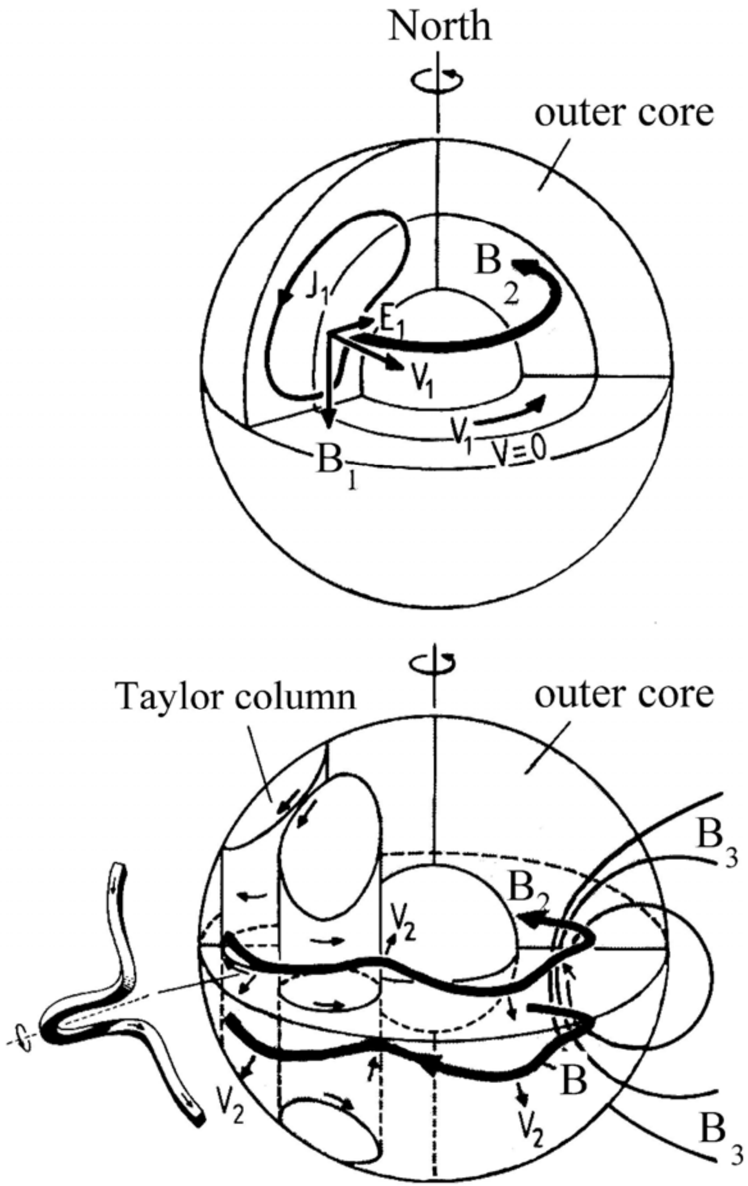


http://geomag.usgs.gov/intro.html

- Mainly due to polar wandering
- Declination at a fixed position can vary by a few 10° during some decades.
- Large and highly variable inclinations predominately close to the magnetic poles.

Geomagnetic dynamo

- Differential rotation between inner and outer core creates a toroidal field.
- Stochastic motion inside the Taylor columns twists the fields and produce a helical field out of the toroidal one.
- The resulting current leads to a dipole field on the surface as observed.

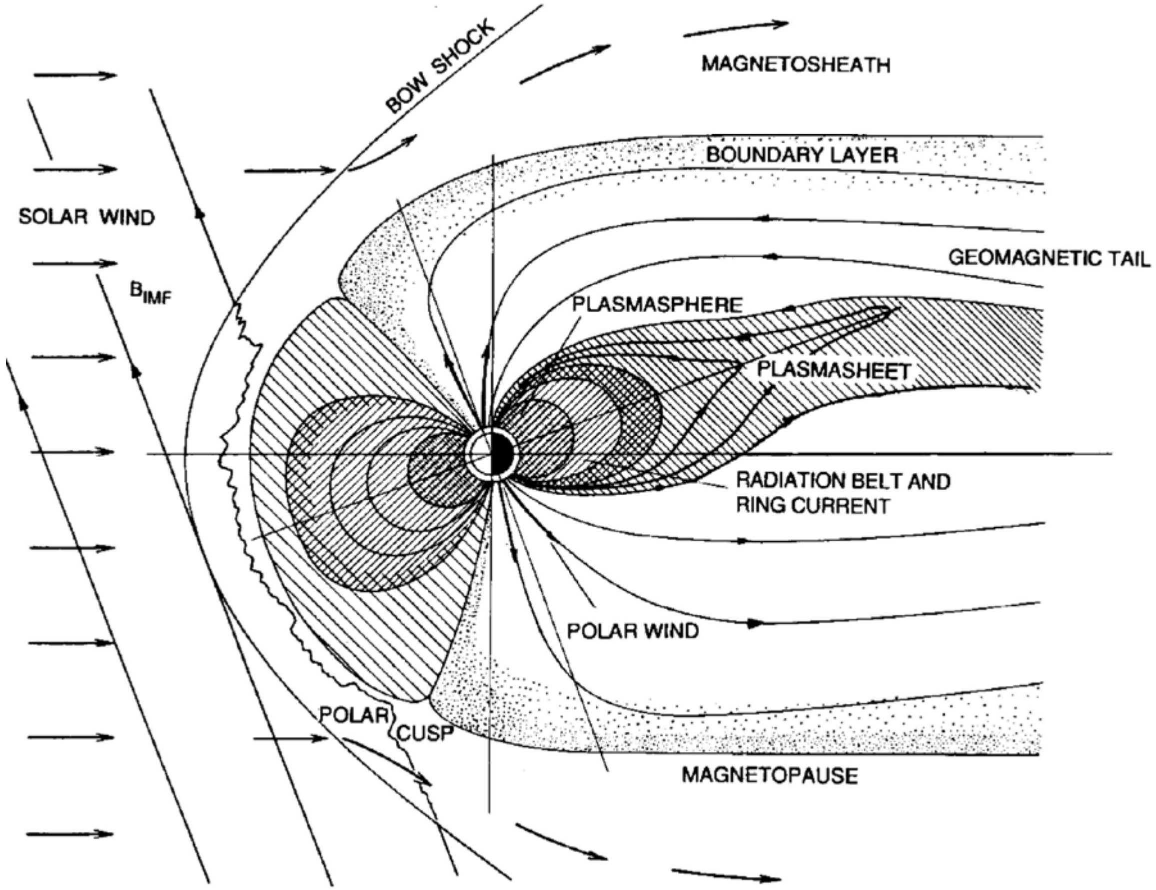


Strohbach,1991, Unser Planet Erde, Borntraeger

Magnetosphere

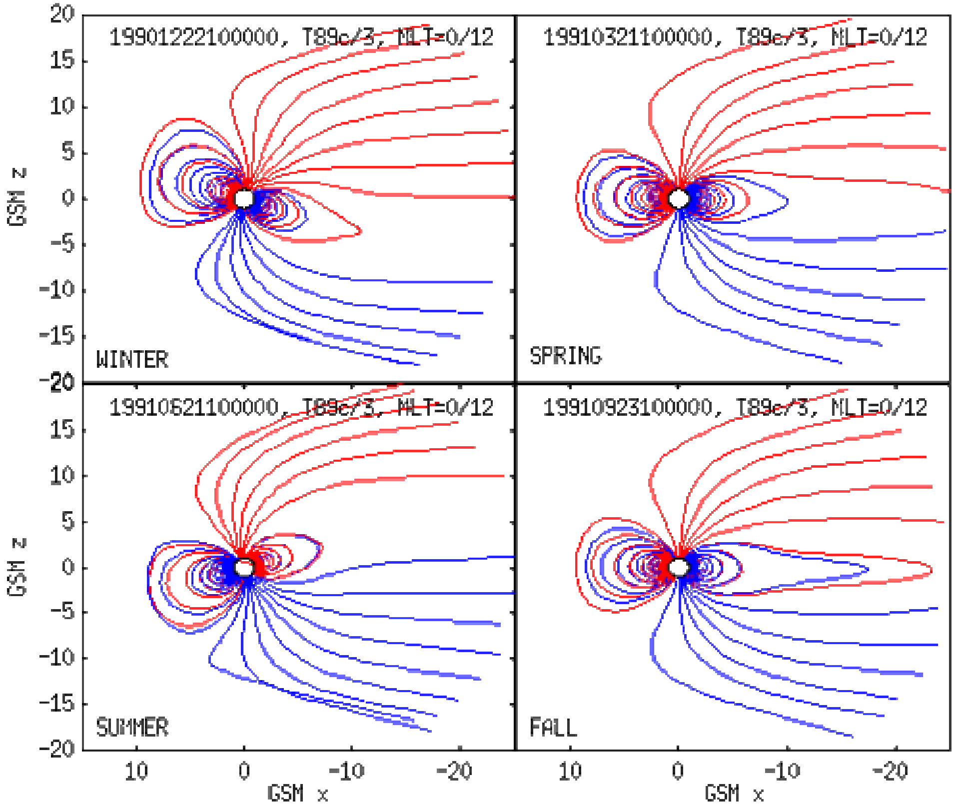
- Topology:
  - Magnetopause,
  - Polar Cusps,
  - Tail,
  - Polar Caps,
  - Magnetosheath,
  - Bow shock.

- Dynamics:
  - Reconnection in the tail and at the dayside,
  - Convection over the polar caps.



Parks, 1991, Physics of Space Plasmas, Addison-Wesley

Seasonal dependence



http://www.oulu.fi/~spaceweb/textbook/bmodels.html

- Earth axis inclined relative to the plane of ecliptic,
- Dipole axis inclined relative to the axis of rotation,
- Daily precession of the dipole axis around the axis of rotation,
- Axis of rotation fixed in space → different average inclinations of the magnetic dipole axis,
- Equinox: dipole axis roughly perpendicular to the plane of ecliptic.

Magnetopause

- Boundary layer between interplanetary and geomagnetic plasmas and fields.

- Equilibrium between the dynamic pressure of the solar wind and the magnetic pressure of the terrestrial field:

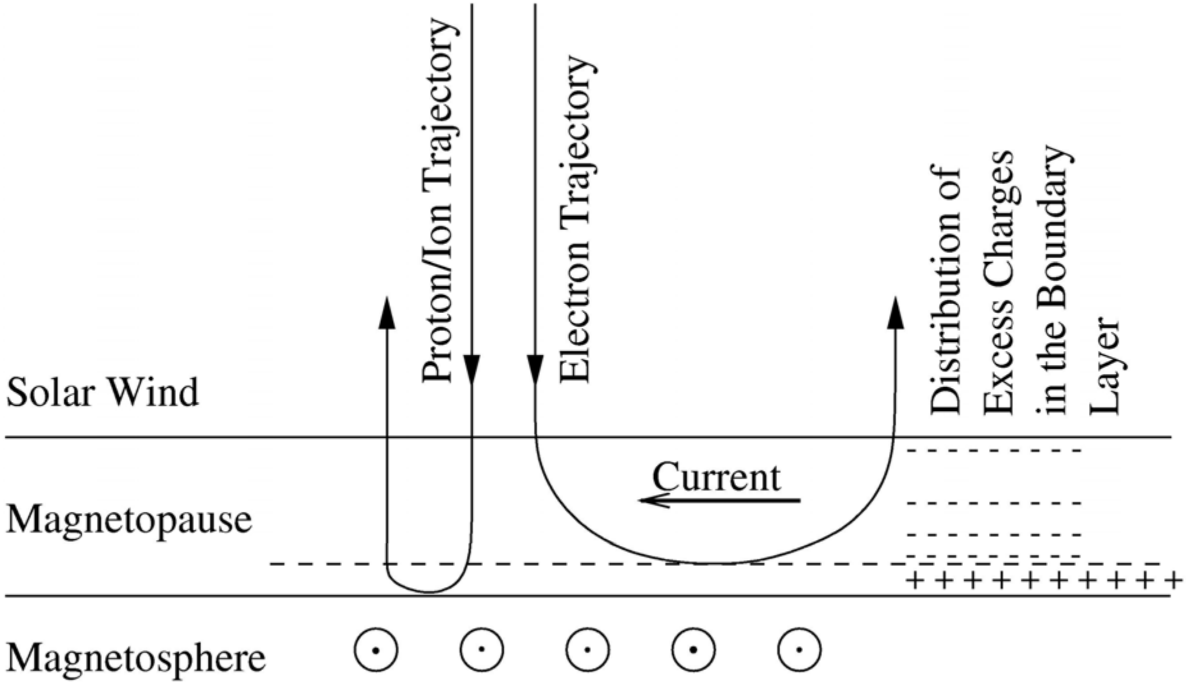
$$2\varrho u_{\mathrm{sowi}}^2 \cos^2\psi = \frac{B_{\mathrm{t}}^2}{2\mu_{\mathrm{o}}}$$

- Standoff-distance of magnetopause along the Sun-earth line:

$$d_{\mathrm{so}} = \sqrt[6]{\frac{4B_{\mathrm{o}}^2}{2\mu_{\mathrm{o}} K \varrho u_{\mathrm{sowi}}^2}}$$

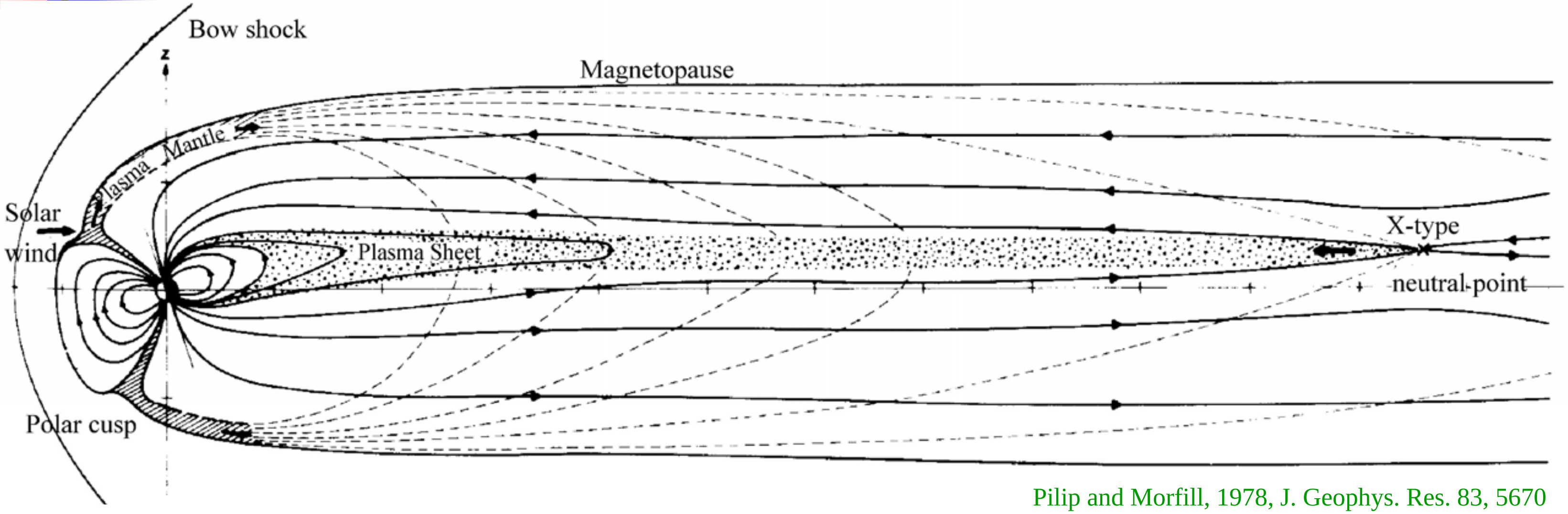
average solar wind conditions: 10 earth radii (variations between 5 and 20 earth radii; speed of the magnetopause up to 600 km/s).

Chapman-Ferraro Current



- Current in the magnetopause due to gradient drift of the solar wind plasma.
- Surplus of positive charges on the dawn and negative charges on the dusk side in low latitudes $\Rightarrow$ dawn-dusk electrical field.
- Different penetration depth of e and p give a polarization field: orbits are elliptical.

Magnetospheric tail



Pilip and Morfill, 1978, J. Geophys. Res. 83, 5670

- Magnetic flux inside the polar cap: integration of the field's vertical component over the cap

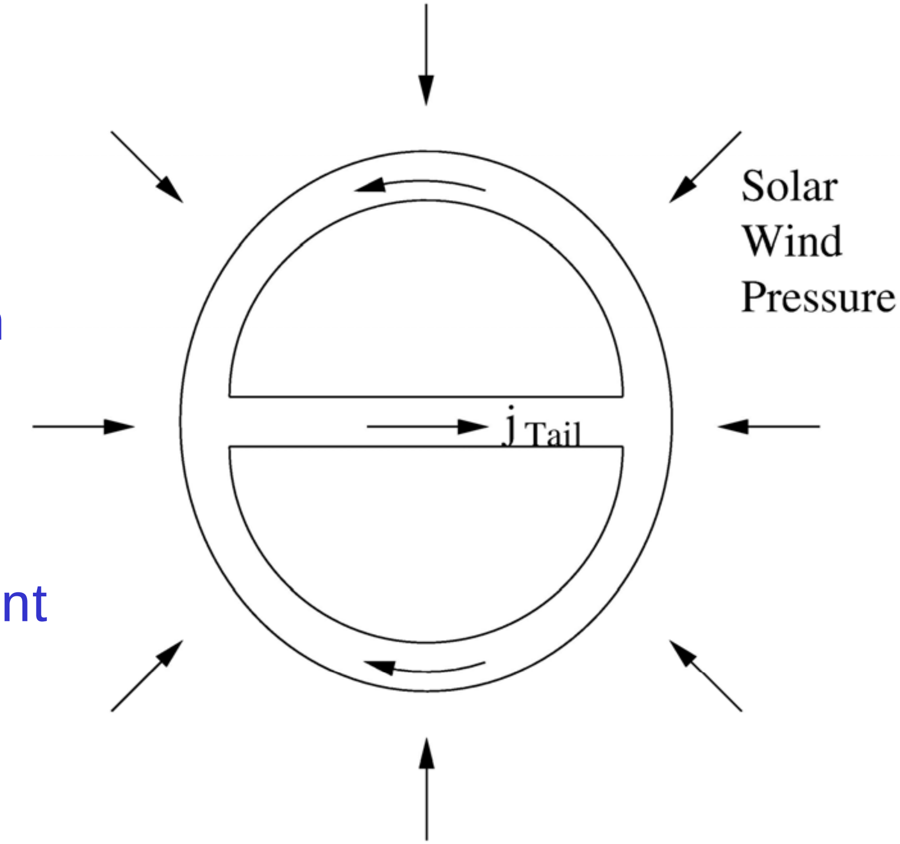
$$\Phi_{\mathrm{PC}} = 2\pi (r_{\mathrm{E}} \cos\theta_{\mathrm{PC}})^2 B_{\mathrm{o}}$$

- Must be equal to the flux in a tail with radius

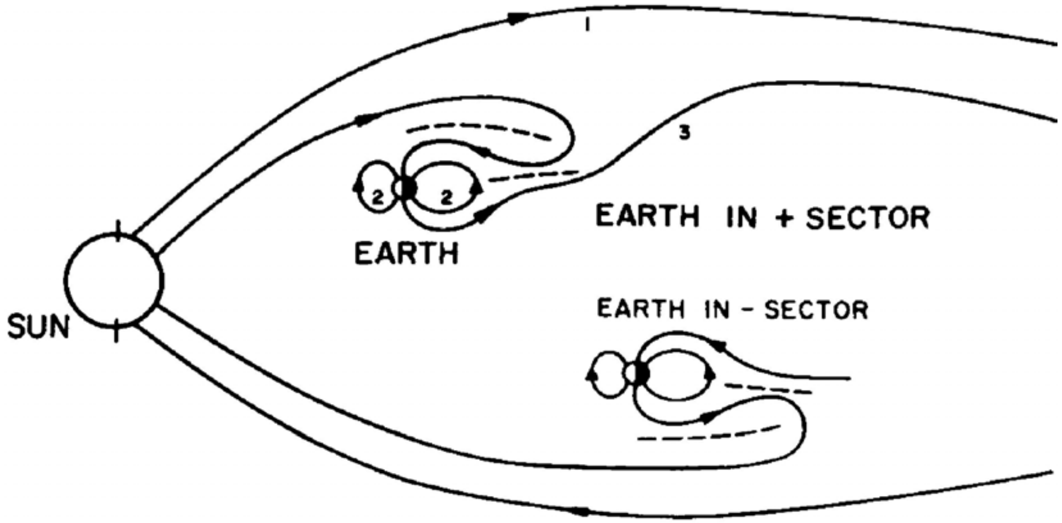
$$\frac{r_{\mathrm{Tail}}}{r_{\mathrm{E}}} = \sqrt{\frac{4B_{\mathrm{o}}}{B_{\mathrm{Tail}}}} \cos\theta_{\mathrm{PC}} \; .$$

Tail currents

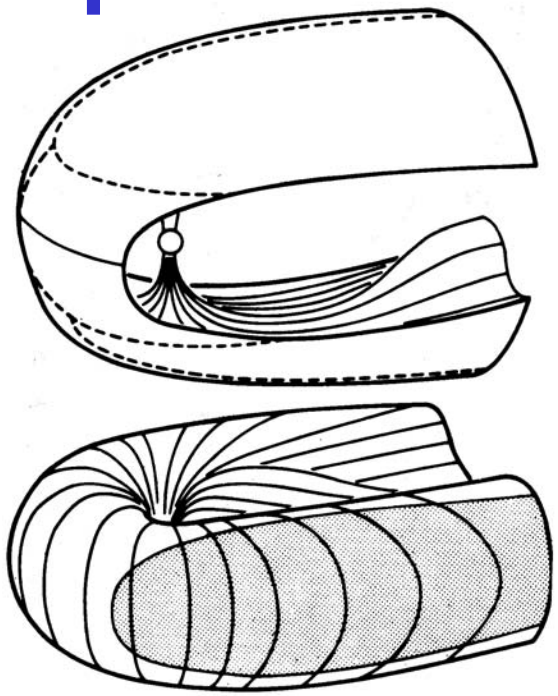
- Current in the magnetopause: Chapman-Ferraro current.
- Continuity requires a current in the equatorial plane: cross tail current.
- At least in the distant tail current system is roughly cylinder symmetrical.



Connection to the heliosphere



Anderson and Lin, 1969, J. Geophys. Res. 74, 3953



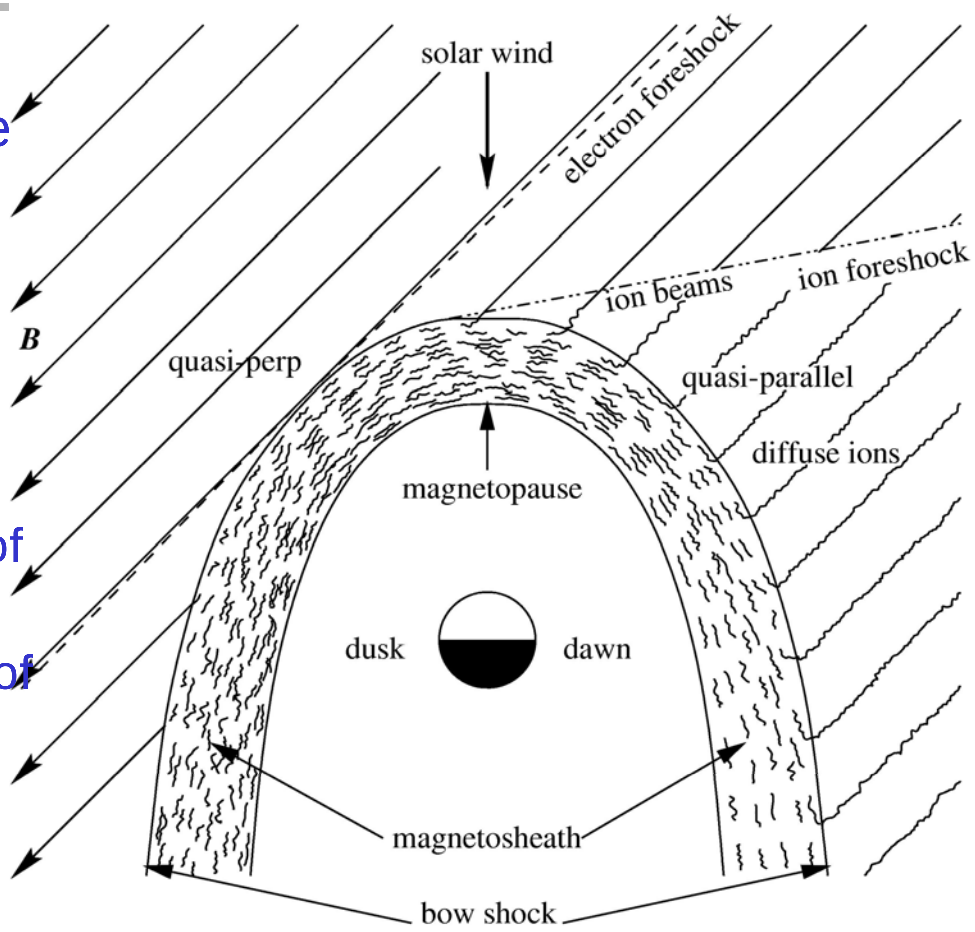
Crooker, 1977, J. Geophys. Res. 82, 3629

- Not all geomagnetic field lines are closed, some are connected to the interplanetary magnetic field.
- Topology of the magnetosphere varies with polarity of the ipl. field.
- Rule of thumb:
  - Field lines in the polar cap are open,
  - Field lines in low latitudes are closed.

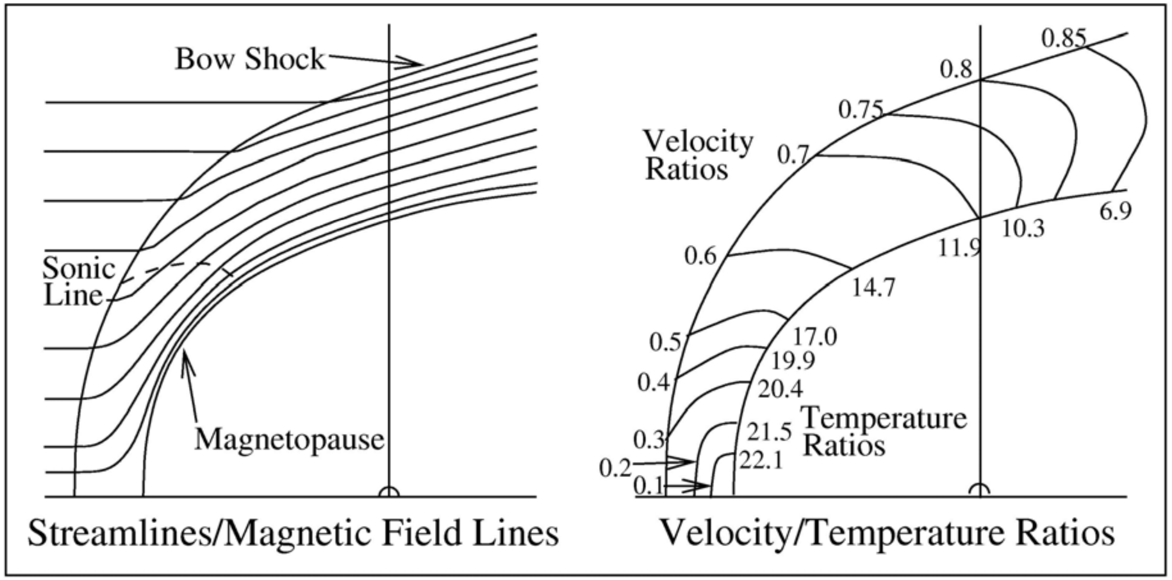
Bow shock and magnetosheath

- Magnetosphere as obstacle in the supersonic solar wind ⇒ bow shock
- Magnetosheath is the transition between
  - interplanetary space (upstream of the bow shock) and
  - Terrestrial plasmas (earthwards of the magnetopause);

  it contains solar wind plasma
  - Decelerated during its passage through the bow shock and
  - Very turbulent.



Magnetosheath

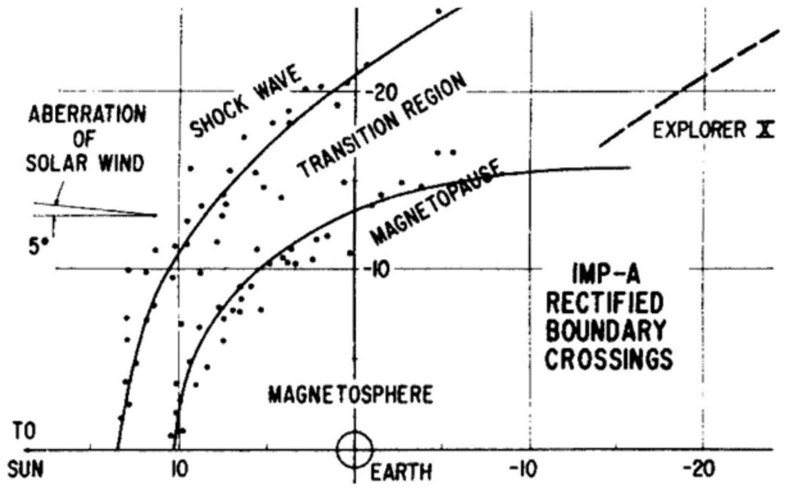


nach Spreiter et al., 1966

- Deflection and deceleration of the solar wind,
- Increase in temperature by a factor of 5 to 10, on the dayside up to a factor of 20,
- Temperature derived from energy balance:

$$\frac{T}{T_\infty} = 1 + \frac{(\gamma_{\mathrm{ad}} - 1) M_\infty^2}{2} \left(1 - \frac{u^2}{u_\infty^2}\right)$$

Magnetopause - observations



Ness et al., 1964, J. Geophys. Res. 69, 3531

Solid lines: model

Symbols: observations

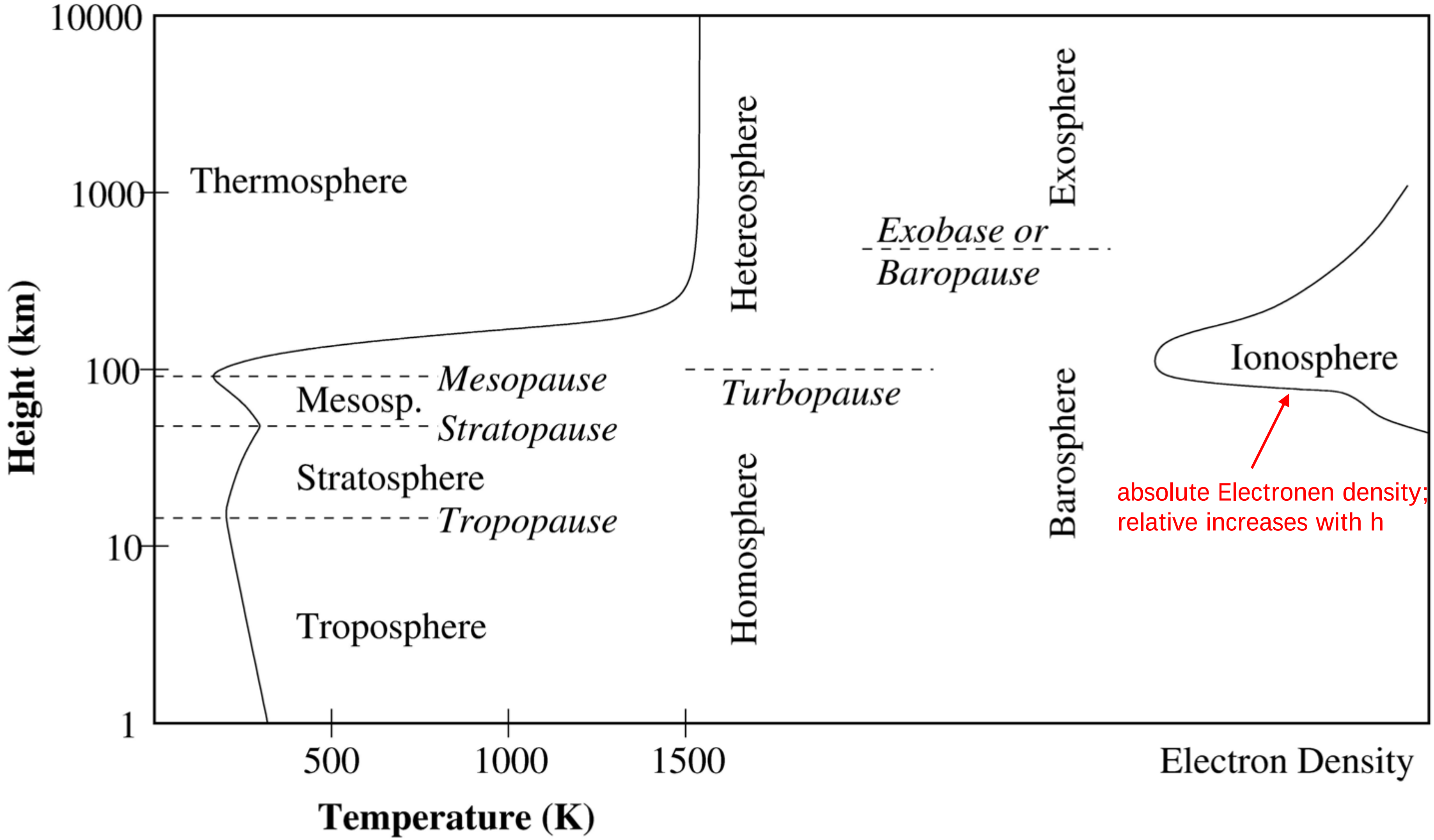
- Simple equilibrium model (pressure balance at the magnetopause, gasdynamics of bow shock and magnetosheath) yield fair agreement between model and observations.
- Scatter in the observations reflects the variability of the solar wind.

Ionosphere

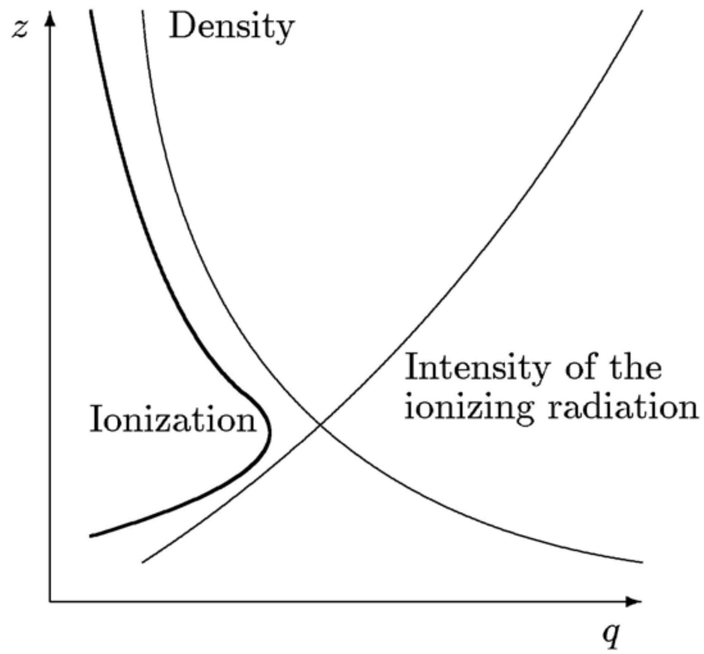
- Magnetosphere determined by current systems:
  - Chapman-Ferraro current in the magnetopause,
  - Cross-field current in the tail,
  - Ring currents due to energetic particles:
    - Equatorial electrojet,
    - Polar electrojet.
  - Vertical currents close the current systems through the ionosphere.

- The ionosphere is the part of the atmosphere where free charges exist.
  - Observation: reflection and absorption of radio waves,
  - Starts at heights of about 80 km,
  - Different layers defined by chemical composition,
  - Total ionization only in the uppermost part of the atmosphere.

Atmosphere - Layering



Chapman layers



- Electron density profile of a single ionospheric layer
  - Decrease density with height

Barometric height formula $$n(z) = n_o \exp\{-z/H\}$$

  - Decrease elmags with depth

Bougert-Lambert-Beer $$\mathrm{d}I/\mathrm{d}z = -I_\infty \sigma_a n$$

- Electron density depending on height and zenith angle

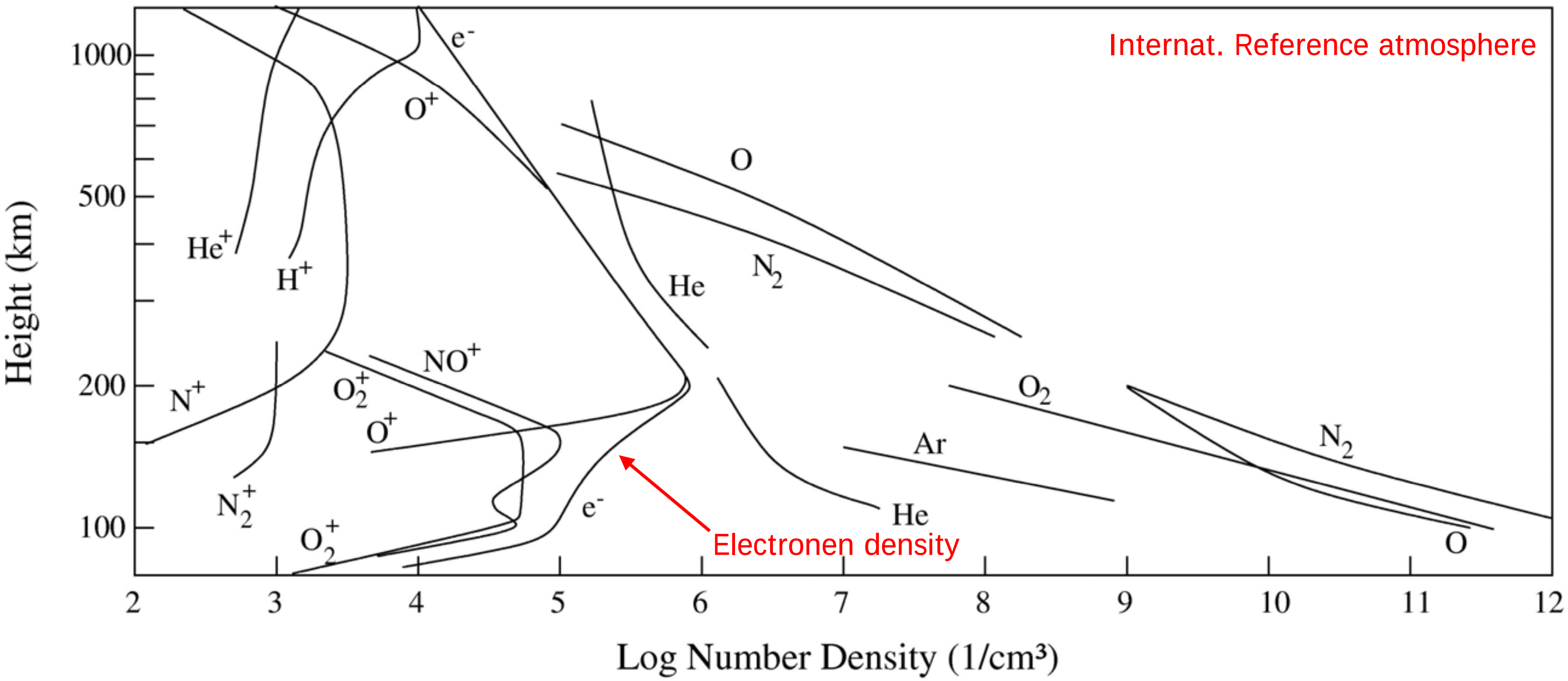
$$q(z) = \sigma_i n_o I_\infty \exp\left\{-\frac{\tau}{\cos\theta} - \frac{z}{H}\right\}$$

with optical depth

$$\tau = \int_z^\infty \sigma_a n(z)\,\mathrm{d}z$$

- Principle applies also to the ozone layer.

Composition atmo- and ionosphere



- With increasing height (above about 100 km):
  - Atomic instead of molecular,
  - Ionized instead of neutral,
  - Low-mass particles instead of heavies (sedimentation).
- Ionospheric layers D,E,F follow the electron density.

Conductivity in the ionosphere

- Determined by:
  - Density of free charges and collisions with neutrals,
  - Inhibition of motion due to a magnetic field,
  - Convection with the neutral wind.

- Conductivity ∥ B: $\sigma_{\|} = \left(\frac{1}{m_{\mathrm{i}} \nu_{\mathrm{i}}} + \frac{1}{m_{\mathrm{e}} \nu_{\mathrm{e}}} \right) n e^2$

- Pederson conductivity ∥ E: $\sigma_{\mathrm{Ped}} = \left[\frac{\nu_{\mathrm{i}}}{m_{\mathrm{i}}(\nu_{\mathrm{i}}^2 + \omega_{\mathrm{i}}^2)} + \frac{\nu_{\mathrm{e}}}{m_{\mathrm{e}}(\nu_{\mathrm{e}}^2 + \omega_{\mathrm{e}}^2)} \right] n e^2$

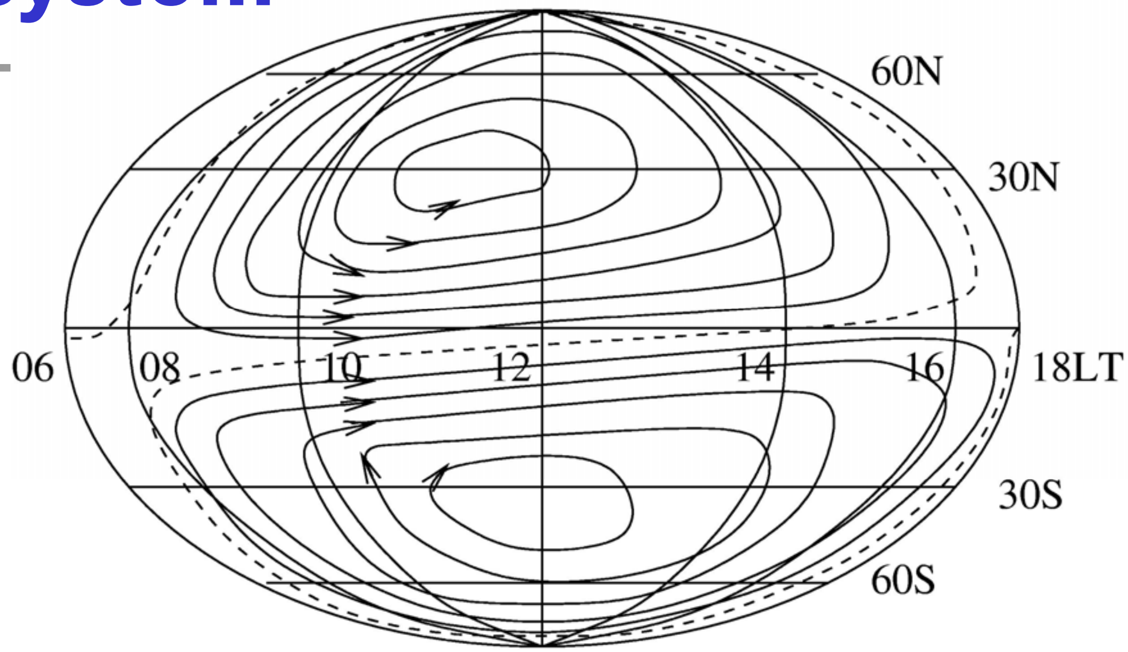
- Hall conductivity ⊥ E and ⊥ B: $\sigma_{\mathrm{Hall}} = \left[\frac{\omega_{\mathrm{i}}}{m_{\mathrm{i}}(\nu_{\mathrm{i}}^2 + \omega_{\mathrm{i}}^2)} + \frac{\omega_{\mathrm{e}}}{m_{\mathrm{e}}(\nu_{\mathrm{e}}^2 + \omega_{\mathrm{e}}^2)} \right] n e^2 \,.$

- Total current and conductivity tensor:

$$\vec{j} = \sigma_{\|} \vec{E}_{\|} + \sigma_{\mathrm{Ped}} \vec{E} + \sigma_{\mathrm{Hall}} \frac{\vec{B} \times \vec{E}}{B} = \sigma \cdot \vec{E} \qquad \sigma = \begin{pmatrix} \sigma_{\mathrm{P}} & -\sigma_{\mathrm{Hall}} & 0 \\ \sigma_{\mathrm{Hall}} & \sigma_{\mathrm{P}} & 0 \\ 0 & 0 & \sigma_{\|} \end{pmatrix}$$

Sq-current system

- E layer (90-120 km):
  - Highest conductivity,
  - Strong neutral winds,
  - Tides.



- Influences on e and p different ⇒ currents

- Consideration of the neutral wind in Ohm's law:

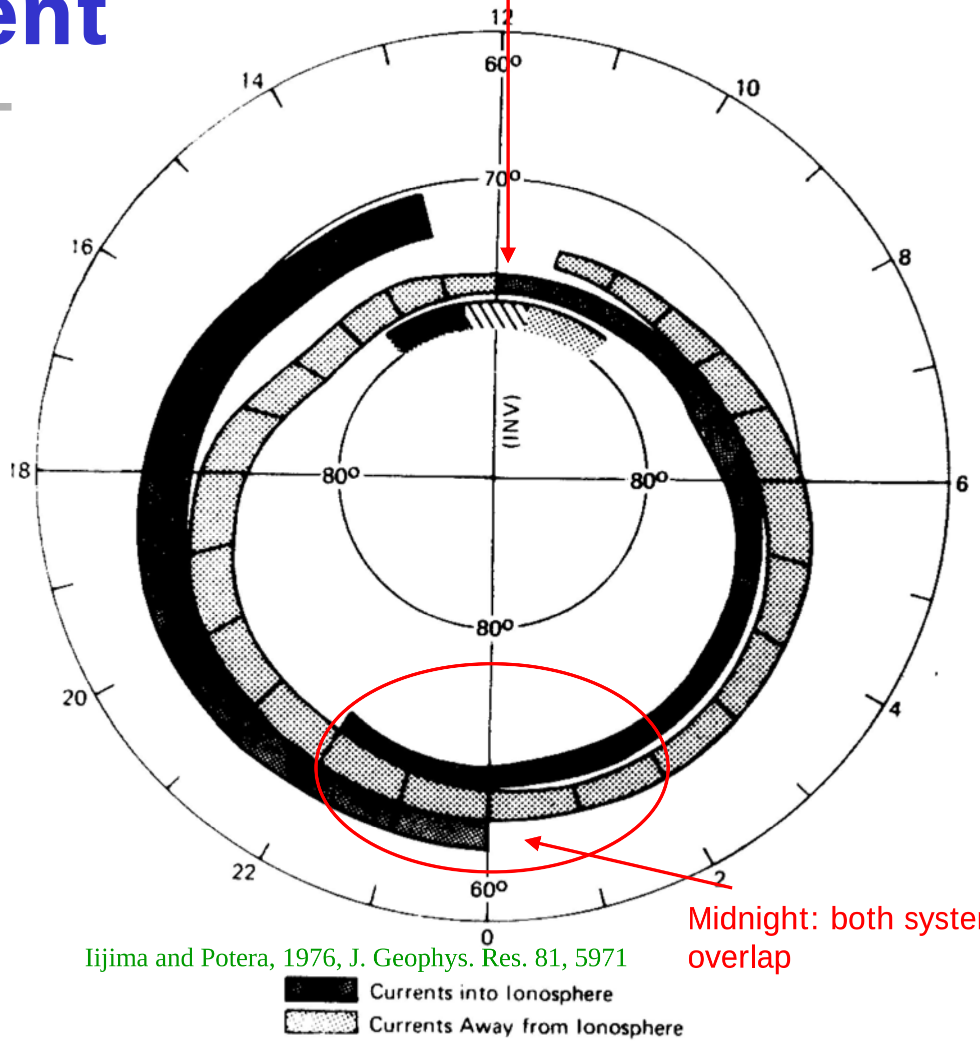
$$\vec{j} = \sigma \left(\vec{E} + \vec{v}_{\mathrm{n}} \times \vec{B} \right)$$

- E layer is a dynamo layer where kinetic energy of the neutral wind is converted into electric field energy.

Birkeland current

- Vertical currents in high latitudes,
- Coupling of ionosphere and magnetosphere
- Region 1 current in higher latitudes:
  - Upwards on the dusk side,
  - Downwards on the dawn side.
- Region 2 current at slightly lower latitudes:
  - Into the ionosphere at dusk,
  - Out of the ionosphere at dawn.

Noon: both systems not clearly separated, highly variable depending on poalrity of the ipl. Magnetic field



Midnight: both systems overlap

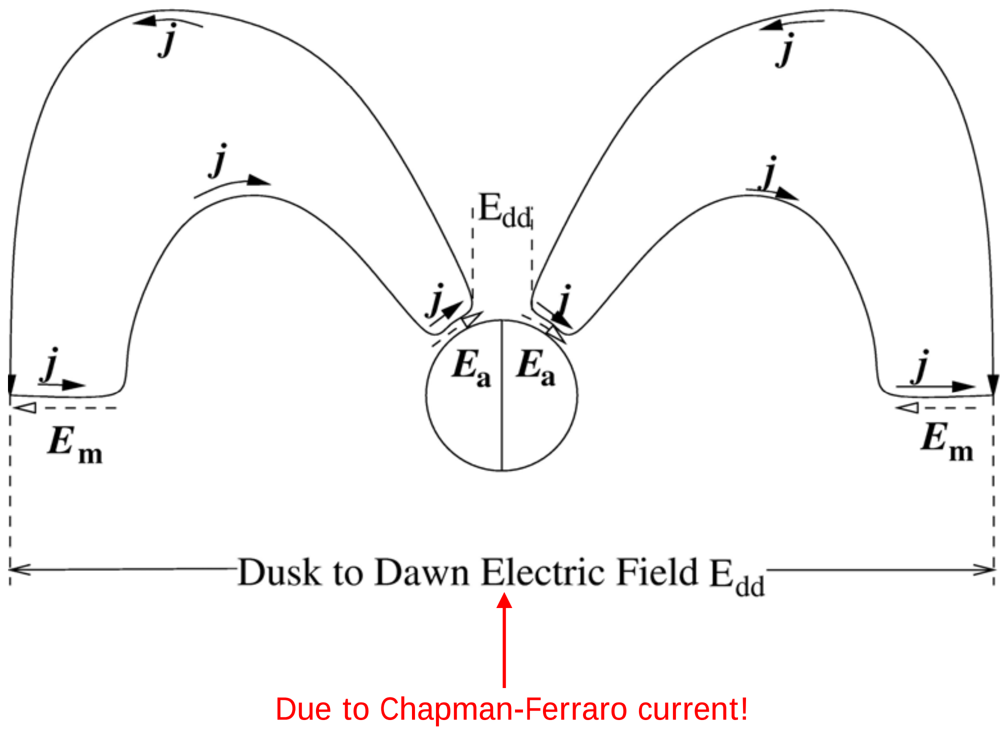
Iijima and Potera, 1976, J. Geophys. Res. 81, 5971

Caution: currents are mainly carried by electrons; an upward current thus means electrons moving from the magnetosphere down into the ionosphere!

Magneto-Ionosphere current system

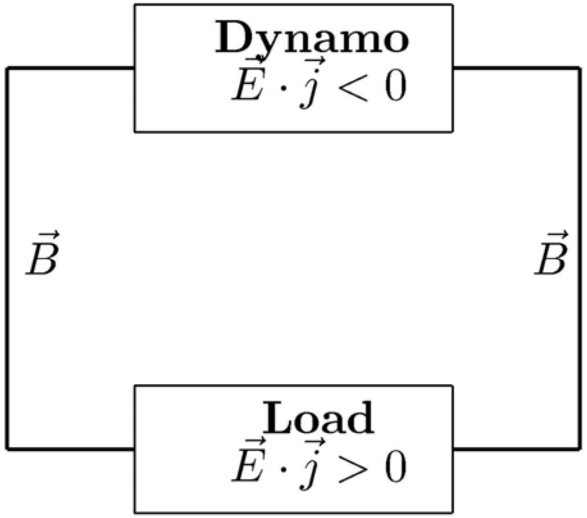
- Region 1 and 2 currents close
  - At high latitudes in the ionosphere,
  - At equatorial latitudes in the magnetosphere.

- Driving force in the magnetosphere is the dusk to dawn electric field resulting from the drift inside the magnetopause (solar wind acts as dynamo!)



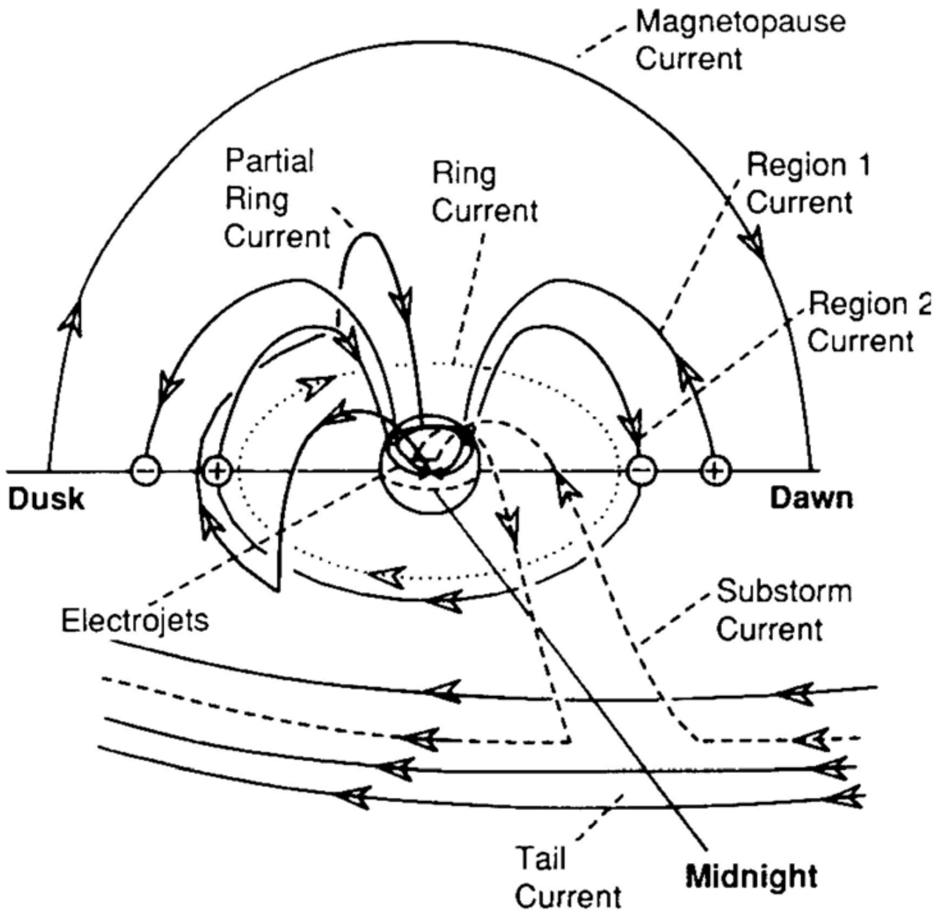
Solar wind – magnetosphere coupling

- Magnetosphere – ionosphere coupling due to Birkeland currents.
- In the equatorial magnetosphere the solar wind acts as dynamo!
- In this system the polar magnetosphere acts as load where energy is dissipated.
- Missing: currents related to geomagnetic activity.



Summary current systems

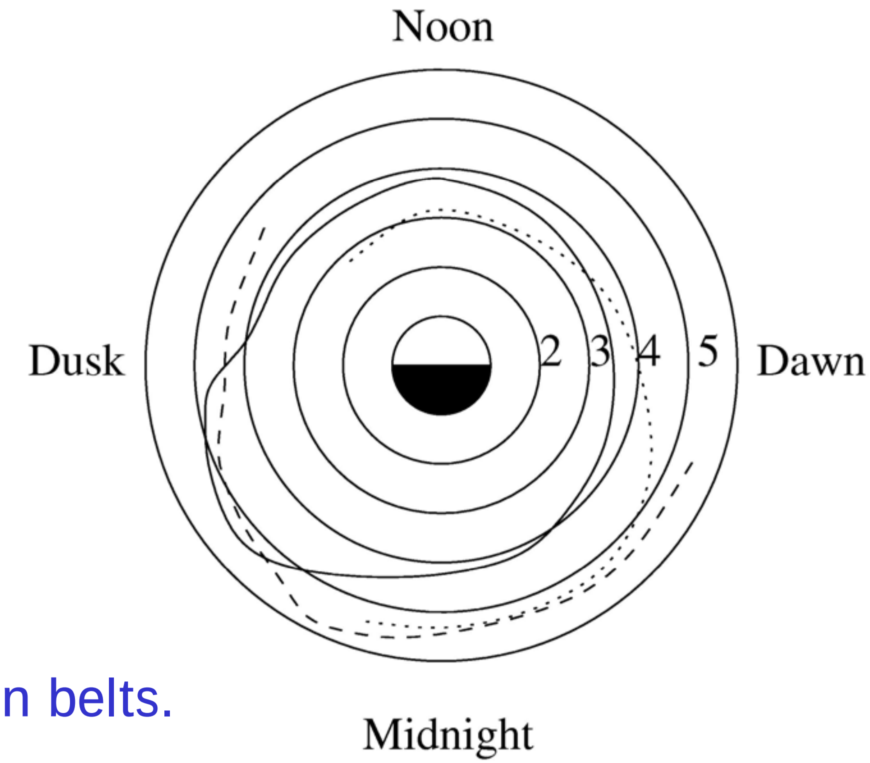
- Currents include:
  - Magnetopause current,
  - Tail current,
  - Region 1 and 2 currents,
  - Ring currents.
- Dynamos due to
  - Dusk-Dawn E-field (driven by the solar wind),
  - E layer in the atmosphere (driven by the neutral wind).
- Geomagnetic activity:
  - Short circuit of the tail current into the region ½ current system.



McPherron, 1996, in Introduction to space pyhsics, Cambridge Univ. Press

Plasmasphere

- Cold and dense plasma of ionospheric origin:
  - high O+/H+,
  - He+, O++, N+, N++,
  - Energy ~1 eV,
  - Density:
    - 1E4/cm³ at 1000 km,
    - 10-100 at the plasmapause



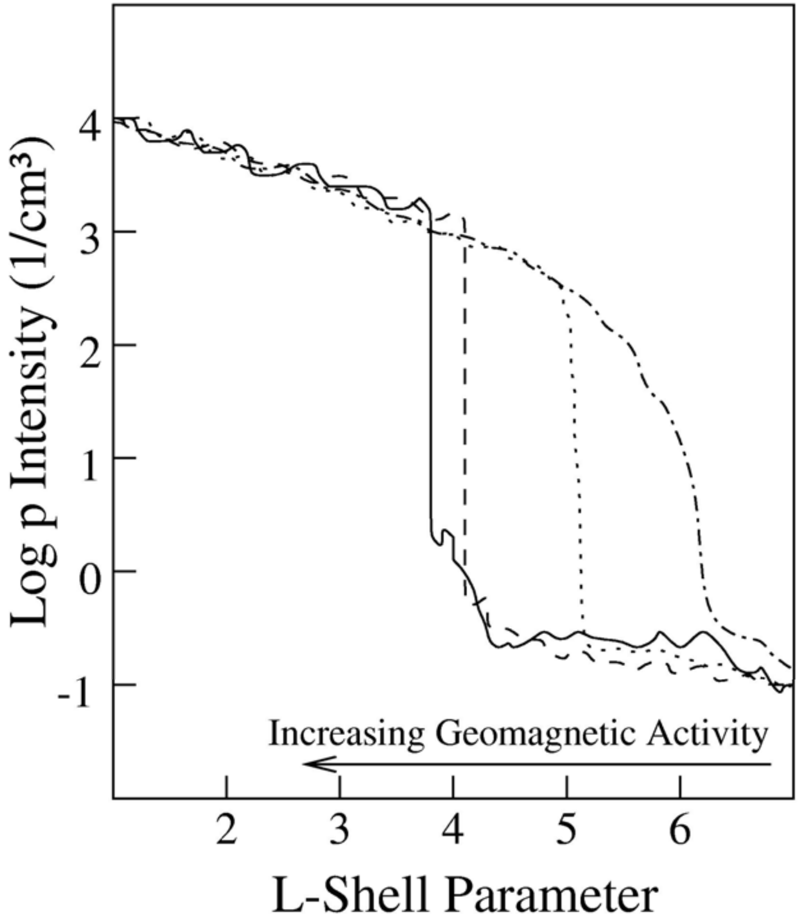
nach Carpenter, 1966, J. Geophys. Res. 71, 693

- Spatially coexistent with the radiation belts.
- Observation: magnetospheric Whistler waves.
- Corotates with earth leading to an electric induction field.

Plasmapause and ipl. medium

- Position of the plasmapause depends on geomagnetic activity: with increasing activity
  - The plasmasphere shrinks,
  - The plasmapause becomes more pronounced.

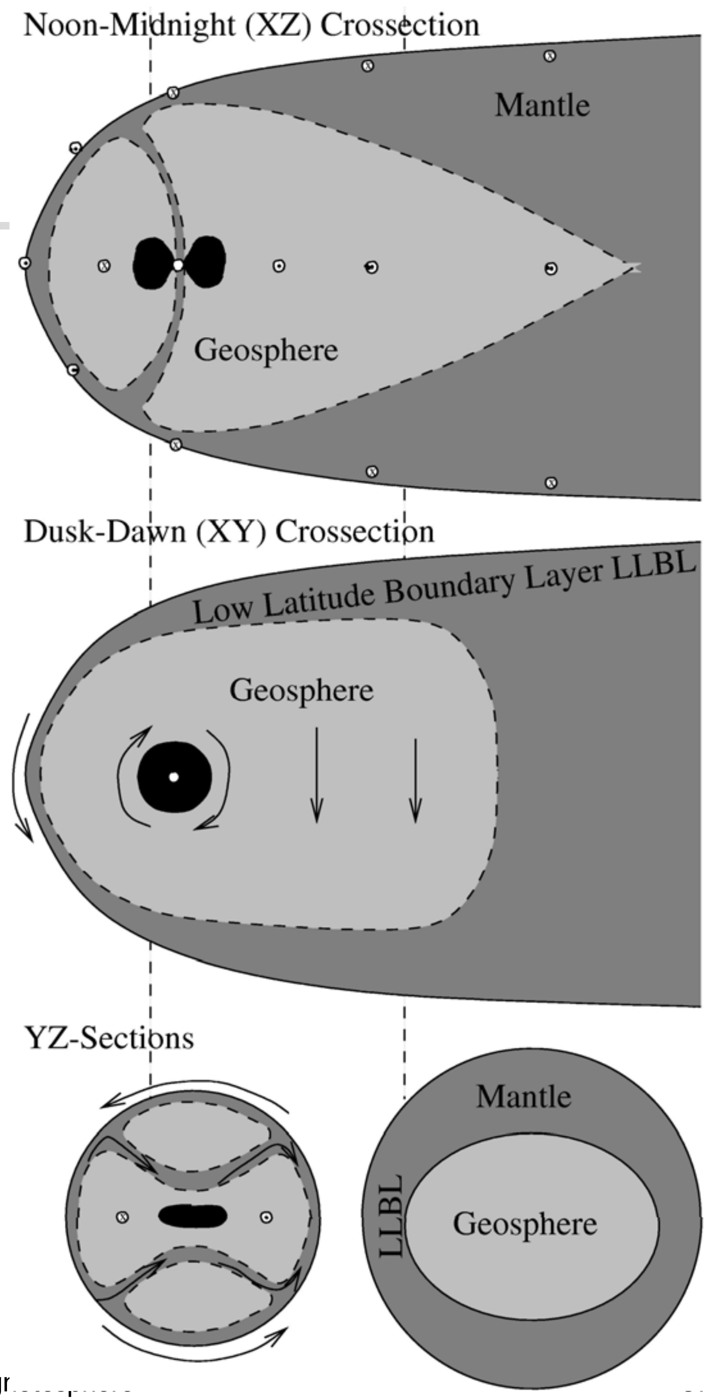
- Causes:
  - General compression of the field on the dayside,
  - Restructuring of the tail current on the night side.



Nach Chappell et al., 1970, J. Geophys. Res. 75, 50

Summary

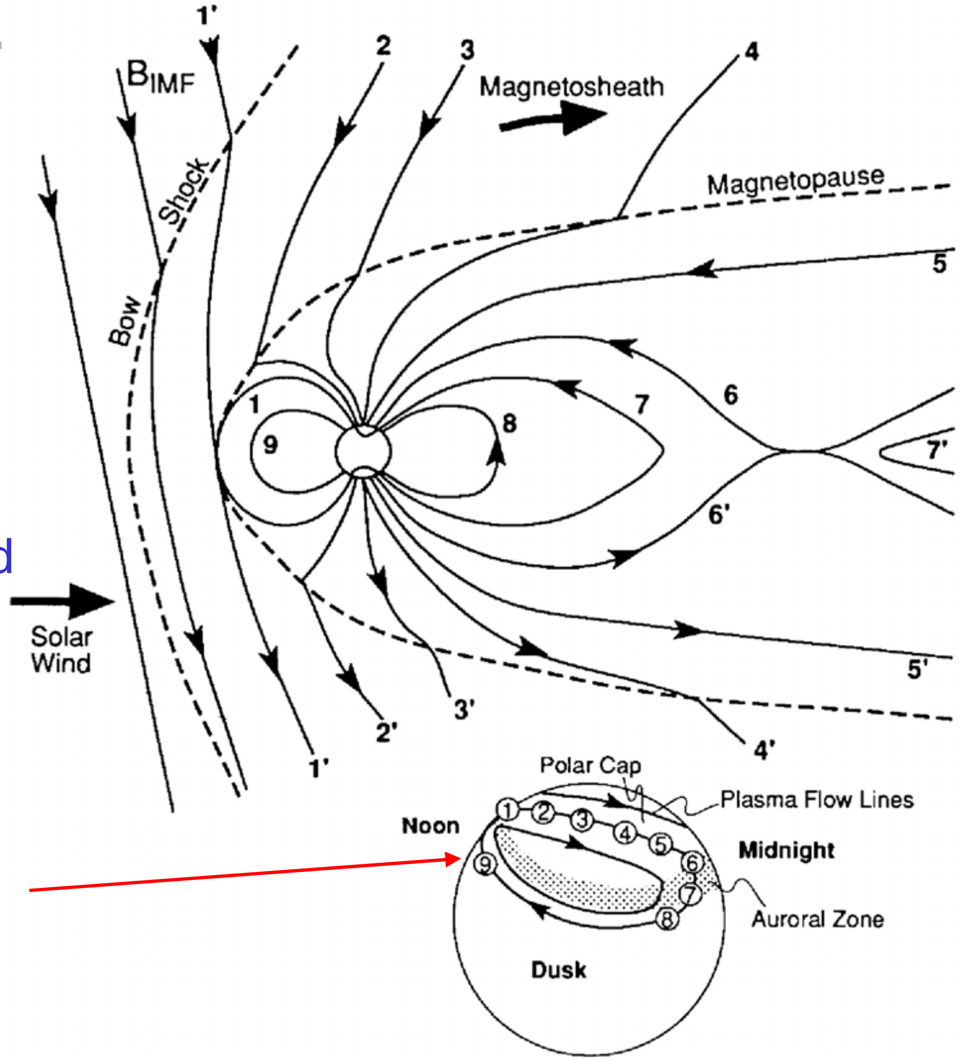
- Plasmasphere (ionospheric plasma) dominates close to the earth.
- Inside the polar cusps the plasma mainly is of solar wind origin.
- In the distant tail solar wind plasma becomes dominant.



Plasma convection

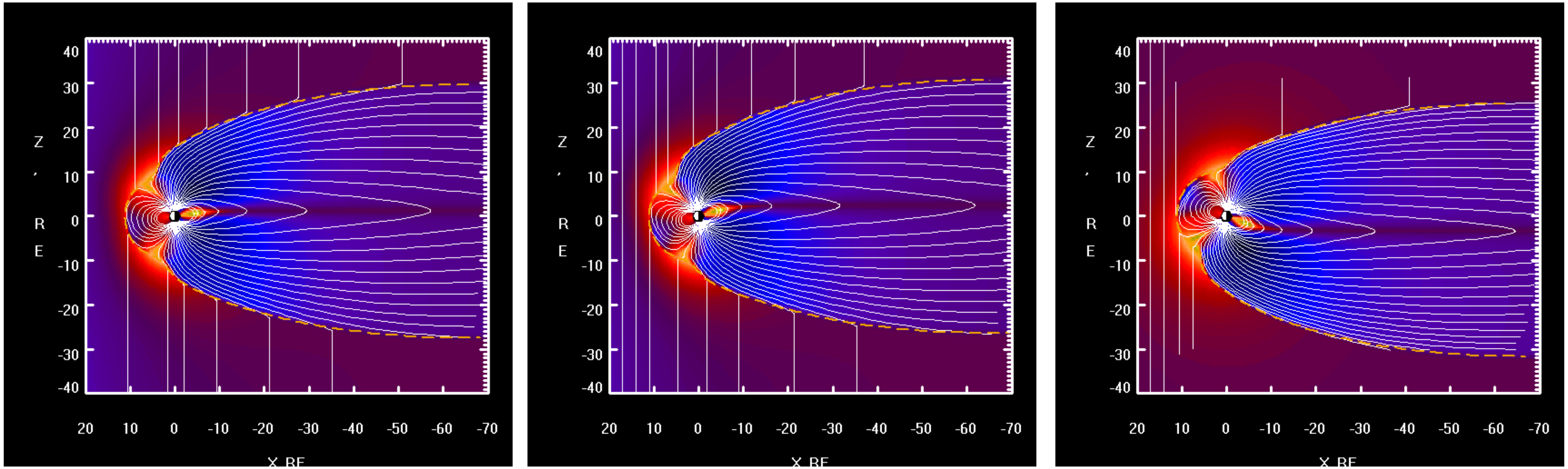
- Transport of solar wind plasma into the tail due to
  - Reconnection at the dayside,
  - Convection of the reconnected mixed field line across the polar cap into the tail,
  - Formation of new planetary field lines due to reconnection inside the tail,
  - Rotation of these field lines to the dayside.

- Observation: Birkeland currents in the ionosphere.



Hughes, 1995, i nIntroduction to space physics, Cambridge Univ. Press

Model

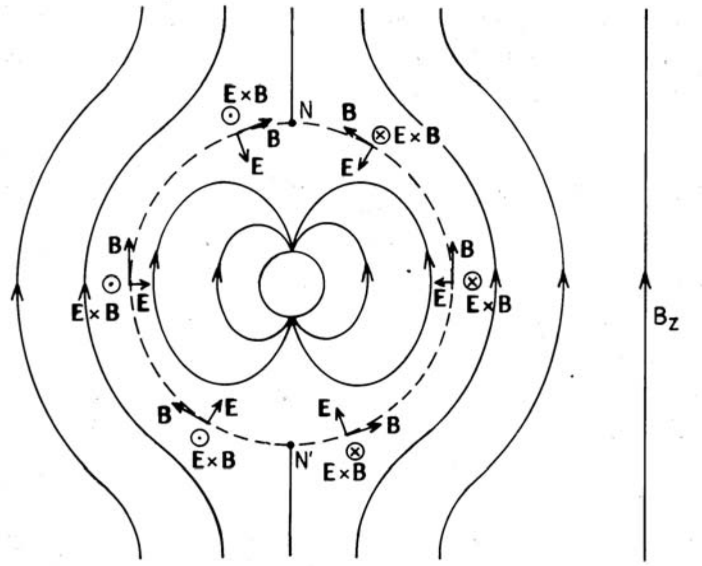


http://nssdc.gsfc.nasa.gov/space/model/magnetos/data-based/modeling.html

- Different positions of the field axis
- Interplanetary field has a southward component – quiet reconnection,
- Substorm

Energy transfer

- Energy is transferred from the solar wind into the magnetosphere:
  - Dusk-Dawn field,
  - Convection across the polar caps.



Brekke, 1997, Physics of the upper polar atmosphere, Wiley

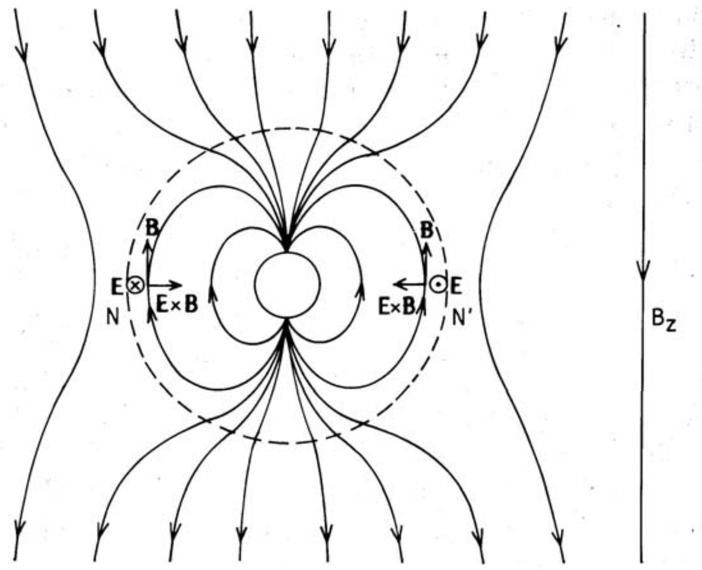
- Energy transfer depends on the polarity of the interplanetary magnetic field.

- Maximum power in the magnetosphere:

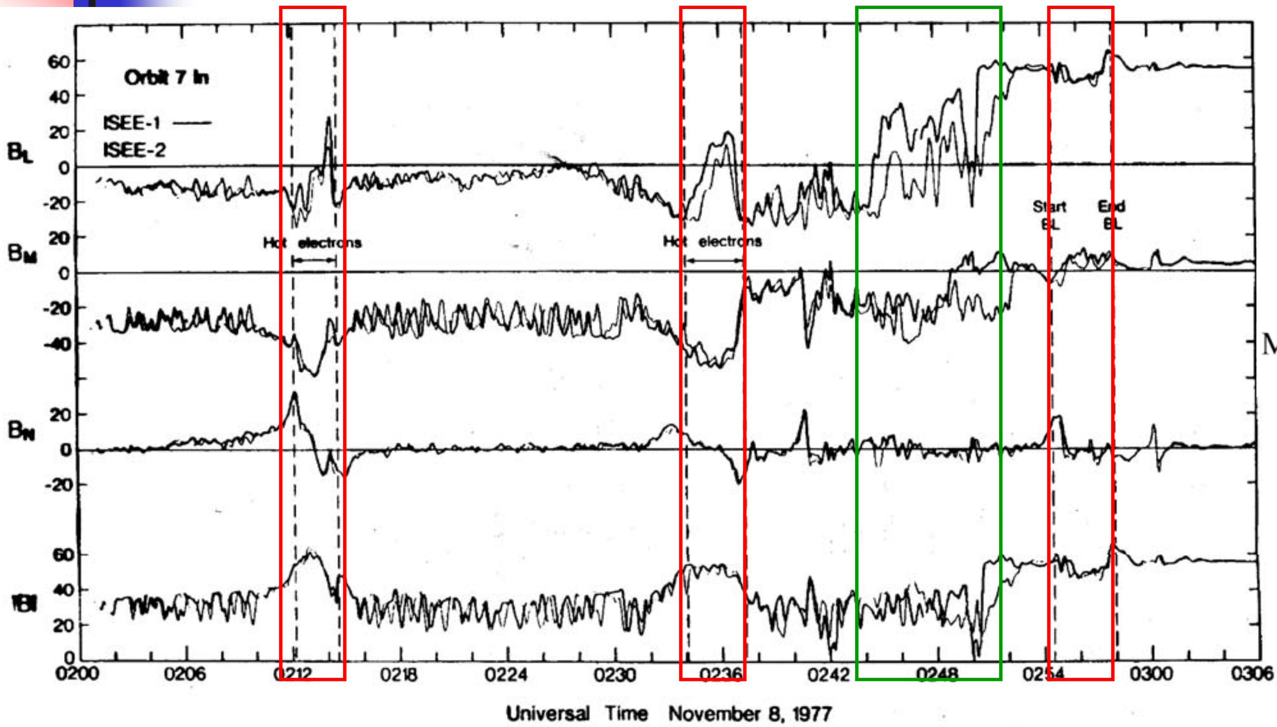
$$P_{\rm in} = u_{\rm sowi} \frac{B_{\rm ip}^2}{2\mu_{\rm o}} \sin^4 \frac{\Theta}{2} 2\pi r_{\rm mp}$$

- Ratio input energy/solar wind kinetic energy:

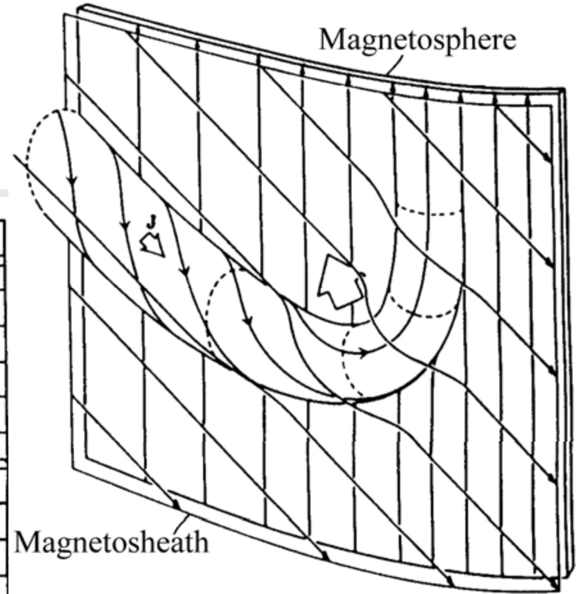
$$\frac{P_{\rm in}}{P_{\rm sowi,kin}} \approx \frac{1}{M_{\rm A}^2}$$



Flux-Transfer-Events



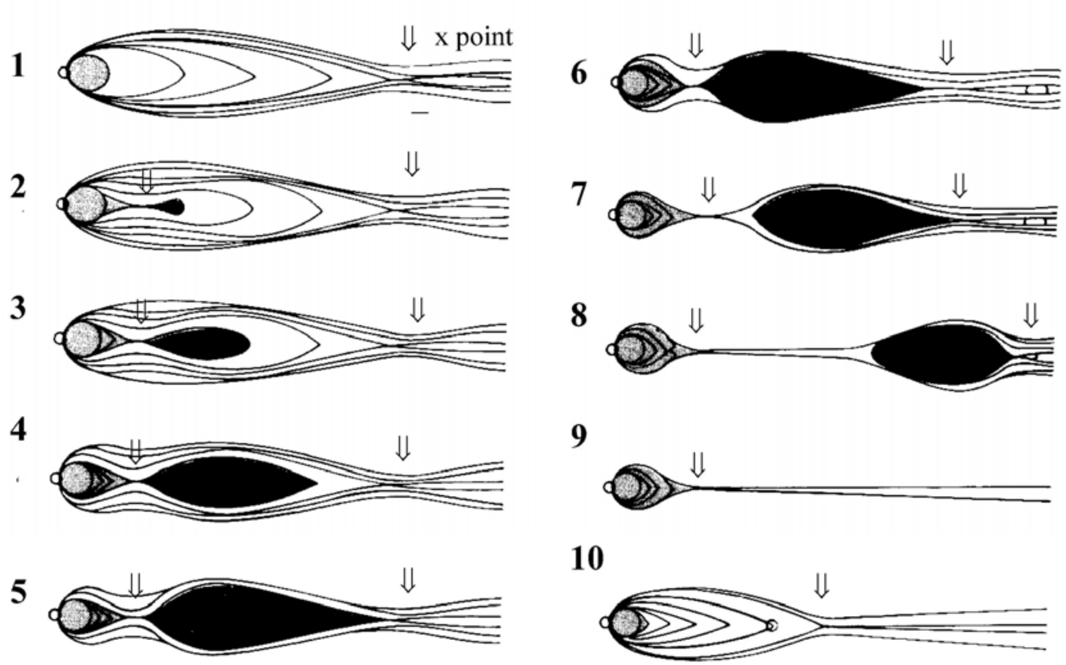
Russel and Elphic, 1979, Geophys. Res. Lett. 6, 33



Russel and Elphic, 1979, Geophys. Res. Lett. 6, 33

- Observational evidence for reconnection on the dayside:
  - Magnetospheric plasma flows in the solar wind,
  - Solar wind plasma flows inside the magnetosphere
- Magnetopause crossing: green part

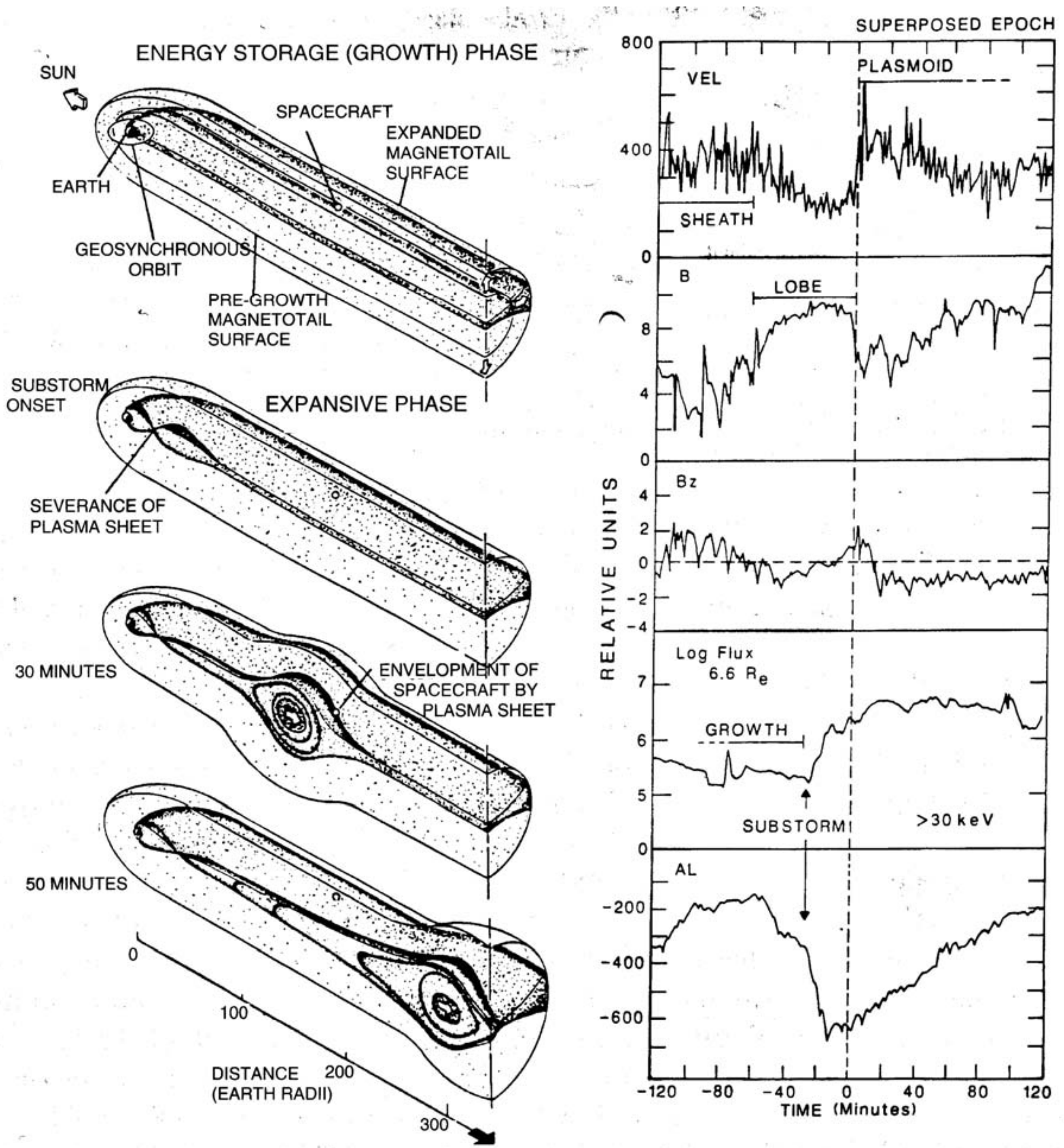
Substorms (Hones Model)



Hones, 1984, Magnetic reconnection, AGU Geophys. Monogr. 30

- Reconnection dayside.
- Convection to the night side.
- Plasma accumulates at the night side.
- Discharge of the night side due to reconnection inside the tail.
- Trigger: geomagnetic disturbances.

Hones Model observations



Scholer, 2003, in Energy conversion and particle acceleration in the solar corona, Lecture Notes in Phys. 612, Springer

Reconnection inside the tail:

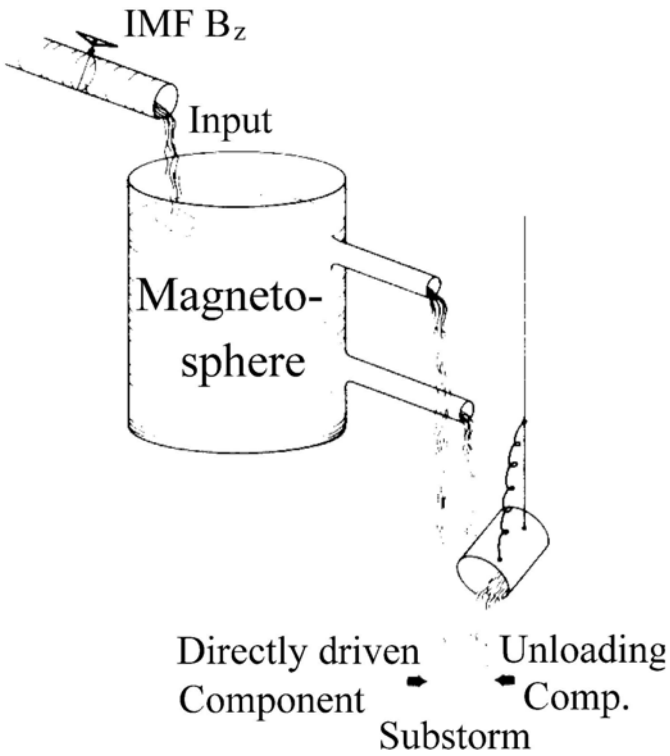
- Plasma accelerated towards the magnetosphere causes aurora.
- Plasma accelerated into the direction of the distant tail can be observed as plasma blob.

Energy transfer solar wind - magnetosphere

- Energy input from the solar wind continuously but modulated by the polarity of the interplanetary magnetic field.

- Output in the tail
  - To a small amount continuous (overflow),
  - Eruptive, triggered by geomagnetic disturbances.

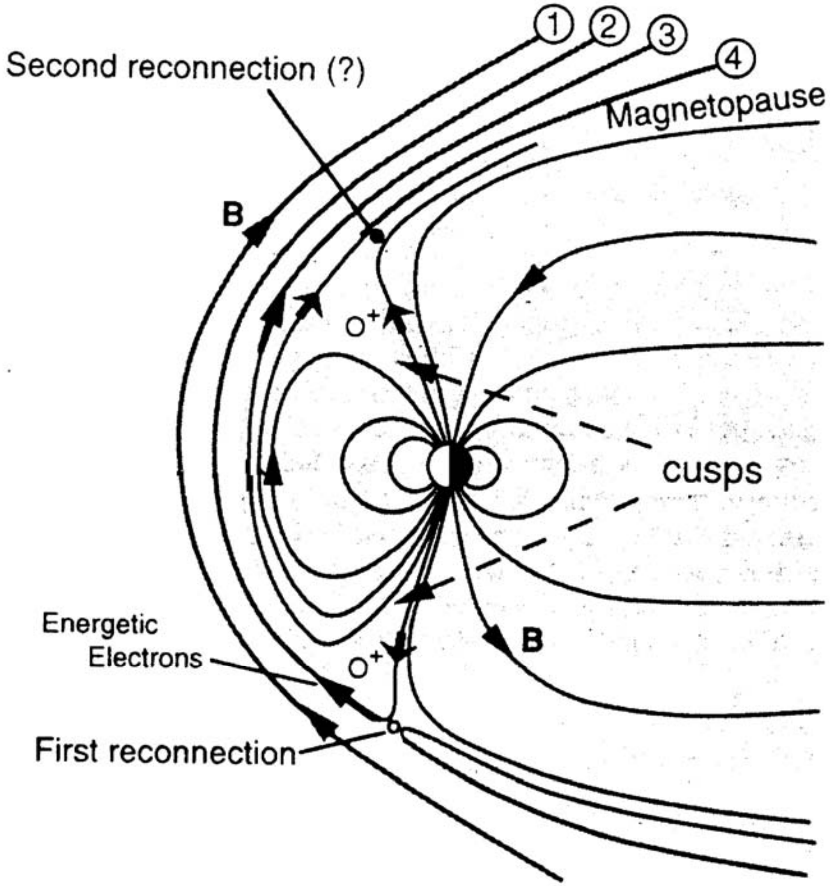
- Energy can be accumulated over a longer time period and can be released spontaneously.



Akasofu, 1989, EOS 70, 529

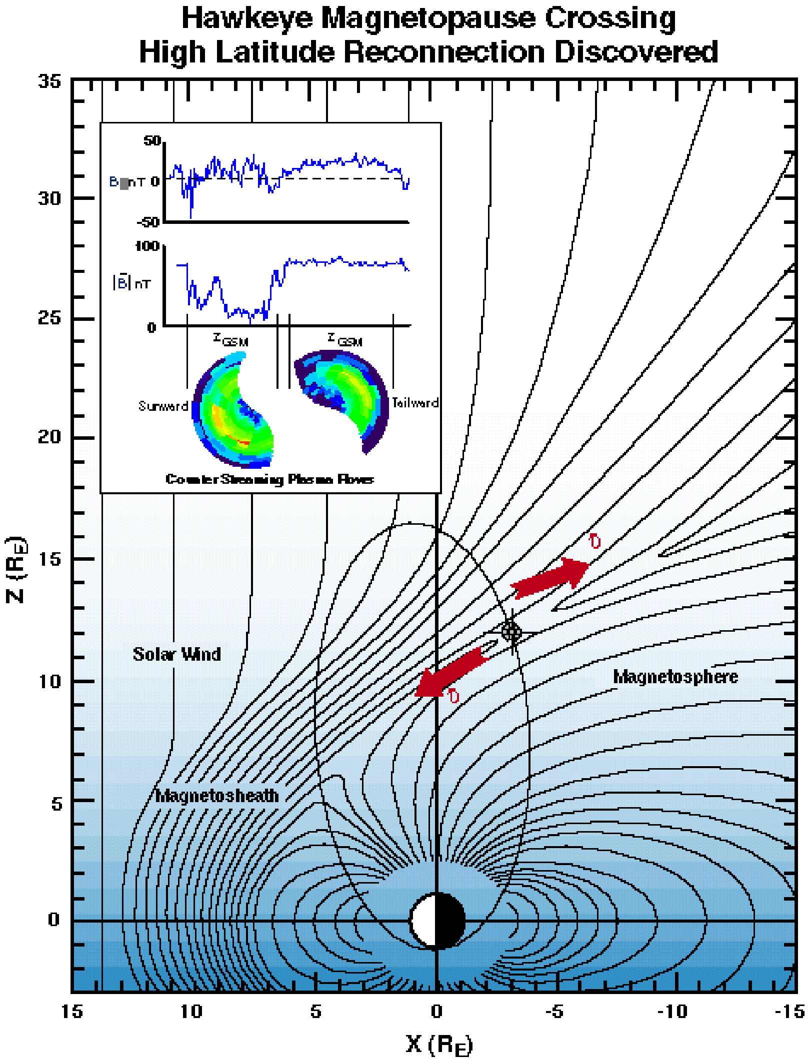
Reconnection in a closed magnetosphere

- Reconnection at the polar cusps also in a closed magnetosphere.
- Observational evidence: ionospheric particles inside the magnetosheath.
- Consequence: there is no such thing like a closed magnetophere.



Fuselier, 2001, J. Geophys. Res. 106, 5967

Reconnection in the polar cap



- Reconnection in a closed magnetosphere.
- Is the concepts of a closed magnetosphere still reasonable?
- Connection between planetary and interplanetary magnetic field complex and highly variable.

http://nssdc.gsfc.nasa.gov/hawkeye/images/hawkeye_reconnection.gif

Geomagnetic variations

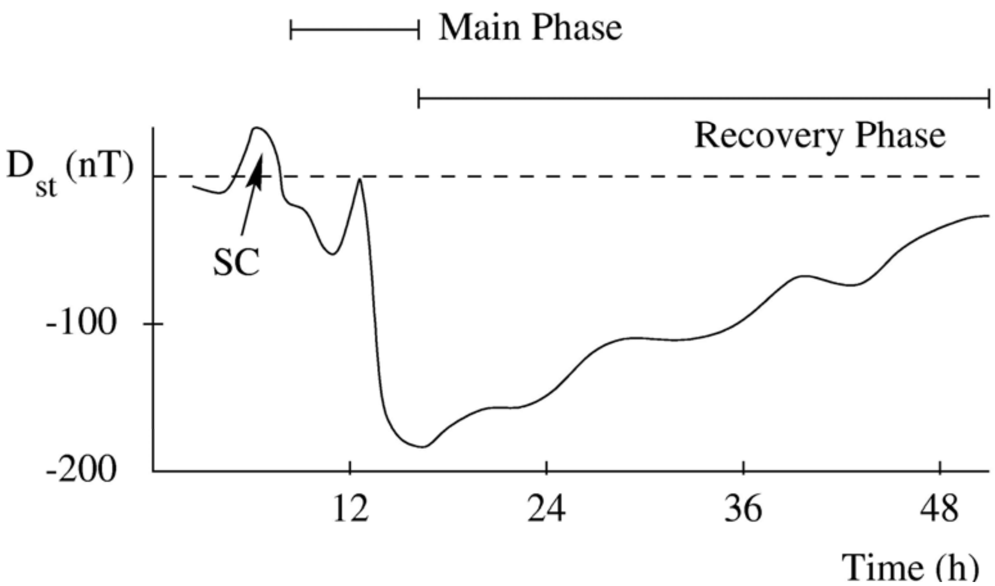
- Systematic variations:
  - Daily variations,
  - Pulsations,
  - Variations with the solar cycle.
- Geomagnetic storms are caused by disturbances in interplanetary space.
- Aurora are the visible (and historically best documented) consequence of geomagnetic disturbances.

Regular variations

- Daily variations caused by the asymmetry of the magnetospheric current system, in particular the Sq current.
  - SFE (solar flare effect): increase in Sq current due to ionization on the dayside.

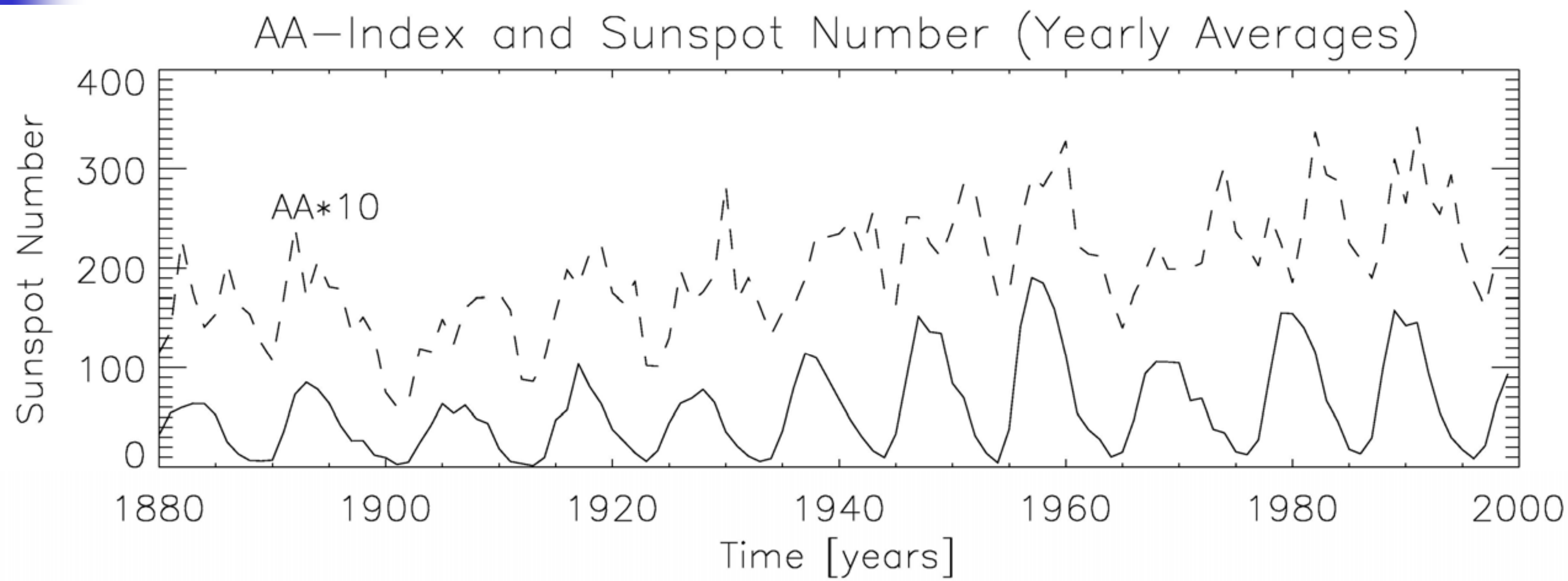
- Indices to quantify variations:
  - K-index: largest deviation of one magnetic field component from the quiet field, measured locally, 3h averages, combined to give a global K-index.
  - a-index: combination pf the 8 K-indices of one day.
  - Dst-index: deviation of the horizontal field component from the nominal one; at equatorial latitudes thus measure for changes in the ring current
  - AE-index: similar to Dst but in high latitudes (auroral electrojet)

Geomagnetic storms



- Sudden commencement: increase in magnetic flux density due to the compression of the magnetosphere by an interplanetary disturbance.
- Decrease due to:
  - Reconnection at the dayside and inside the tail,
  - Changes in equatorial electrojet due to short circuit with the tail current and restructuring of the radiation belts.

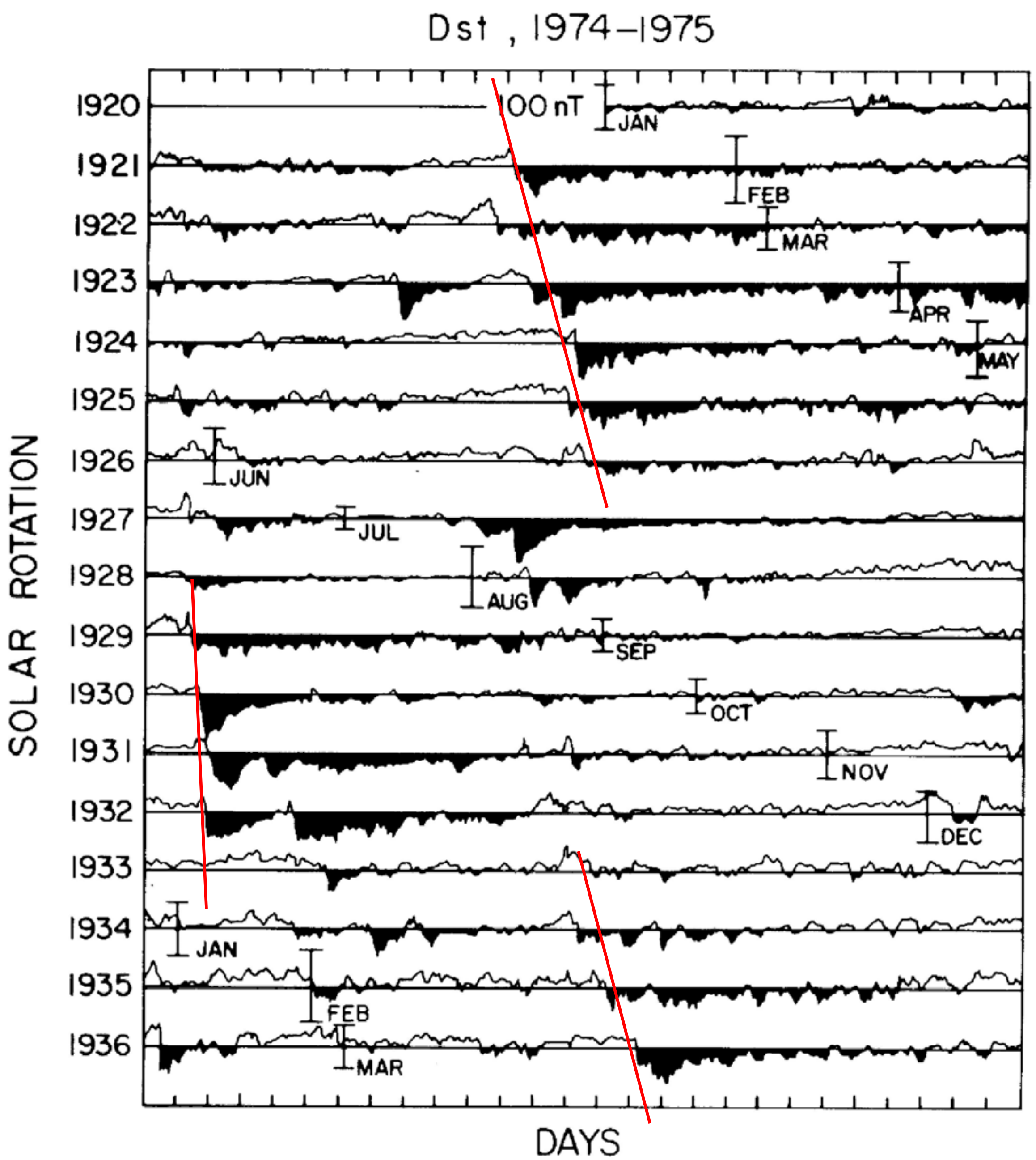
Geomagnetic activity during the solar cycle



- Increased geomagnetic activity during sunspot maximum (mainly shocks and magnetic clouds/CMEs)
- Geomagnetic activity does not vanish during sunspot minimum (CIRs are the main source of geomagnetic activity)
- Geomagnetic activity (aurora) did not vanish during the Maunder Minimum.

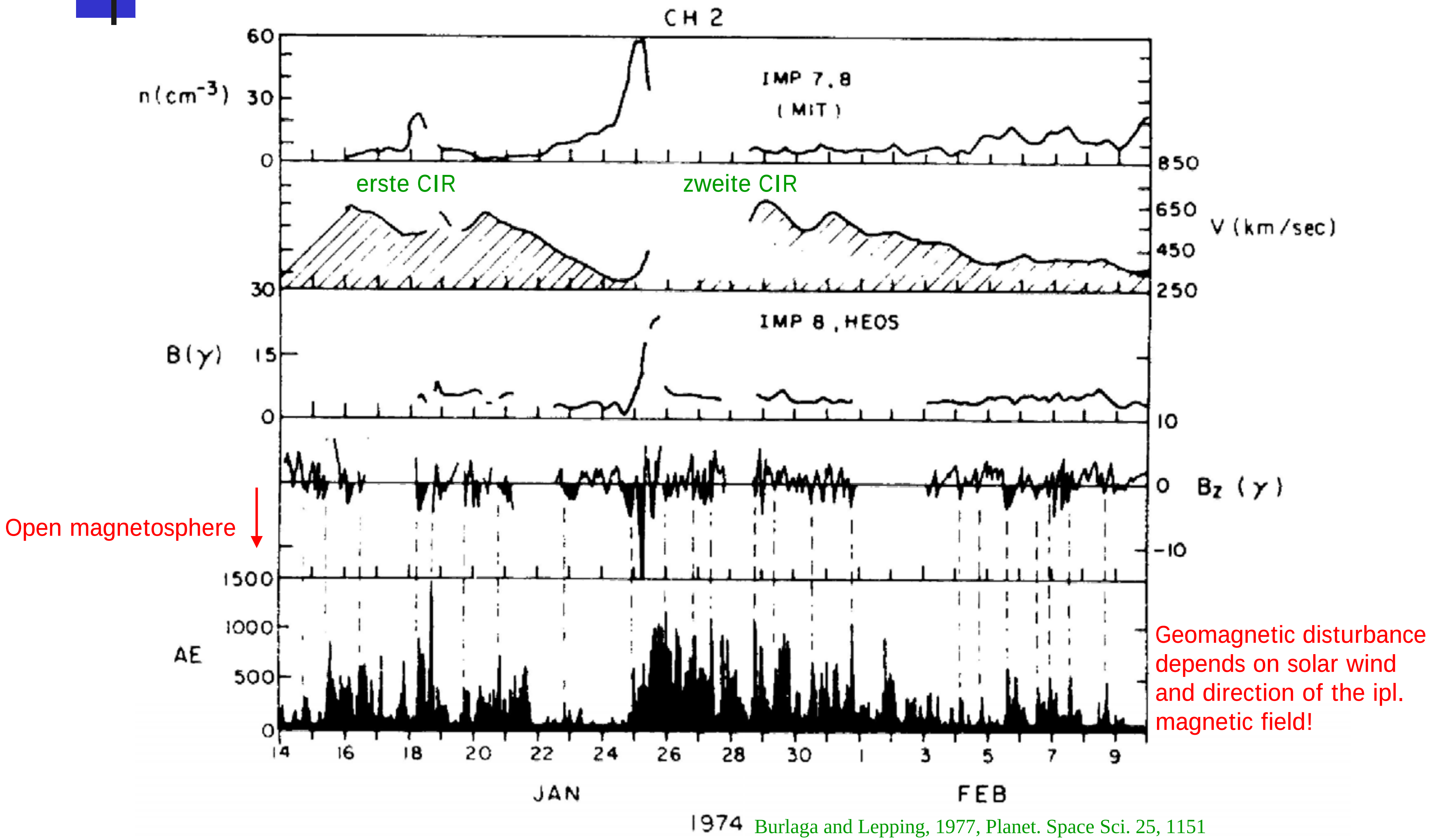
Seasons and CIRs

- Two distinct CIRs (beginning and middle of each rotation)
- First CIR caused geomagnetic activity in fall.
- Second CIR caused geomagnetic activity in winter and spring.



Crooker and Siscoe, 1986, in Physics of the Sun III, Reidel

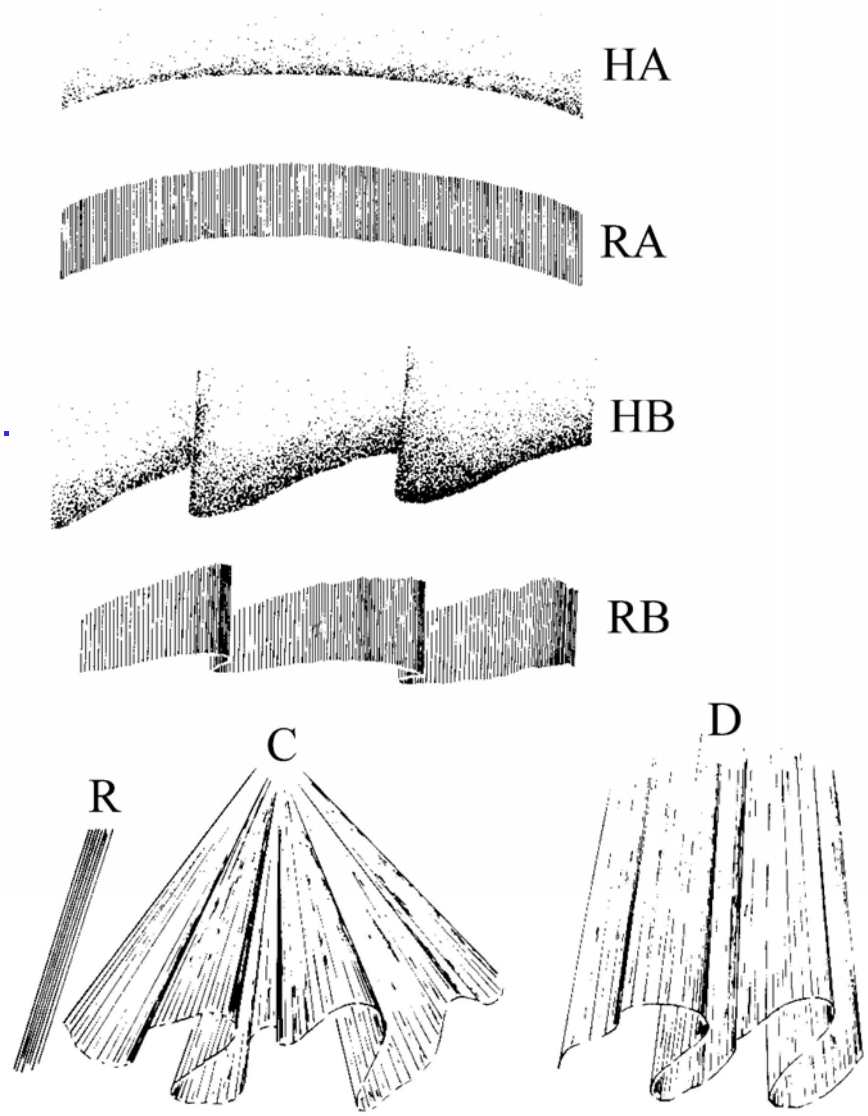
Details CR 1921



Burlaga and Lepping, 1977, Planet. Space Sci. 25, 1151

Aurora

- Optical signal of particle precipitation into the atmosphere.
- Excitation or ionization of the atmosphere.
- Structures modified by magnetic field configuration.
- Historic descriptions:
  - Fighting dragons (Chinesen),
  - Burning cities (Römer),
  - Symbol for disaster (medieval, Europe),
  - Torches in the hands of god (Inuit),
  - Ancestors drifted away to remote islands (Maori),
  - merry dancers (Schottland) ......



Brekke and Egeland, 1983, Northern lights, Springer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http://www.pfrr.alaska.edu/actp


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http://www.pfrr.alaska.edu/actp


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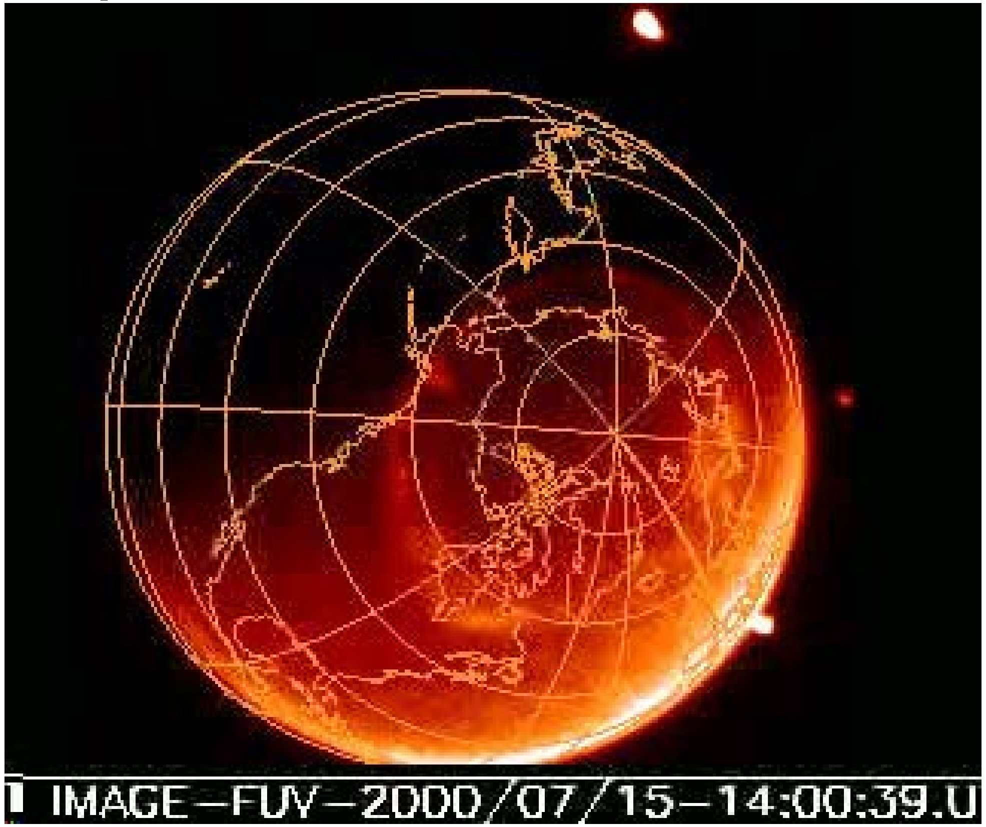
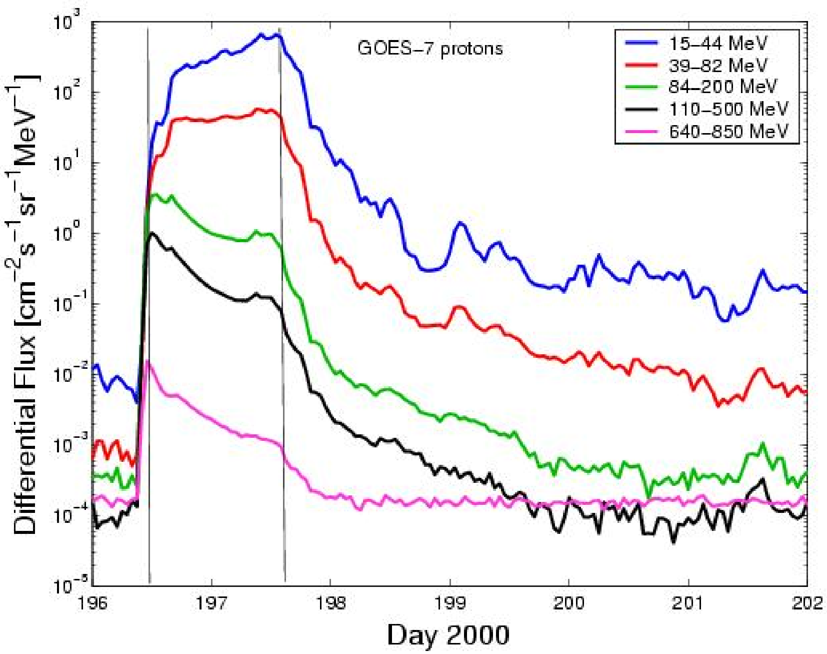
Auroral oval





http://www-spof.gsfc.nasa.gov/istp/polar/

- Satellite image: backscattered UV

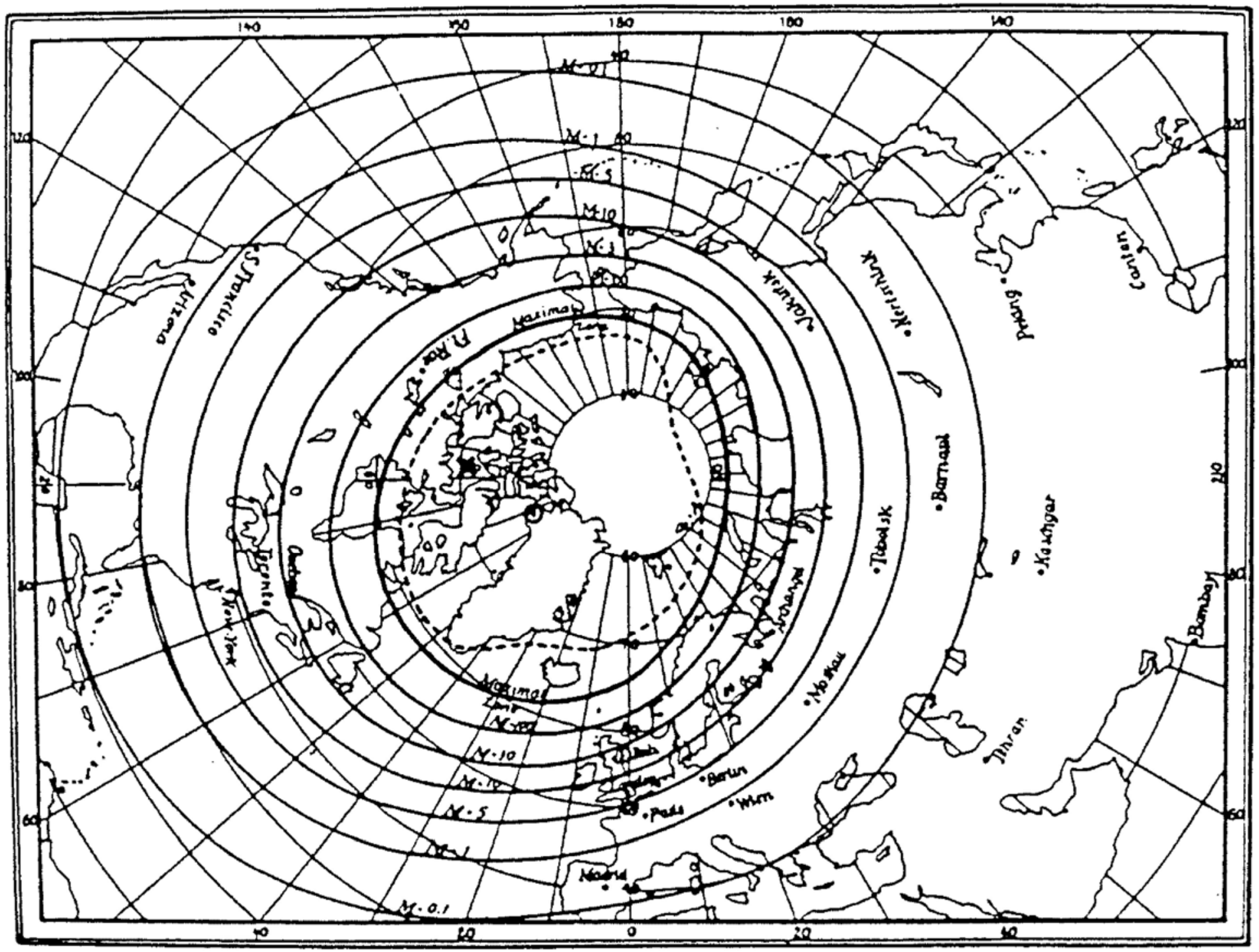
Aurora and folklore

Bamberg, 1560

Kongspeilet (1259): The men who have thought and discussed these lights have guessed at three sources, one of which, it seems, ought to be true. Some hold that fire circles about the ocean and all bodies of water that stream about on the outer side of the globe; and since Greenland lies on the outermost edge of the Earth to the north, they think that it is possible that these fires shine fourth from the fires that encircle the outer ocean. Others have suggested that during the hours of night, when the Sun´s course is beneath the Earth, an occasional gleam of light may shoot up into the sky, for they insist that Greenland lies so far out on the Earth´s edge that the curved surface which shuts out the sunlight must be less prominent there. But there are still others who believe (and it seems to me not unlikely) that the frost and the glaciers have become so powerful there that they are able to radiate forth these flames.

Isochasms

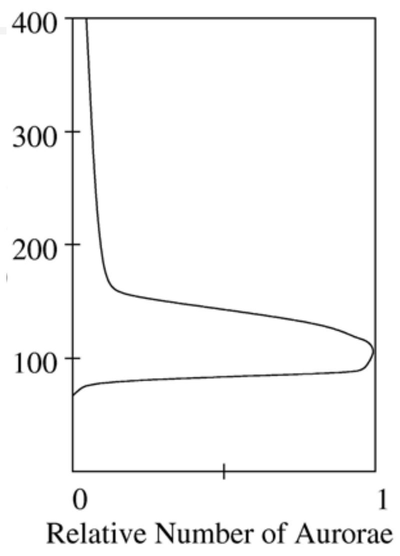
Lines of equal probability for the occurrence of dreadful apparitions.



Fritz, 1881, Das Polarlicht, Brockhaus

Scientific description

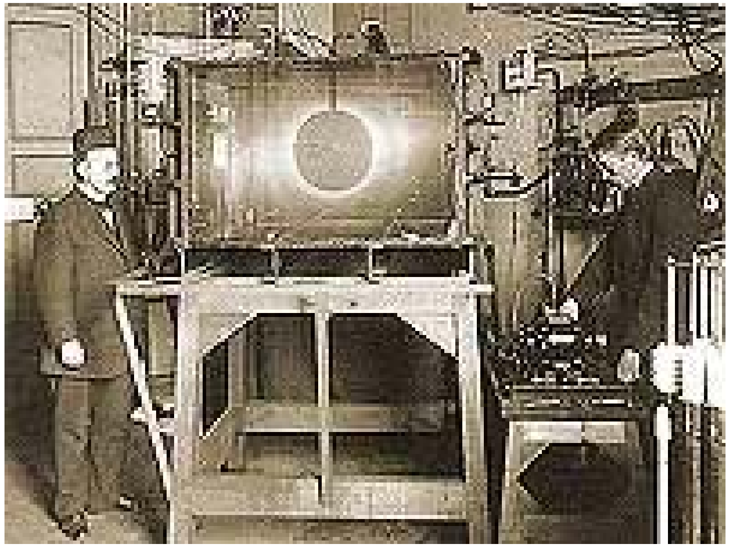
- Relation to geomagnetic disturbances
- Height distribution (excludes reflection at clouds)
- Line spectrum (excludes reflection, allows identification of some of the participating gases)

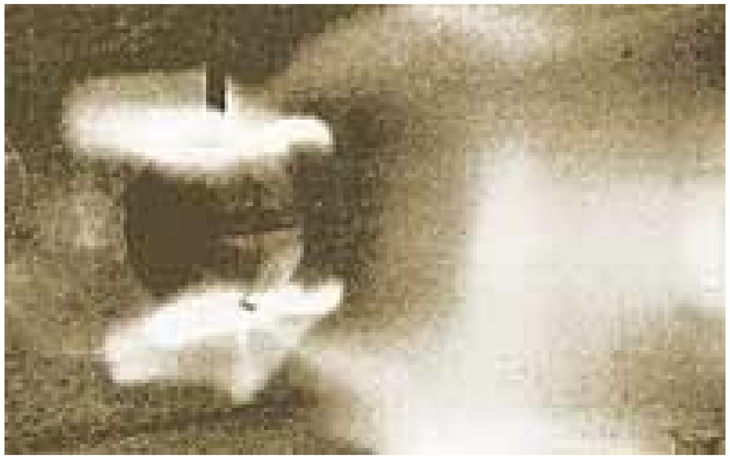


Wavelength (nm)	Emitting species	Altitude (km)	Visual color
391.4	N^+	1000	violet-purple
427.8	N^+	1000	violet-purple
557.7	O	90–150	green
630.0	O	>150	red
636.4	O	>150	red
656.3	$H\alpha$	200–600	red
661.1	N_2	65–90	red
669.6	N_2	65–90	red
676.8	N_2	65–90	red
686.1	N_2	65–90	red

Birkeland´s Terrella

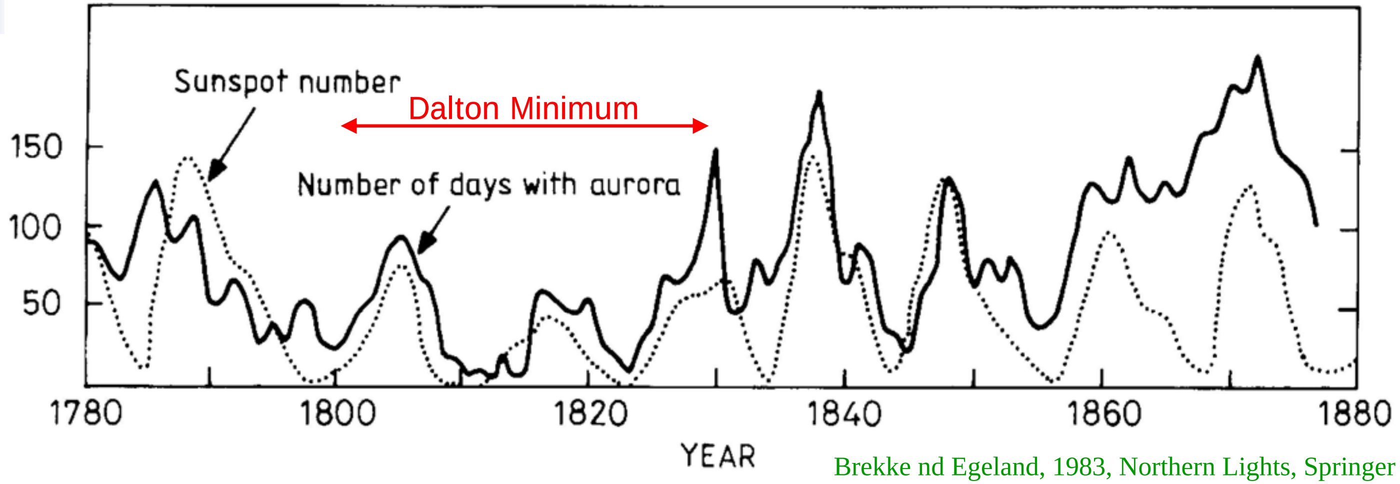
- Aurora is made of
  - Energetic charged particles,
  - Which are guided by the magnetic fields into the auroral oval,
  - And produce light on hitting a screen (the atmosphere=.
- Laboratory experiment by Birkeland 1908:





http://www.uio.no/miljoforum/stral/t3/terrella.shtml

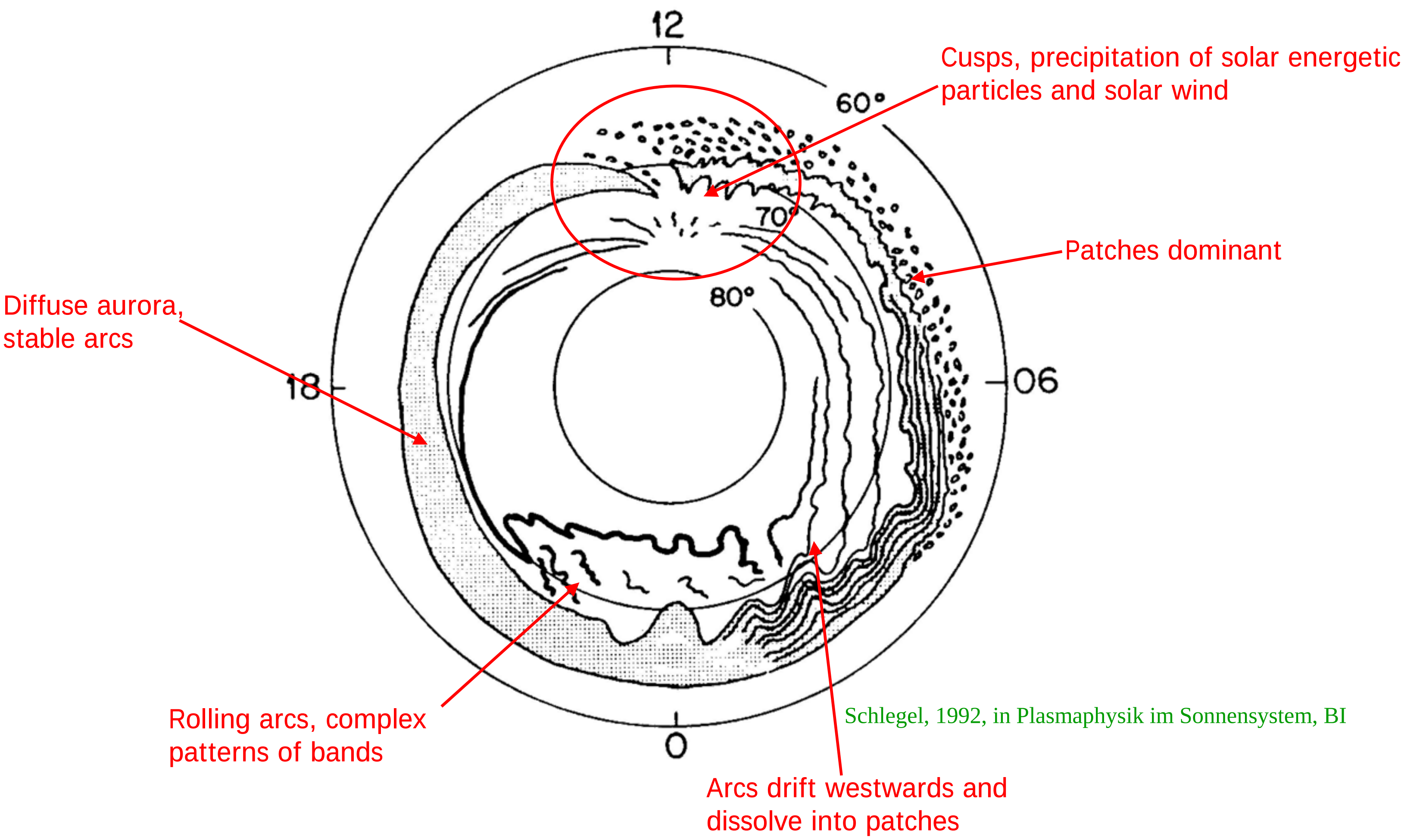
Aurora and sunspots



Brekke nd Egeland, 1983, Northern Lights, Springer

- Aurora roughly correlated with solar cycle.
- Similar to geomagnetic disturbances, aurora also is observed during solar minimum (produced by CIRs).
- Low number of aurora during Dalton-Minimum: aurora can be used as a proxy for solar activity.

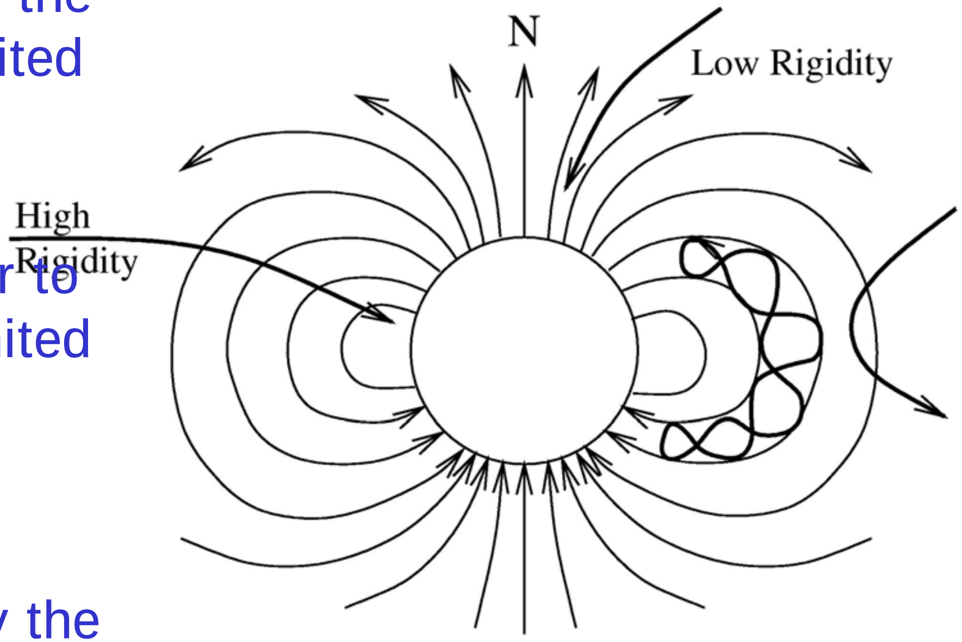
Aurora – variations during the day



Schlegel, 1992, in Plasmaphysik im Sonnensystem, BI

Energetic particles in the magnetosphere

- Solar wind: already reflected at the magnetopause, penetration limited to polar cusps.
- Solar energetic particles: similar to the solar wind, precipitation limited to the polar cap.
- Galactic cosmic rays: global precipitation, orbits modified by the magnetic field.
- Trapped particles: radiation belts.



Radiation belts

- Motion described by the longitudinal invariant (Chap. 2).
- Largest equatorial pitch angle:

$$\sin^2\alpha_{\rm eq} = \frac{B_{\rm eq}}{B_{\rm m}} = \frac{\cos^6\Lambda_{\rm m}}{\sqrt{1+3\sin^2\Lambda_{\rm m}}}$$

- Bounce period:

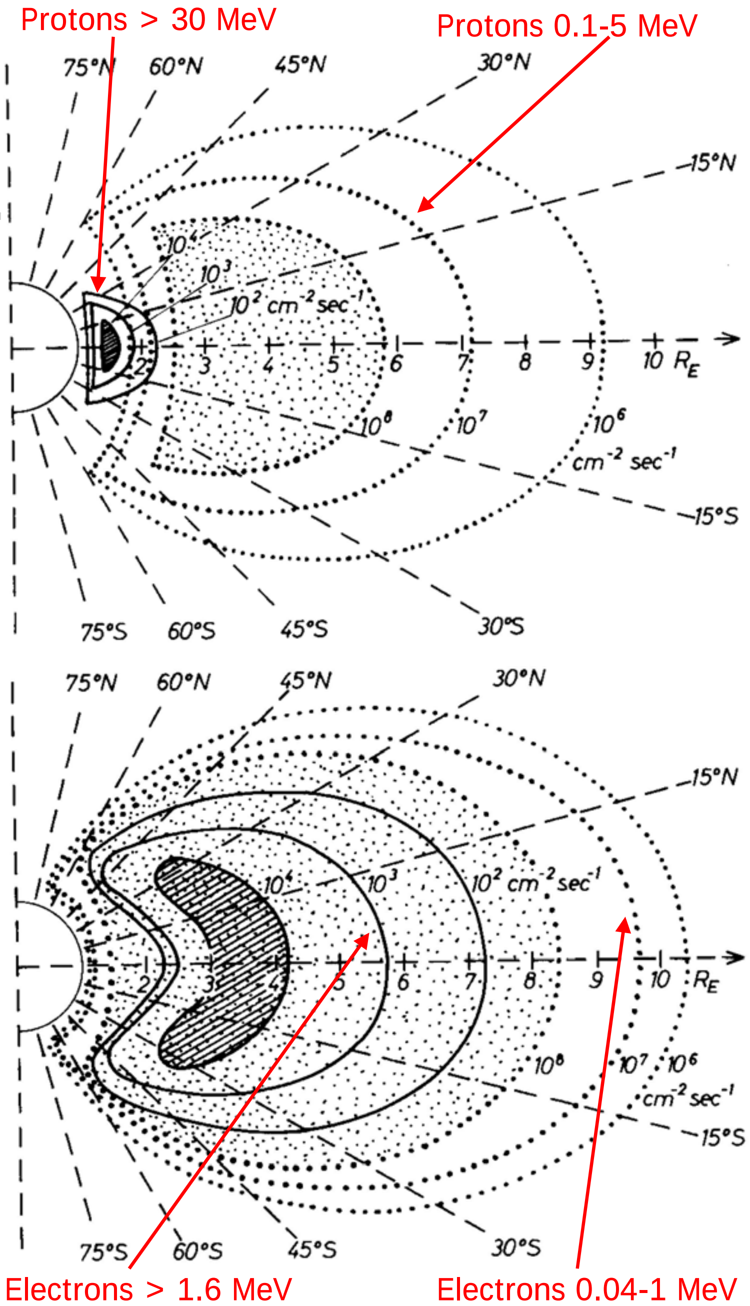
$$\tau_{\rm b} \approx \frac{LR_{\rm E}}{\sqrt{W_{\rm kin}/m}}\,(3.7 - 1.6\sin\alpha_{\rm eq})$$

- Drift (flux invariant):

$$\langle v_{\rm D}\rangle \approx \frac{6L^2 W_{\rm kin}}{qB_{\rm E}R_{\rm E}}\,(0.35 + 0.15\sin\alpha_{\rm eq})$$

$$\langle \tau_{\rm D}\rangle = \frac{2\pi L R_{\rm E}}{\langle v_{\rm D}\rangle} \approx \frac{\pi q B_{\rm E} R_{\rm E}^2}{3LW_{\rm kin}}\,(0.35 + 0.15\sin\alpha_{\rm eq})$$

- Equatorial drift current: $j_{\rm d} = \frac{3L^2 n W_{\rm kin}}{B_{\rm E}R_{\rm E}}$



Kertz, 1971, Einführung in die Geophysik, BI

Radiation belts: losses

- Losses due to pitch angle scattering into the loss cone and interaction with the atmosphere:

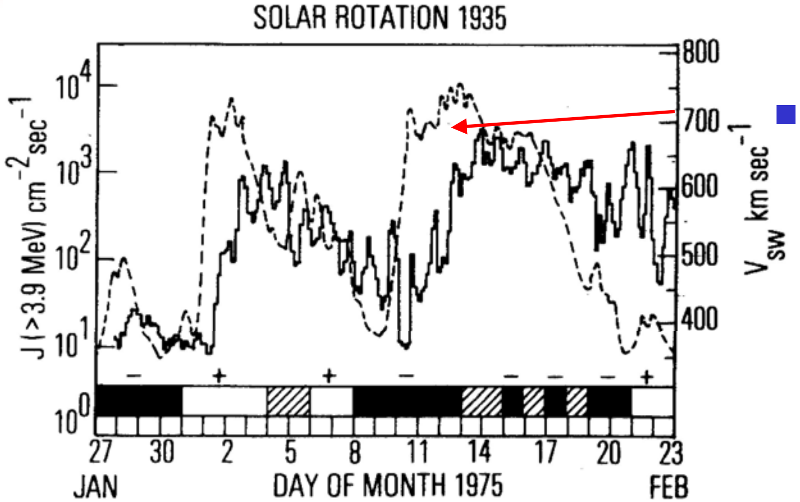
$$\sin \alpha_{\mathrm{eq}}^2 = \sqrt{4L^6 - 3L^5}\,.$$

  loss cone small for r > 3 earth radii.

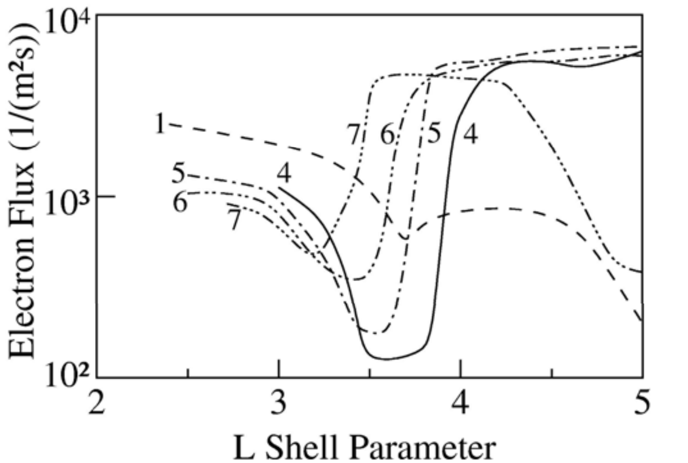
  - Charge exchange with particles of the neutral atmosphere,
  - Coulomb interaction (Bethe-Bloch),
  - Hadronic interaction (only very high energies).

- Losses increase with increasing geomagnetic activity because scattering is increased.

Radiation belts: sources



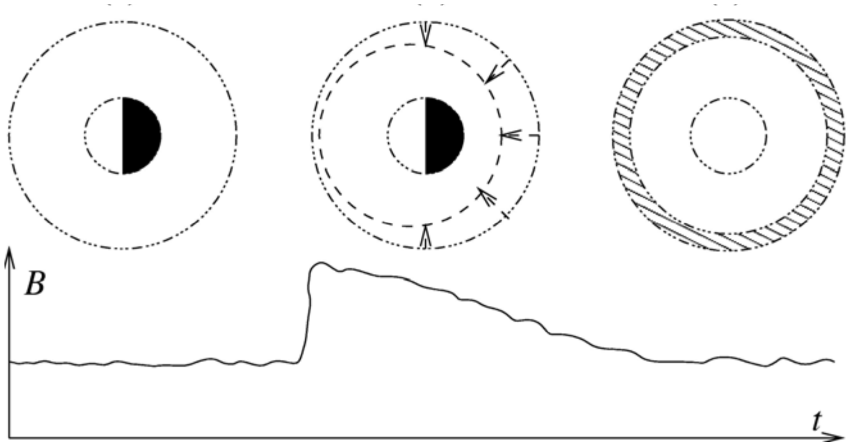
Paulikas and Blake, 1979, in Quantitative modeling of magnetospheric processes, Americ. Geophys. Union



nach Frank et al., 1964, J. Geophys. Res. 69, 2171

- Generation of particles:
  - CRAND: cosmic ray albedo neutron decay,
  - Recombination in the outer magnetosphere and ionization on the dayside in the inner magnetosphere.
- Particle transport:
  - During geomagnetic activity increase in particle fluxes in the outer magnetosphere (decreases in inner magnetosphere),
  - Transport inwards combined with acceleration (L shell diffusion).

L-shell diffusion



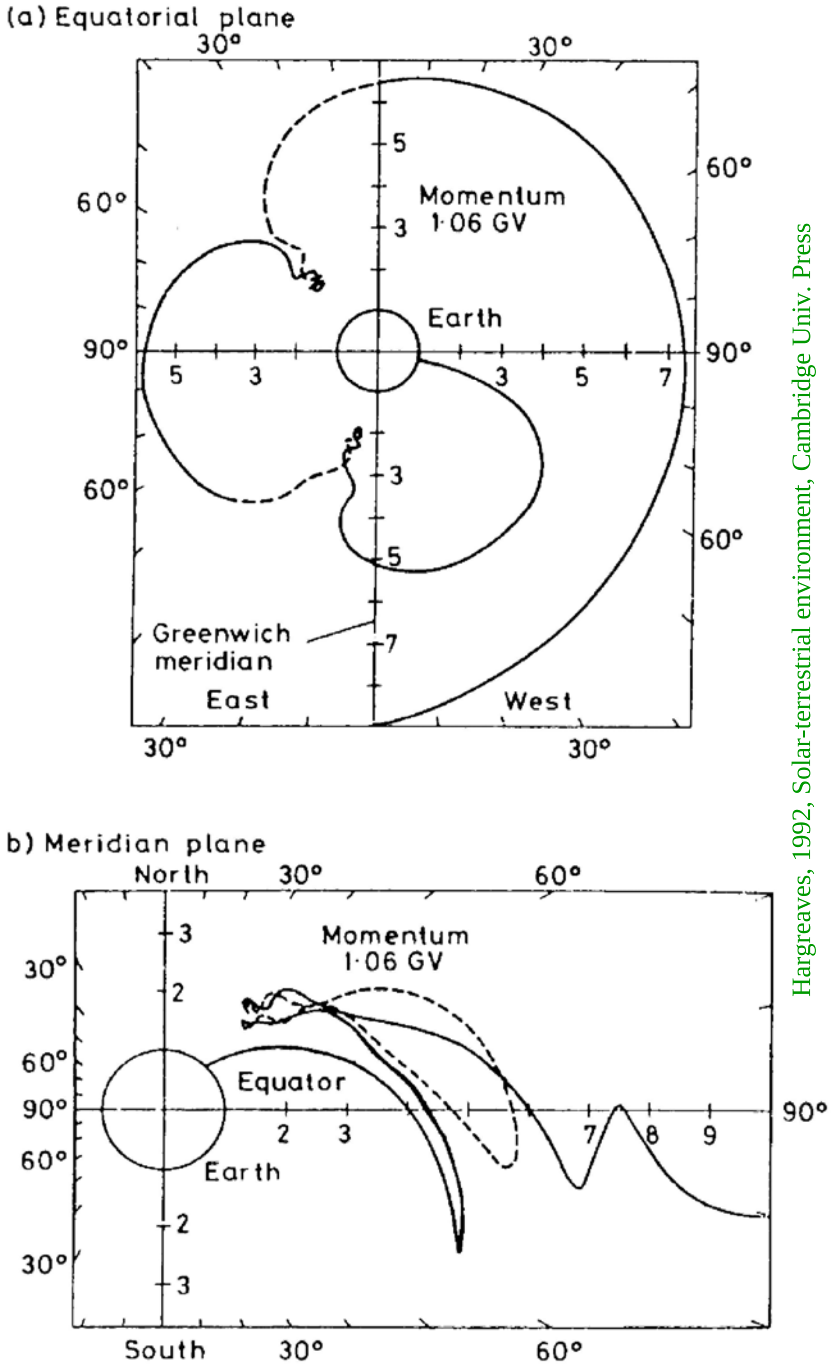
- Sudden compression of the magnetosphere widens particle distribution and accelerates particles moving inwards.
- Betatron effect $W_{\rm kin} = mv^2/2 \sim \omega_{\rm c} \sim B$ leads to an acceleration due to the inward motion (perpendicular to the field).
- Fermi-effect (longitudinal invariant) leads to acceleration due to the reduced distance between the mirror points.

$\Rightarrow$ Adiabatic heating has a parallel and a perpendicular component:

$$\frac{W_{\|}}{W_{|0}} = \left(\frac{L_{\rm o}}{L}\right)^{\kappa} \qquad \frac{W_{\perp}}{W_{\perp.0}} = \left(\frac{L_{\rm o}}{L}\right)^{3}$$

Størmer orbits

- Integration of the equation of motion,
- Motion depends on
  - The particle's rigidity,
  - The position of incidence,
  - The angle of incidence.
- In general: with increasing magnetic rigidity the cutoff latitude decreases.



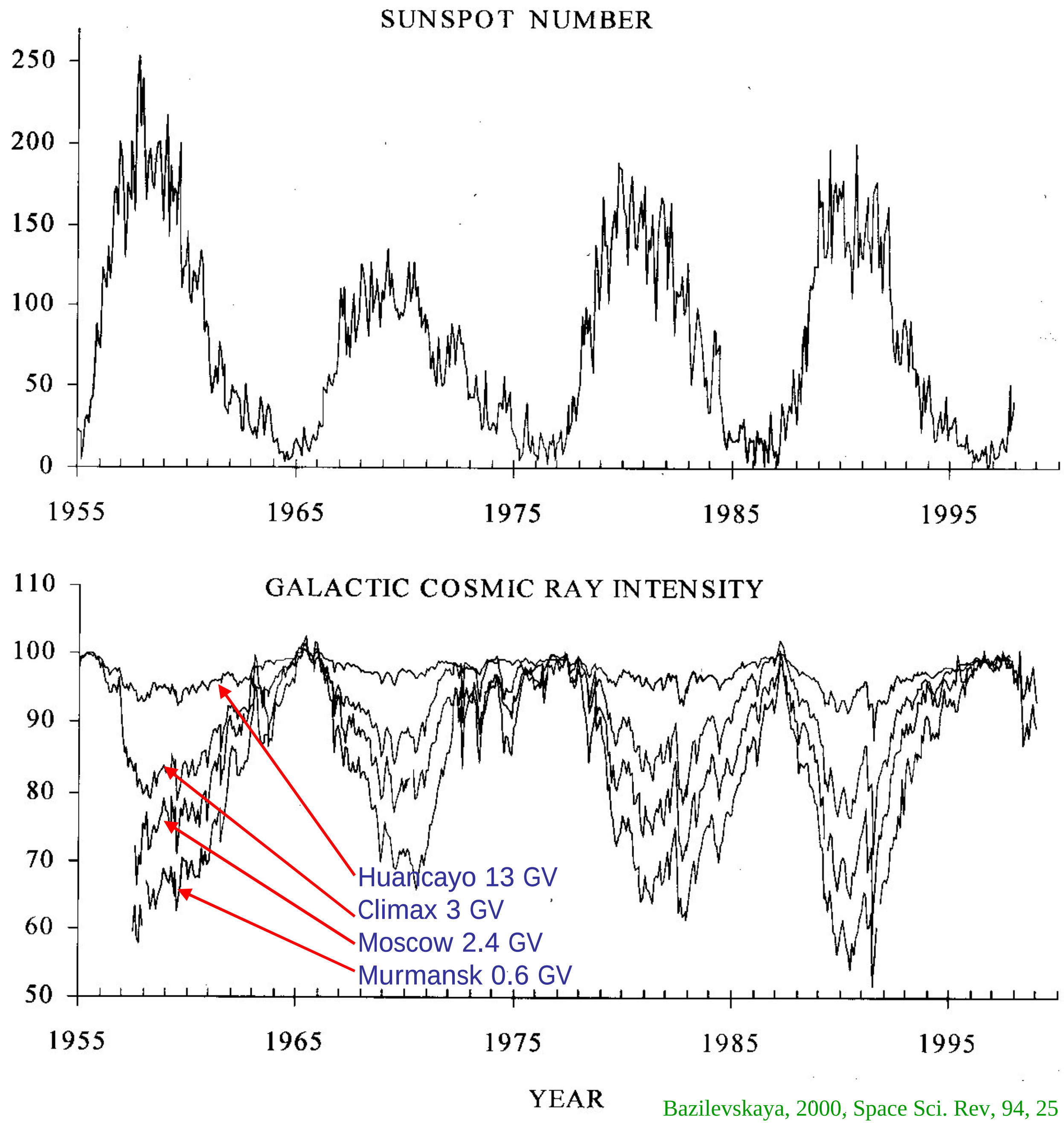
Hargreaves, 1992, Solar-terrestrial environment, Cambridge Univ. Press

Cutoff

- Cutoff rigidity: lowest rigidity with which a particle at a certain geomagnetic latitude is able to reach the ground

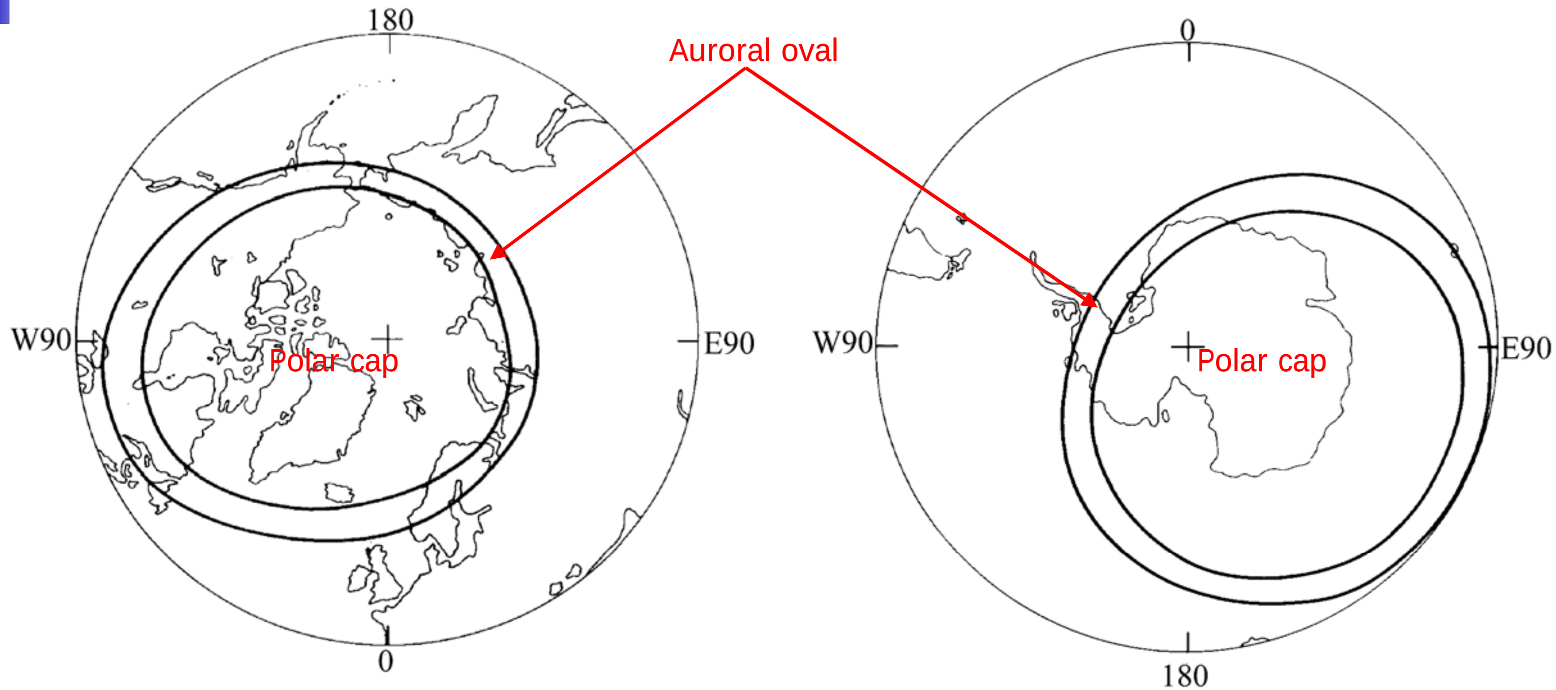
- Equator: 14.9 GV

- Variation with geomagnetic latitude as cos^4



Bazilevskaya, 2000, Space Sci. Rev, 94, 25

Polar cap absorption (PCA)



Reid, 1986, Physics of the Sun III, Reidel

- Disruption of radio communication over the polar cap due to its ionization by precipitating energetic particles.
- PCAs define the spatial area over which solar particles can hit the atmosphere ($\rightarrow$ ozone, Chap. 10)