Space Climatology

- Some first steps -

Karl-Heinz Glassmeier and Anja Neuhaus
Technical University of Braunschweig

Joachim Vogt
International University of Bremen

Invited presentation

Alpach Summer School 2002
Space Weather: Physics, Impacts and Predictions

.

Abstract I

Sun and Earth are not only coupled by the solar radiation and its impact on the terrestrial climate, but also via the solar wind and its interaction with the geomagnetic field. The dynamics of the coupled solar wind-magnetosphere systems gives rise to a number of dynamic phenomena such as magnetic storms and substorm which may even effect anthropogenic systems such as power lines and communication spacecraft. In view of this importance of the physical processes in the outer fringes of our geosphere the new discipline “Space Weather Research” has emerged.

Much as the atmospheric weather space weather effects have a long-term trend, that is it is useful to study the space climatology.

The two players in this field are the Sun and its long-term variations as well as the geomagnetic field with its dramatic polarity reversals happening on a time scale of about every few 100,000 years.

Studying space climatology requires to study the complex coupled system Sun-Solar Wind-Magnetosphere-Atmosphere-Geomagnetic Field,

Abstract II

a system much too complicated for our current understanding of the underlying physical processes. Thus, first simple attempts are required to tackle the complexity of this system. And we need observations, from the past and reaching into the future. Long-term trends, by their very nature, can only be studied if long lasting records of the important parameters are available. Historic data as well as proxi archives are the only means to access the past.

In this presentation some first attempts are made to understand space climatology. Long-term variations of the Sun are briefly discussed, while more emphasize is paid to the question of the magnetosphere and its possible long-term variations. The magnetosphere and the geomagnetic field are important as they moderate the precipitation of high-energy galactic cosmic rays and solar particles into the terrestrial atmosphere.

Some simple scaling laws are discussed which will allow to learn about the long-term variation of magnetospheric parameters such as the

Abstract III

magnetopause distance, the polar cap width, plasma pause position, ring current and polar electrojet strength as well as the topology of the magnetospheric structure.

As a more general result one may state that with respect to the above mentioned parameters long-term magnetospheric variations or space climate changes are within the range of todays magnetospheric variability caused by the ever changing solar wind. It is only during intervals of geomagnetic polarity transitions when more drastic effects are expected. However, current tools do not allow a very detailed analysis of the expected effects. But it seems clear that significant modifications of the atmospheric NO_x and even the stratospheric ozon are to be expected with direct implications for the terrestrial atmosphere.

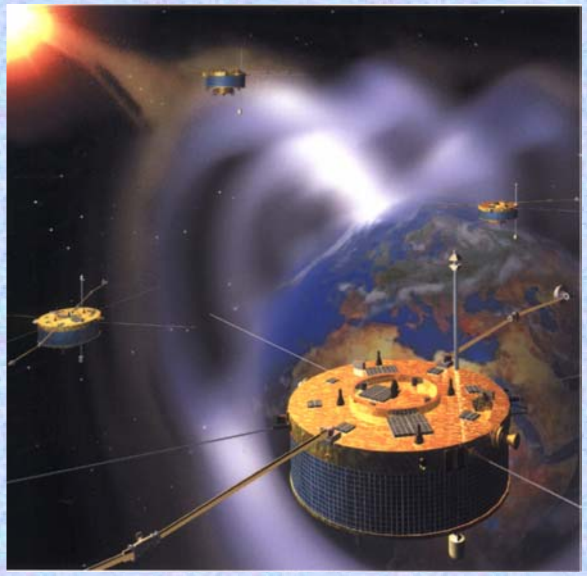
Some of these possible effects are discussed.

Space Climatology

- Some first steps -

Karl-Heinz Glassmeier and Anja Neuhaus (Technische Universität Braunschweig)

Joachim Vogt (International University of Bremen)



What is space climatology & who are the players ?

How can we address the problem ?

What is the importance of the geomagnetic field ?

How is the magnetosphere changing in time ?

Are there effects on the atmosphere ?

What is Space Climatology ?

Space weather

- dynamic changes of the plasma environment of the Earth and the planets, either internally or externally triggered

Space climate

- slow and long-term variations of our plasma environment

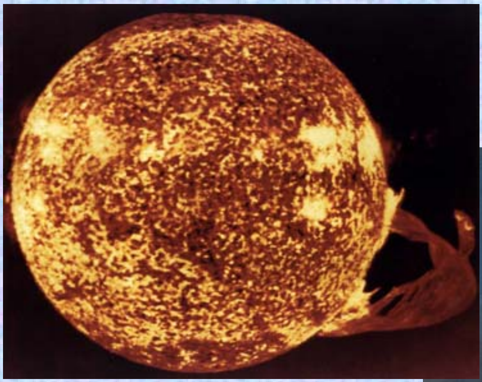
Space climatology

- studying the slower-acting influences on magnetospheric systems

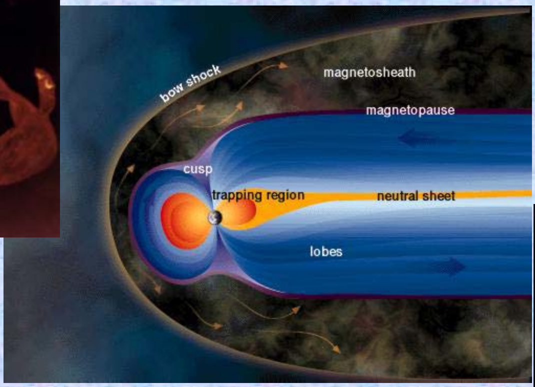
Space Climate Depends on….

- solar and solar wind conditions
- planetary magnetic fields and their variations
- internal processes of a magnetospheric system
- antropogenic influence (?)

Two Players and a Possible Victim



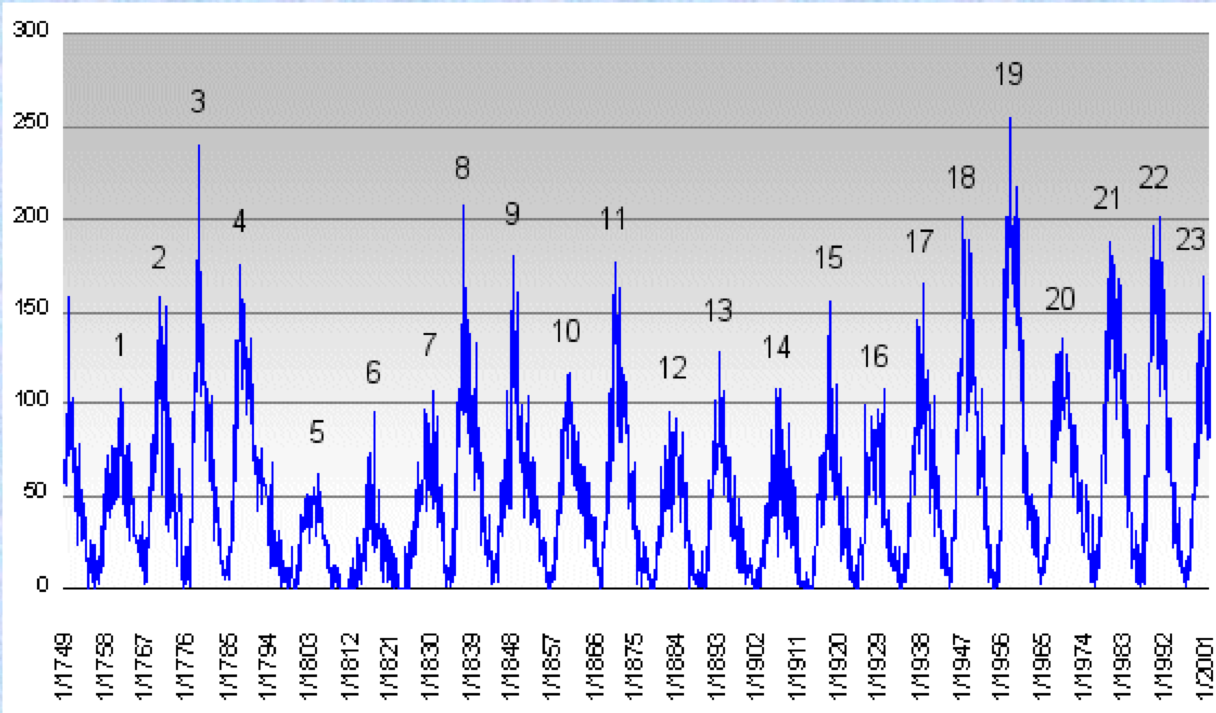
Sun



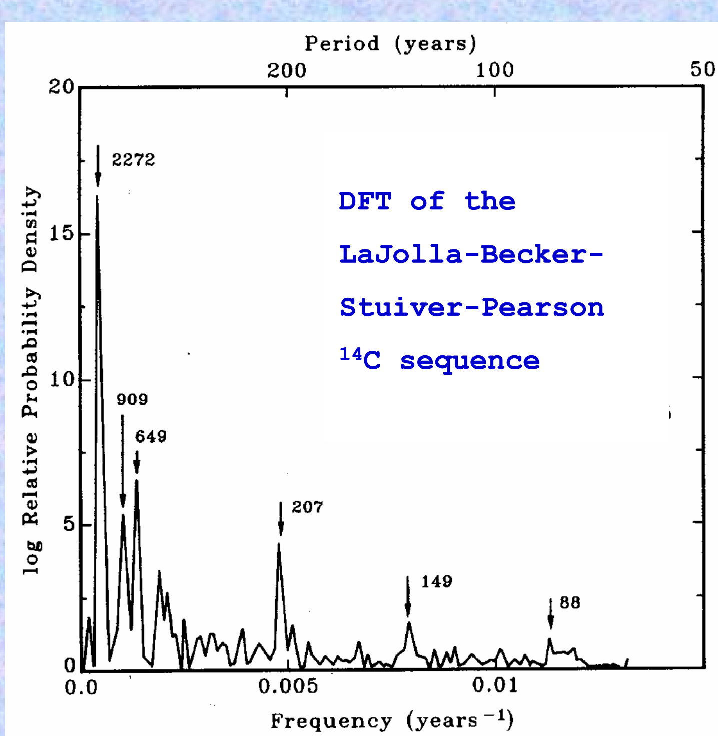
Geomagnetic Field

Earth

Player I: The Sun in Time



Solar Variability



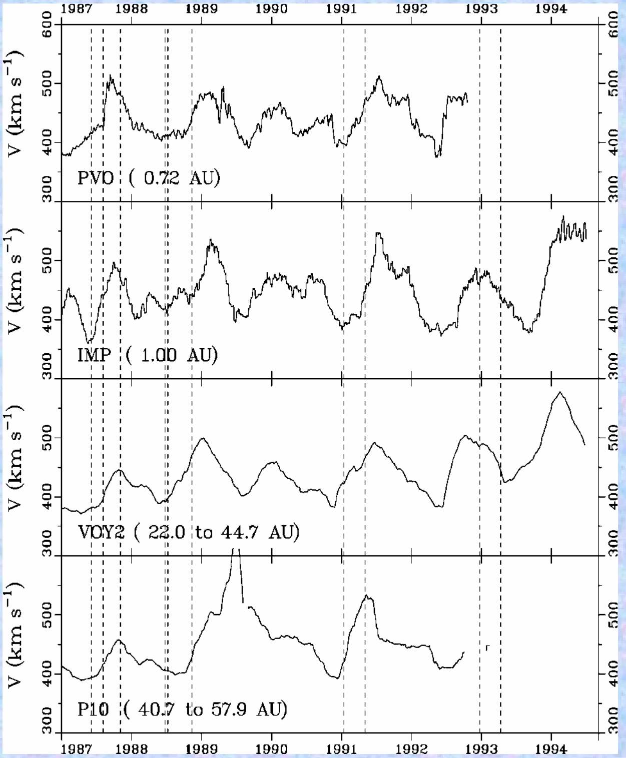
(From Damon and Sonett, 1991)

Some of the ^{14}C variability is thought to originate due to solar wind modulation of galactic cosmic rays causing an atmospheric neutron sea via spallations and the nuclear reaction $^{14}N(n,p) \rightarrow {}^{14}C$

Possible periodicities:

88 years	Gleissberg cycle
207 years	Maunder–Spörer cycle
2272 years	Houtermans cycle

Mid-Term Solar Wind Variations

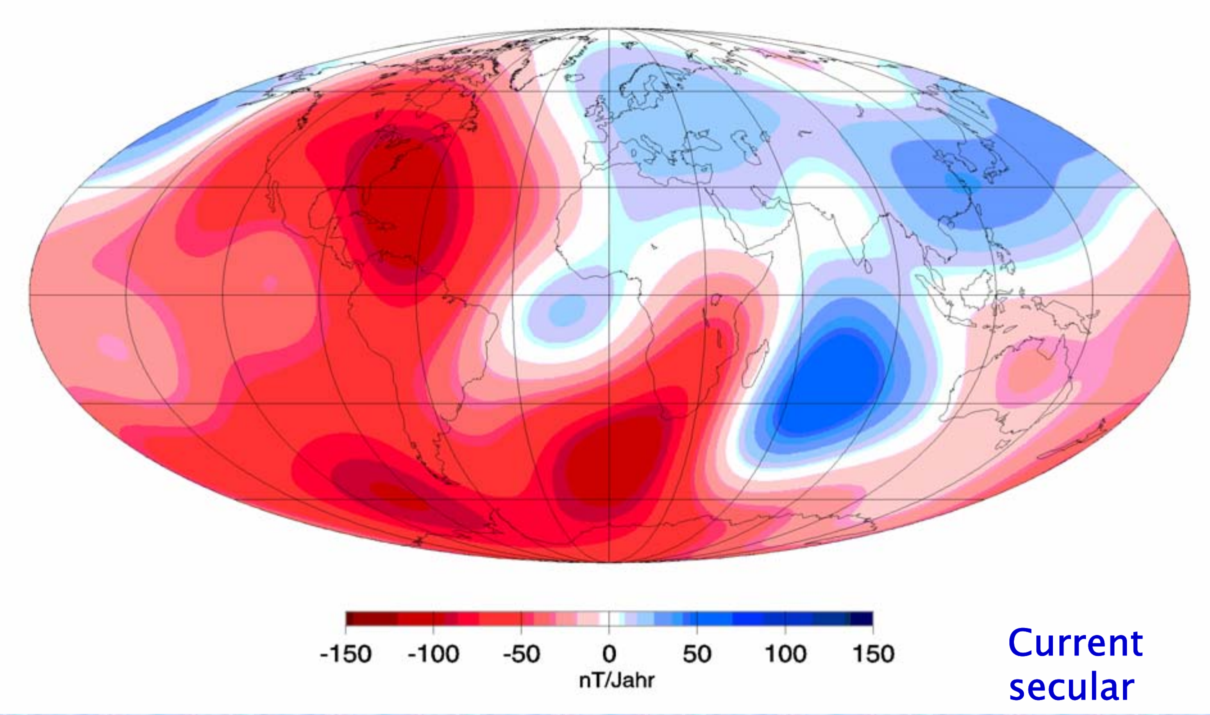


100-day averages of the solar wind speed at various distances from the Sun.

The variability is of the order of ±150 km/s.

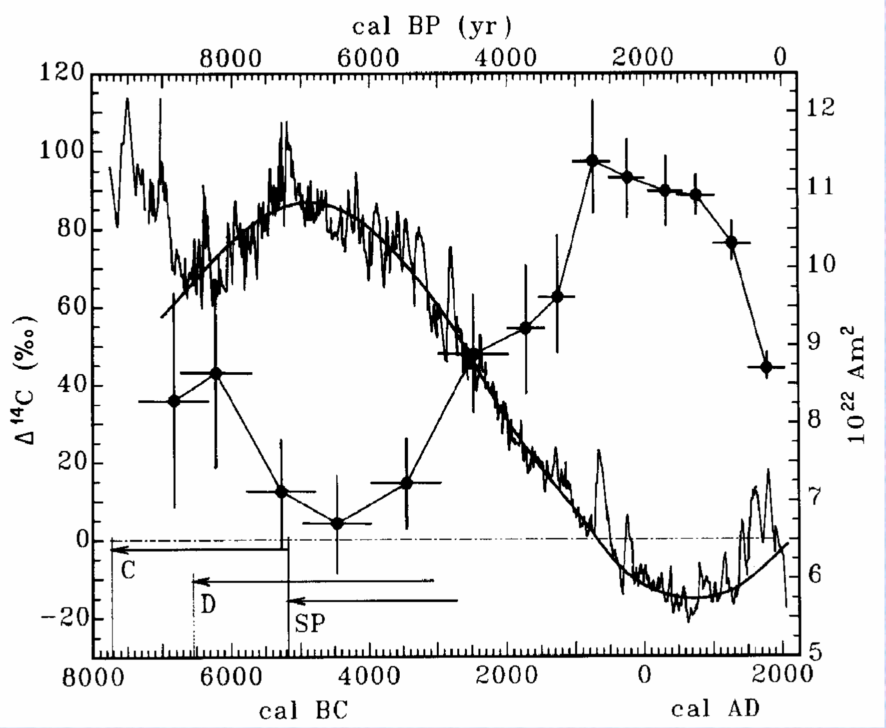
(from Gazis, 1996)

Player II: The Geomagnetic Field



Current secular variation rate

The Geomagnetic Field and ^{14}C-Concentrations



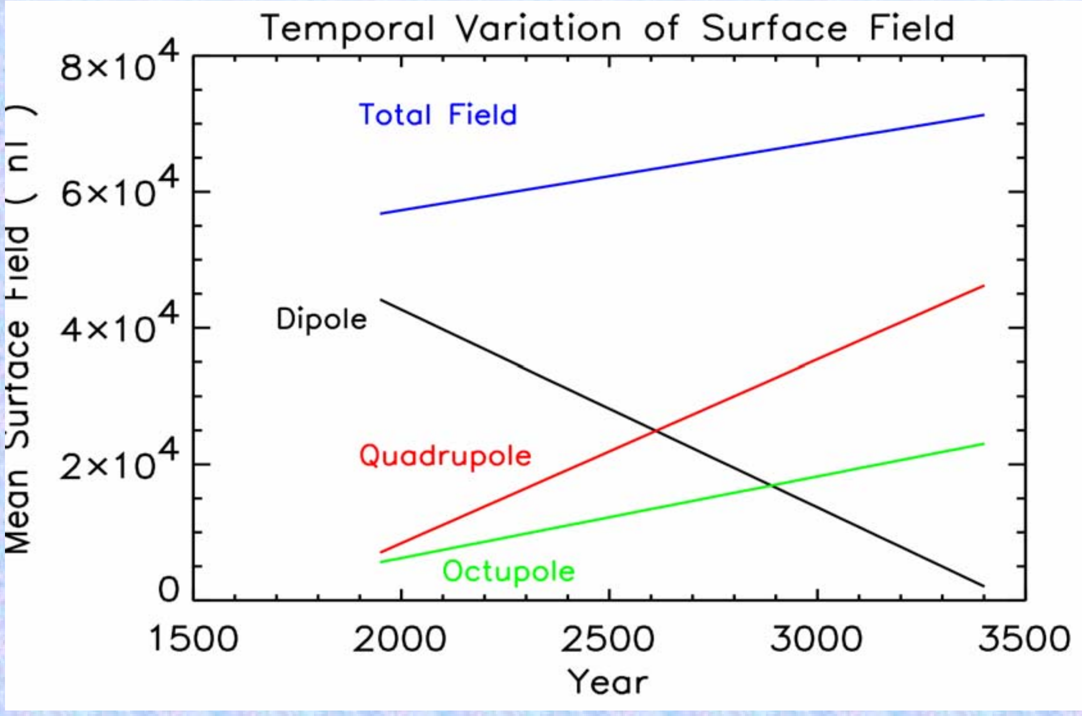
(from Damon and Sonett, 1991)

The stronger the geomagnetic field the smaller the ^{14}C concentration !

This is a clear hint on the geomagnetic field modulating the cosmic ray flux into the terrestrial atmosphere.

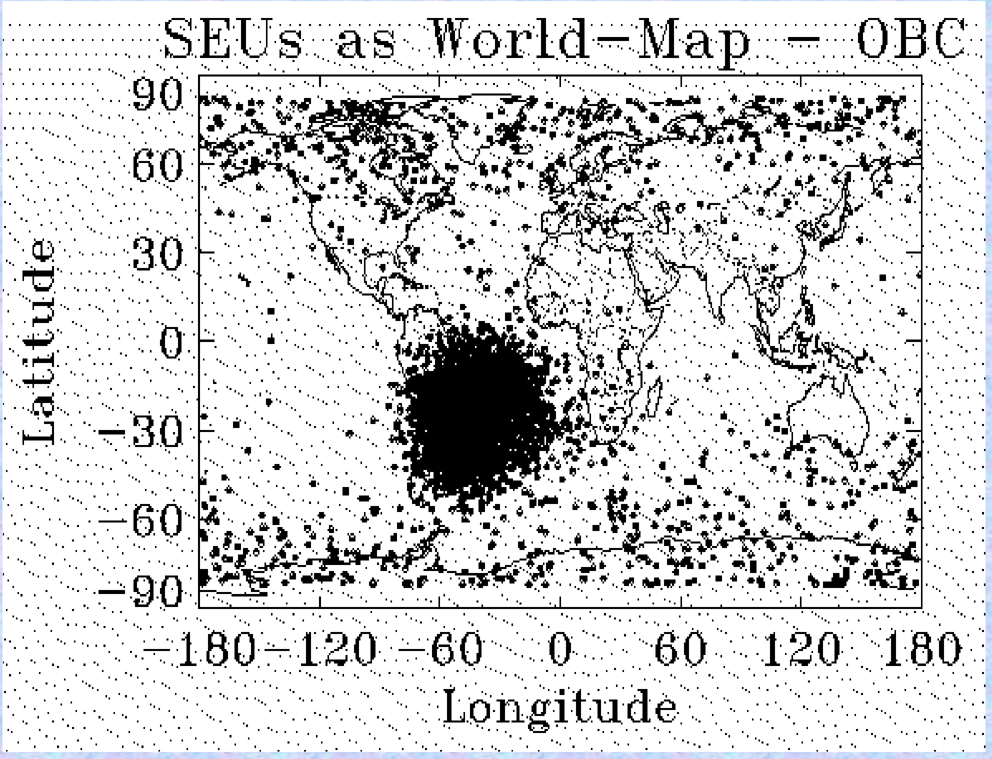
The geomagnetic fields plays with the cosmic particles !!!!

In the year 3500……



The dipole field currently decreases while higher multi–poles increase in strength. Thus, overall field increases in strength and complexity

The Geomagnetic Field and Radiation Effects on Spacecraft

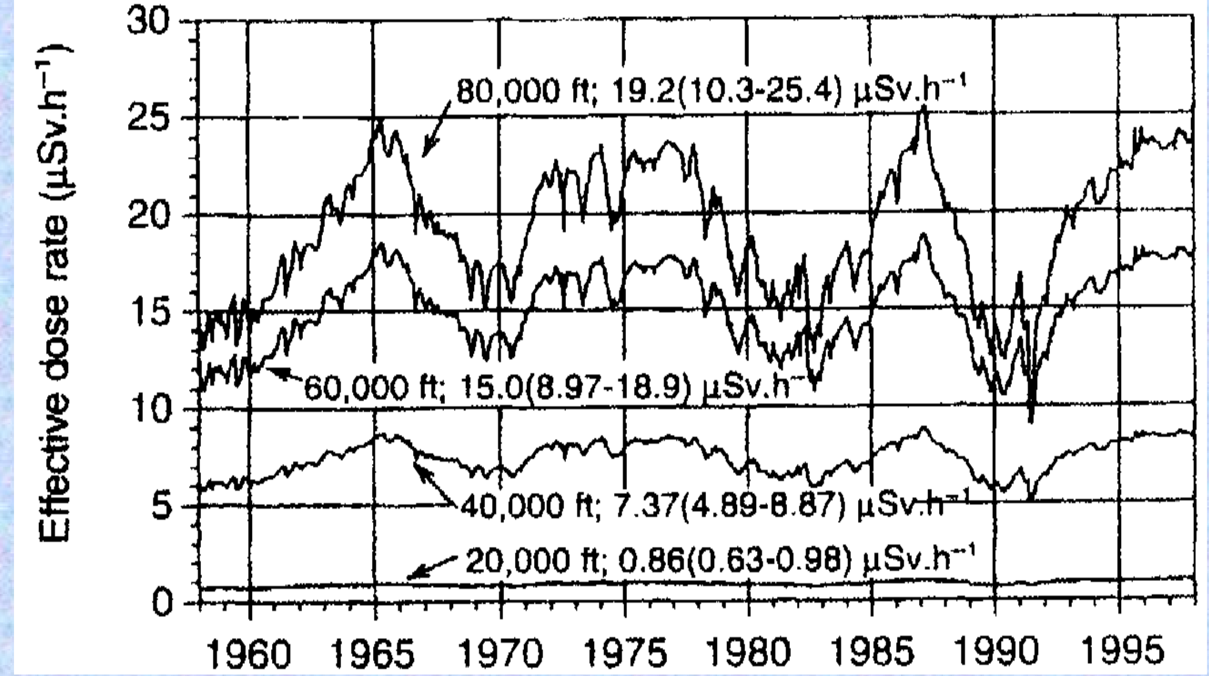


Cosmic ray induced single event upsets observed by the UoSAT-2 between 9/1988 and 5/1992;

The majority of events occurs over the south atlantic anomaly

Dyer, 2002

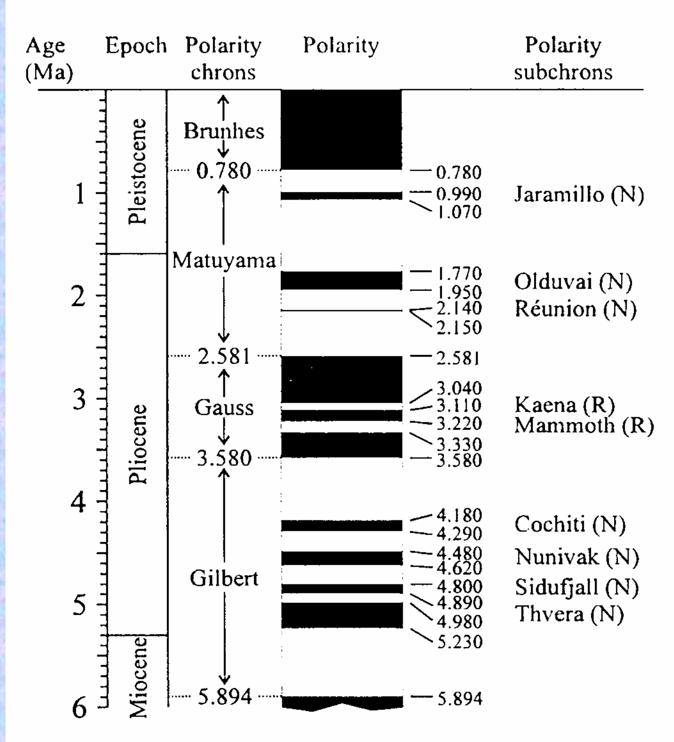
The Geomagnetic Field – A Shield Against Radiation ?

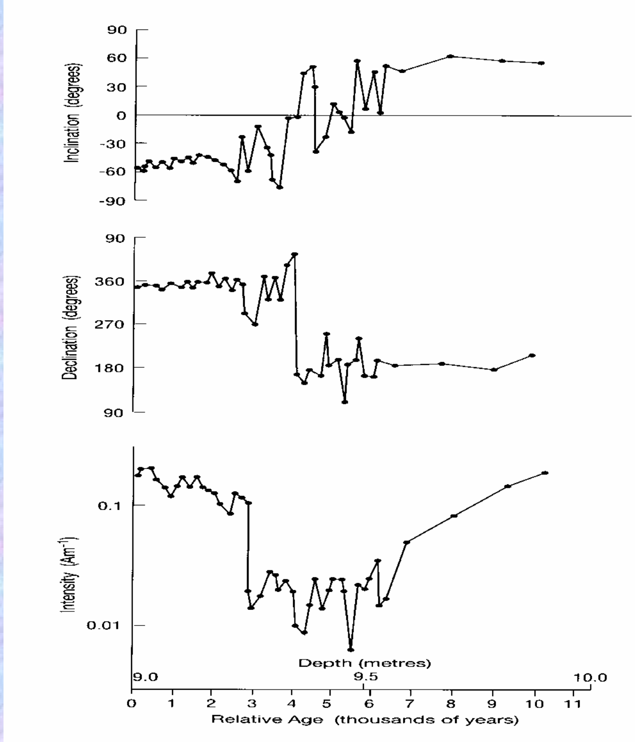


1 µSv/h = 1 rem/year

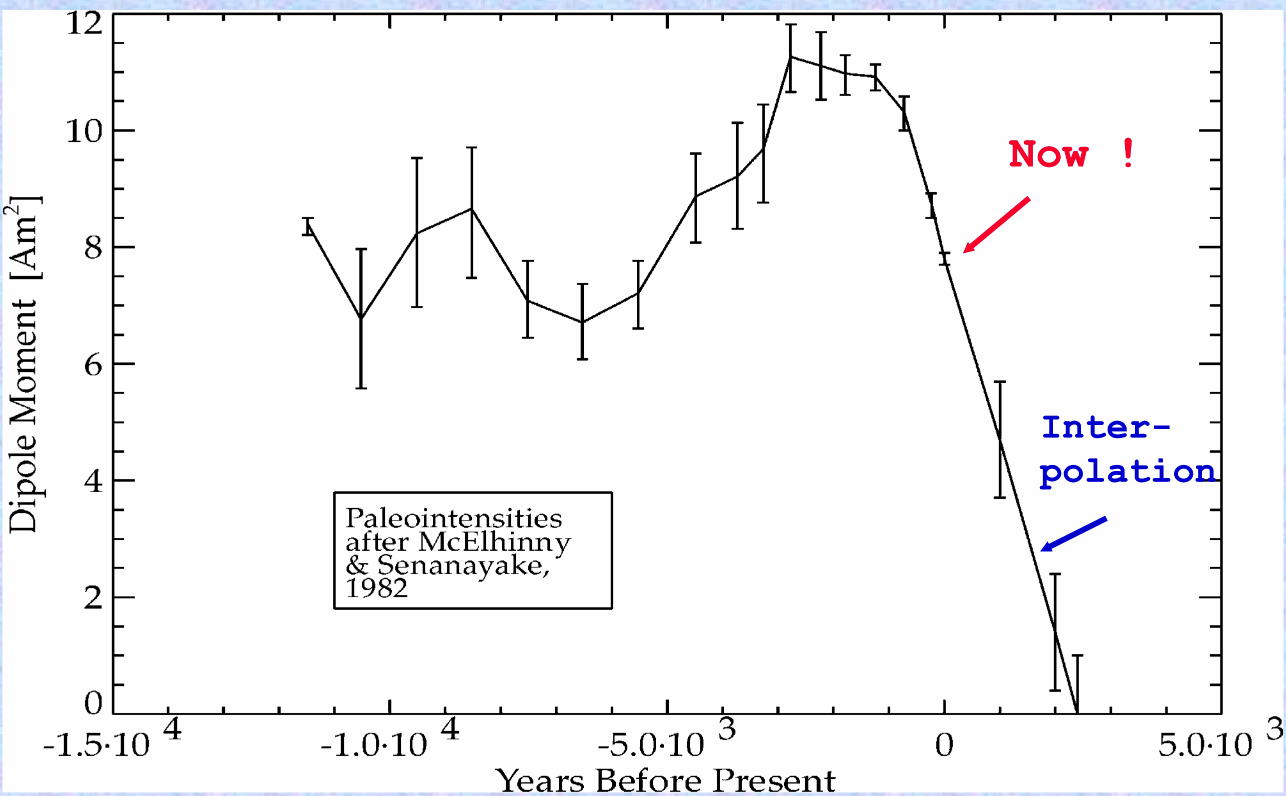
Shea and Smart., 2001

Polarity Transitions





Secular Variations: Past, Present, Future



Scaling Relations for the Magnetosphere

Here, we make the assumption that the geomagnetic field is always dominated by its dipole component. Higher order moments are neglected.

The dipole axis is assumed to be aligned with the rotation axis.

The relations derived are simple, but allow a first guess on what the climatology of the magnetospheric structure is.

Scaling the Magnetosphere

Magnetopause stand-off distance: $R_{MP} \propto M^{1/3}$

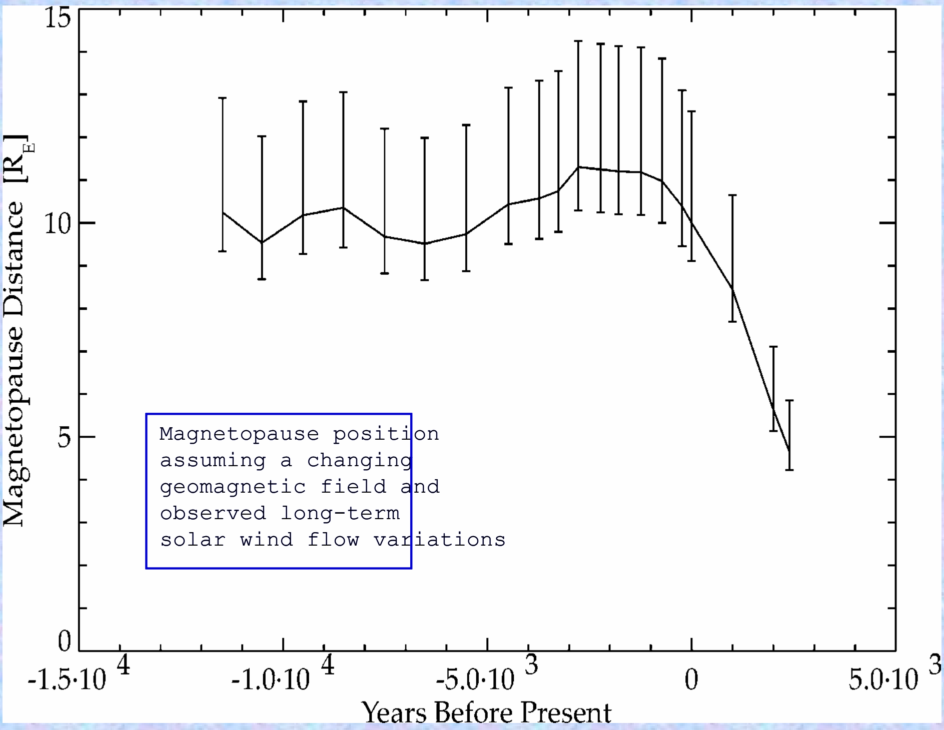
where M is the magnetic moment

Tail radius: $R_T \propto M^{1/3}$

Polar cap width: $\cos\theta \propto M^{-1/6}$

Siscoe & Chen (1975), Vogt & Glassmeier, (2001)

The Magnetopause in Time

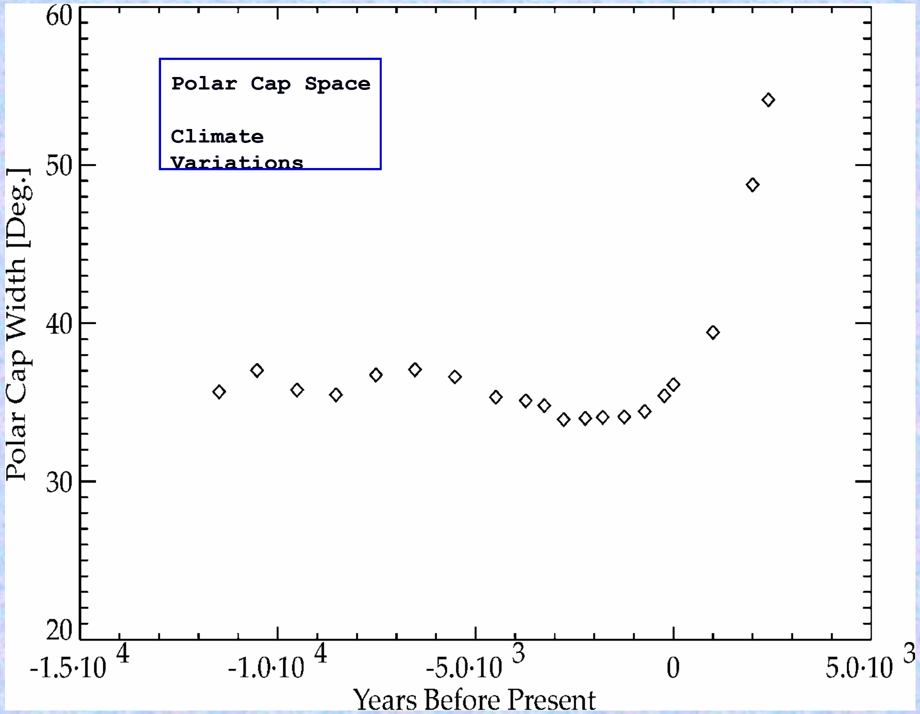


Even during polarity Transitions the magneto-pause never moves closer than about 5 R_E

During strong solar wind activity these close distances are also observed nowadays.

Climatic variations are within current weather variability

The Polar Cap Width in Time

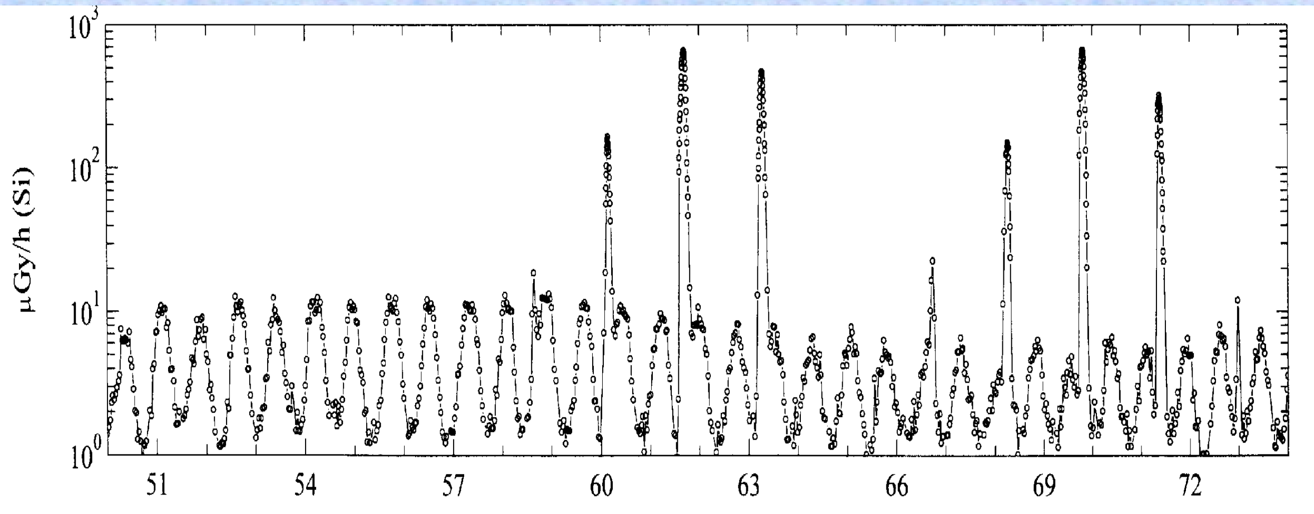


The polar cap width is rather stable for most climatic con-ditions.

Only during times of extreme geo-magnetic conditions, i.e. polarity transi-tions, the polar cap widens considerably.

The atmosphere becomes more accessable to energetic particles !!!!

Polar Cap and Equatorial Radiation at 350 km Height



Radiation at shuttle height during solar minimum conditions, that is maximum galactic cosmic ray conditions indicates an order of magnitude higher dose over the polar cap

Beaujean et al., 1999

Scaling the Plasmasphere

The convection electric field potential can be approximated by

$$\Phi = \eta v_{sw} B_{sw} L R_E \sin\varphi$$

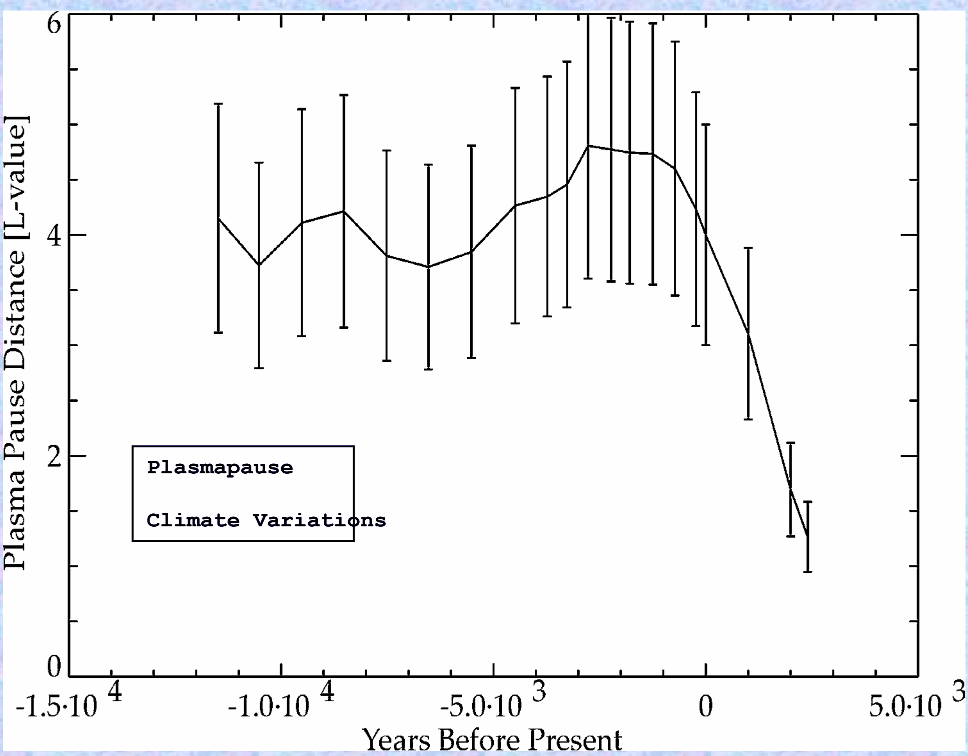
The corotation electric field potential is given as

$$\Psi = -\frac{\Omega_E B_E R_E^2}{L}$$

The plasmapause position may be approximated by

$$L_{PP} = \sqrt{\Omega_E B_E R_E \Big/ \eta v_{sw} B_{sw}} \quad \text{or} \quad L_{PP} \propto \sqrt{M}$$

The Plasmasphere in Time



Climate variations of the plasmapause position are of the order of the pp activity.

Only at times of a polarity transition the pp comes very close to the upper atmosphere.

Scaling the Polar Electrojets I

The polar electrojet magnetic field b_G is approximated by the ionospheric Hall current

$$b_G \propto \Sigma_H \; E_{iono}$$

where Σ_H and E_{iono} are the Hall conductance and the ionospheric electric field

The auroral region ionospheric electric field scales as

$$E_{iono} \propto \psi \, / \, 2 \, R_E \cos \theta \;\propto M^{-1/2}$$

where $\psi \propto v_{SW} \cdot B_{SW} \cdot R_{MP}$ is the polar cap electric potential

Scaling the Polar Electrojets II

$$\sigma_P = \left(\frac{n_i \nu_i}{m_i(\nu_i^2 + \Omega_i^2)} + \frac{n_e \nu_e}{m_e(\nu_e^2 + \Omega_e^2)} \right) e^2.$$

$$\Sigma_P \propto M^{-2}$$

$$\sigma_H = \left(\frac{-n_i \Omega_i}{m_i(\nu_i^2 + \Omega_i^2)} + \frac{n_e \Omega_e}{m_e(\nu_e^2 + \Omega_e^2)} \right) e^2,$$

$$\Sigma_H \propto M^{-1}$$

Here m, n, ν, and Ω are the mass, number density, collision frequency, and gyro frequency of ionospheric electrons and ions.

These scaling relations are justified if the influence of n(Height) may be neglected.

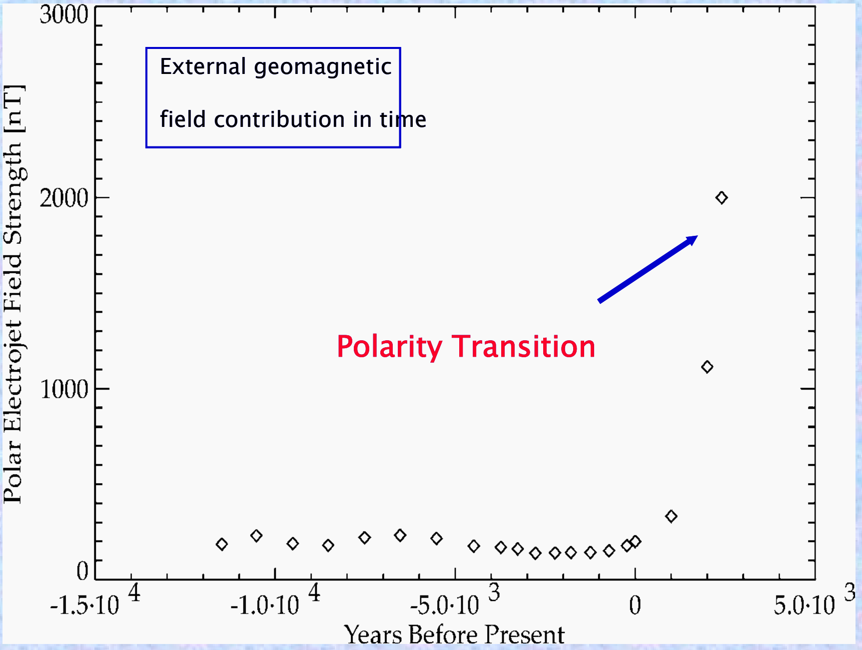
Scaling the Polar Electrojets III

The polar electrojet magnetic field scales as:

$$b_G \propto M^{-5/6}$$

The external magnetic field increases with decreasing internal field contribution

The Polar Electrojets in Time



During polarity transitions the polar electrojet fields may become as large as the internal field !!!!

There will be strong induction effects !!!!

This implies a very different magnetosphere.

Glassmeier et al., 2002

Scaling the Ring Current

Dessler-Parker-Sckopke theorem: $D_{st} \propto W_{RC} / M$

where W_{RC} is the ring current total energy and D_{st} its surface magnetic field

W_{RC} scales with the cross section of the magnetosphere and the ring current volume:

$$W_{RC} \propto R^2_T \bullet R^3_{MP}$$

Thus, $D_{st} \propto M^{2/3}$

Magnetospheric Configuration I

The magnetospheric magnetic field is the result of the superposition of mainly two contributions

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

where the Chapman-Ferraro currents at the magnetopause cause the contribution B_{CF}.

With the magnetospheric boundary condition

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

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

Magnetospheric Configuration II

and

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

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

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

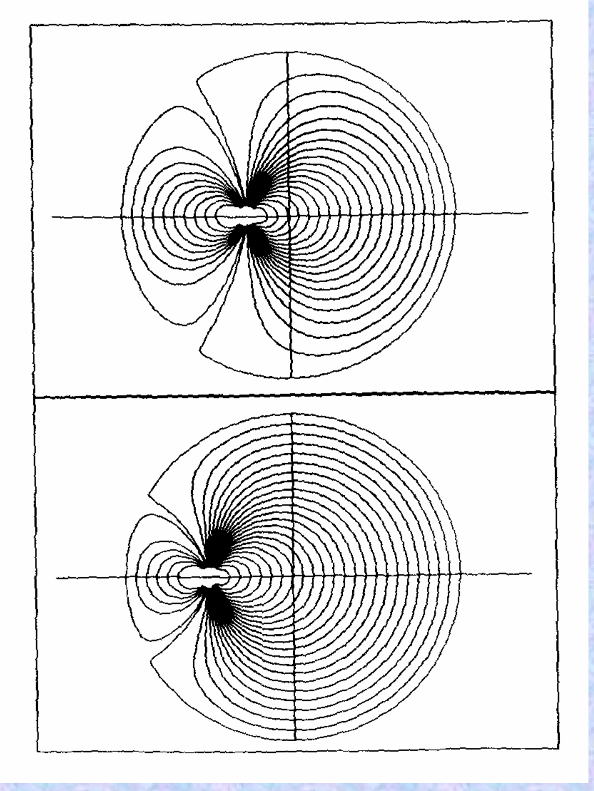
$$\nabla^2 \Phi_{CF} = 0$$

With the boundary condition $\vec{n} \cdot \vec{B}_{Total} = 0$,which specifies a closed magnetosphere, and prescribing the magnetopause shape allows one

to determine the field topology as well as the CF-current density

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

Magnetospheric Configuration: Dipole in a Sphere



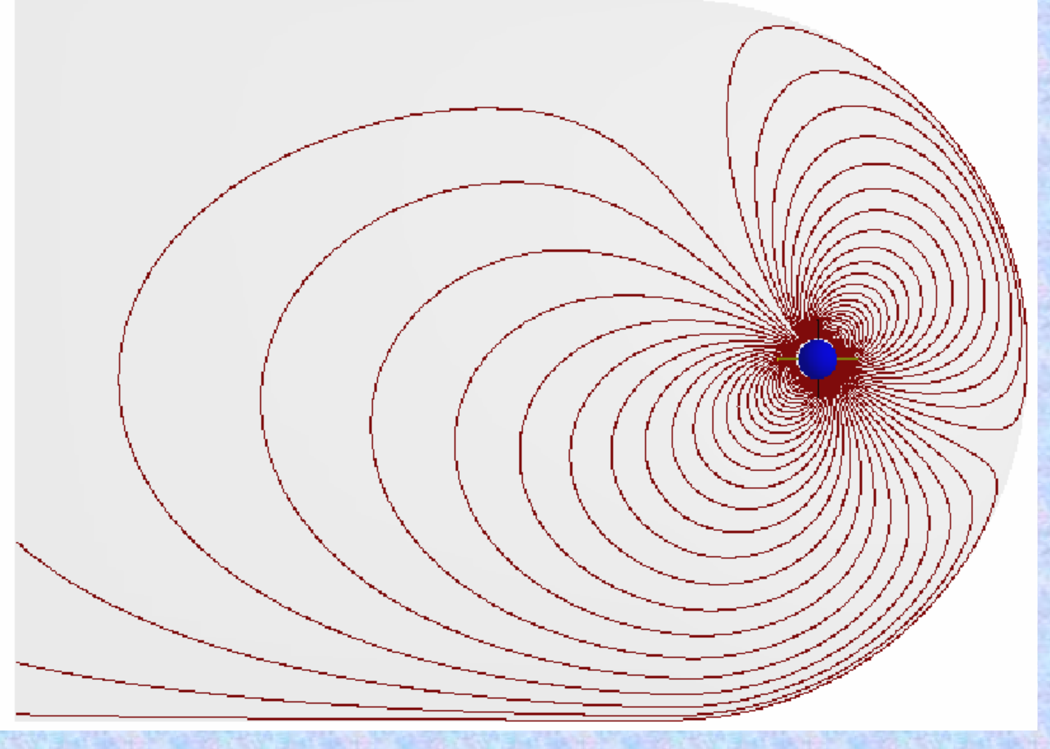
Internal field due to dipole

Magnetopause is a sphere

Shift of dipole from center simulates decreasing magneto-pause distance

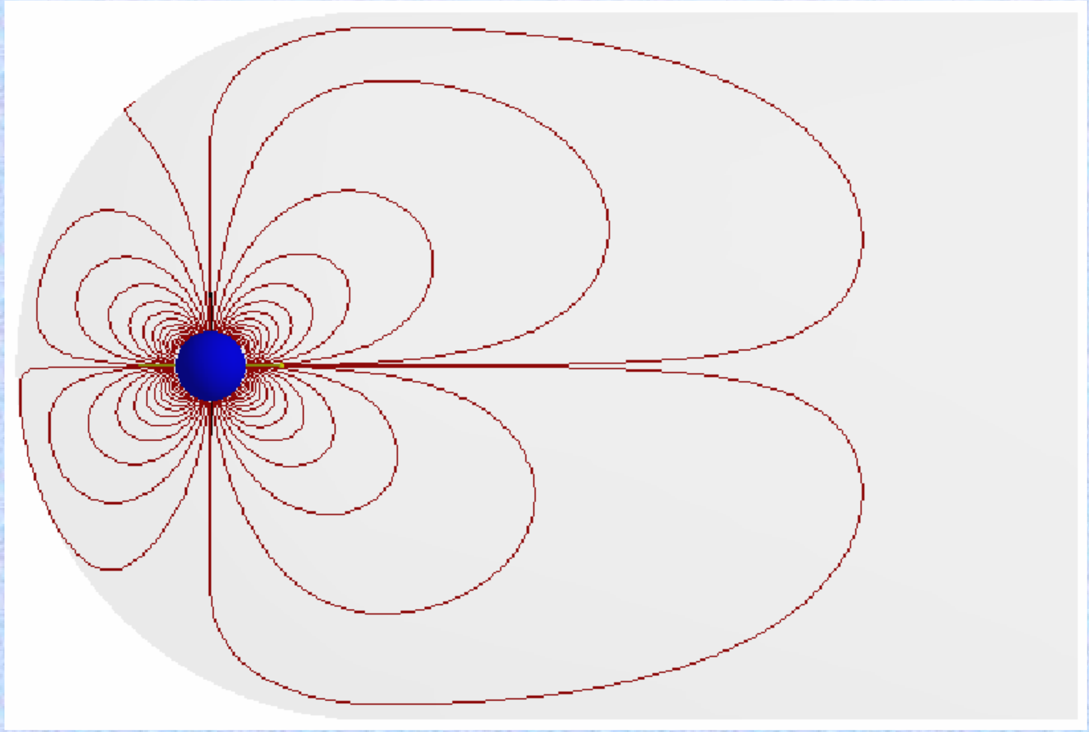
Cusp region moves to lower latitudes for decreasing mp position

The Paleomagnetosphere: Tilted Dipole



The polar cap moves to much lower latitudes during a reversal Neuhaus et al., 2002

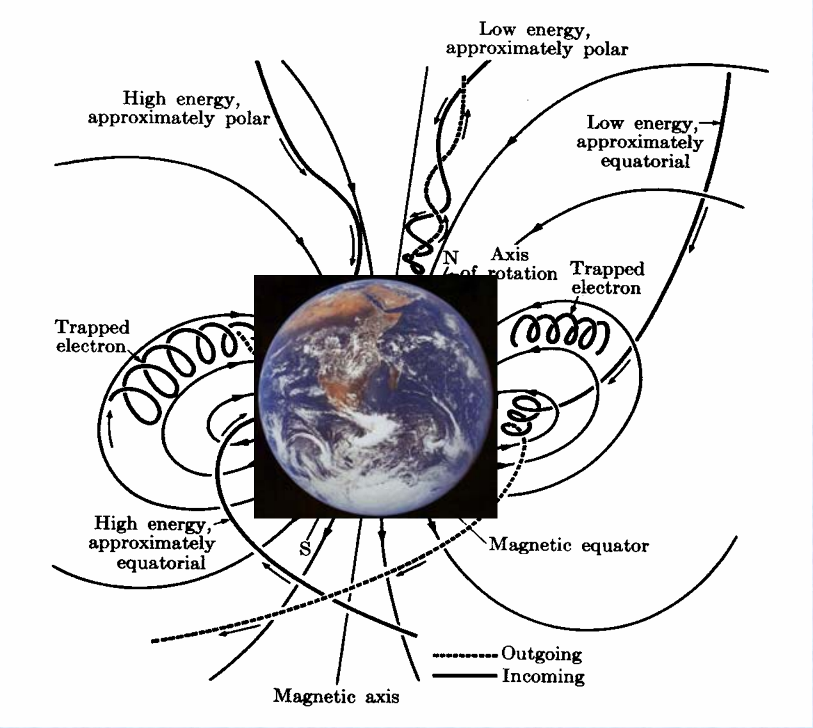
The Paleomagnetosphere: Quadrupole Situation



Now we have four polar cusp regions !!!

Neuhaus et al., 2002

Particle Motions in the Paleomagnetosphere



Aim:

Determine for different configurations of the paleomagnetosphere where and at what rate energetic particles enter the atmosphere

Anja Neuhaus is working on the details..................

Effects of High-Energy Particles Precipitating into the Atmosphere I

P.J. Crutzen, G.C. Reid, S. Solomon (1975, 1976, 1980):

Precipitation of high-energy protons into the atmosphere cause the production of NO_X and also impacts the ozon budget of the stratosphere.

This is a proven process in the current atmosphere, but has no atmospheric climate relevance due to its event character.

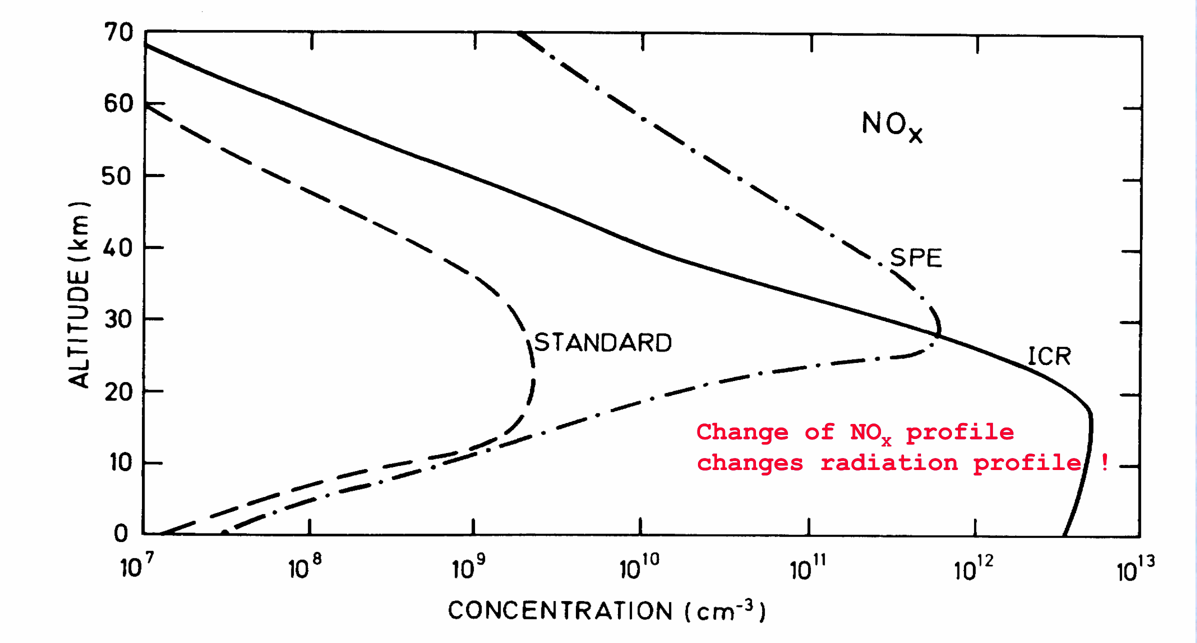
Effects of High-Energy Particles Precipitating into the Atmosphere II

What happens during times of small geomagnetic field ?

How is the high-energy particle precipitation moderated by the geomagnetic field ?

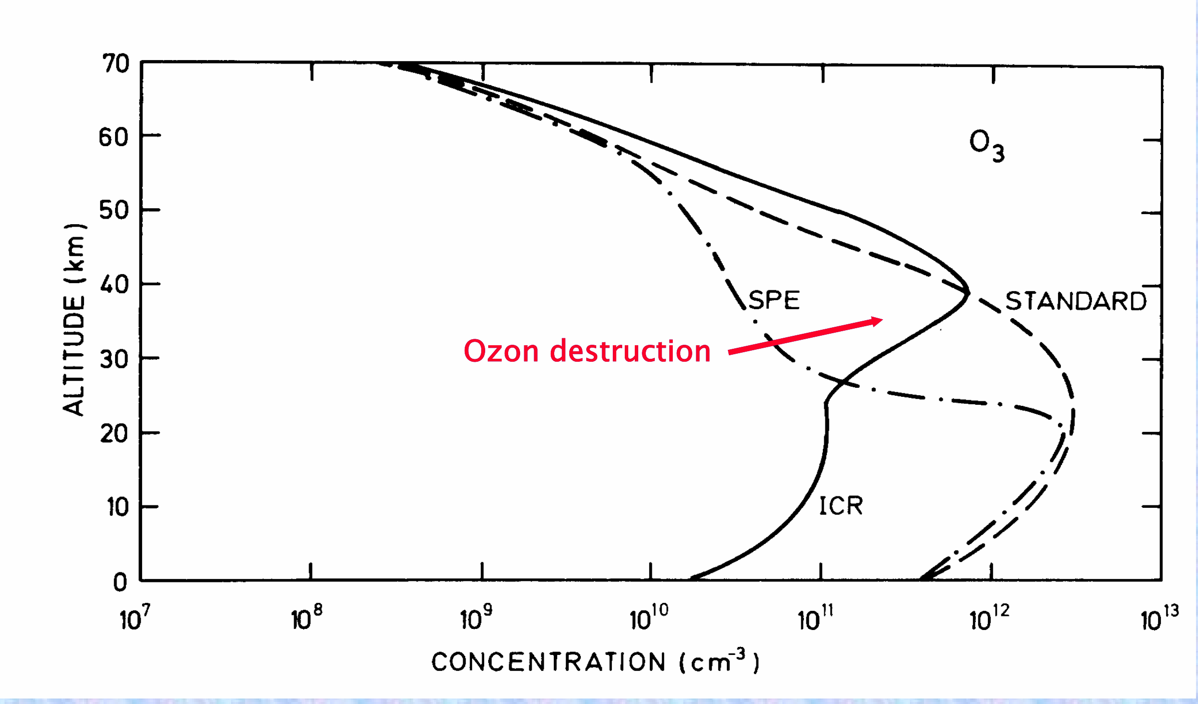
Is there a possibility that the R-C-S mechanism has an influence on the atmospheric climate ?

A First Approach: NO_X Production



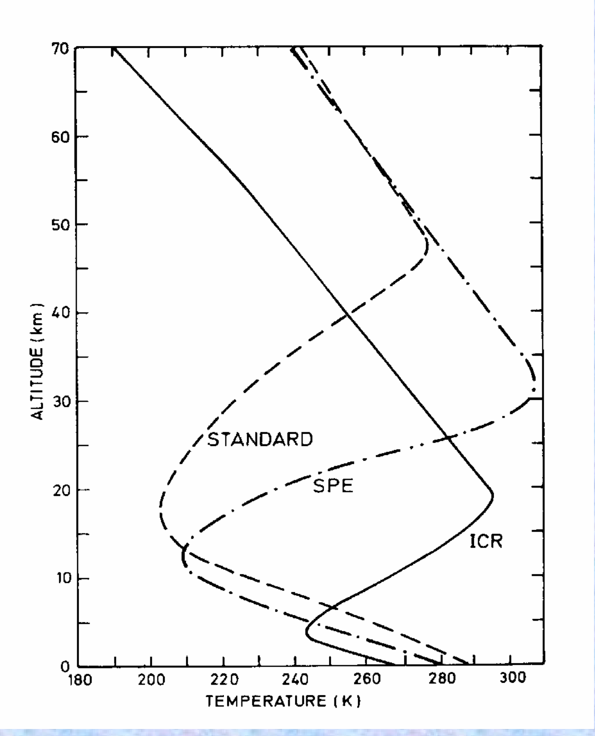
Hauglustaine & Gerard, 1990

A First Approach: Stratospheric O_3



Hauglustaine & Gerard, 1990

A First Approach: Surface Temperature



Increased precipitation of high-energy protons may lead to drastic atmospheric changes, but model used may be too simple !

But here we have a nice problem which deserves further attention !

The University of Bremen Model Approach

2 D (latitude/altitude) time-dependent coupled chemical-dynamic model of the atmosphere

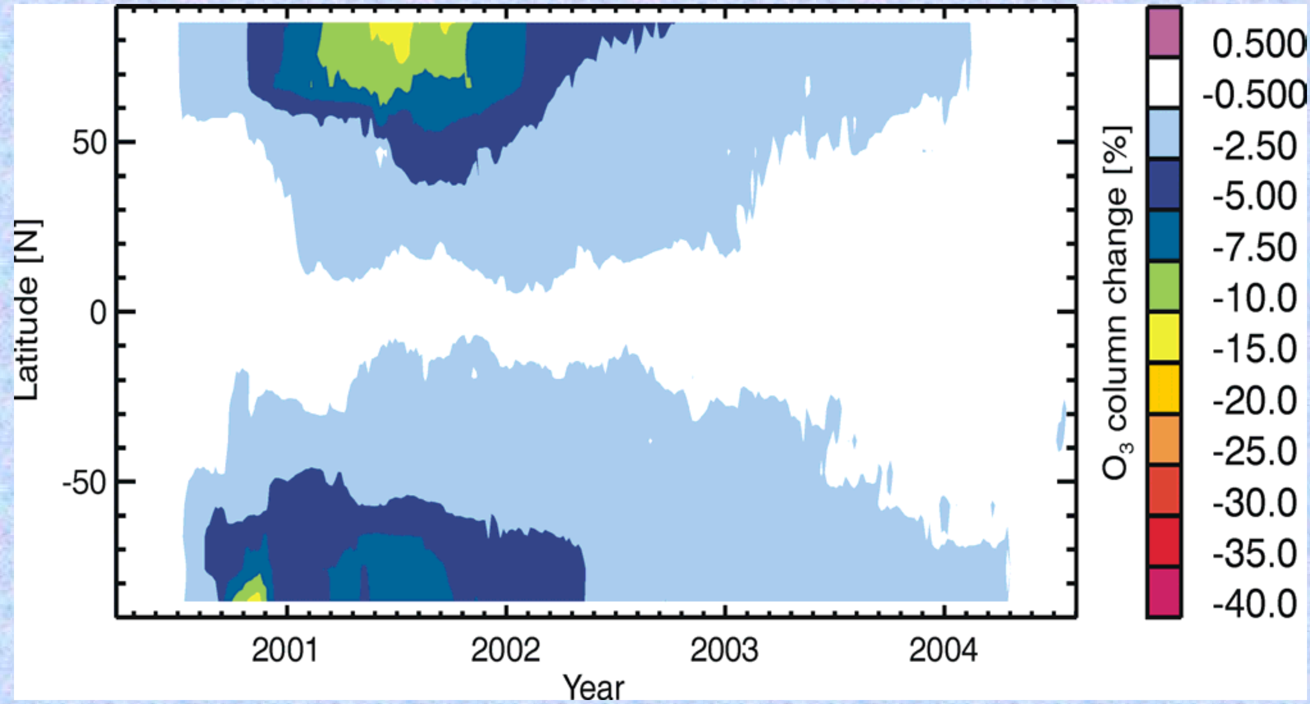
Current magnetic field: precipitation into polar cap only

Polarity transition: precipitation isotropic

Modelled situation: 3 x October 1989 Solar Proton Event

Miriam von König et al., 2002

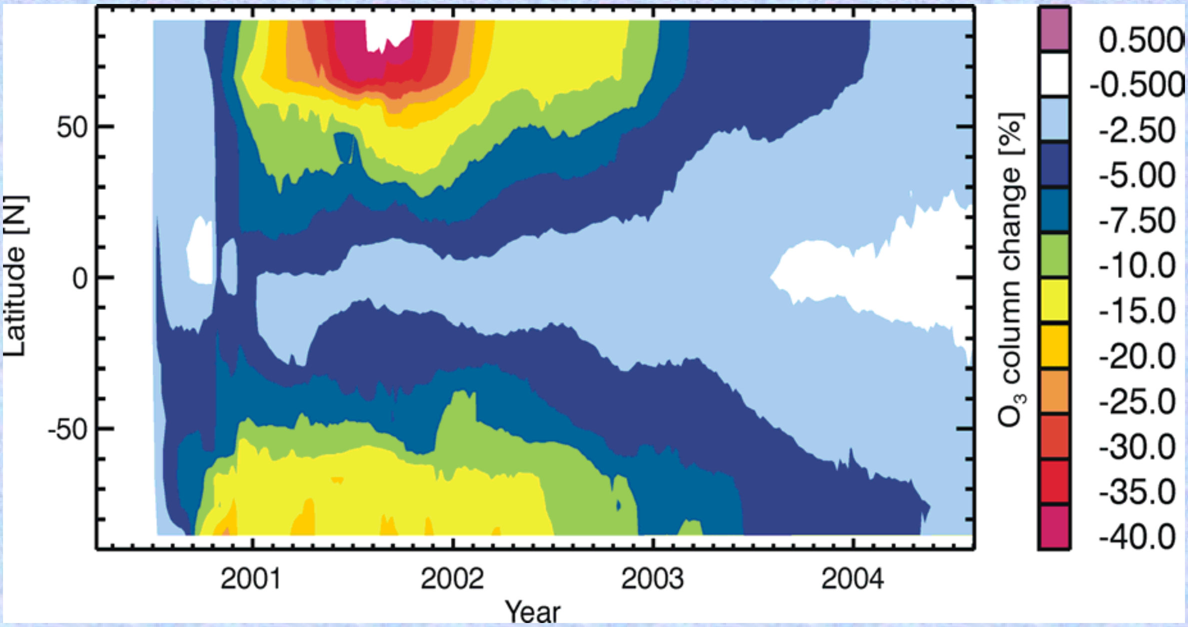
Ozon Column Density Change for Present Day Field



NO_X production and ozone loss due to SPEs are well reproduced by the model

Miriam von König et al., 2002

Ozon Column Density Change for Polarity Transition



A change of magnetic field strengths has a potentially large impact on stratospheric ozone, but restricted to polar regions and only if a period of small magnetic field strengths coincides with a large solar activity

Summary

Space climatology is a new and demanding area of research

Long-term evolution of the solar activity and the geomagnetic field need to be considered

Only during polarity transitions major effects on the NO_x production in the atmosphere due to increased energetic particle precipitation is expected

The „climate“ variations of the magnetospheric structure and dynamics are comparable to current solar wind induced variability for non-transition times

Current proxi archives need to be refined to upgrad the observational basis

New proxi archives are required

Long-term observations are required: We need geospace observatories

SUSTAIN: A Mission for Mars Colonization

Develope cheap and autonomous μ-stations

measuring the magnetic field, temperature, and cosmics particle flux

at various places on the Marsian surface

with the data read out accomplished in a hundred years or so.

Our grand-grand-grand-children will appreciate this when starting

to colonize our sister planet in future years.

Some References I

Beaujean, R., G. Reitz, and J. Kopp, Recent European Measurements inside Biorack, Mutation Research, 430, 183-189, 1999.

Crutzen, P. J., S. Solomon, Response of mesospheric ozone to particle precipitation, Planet. Space Sci., 28, 1147-1153, 1980.

Damon, P. and C. P.Sonett, Solar and terrestrial components of the atmospheric ^{14}C variation spectrum, in: C. P. Sonett, M. S. Giampapa, M. S. Matthews, The Sun in Time, pp. 360-388, Arizona University Press, 1991.

Dyer, C., Radiation effects on spacecraft and aircraft, Proc. SOLSPA: The Second Solar Cycle and Space Weather Euroconference, ESA SP-477, p. 505-512, 2002.

Gazis, P. R., Long-term enhancements in the solar wind speed, J. Geophys. Res., 101, 415-424, 1996.

Glassmeier, K. H., J. Vogt, A. Neuhaus, and S. Buchert, External Geomagnetic Variations During Polarity Transitions, Ann. Geophys., in preparation, 2002.

Hauglustaine, D. and J.-C. Gerard, Possible composition and climatic changes due to past intense energetic particle precipitation, Ann. Geophys., 8, 87-96, 1990.

Merrill, R.T., and P. L. McFadden, Geomagnetic polarity transitions, Rev. Geophys., 37, 201-226, 1999.

McCracken, K. G., G. A. M. Dreschhoff, E. J. Zeller, D. F. Smart, and M. A. Shea, Solar cosmic ray events for the period 1561-1994. 1. Identification in polar ice, 1561-1950, J. Geophys. Res., 106, 21585-21598, 2001.

Neuhaus, A., J. Vogt, K. H. Glassmeier, M. B. Kallenrode, G. H. Voigt, Quantitative modelling of the paleomagnetosphere, Ann. Geophys., in preparation, 2002.

Some References II

Opdyke, N. D., D. V. Kent, and W. Lowrie, Details of magnetic polarity transitions recorded in a high deposition rate deepsea core, Earth Planet. Sci. Lett., 20, 315-324, 1973.

Sckopke, N., A general relation between the energy of trapped particles and the disturbance field near the Earth, J. Geophys. Res., 71, 3225-3230, 1966.

Shea, M.A., and D.F. Smart, Comment on galactic cosmic radiation dose to air crews, Proc. 27th Int. Cosmic Ray Conf 10, 4071-4074, 2001.

Siebert, M., Auswirkungen der säkularen Änderung des Erdmagnetischen Hauptfeldes auf Form und Lage der Magnetosphäre und die Stärke der erdmagnetischen Aktivität, Abhandlungen der Braunschweigischen Wissenschaftlichen Gesellschaft, 37, 281 pp, 1977.

Siscoe, G. L., and C. K. Chen, The paleomagnetosphere, J. Geophys. Res., 80, 4675-4680, 1975.

Voigt, G. H., Magnetospheric configuration, in: Volland, H., Handbook of atmospheric electrodynamics, Vol. II, p. 333-388, CRC Press, 1995.

Vogt, J., and K. H. Glassmeier, On the location of trapped particle populations in quadrupole magnetospheres, J. Geophys. Res., 105, 13063-13071, 2000.

Vogt, J., and K. H. Glassmeier, Modelling the paleomagnetosphere: Strategy and first results, Adv. Space Res., 28, 863-868, 2001.

von König, M., J. Burrows, and K. Künzi, Variation of ozone in the middle atmosphere in the presence of a varying Earth magnetic field, DFG-Symposium on Earth Magnetic Field Variations, Munich, 2002. Paper in preparation.