Solar Terrestrial Influences on Climate during Geomagnetic Reversals

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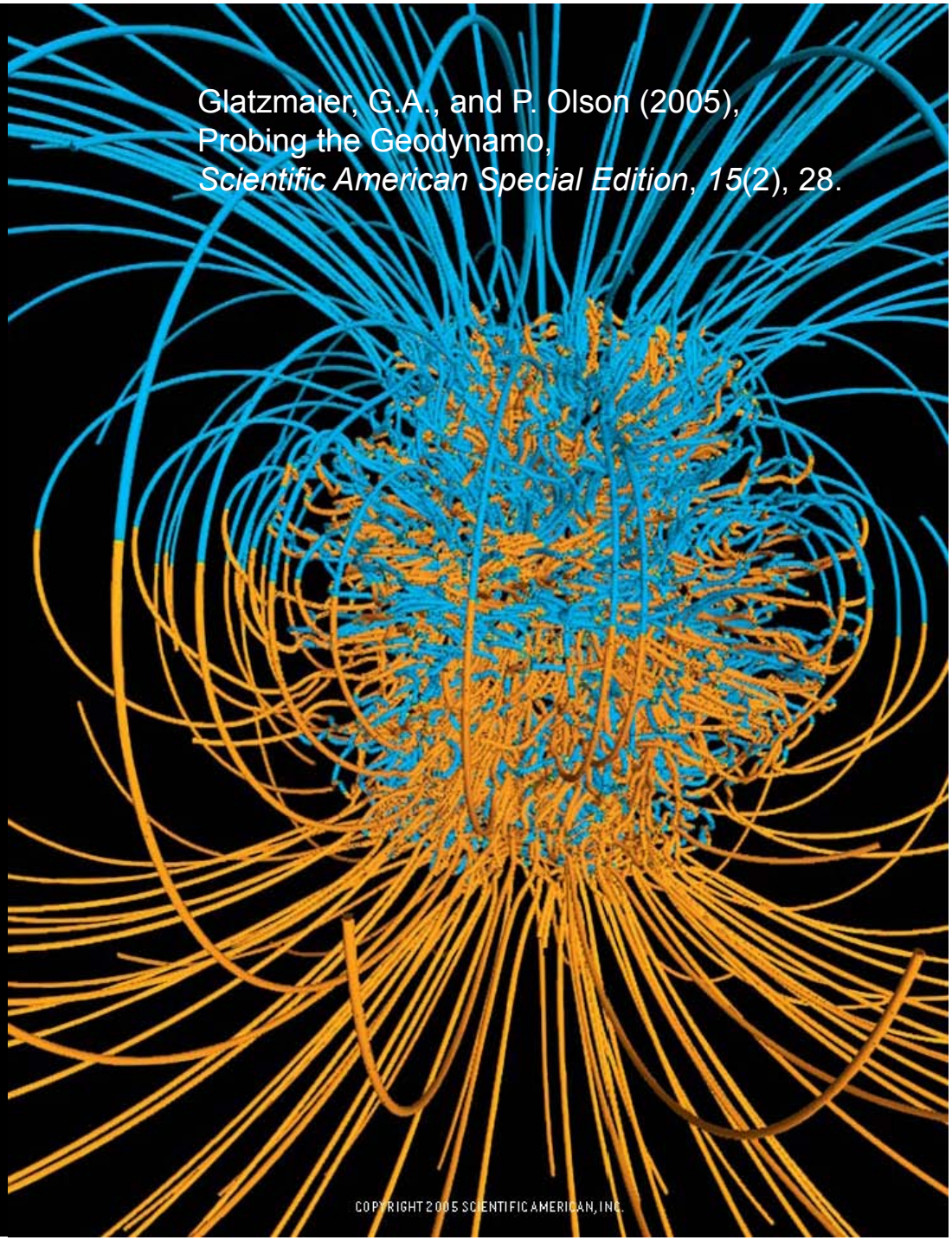
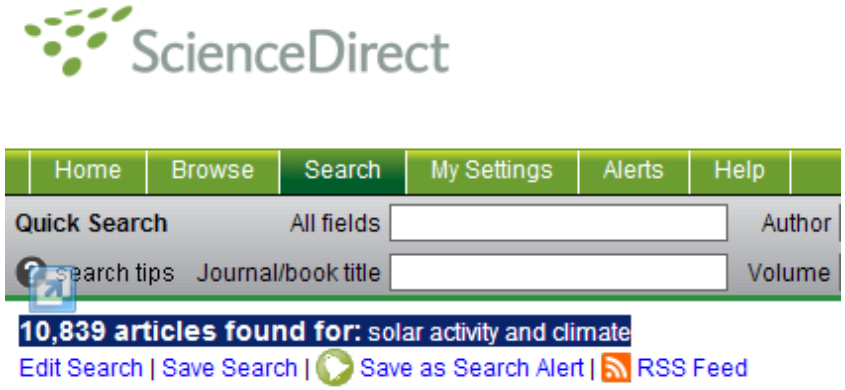


A Search for "*Solar Activity and Climate*"!

- Found 10,839 articles!
- Limit the topic to "geomagnetic reversals" giving 37 articles

- Actually there are only two authors who have really examined effects of changes in the dipole field on geomagnetic activity
- Even so, a ~15 min talk cannot cover much of this topic, particularly when the audience is so diverse



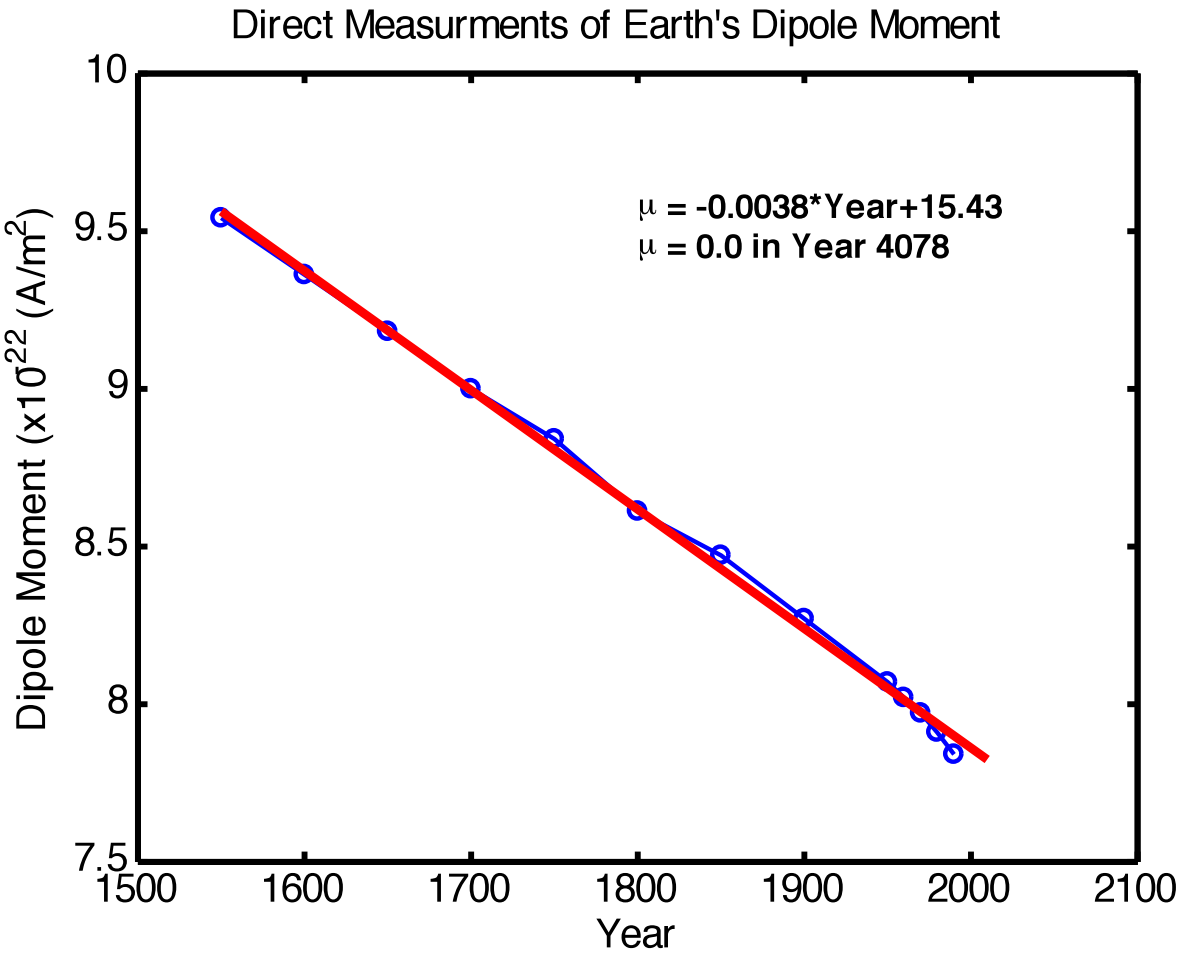
Should we be worried about a reversal?

Gubbins, D. (2008), Earth science - Geomagnetic reversals, *Nature*, *452*(7184), 165-167.

- More cosmic radiation reaching Earth's surface
- More auroral activity
- Species that use the magnetic field for navigation might become extinct
- Increased geomagnetic activity means more disruption to electronic communication and power distribution
- Whether a reversal would present a health risk to humans is less clear
- ***"The human race has survived many excursions and a few reversals already: so we are likely to come through the next one unscathed."*** ■

Apparent Decay of Dipole Moment

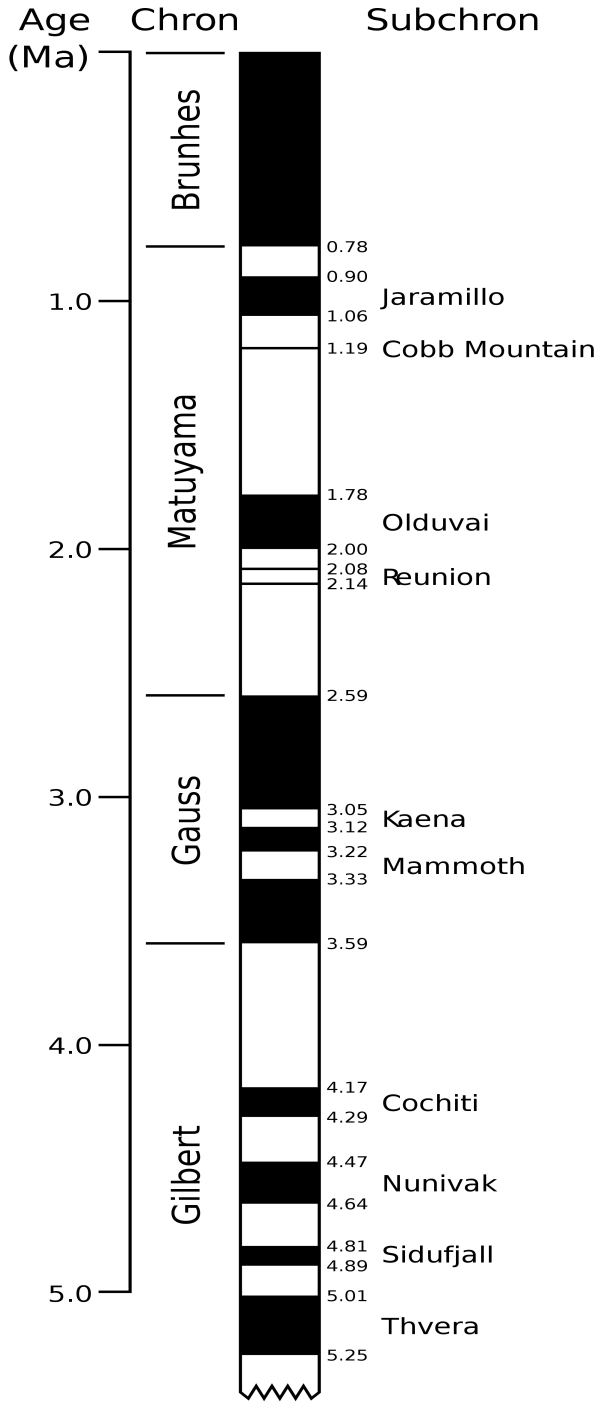
- The earth's dipole moment appears to be decaying linearly with time since the first measurements
- The rate is about 5% per century
- A linear extrapolation would suggest that the moment would vanish in year 4078



Recent Geomagnetic Polarity

- Vertical axis shows time backwards in millions of years
- Dark bars indicate current polarity of the dipole moment and white the opposite
- The last reversal occurred 780,000 years ago

- ***Reversals of the field are not likely to be a significant problem for humans***

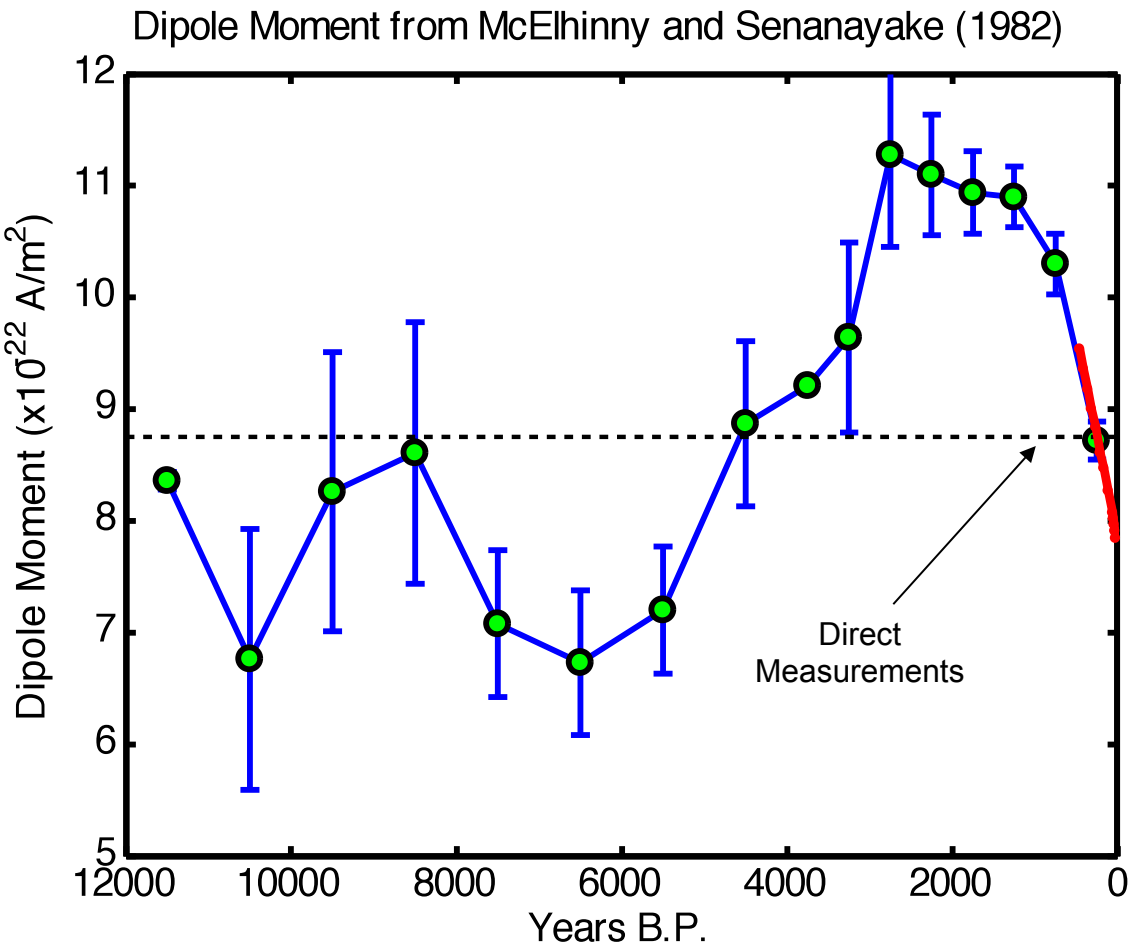


Archaeomagnetic Dipole Moments

Merrill, R.T., and M.W. McElhinny, *The Earth's Magnetic Field*, Academic Press, London, England.

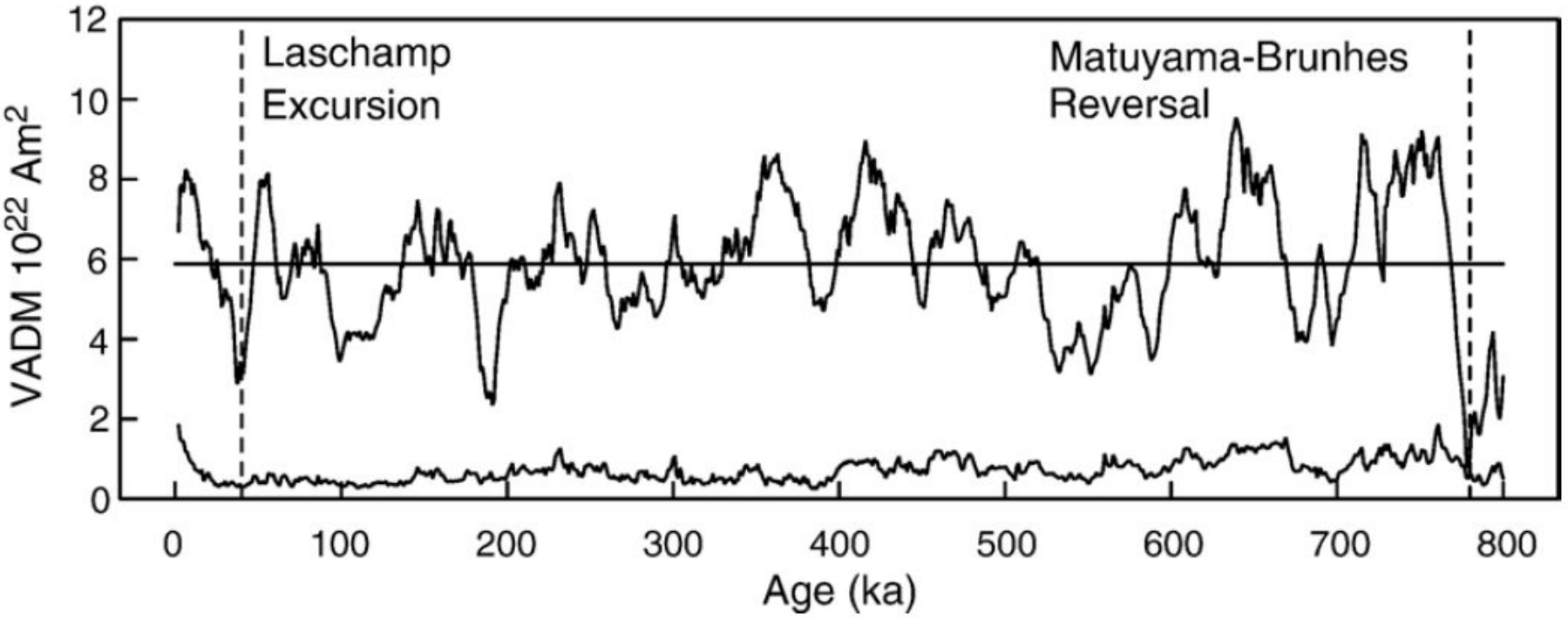
- The blue line shows estimates of the dipole moment made with archeological artifacts
- The red line shows direct measurements from maps of the Earth's field
- The measured moment changes significantly in several thousand years
- Much of this variation could be contributions from the non-dipole field

- ***The red line superposes the recent direct measurements which could be interpreted as the start of a reversal***



Excursions and Reversals

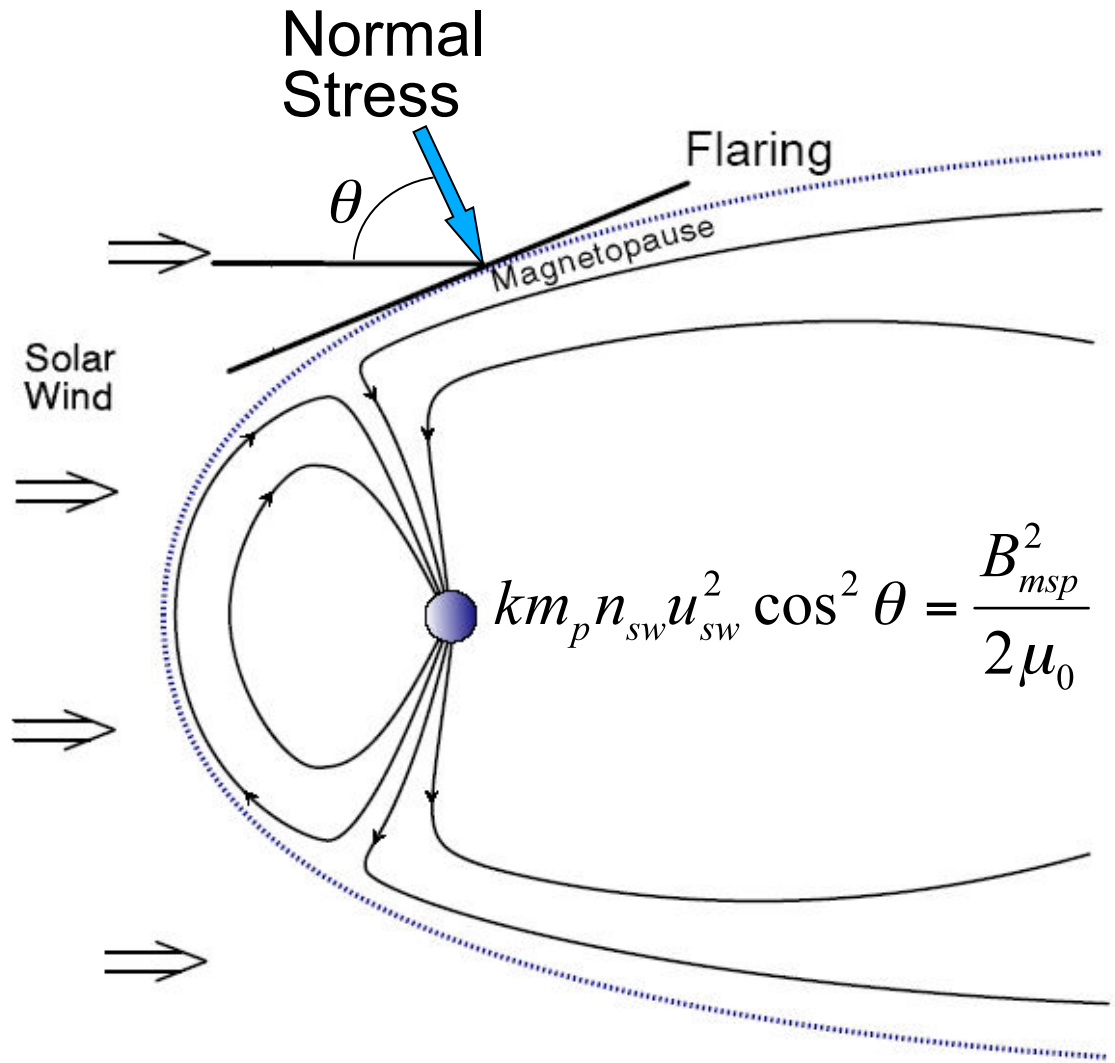
- An **excursion** is a temporary decrease in the strength of the dipole moment
- A **reversal** is when the direction of the dipole moment changes
- A plot of the Virtual Axial Dipole Moment (VADM) for the last 800 K years
- Note the continuous changes in strength of the inferred moment with the minima corresponding to excursions
- The last reversal occurred 780,000 years ago



Scaling the Magnetosphere for Changing Dipole Moment

- The magnetosphere is created by a combination of normal and tangential forces on the magnetic field
- Dynamic pressure of the solar wind (perpendicular to boundary) confines the field to a volume of space by creating a current sheet called the magnetopause

- ***A decrease in dipole moment will decrease the magnetic field at the boundary allowing the solar wind to create a boundary closer to Earth***



Scaling the Magnetopause and Plasmapause

Siscoe, G., and C.-K. Chen (1975), The Paleomagnetosphere, *Journal of Geophysical Research*, *80*(34), 4675-4680.

- Balance the dynamic pressure of solar wind against magnetic pressure of dipole
- Assume the standoff field is twice the dipole at a given distance
- Solve for relation of stagnation distance to dipole moment and dynamic pressure

- ***A decrease in dipole moment shrinks the magnetosphere***

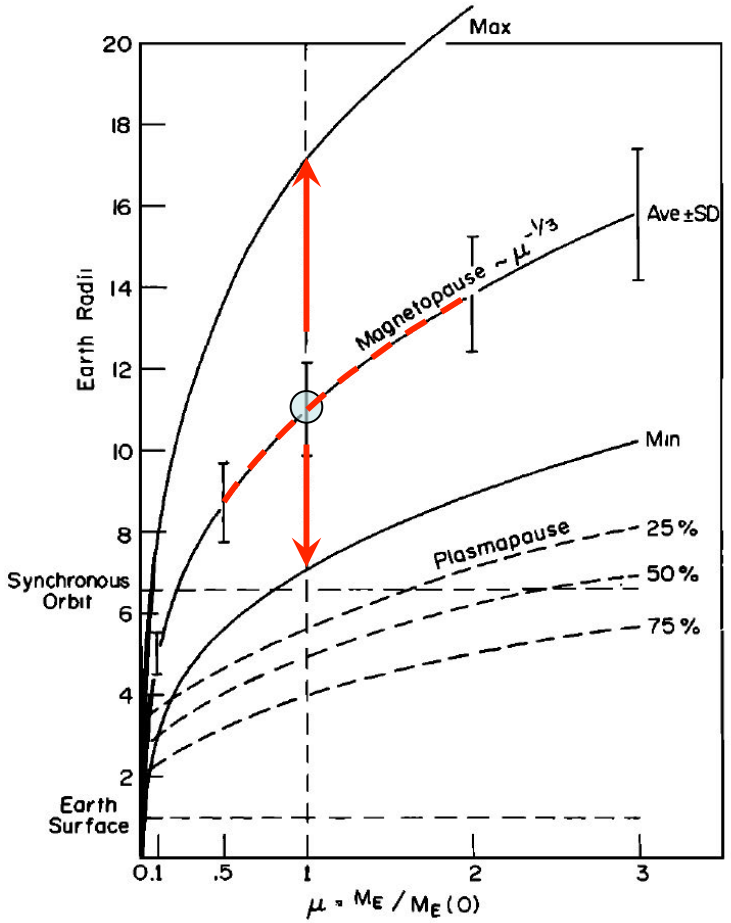
$$P_d = P_m$$

$$\rho V^2 = \frac{\left(2B_o / L_m^3\right)^2}{2\mu_0}$$

$$B_0 = \frac{\mu_0 M}{4\pi}\frac{1}{R_e^3}$$

$$L_m = \frac{r_m}{R_e}$$

$$r_m = CM^{1/3}P_d^{1/6}$$

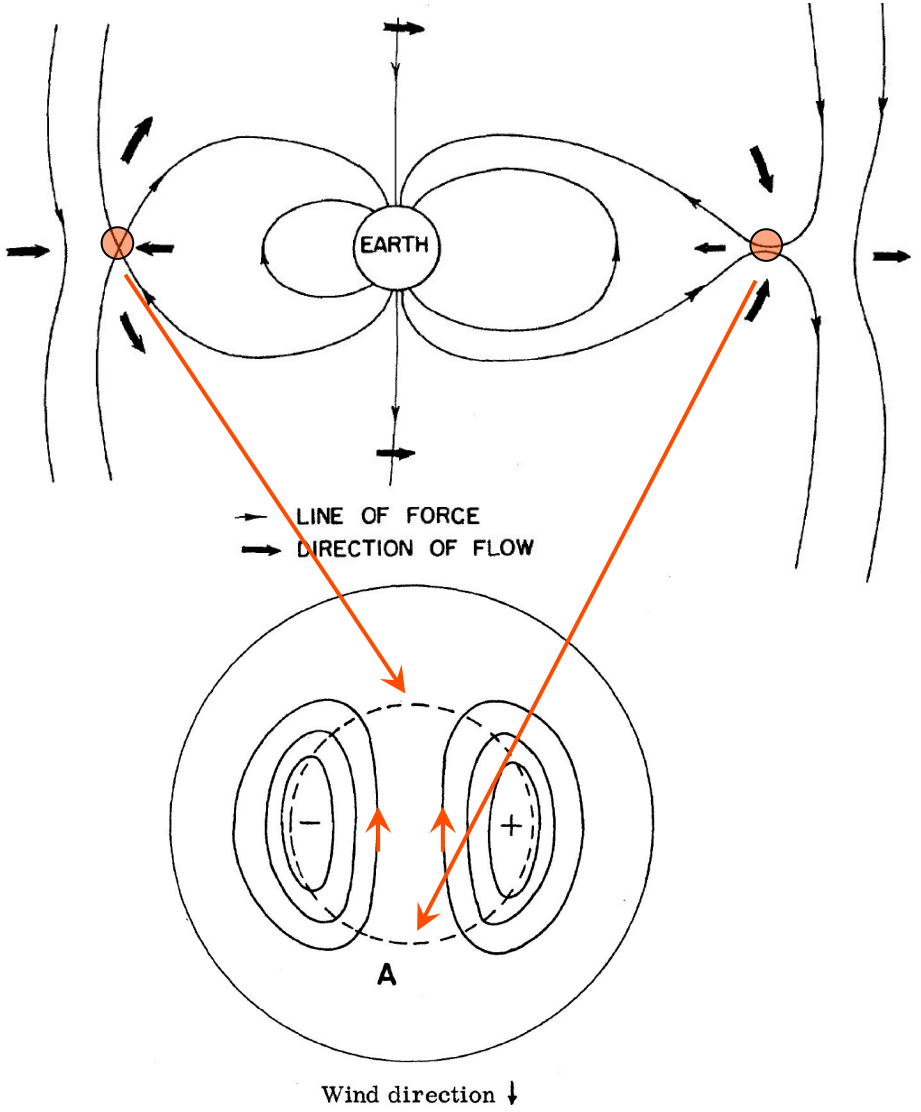


Vertical arrows show changes due to solar wind
Dashed line shows factor of 2 change in moment

Neutral Points in the Solar Wind-Magnetosphere

Dungey, J.W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Res. Letters*, *6*, 47-48.

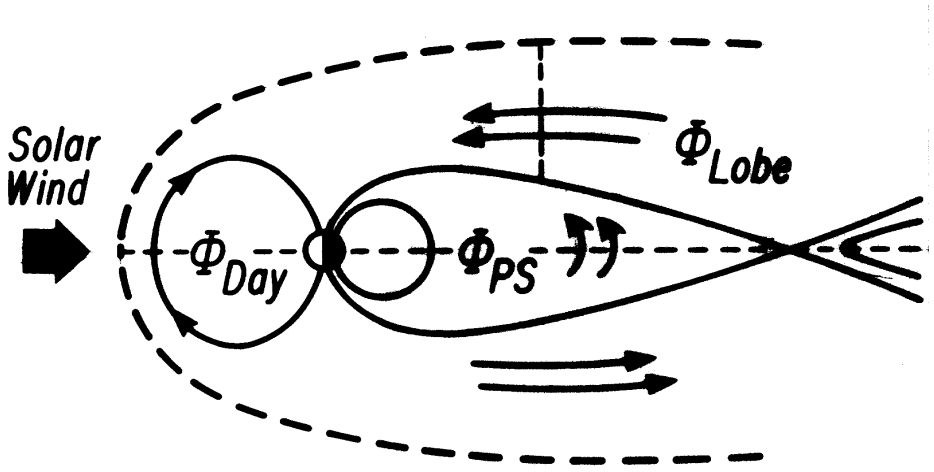
- Dungey considered Hoyle's suggestion that a southward IMF added to the dipole field would create two neutral points connected by a line in the equatorial plane. Specific flow patterns are created by these NP as shown by arrows
- The electric field created by these flows in the solar wind is transmitted to the ionosphere along field lines and drives Hall currents in the ionosphere
- The pattern inferred is similar to that observed during disturbed times (Sd) suggesting the truth of this hypothesis



Unbalanced Flux Transfer

McPherron, R., C. Russell, and M. Aubry (1973), 9. Phenomenological Model for Substorms, *J. Geophys. Res.*, *78*(16), 3131-3149.

- No reason to expect merging, reconnection or return rates to be the same
- If not, then total magnetic flux in three reservoirs may change with time
- Substorm phases are produced by systematic changes in the various flux reservoirs
- In growth dayside reconnection dominates
- In expansion nightside reconnection dominates



$$\Delta\Phi_{Day} = \int_0^t [R-M]\,dt$$

$$\Delta\Phi_{Lobe} = \int_0^t [M-\mathcal{R}]\,dt$$

$$\Delta\Phi_{\substack{Plasma\\sheet}} = \int_0^t [\mathcal{R}-R]\,dt$$

Scaling the Polar Cap

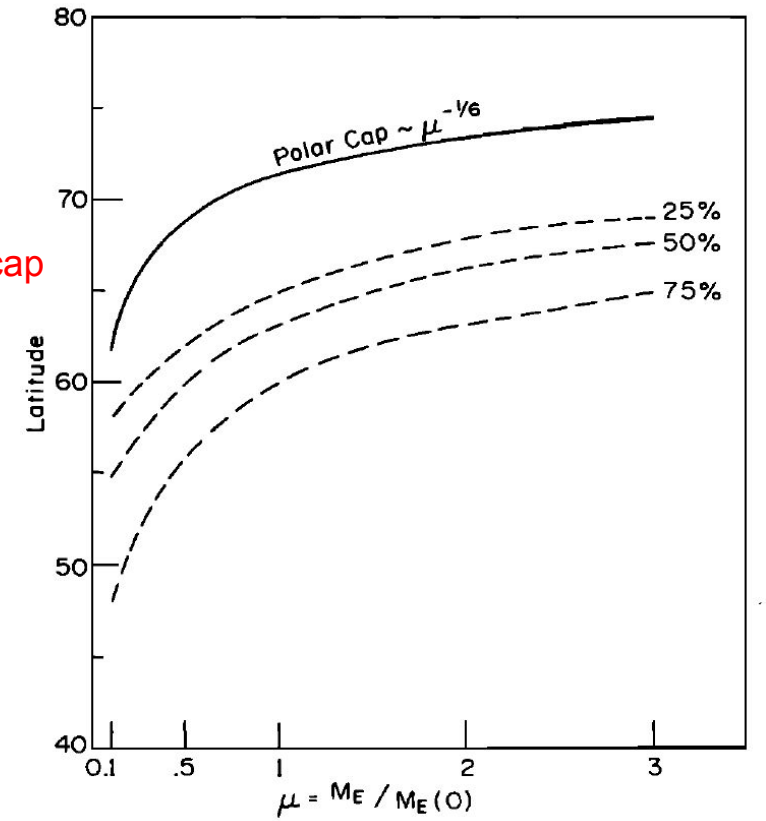
Siscoe, G., and C.-K. Chen (1975), The Paleomagnetosphere, *Journal of Geophysical Research*, *80*(34), 4675-4680.

- Scale the magnetic flux in tail to determine the radius of the polar cap and hence the location of the aurora
- Assume the shape of the magnetosphere does not change with M
- The radius of the tail scales as does the standoff distance and the field in the tail scales as the field at the standoff point
- The flux in the tail is the same as flux from the polar cap, but this flux gets smaller when M decreases

- ***However, the radius of the polar cap increases with decreasing M!***

$$\cos\lambda_p = \left(\frac{M}{M_0}\right)^{-1/6} \left(\frac{P}{P_d^*}\right)^{1/12} \cos\lambda_p^*$$

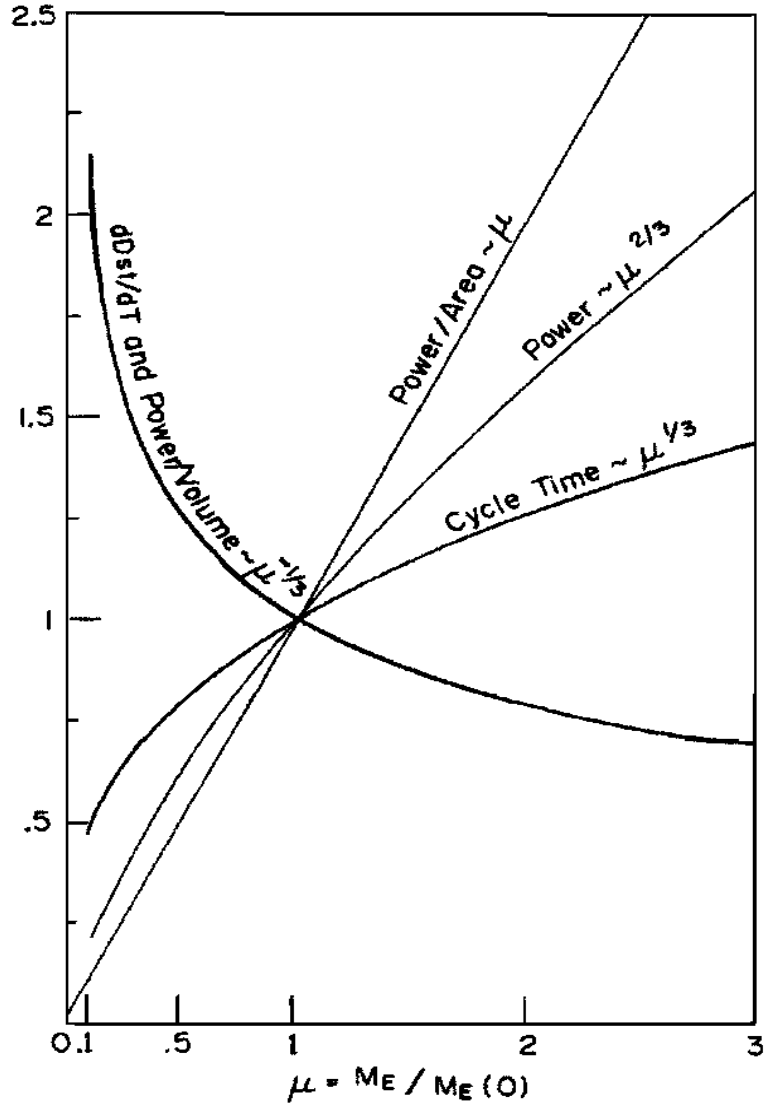
Bigger cap



Scaling the Ring Current

- Energy is input to the magnetosphere through the processes of viscous interaction and magnetic reconnection (tangential forces on magnetopause)
- This energy is first stored in the magnetic field of the tail and later in the ring current
- The ring current is dissipated in the ionosphere by Joule heating and particle precipitation

- ***Plasma transport time, power, and power per unit area all decrease with moment, but the rate of change of Dst (index of ring current strength) increases***



Glassmeier, K.H., J. Vogt, A. Stadelmann, and S. Buchert (2004), Concerning long-term geomagnetic variations and space climatology, *Annales Geophysicae*, *22*(10), 3669-3677.

- The authors extend the earlier work of Siscoe to additional parameters
- They consider possibility that tail field scales as M^{γ} where γ*=1/3* in Siscoe
- They take issue with other Siscoe assumptions and obtain different scaling for the ring current Dst index

	General	$\gamma=1/3$	$\gamma=0$	$\gamma=1/2$
R_{MP}	$M^{1/3}$	$M^{1/3}$	$M^{1/3}$	$M^{1/3}$
R_{PP}	$M^{3\gamma-11/6}$	$M^{-5/6}$	$M^{-11/6}$	$M^{-1/3}$
R_T	M^{γ}	$M^{1/3}$		$M^{1/2}$
$cos\vartheta$	$M^{\gamma-1/2}$	$M^{-1/6}$	$M^{-1/2}$	
D_{st}	$M^{2\gamma}$	$M^{2/3}$		M
$E_{Iono,s}$	$M^{\gamma+11/6}/\Sigma_0$	$M^{13/6}/\Sigma_0$	$M^{11/6}/\Sigma_0$	$M^{7/3}/\Sigma_0$
b_G	$M^{-\gamma+1/2}$	$M^{1/6}$	$M^{1/2}$	
b_{EEJ}	$M^{-2/3}$	$M^{-2/3}$	$M^{-2/3}$	$M^{-2/3}$

Why are Scaling Laws Important?

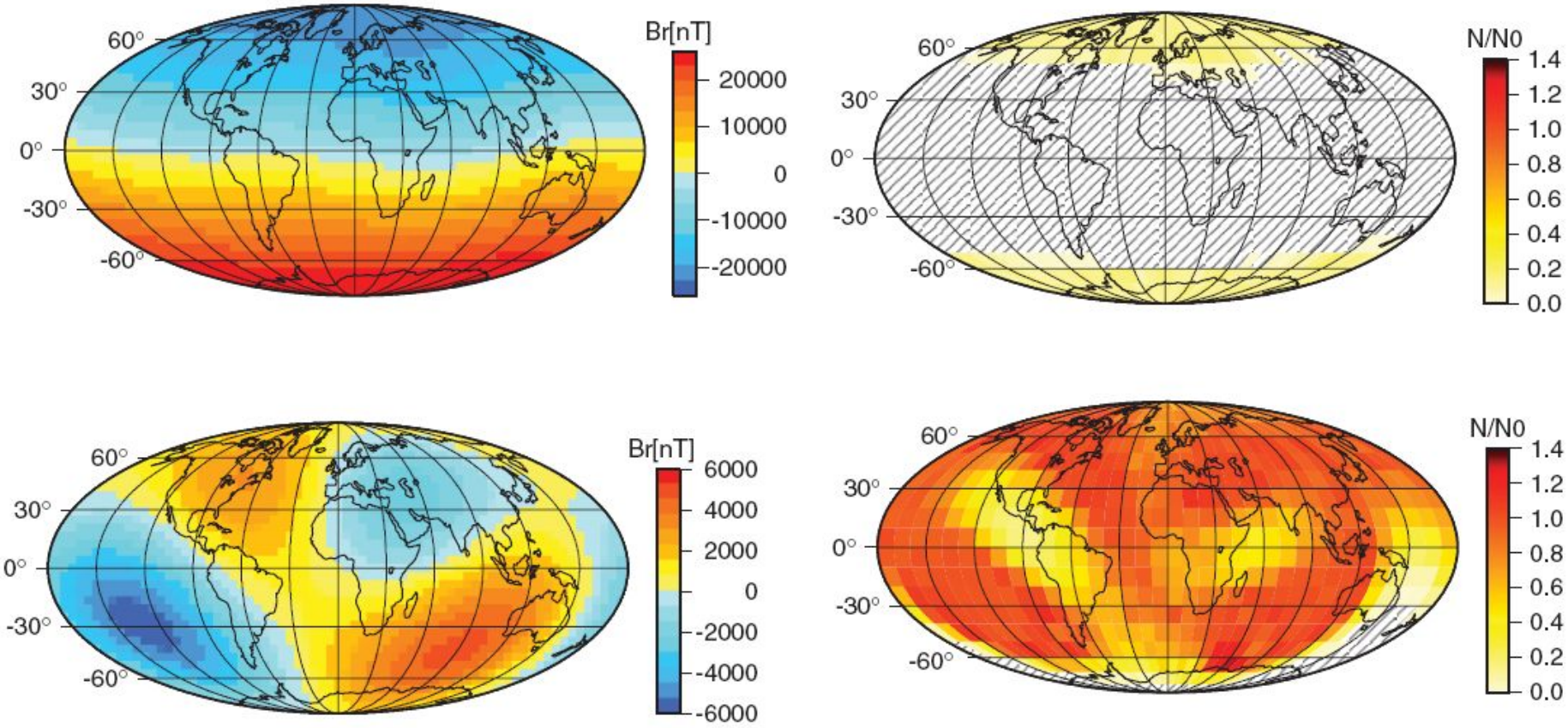
- Interpretations of paleomagnetic measurements assume that external fields are negligible. If storms and substorms produce fields comparable to surface field from core then it is possible that the field frozen in a lava flow is not representative of the main field.
- If the dipole contribution around the Earth shrinks then current systems generated in space might dominate the external field greatly altering the interaction with the solar wind in unexpected ways
- The authors disagree with the Siscoe scaling of the ring current and find none of the other space weather systems produce sufficiently large perturbations to be of concern provided the Earth's total field is not reduced below 25% of its current value

- ***"we conclude that the secular change of the dipole component of the geomagnetic field is of minor importance compared to the overall solar wind induced variability."***

Access of 256 MeV Solar Protons

Glassmeier, et al., (2009)

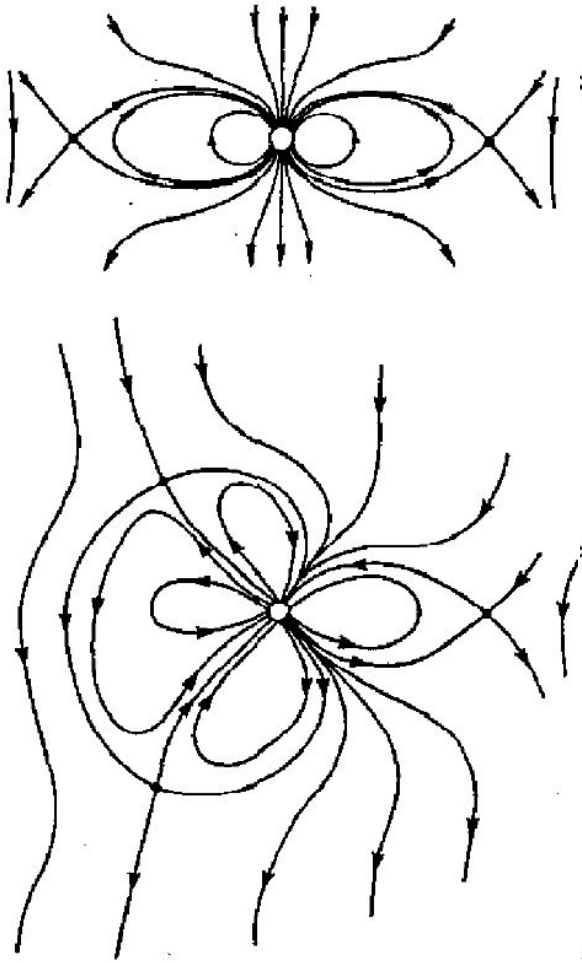
- Top rows shows current situation before reversal and bottom row shows situation during a reversal
- In current field solar protons only have access to the polar caps (top right)
- During a reversal these protons could access almost the entire Earth (bottom right)

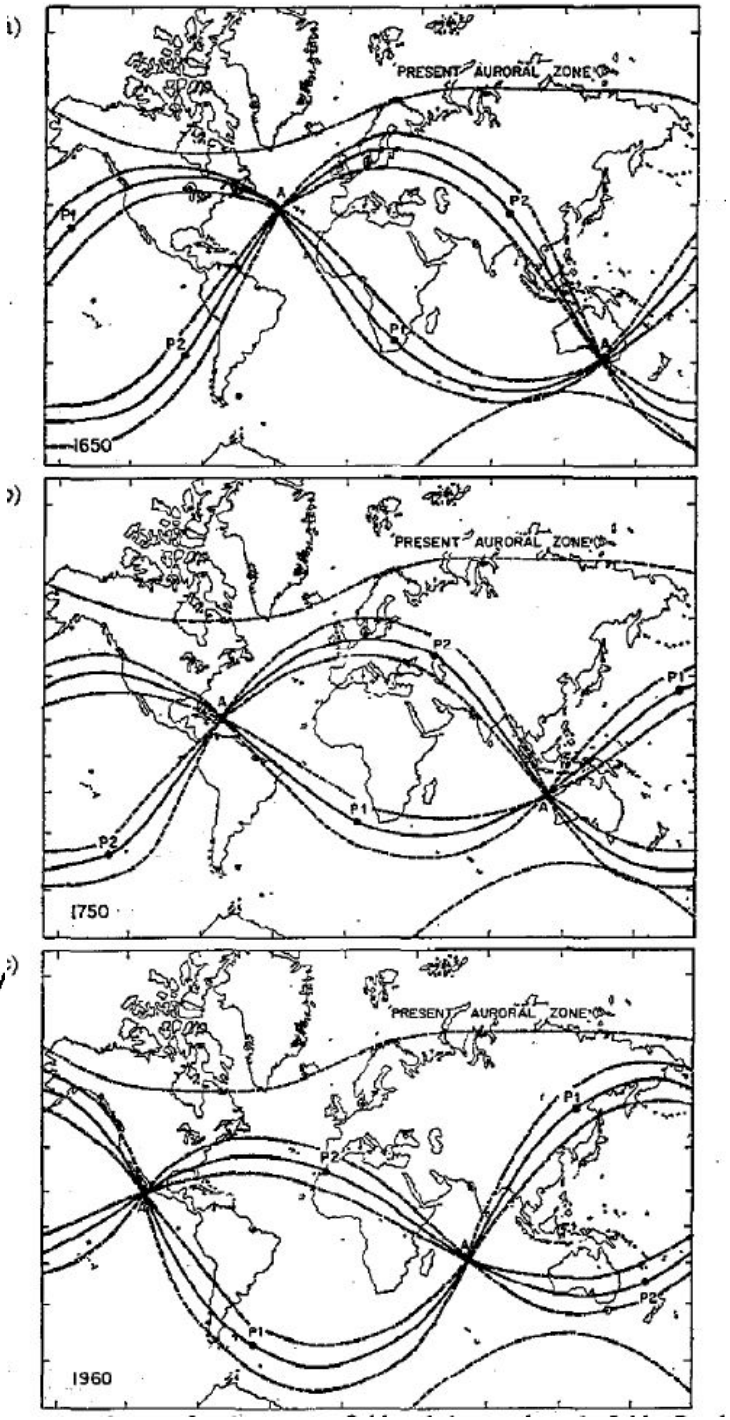


Dipole and Quadrupole Magnetospheres

Siscoe, G.L., and N.U. Crooker (1976), Auroral zones in a quadrupole magnetosphere, *Journal of Geomagnetism and Geoelectricity*, *28*(1), 1-9.

- Add a uniform southward field to the dipole field
- At some distance from Earth an x-line forms
- The dipole auroral zone is a circle around field lines that extend to infinity from single points (the poles)
- In a quadrupole field the same type of field lines emanate from great circles
- The auroral zones will be bands around these circles as shown in the right diagram for three different eras

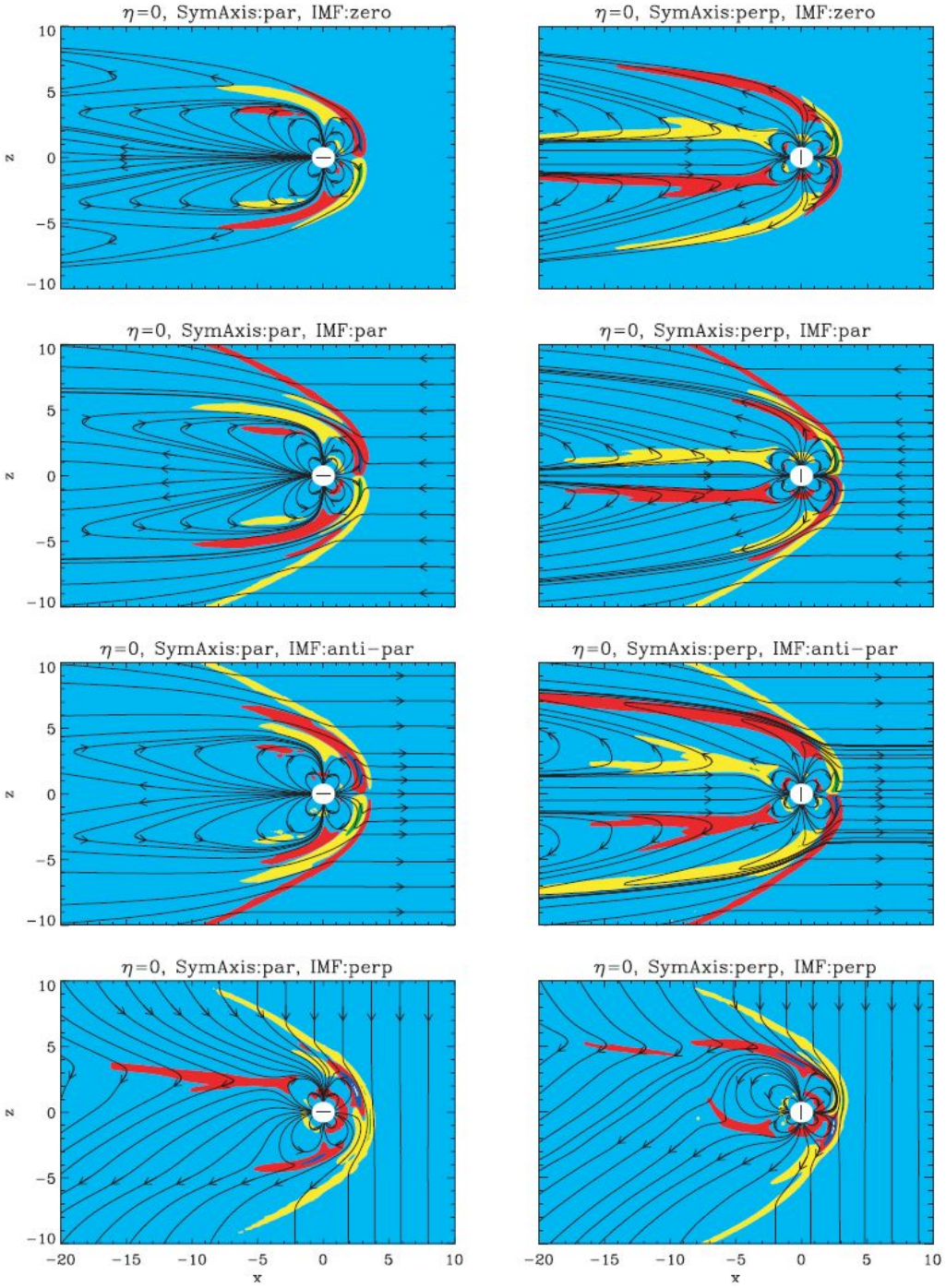




Simulation of Quadrupole Magnetosphere

Vogt, J., B. Zieger, A. Stadelmann, K.H. Glassmeier, T.I. Gombosi, K.C. Hansen, a A.J. Ridley (2004), MHD simulations of quadrupolar paleomagnetospheres, *Journa Geophysical Research-Space Physics*, *1* (A12).

- Use MHD simulation to study solar wind interaction with a quadrupole
- Current into plane is in red and out of plane is in yellow
- Left panels are for axis of symmetry parallel to solar wind and right panels for perpendicular
- Note complexity of internal field for different orientations of IMF
- Additional complexity comes for different shape factors (η)



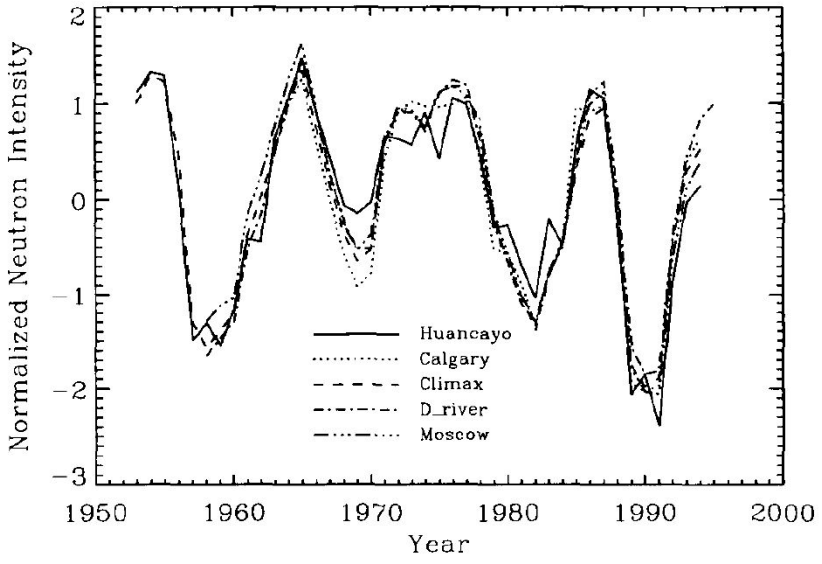
Possible Effects on Climate

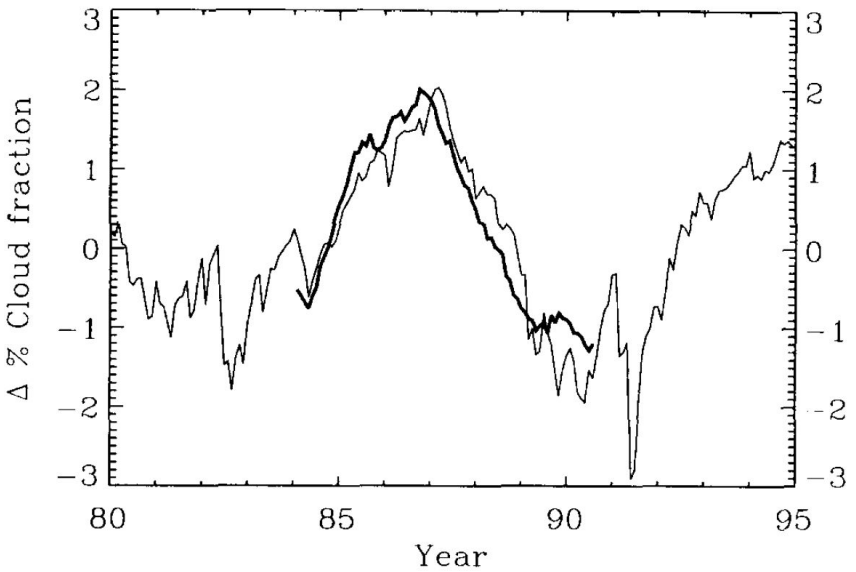
- significant changes in the absorption of solar radiation or the emission of infrared radiation by the lower atmosphere and Earth's surface
- ionization effects of galactic cosmic rays affect sulphate aerosol formation and cloud nucleation in the vicinity of the tropopause
- It has been estimated that an 8% increase in cloud cover would be equivalent to a 2% decrease in the solar constant.

Cosmic Rays and Cloud Cover

Svensmark, H., and E. Friis-Christensen (1997), Variation of cosmic ray flux and global cloud coverage - A missing link in solar-climate relationships, *Journal of Atmospheric and Solar-Terrestrial Physics*, *59*(11), 1225-1232.

- Left panel shows normalized cosmic ray intensity measured by neutron monitor. Maxima occur at the minimum of solar cycle.
- Right panel compares an index of cloudiness and cosmic ray flux over a recent solar cycle.
- The correlation suggests an increase in cosmic rays due to a decrease in interplanetary magnetic field may cause an increase in cloud cover





Glassmeier, K.H., O. Richter, J. Vogt, P. Mobus, and A. Schwalb (2009), The Sun, geomagnetic polarity transitions, and possible biospheric effects: review and illustrating model, *International Journal of Astrobiology*, *8*(3), 147-159.

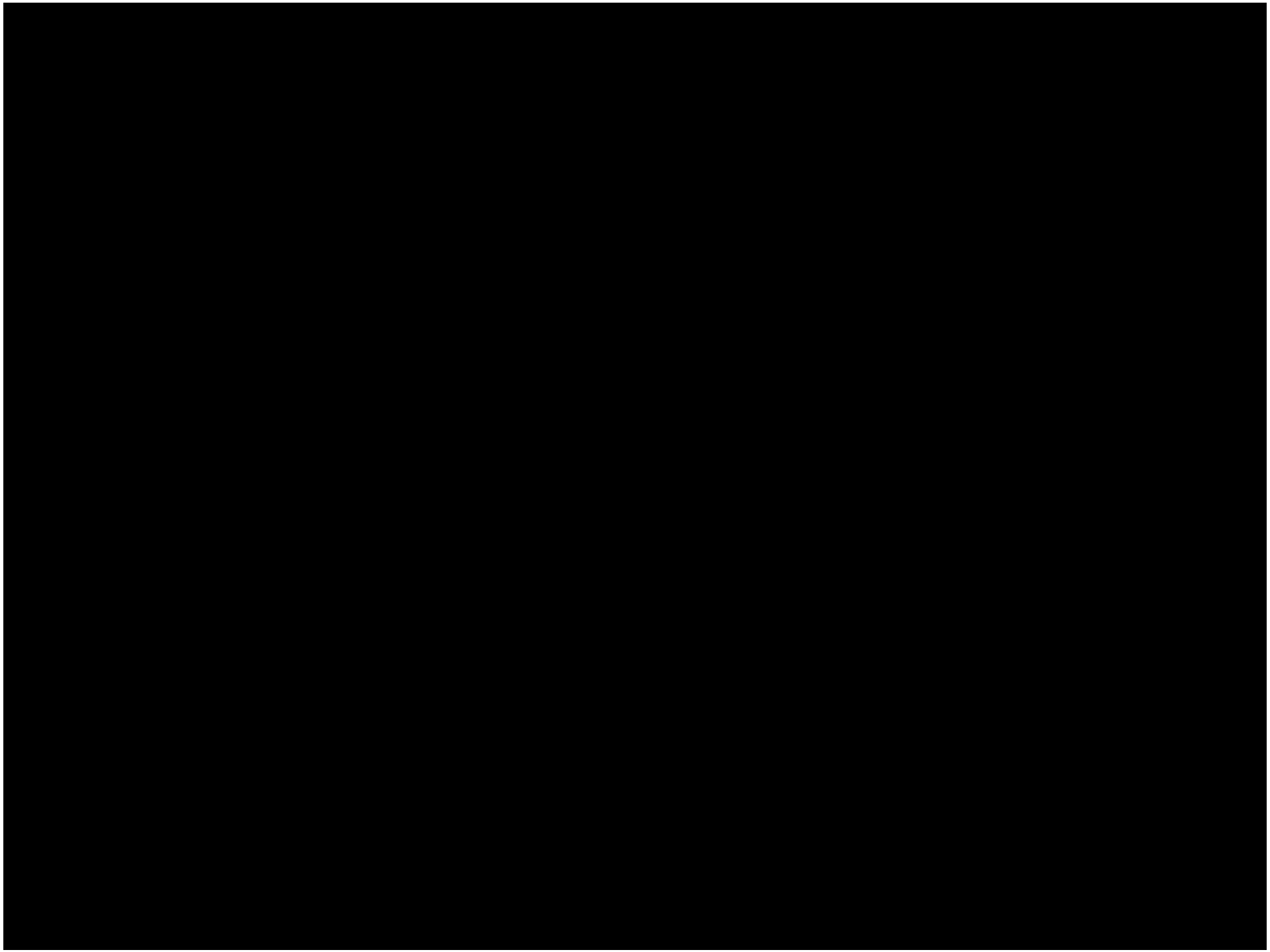
- "…galactic cosmic ray (GCR) theory has been advocated suggesting a link between geomagnetic field modulations of the GCR flux and climate variations."
- A reduction of the dipole moment will allow energetic solar protons to impact most of the Earth. These produce NOx particles that might destroy ozone in polar regions producing a large ozone hole.
- Increased ultraviolet illumination could have strong effect on phytoplankton

- ***"All recent studies do not yet allow one to decide whether a polarity transition is a cataclysm to the Earth system or not."***

Possible Consequences

Constable, C., and M. Korte (2006), Is Earth's magnetic field reversing?, *Earth and Planetary Science Letters*, *246*(1-2), 1-16.

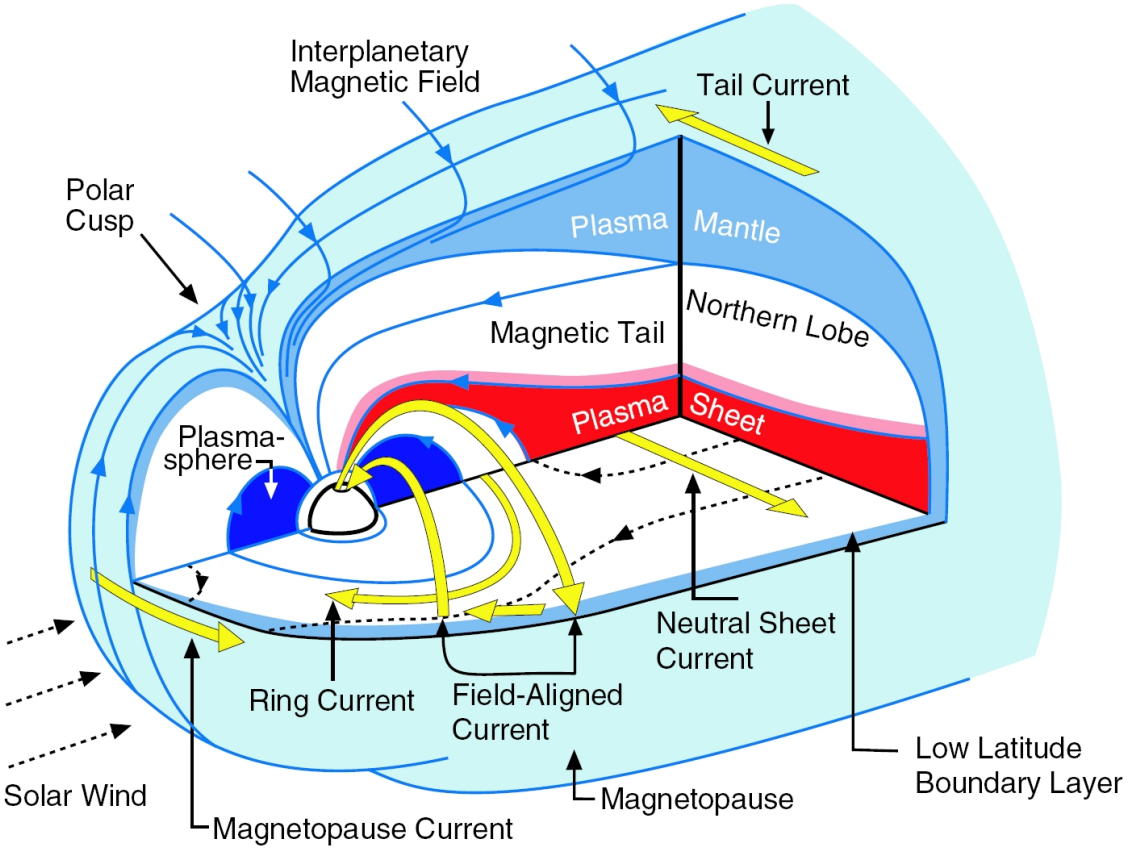
- Reduced dipole moment allows more cosmic rays to hit earth with possible increase in cloud cover
- Greater access of solar protons to upper atmosphere might result in the creation of NOx that could decrease ozone
- Reduced ozone allows more UV that changes atmospheric temperature and circulation
- The influence of solar variability on cosmogenic isotope production plays an important role in paleoclimate studies

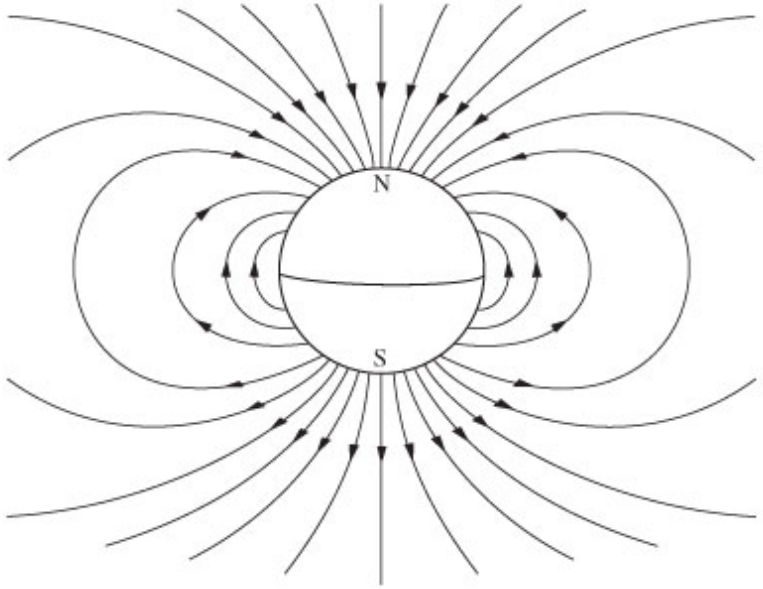


The 3-D Magnetosphere

- Magnetic reconnection between the interplanetary magnetic field and the Earth's field produces a long tail behind the Earth
- Plasma moves up the tail during geomagnetic activity and enters the ring current creating a magnetic storm
- Eventually the energy of these particles is dissipated in ionosphere by Joule heating and particle precipitation

- ***Magnetic storms and substorms (auroral displays) are a localized source of energy at the top of the atmosphere***





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