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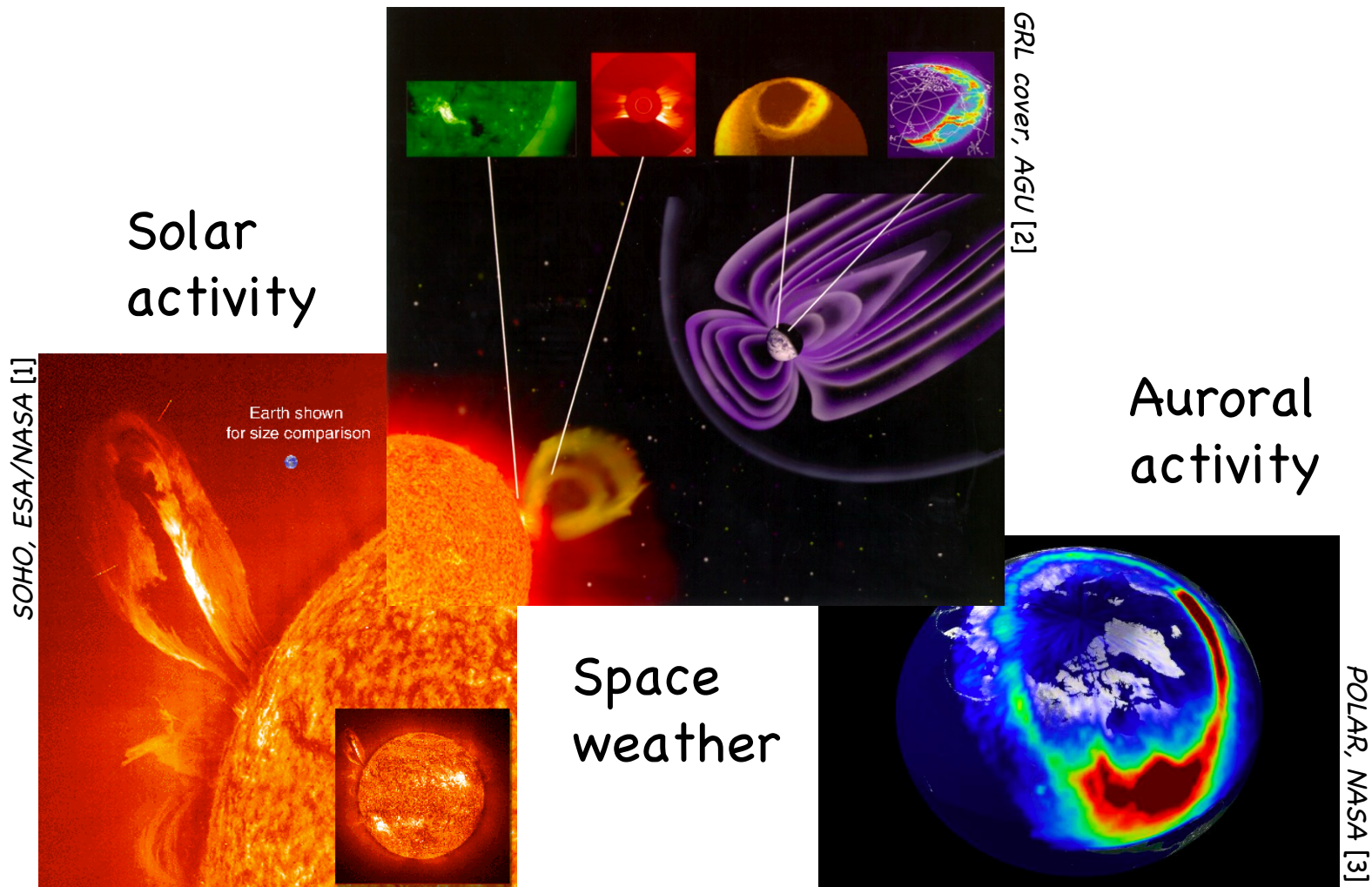
STIMM-2 Sinaia
12-16 June 2007



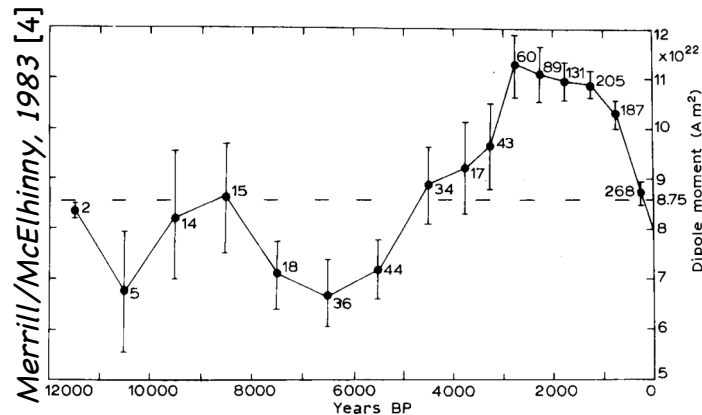
Paleomagnetospheric processes

Joachim Vogt, B. Zieger (Jacobs University)
K.-H. Glassmeier, A. Stadelmann (TU BS)

Effects of solar variations

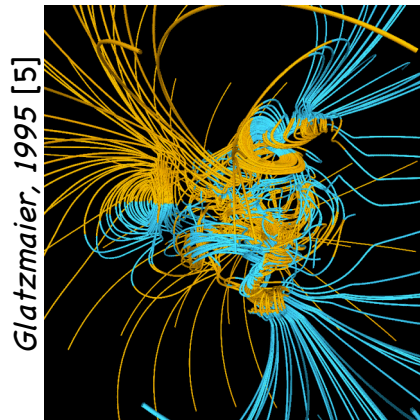


Geomagnetic variations



Dipole moment magnitude

- Significant variations on time scales of several 1000 years
- Current rate of decrease: 1% in 20 years



Geomagnetic field reversals

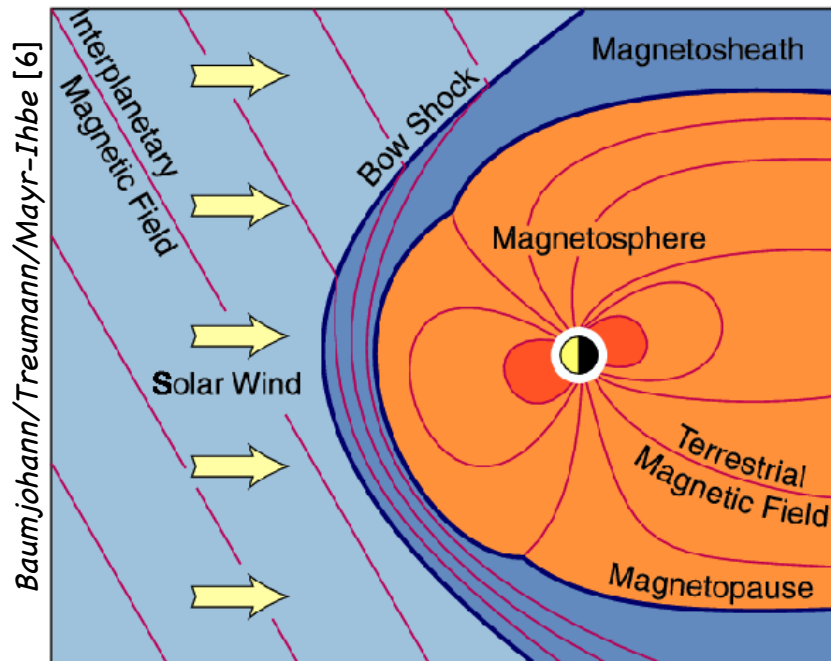
- Polarity flips within a few 1000 years

Transition field scenarios

- Rotation of the dipole axis
- Higher-order multipoles

The outer magnetosphere

Magnetized planets are obstacles in the supermagnetosonic and collisionless plasma of the solar wind.

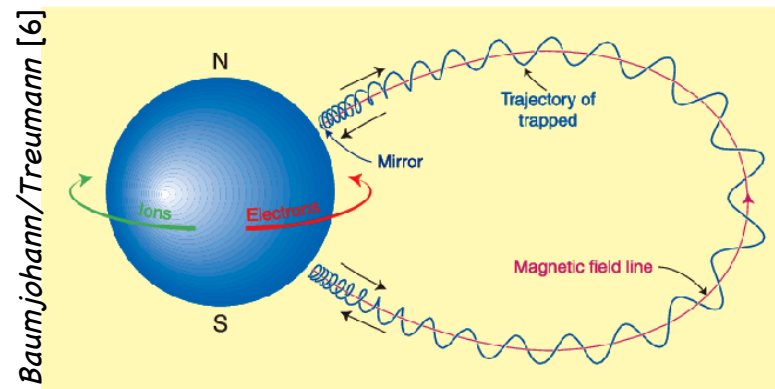
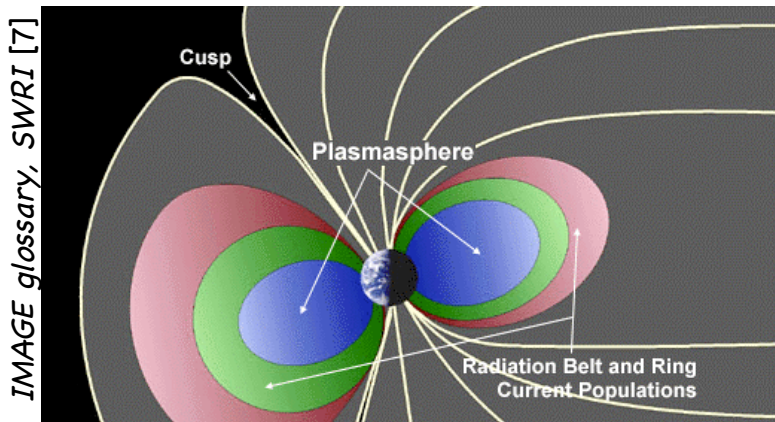


Dayside magnetopause :

$$\text{SW ram pressure} = \text{magnetic pressure of the geomagnetic field}$$

→ *Stand-off distance changes also with the Earth's internal magnetic field*

The inner magnetosphere



Plasmasphere

- Cold plasma population that co-rotates with the geomagnetic field

Radiation belts

- Energetic particles trapped in the dipolar configuration

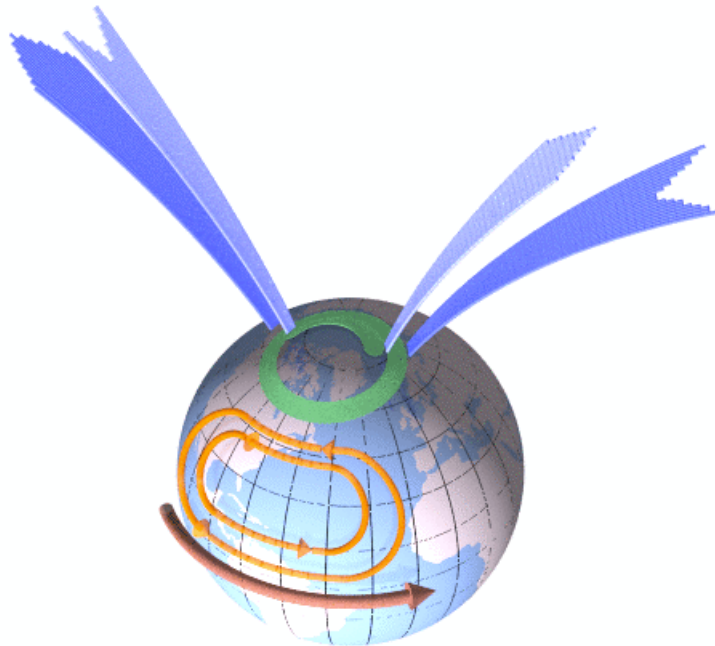
Ring current

- Drift motion of radiation belt particles

➔ *Also controlled by the internal magnetic field*

Ionospheric current systems

GFZ Potsdam, SWARM [8]



Auroral (polar) electrojet

- Fed by FACs during geomagnetic activity

Sq current system

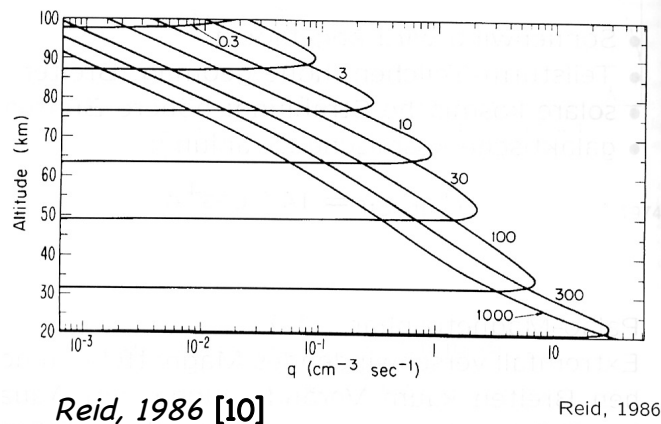
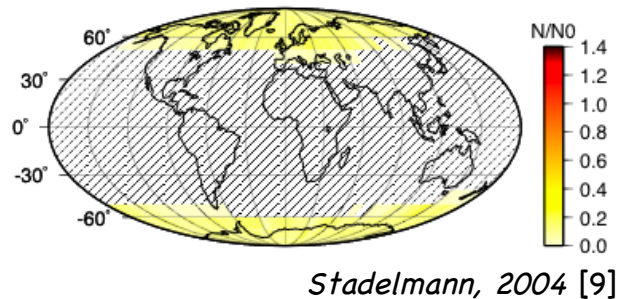
- Driven by tidal winds

Equatorial electrojet

- Pronounced equatorial part of the Sq system

→ *How do variations of the internal field affect these currents?*

Energetic particles in geospace



Galactic cosmic rays (GCRs)

- Dominate particle fluxes for energies > 100 MeV
- Distribution latitude & longitude: inner MS, internal field
- Can reach lower atmosphere

Solar energetic particles (SEPs):

- Most important in the energy range 1-100 MeV
- Distribution latitude & longitude: outer MS, open field lines
- Effects on middle atmosphere

Paleomagnetosphere - open questions

The varying internal geomagnetic field is a key factor in the formation of the Earth's magnetosphere (MS) ...

How do plasma boundaries, current systems, and other magnetospheric phenomena change with the internal field?

If the internal field is weaker than today, and external current systems may be even stronger ...

Could external currents affect paleomagnetic reconstructions?

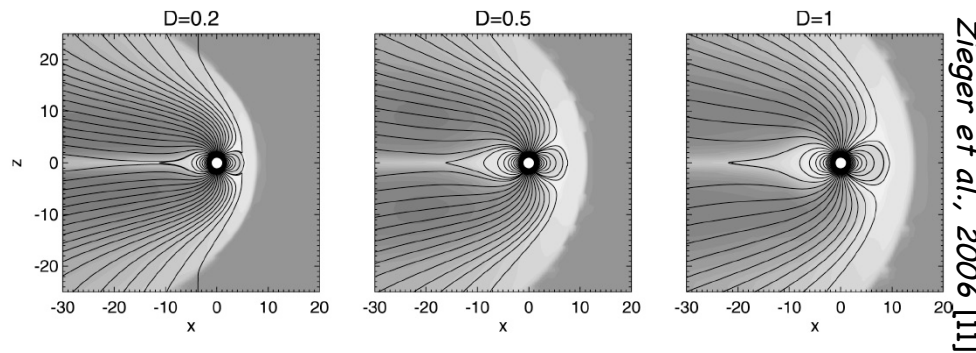
The geomagnetic field shields the Earth's atmosphere from energetic particles of solar and cosmic origin ...

How large are the fluxes of GCRs (inner MS, internal field) and SEPs (outer MS, open field lines) into the Earth's atmosphere?

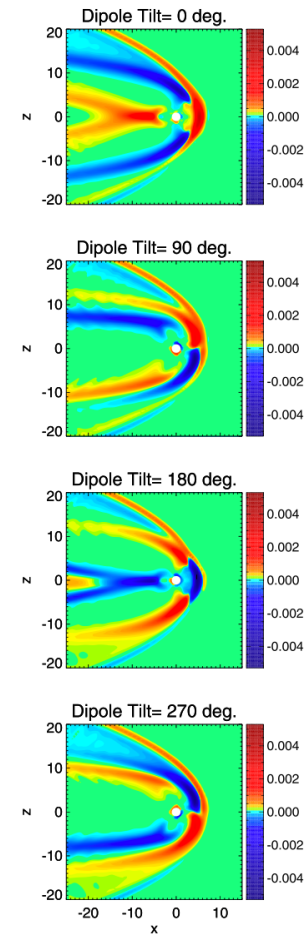
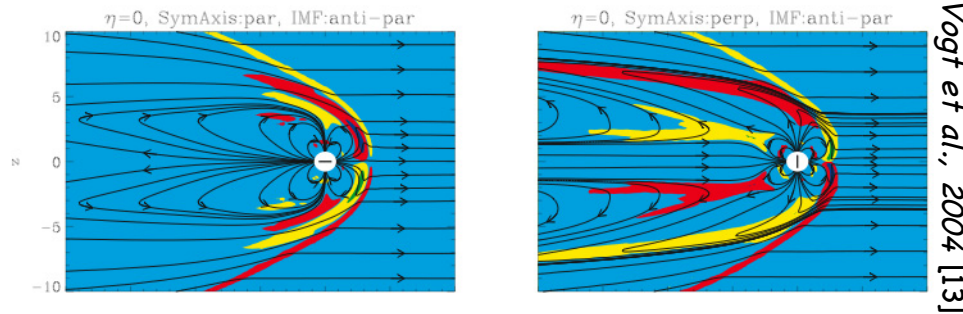
Paleomagnetospheric configurations

Variation scenarios considered here

(1) Dipole moment magnitude



(3) Non-dipolar paleomagnetospheres



(2)
Equatorial
dipole:
strong
diurnal
variations

Overview

Introduction to the paleomagnetosphere

Variations of the dipole moment

- Scaling of magnetopause, polar cap, transpolar potential
- Ionospheric current systems and the surface field

Equatorial dipolar paleomagnetospheres

Non-dipolar paleomagnetospheres

- Inner and outer quadrupole magnetospheres
- Dipole-quadrupole configurations, polar cap scaling

Energetic particles in the paleomagnetosphere

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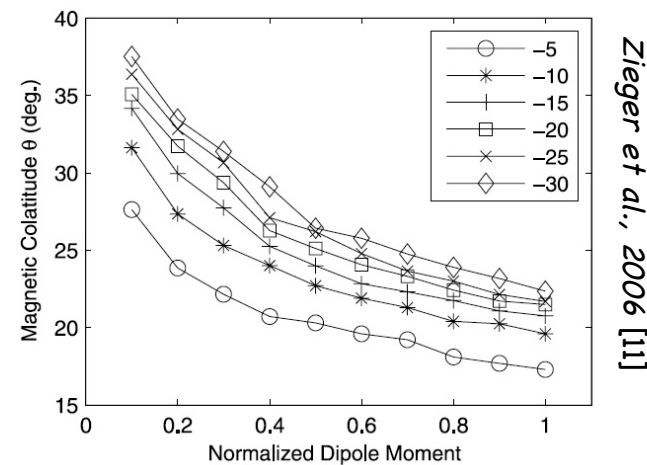
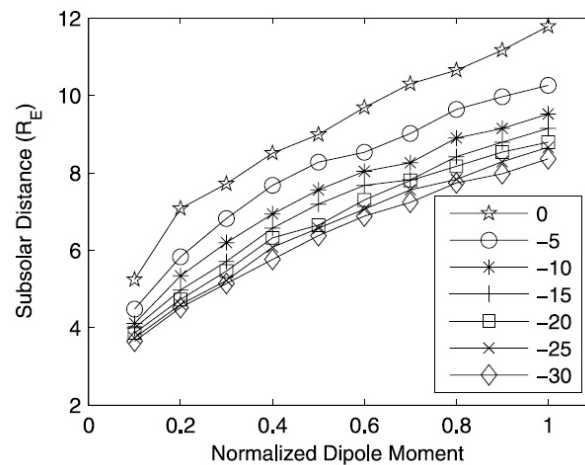
Scaling of magnetopause and polar cap

Siscoe and Chen (1975), assuming self-similarity

- Magnetopause subsolar distance : $M^{1/3}$
- Polar cap size $\sin(\theta)$: $M^{-1/6}$

Vogt and Glassmeier (2001), Zieger et al. (2006a, 2006b),
magnetohydrodynamic simulations

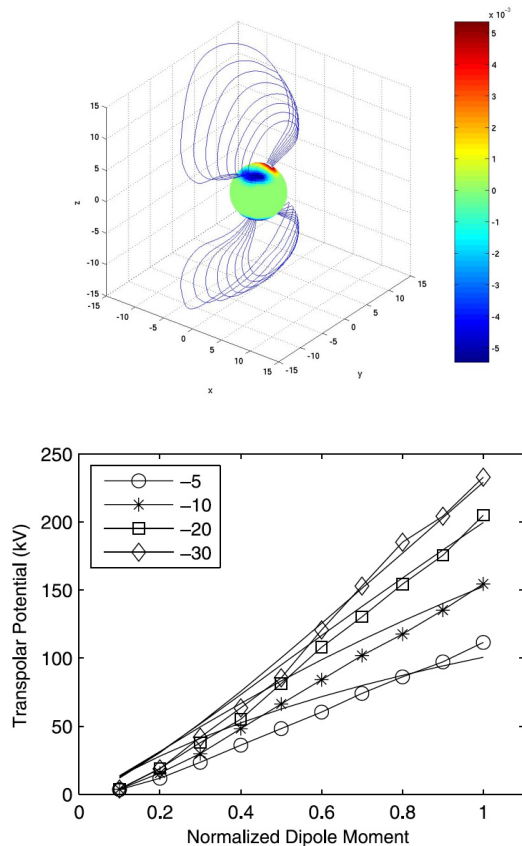
→ Scaling relations depend strongly on IMF B_z



Zieger et al., 2006 [11]

Transpolar cap potential saturation

Zieger et al., 2006 [11]



Transpolar cap potential

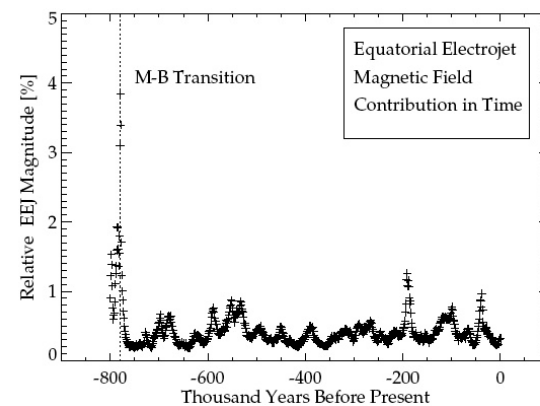
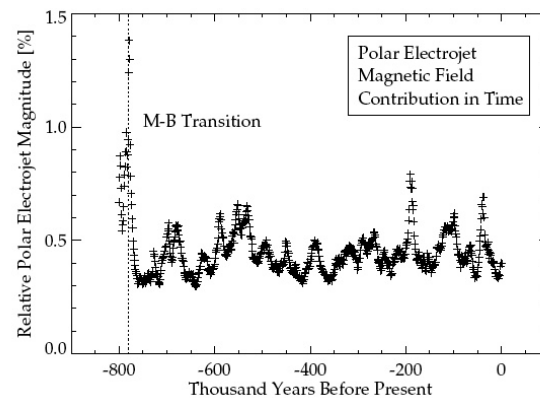
- Increase with solar wind electric field, saturation for large input values
- Analytical Hill-Siscoe model (1976, 2002) does not take into account magnetosphere size variation with IMF Bz
- MHD simulation results allow to apply a correction to the Hill-Siscoe model

Scaling of ionospheric current systems

In a weak dipole field, how much could external current systems contribute to the surface magnetic field?

Glassmeier et al. (2004) derived scaling relations for the surface magnetic effects of the most important external currents

- Ring current : $M^{2/3}$ / Auroral EJ : $M^{1/6}$ / Equatorial EJ : $M^{-2/3}$
- Insufficient to affect interpretation of paleomagnetic observations



Glassmeier et al., 2004 [14]

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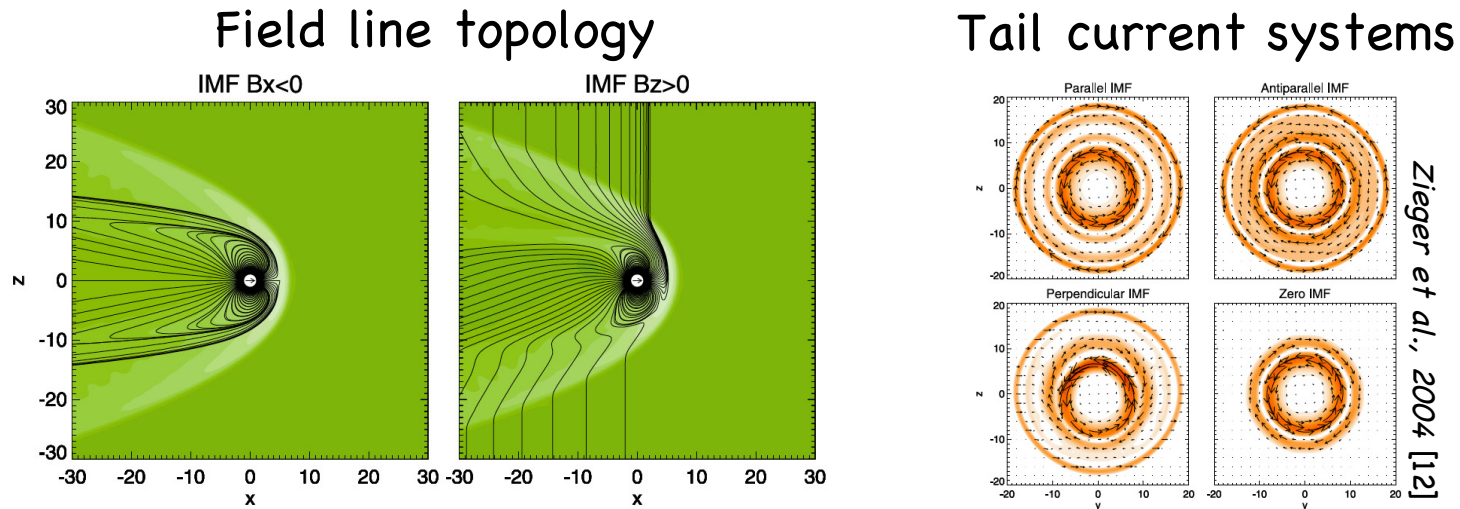
Equatorial dipolar paleomagnetospheres

Non-dipolar paleomagnetospheres

- Inner and outer quadrupole magnetospheres
- Dipole-quadrupole configurations, polar cap scaling

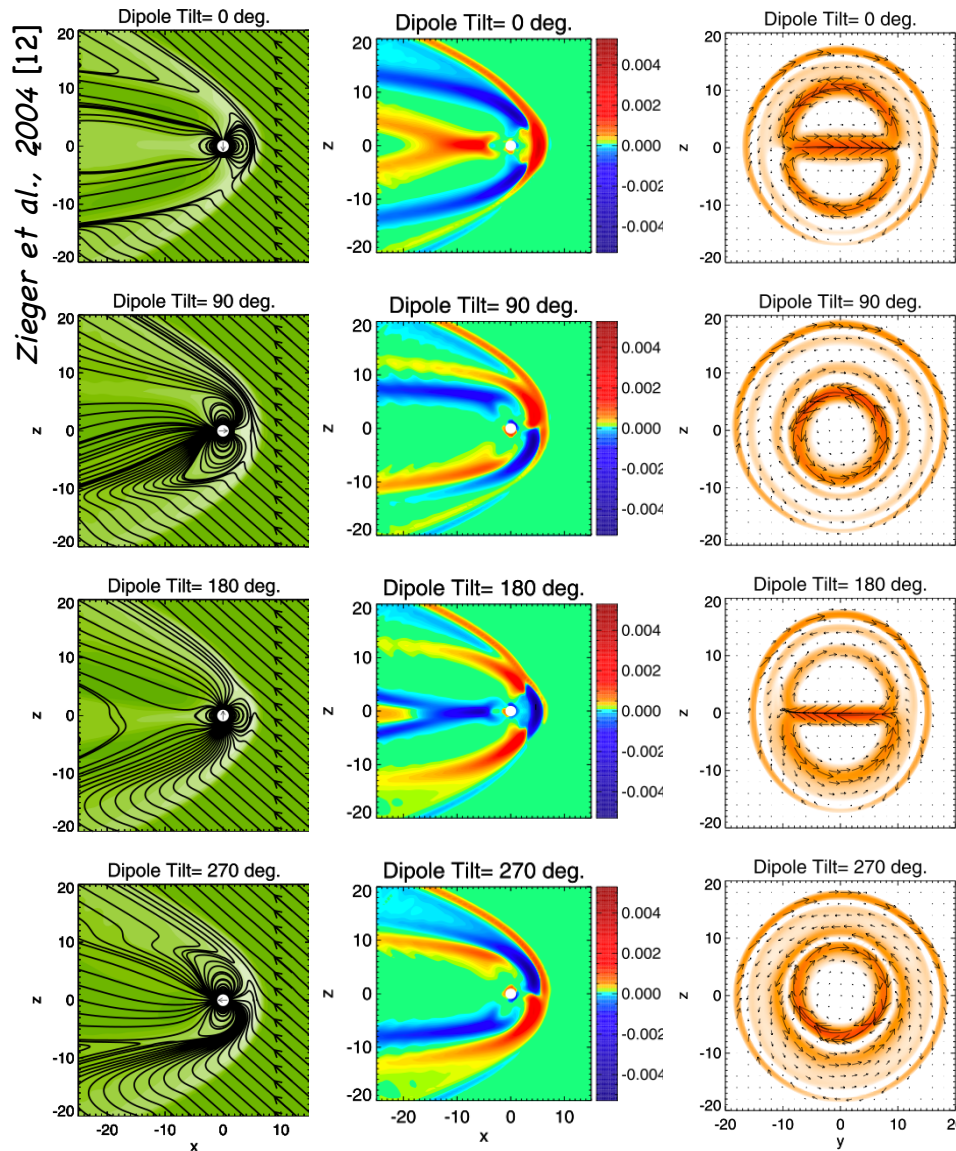
Energetic particles in the paleomagnetosphere

Dipolar pole-on configuration



MHD simulations of the pole-on case by Zieger et al. (2004)

- Field line topology depends also on parallel IMF
- Tail current systems are circular in shape, not connected with magnetopause currents
- Open field line region still around the geomagnetic poles



Equatorial dipolar magnetosphere

Dipole and rotation axis are perpendicular → global reconfigurations within each day

- Field line topology
- Magnetopause current
- Tail currents

Solar system analogy: Neptune?

Overview

Introduction to the paleomagnetosphere ✓

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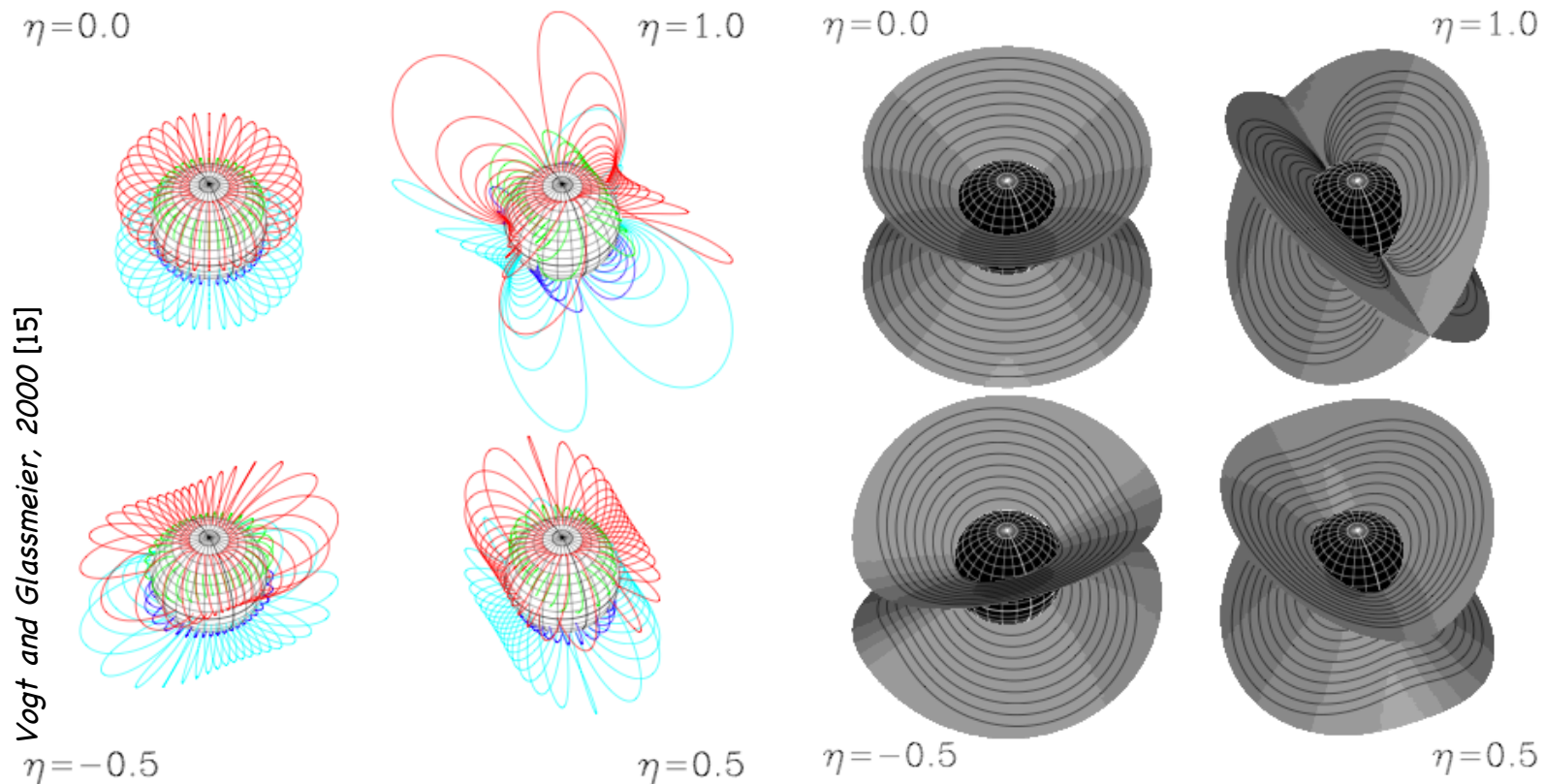
Equatorial dipolar paleomagnetospheres ✓

Non-dipolar paleomagnetospheres

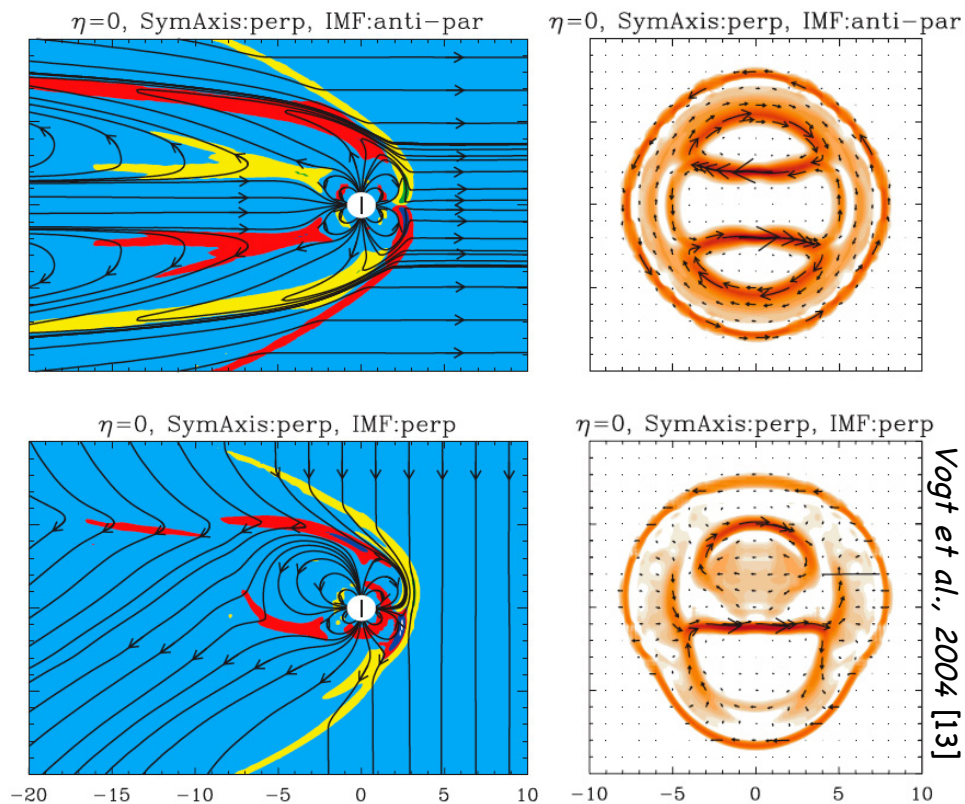
- Inner and outer quadrupole magnetospheres
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Energetic particles in the paleomagnetosphere

Topology of quadrupolar core fields and drift orbits of trapped particles



The outer quadrupole magnetosphere in MHD simulations (1)



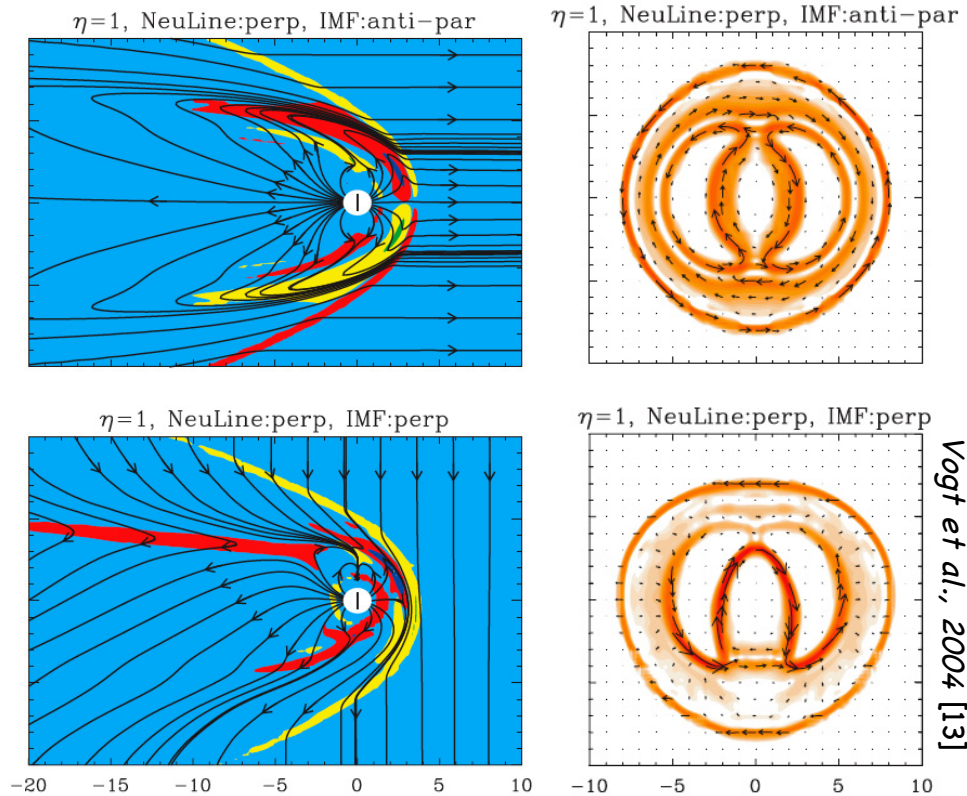
Control parameters

- Topology (η)
- Orientation w.r.t. the solar wind flow
- IMF direction

Axially symmetric core field, perpendicular to solar wind flow

- IMF parallel: two tail current sheets
- IMF perpendicular: two hemispheres, open and closed

The outer quadrupole magnetosphere in MHD simulations (2)



Quadrupole core fields with neutral lines

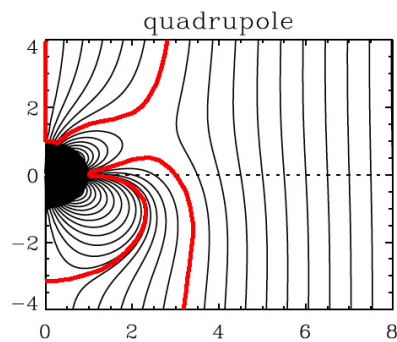
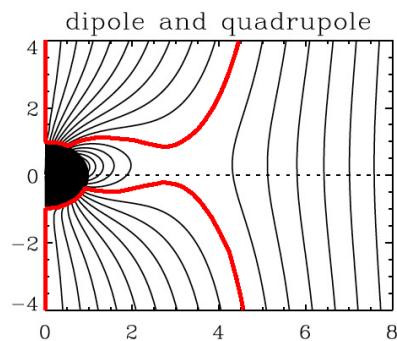
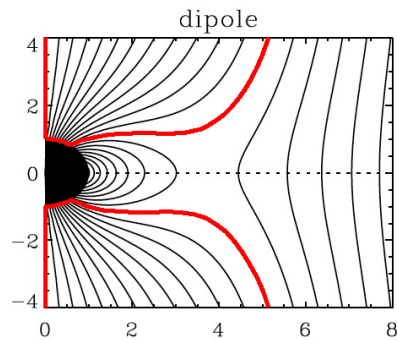
Weak field regions in the magnetosphere?

→ Field line "draping" due to interaction with the solar wind.

Complex current systems, essentially three-dimensional.

Vogt et al., 2004 [13]

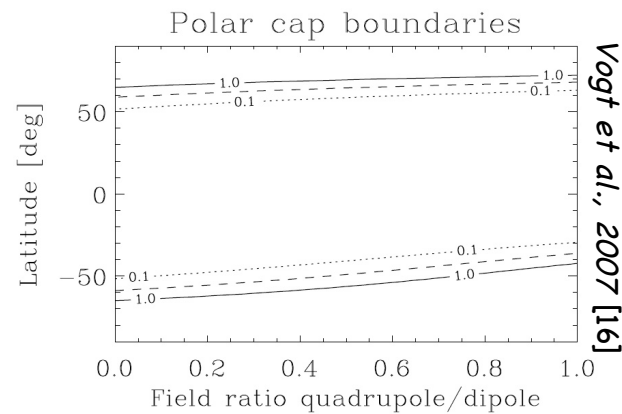
Mixed dipole-quadrupole paleomagnetospheres



Open field lines - entry regions for particles of lower energy (up to several 10 MeV)

- Mixed dipole-quadrupole configuration:
→ polar caps are different in size

Generalized polar cap scaling model: one p.c. boundary may reach 30 degrees latitude



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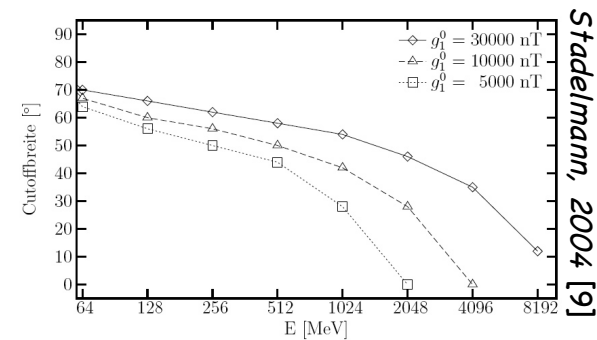
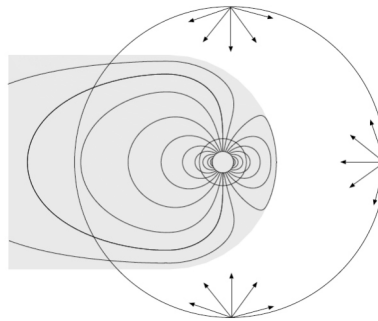
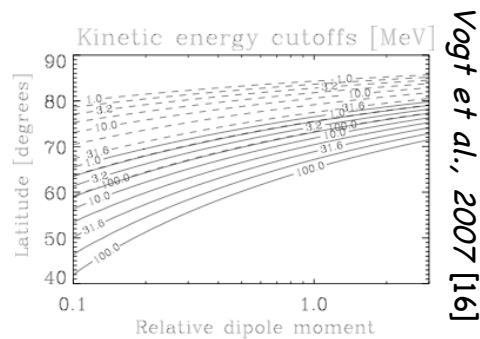
Equatorial dipolar paleomagnetospheres ✓

Non-dipolar paleomagnetospheres ✓

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Energetic particles in the paleomagnetosphere

Particles in dipolar magnetospheres



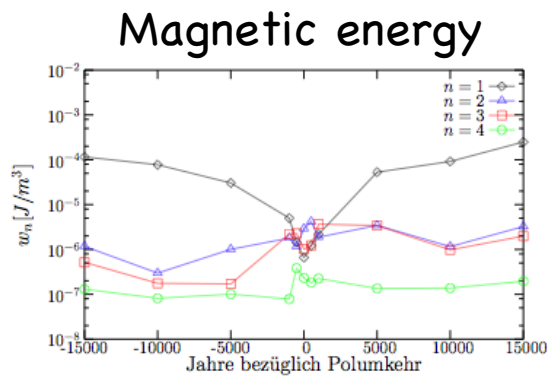
Low-energy (up to a few 10 MeVs) particles enter magnetosphere (MS) mostly along open field lines → outer MS, polar cap scaling

Higher (100 MeVs and more) energies → inner MS, core (dipole) field

- Analytical approach: Stoermer formula
- Validation of numerical particle tracing scheme (Stadelmann 2004)

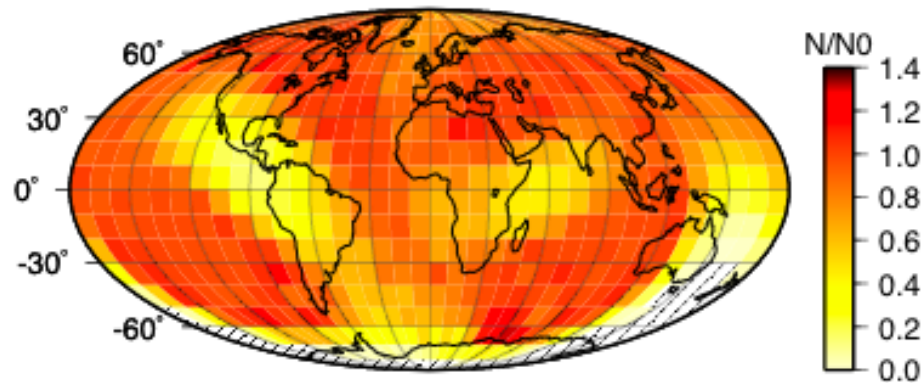
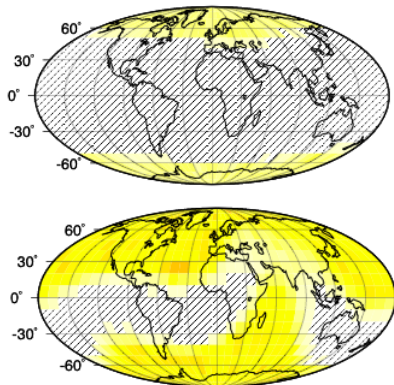
Numerical particle tracing in a modeled reversal magnetosphere

Stadelmann, 2004 [9]

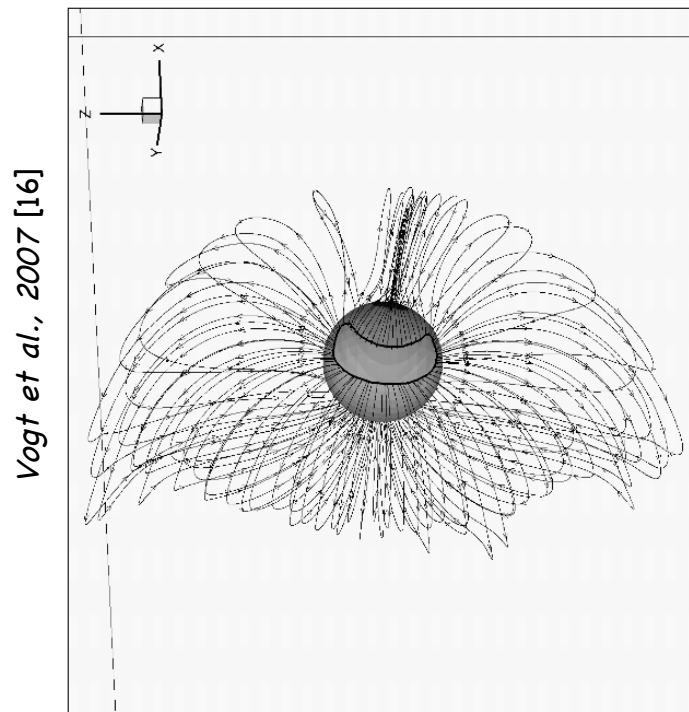


Potential field model developed by

- Stadelmann (2004) using the
- Glatzmaier (1995) coefficients
- ➔ Particle impact area for a wide range of high energies (above 100 MeV, galactic cosmic rays)



Open field line regions in a simulated reversal magnetosphere



Solar energetic particles (up to several 10 MeVs)

- are affected by the outer MS
- identify open field lines

Work in progress:

- Transition field coefficients from paleomagnetic reconstruction (Leonhardt & Fabian)
- MHD simulations (Zieger & Vogt)
- Open field line information used to model ionization (Kallenrode) and atmospheric chemistry (Winkler & Sinnhuber)

Summary

Dipolar paleomagnetospheres

- Scaling relations for plasma boundaries, current systems, open field line regions - some of them improved by MHD simulations
- External current systems are unlikely to affect paleomagnetic data

Equatorial dipolar paleomagnetospheres: regular global reconfigurations in the course of one day

Non-dipolar paleomagnetospheres

- Topologically new structures in quadrupolar magnetospheres
- Magnetospheric dynamics less sensitive to solar wind parameters
- Dipole-quadrupole configurations may yield huge polar caps

Polarity transitions: enhanced particle fluxes into the atmosphere, ozone layer is significantly affected during solar particle events

Figures and references

- [1] Image taken from the SOHO (ESA/NASA) website
<http://sohowww.nascom.nasa.gov/bestofsoho/> (2006/09/26).
- [2] GRL cover picture, image credit: AGU. Downloaded from NASA:
<http://pwg.gsfc.nasa.gov/istp/outreach/theretohere.html> (2006/09/26).
- [3] Image based on data from POLAR, credit: Greg Shirah. Downloaded from
<http://pwg.gsfc.nasa.gov/istp/outreach/afromspace.html> (2006/09/26).
- [4] Figure taken from the book of R.T. Merrill and M.W. McElhinny, *The Earth's Magnetic Field*, Academic Press, London 1983.
- [5] Geodynamo simulations by G. Glatzmaier and P.H. Roberts, see
<http://www.es.ucsc.edu/~glatz/geodynamo.html> (2005/09/25).
- [6] Colorized versions of figures from the book *Basic Space Plasma Physics* by W. Baumjohann and R. Treumann. The PDF files of the color figures were kindly provided by R. Mayr-Ihbe, MPE Garching.
- [7] Image from the IMAGE mission web page, Southwest Research Institute (SWRI): <http://pluto.space.swri.edu/IMAGE/glossary/plasmasphere.html> (2006/09/27).

Figures and references (continued)

- [8] Image credit: GeoForschungsZentrum (GFZ) Potsdam, Swarm mission: <http://www.gfz-potsdam.de/pb2/pb23/SatMag/Swarm/Img/l03.gif> (2005/04/04).
- [9] Stadelmann, Anja (2004), Globale Effekte einer Magnetfeldumkehr, PhD thesis, Technical University Braunschweig.
- [10] Reid, G.C. (1986), Solar energetic particles and their effects on the terrestrial environment, in: *Physics of the Sun*, Vol. III, Reidel Publ.
- [11a] Zieger, B., J. Vogt, A.J. Ridley, and K.-H. Glassmeier (2006a), A parametric study of magnetosphere-ionosphere coupling in the paleomagnetosphere, *Adv. Space Res.*, 38, 1707-1712.
- [11b] Zieger, B, J. Vogt, and K.-H. Glassmeier (2006b), Scaling relations in the paleomagnetosphere derived from MHD simulations, *J. Geophys. Res.*, 111, A06203.
- [11c] Vogt, J., and K.-H. Glassmeier (2001), Modelling the paleomagnetosphere: strategy and first results, *Adv. Space Res.*, 28, 863-868.

Figures and references (continued)

- [12] Zieger, B., J. Vogt, K.-H. Glassmeier, and T. Gombosi (2004), Magnetohydrodynamic simulations of an equatorial dipolar paleomagnetosphere, *J. Geophys. Res.*, 109, A07205.
- [13] Vogt, J., B. Zieger, A. Stadelmann, K.-H. Glassmeier, T.I. Gombosi, K.C. Hansen, and A.J. Ridley (2004), MHD simulations of quadrupolar paleomagnetospheres, *J. Geophys. Res.*, 109, A12221.
- [14] Glassmeier, K., J. Vogt, A. Stadelmann, and S. Buchert (2004), Concerning long-term geomagnetic variations and space climatology, *Ann. Geophys.*, 22, 3669-3677.
- [15] Vogt, J., and K.-H. Glassmeier (2000), On the location of trapped particle populations in quadrupolar paleomagnetospheres, *J. Geophys. Res.*, 105, 13,063-13,071.
- [16] Vogt, J., B. Zieger, K.-H. Glassmeier, A. Stadelmann, M.-B. Kallenrode, M. Sinnhuber, and H. Winkler (2007), Energetic particles in the paleomagnetosphere: reduced dipole configurations and quadrupolar contributions, *J. Geophys. Res.*, 112, A06216.