Last lecture (7)

- Aurora
- Aurora on other planets
- How to measure currents in space

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Today's lecture (8)

- Magnetospheric dynamics
- Geomagnetic activity
- (Cosmic radiation, interstellar plasma)

Today

Activity	Date	Time	Room	Subject	Litterature
L1	28/8	15-17	Q21	Course description, Introduction, The Sun 1	**CGF** Ch 1.1,1.2, 1.4, 5, (p 110-113), 6.3
L2	29/8	13-15	Q2	The Sun 2, Plasma physics 1	**CGF** Ch 1.3, 5 (p 114-121)
L3	4/9	10-12	E2	Solar wind, The ionosphere and atmosphere 1, Plasma physics 2	**CGF** Ch 6.1, 2, 3.1-3.2, 3.5, **LL** Ch III, Extra material
T1	6/9	8-10	Q21	Mini-group work 1	
L4	6/9	15-17	Q2	The ionosphere 2, Plasma physics 3	**CGF** Ch 3.4, 3.7, 3.8
T2	10/9	15-17	Q21	Mini-group work 2	
L5	11/9	10-12	E3	The Earth's magnetosphere 1, Plasma physics 4	**CGF** 4-1-4.3, **LL** Ch I, II, IV.A
T3	17/9	8-10	Q21	Mini-group work 3	
L6	18/9	13-15	Q33	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
L7	19/9	13-15	Q2	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
T4	24/9	8-10	Q2	Mini-group work 4	
L8	24/9	15-17	V3	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
T5	2/10	8-10	Q31	Mini-group work 5	
L9	2/10	13-15	Q2	Alfvén waves, Interstellar and intergalactic plasma, Cosmic radiation	**CGF** Ch 7-9, Extra material
T6	8/10	15-17	Q21		
L10	9/10	10-12	Q2	Guest Lecture by Swedish astronaut Christer Fuglesang	
Written examination	16/10	14-19	L21, L22, L31		

Mini-groupwork 4

a)

$$\rho_{SW} v_{SW}^2 = \left[\frac{\mu_0 a}{4\pi} \frac{1}{r^3} \right]^2 / 2\mu_0 \quad \Rightarrow$$

$$r = \left(\frac{\mu_0 a}{4\pi} \right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2 \right)^{-1/6}$$

Assuming the solar wind consists of protons

$$\rho_{SW} = n_{e,SW} m_p = 1.7 \cdot 10^{-22} \; kg\, m^{-3}$$

Thus

$r = 2.7 \cdot 10^9$ m $\approx 38\ R_J$

Mini-groupwork 4

b)

$$\rho_{SW} v_{SW}^2 = \left[\frac{\mu_0 a}{4\pi} \frac{1}{r^3} \right]^2 / 2\mu_0 + n_e k_B T \quad \Rightarrow$$

$$\rho_{SW} v_{SW}^2 = \left[\frac{\mu_0 a}{4\pi} \frac{1}{r^3} \right]^2 / 2\mu_0 + n_{e0} \left(\frac{R_J}{r} \right)^3 k_B T$$

Substitute $x = 1/r^3$. This gives you an equation on the form

$ax^2 + bx + c = 0$

with

$$a = \left[\frac{\mu_0 a}{4\pi} \right]^2 / 2\mu_0 = 1.02 \cdot 10^{46}$$

$$b = n_{e0} R_J{}^3 k_B T = 1.78 \cdot 10^{18}$$

$$c = -\rho_{SW} v_{SW}^2 = -2.7 \cdot 10^{-11}$$

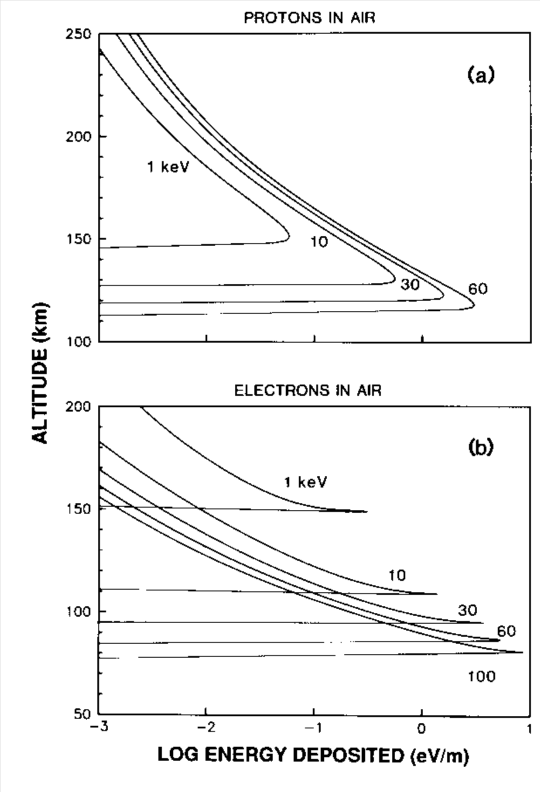
$$x = -\frac{b}{2a} \pm \sqrt{\frac{b^2}{4a^2} - \frac{c}{a}} =$$

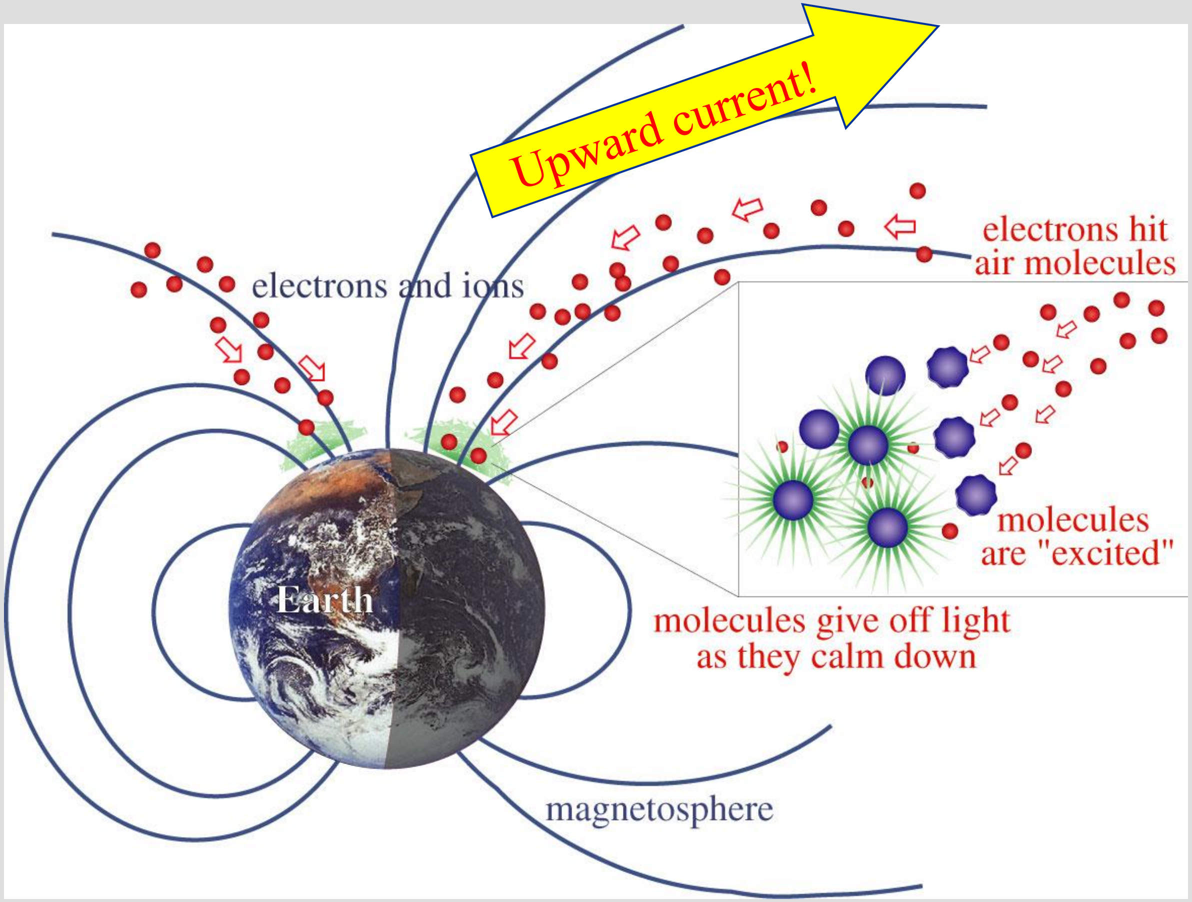
$$-8.768 \cdot 10^{-29} + \sqrt{7.689 \cdot 10^{-57} + 2.635 \cdot 10^{-57}} =$$

$$= -8.768 \cdot 10^{-29} + 1.01610^{-28} = 1.39 \cdot 10^{-29} \text{ m}$$

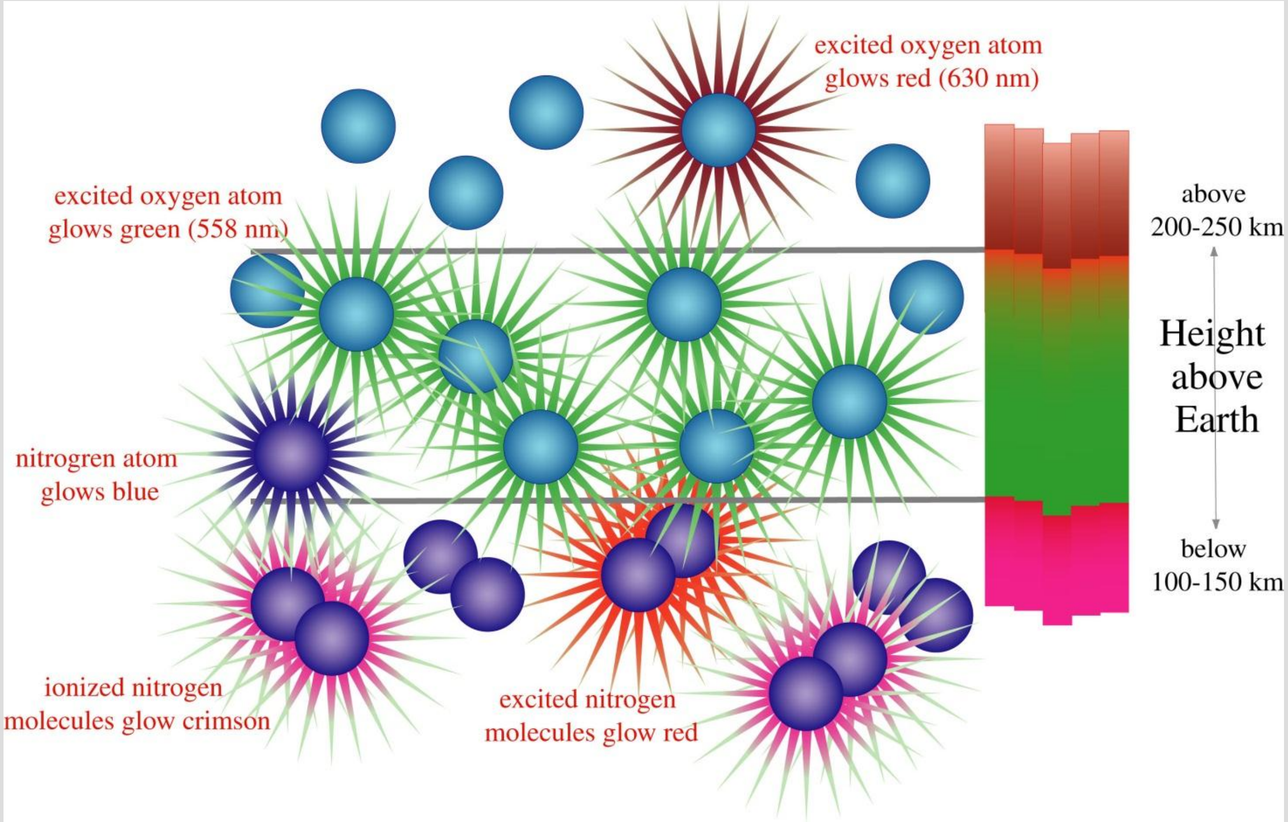
From this you get $r \approx 59\ \mathrm{R_J}$

Collisions - emissions





Emissions



excited oxygen atom
glows red (630 nm)
excited oxygen atom
glows green (558 nm)
nitrogren atom
glows blue
ionized nitrogen
molecules glow crimson
excited nitrogen
molecules glow red
above
200-250 km
Height
above
Earth
below
100-150 km

Larger scales

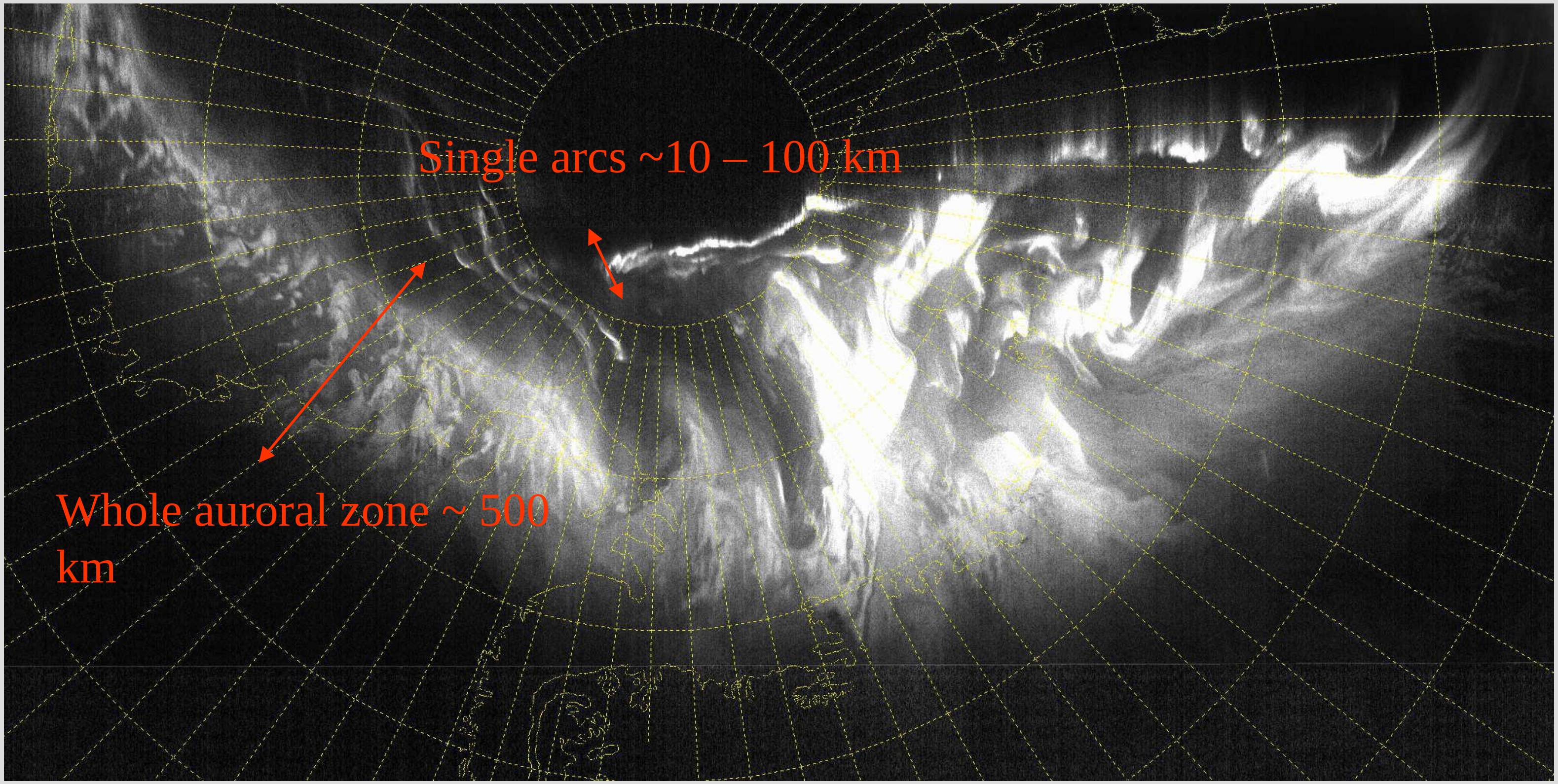
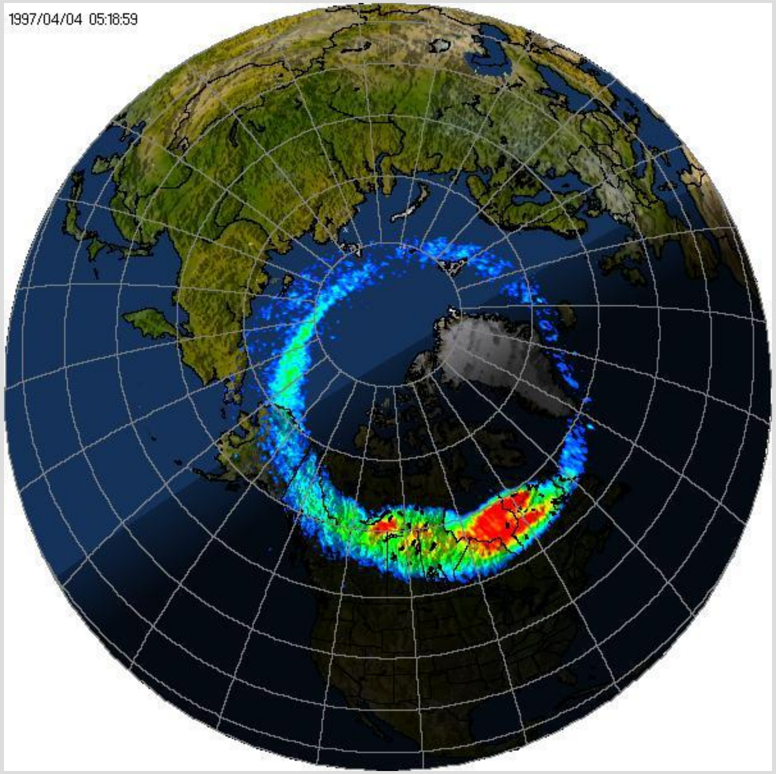
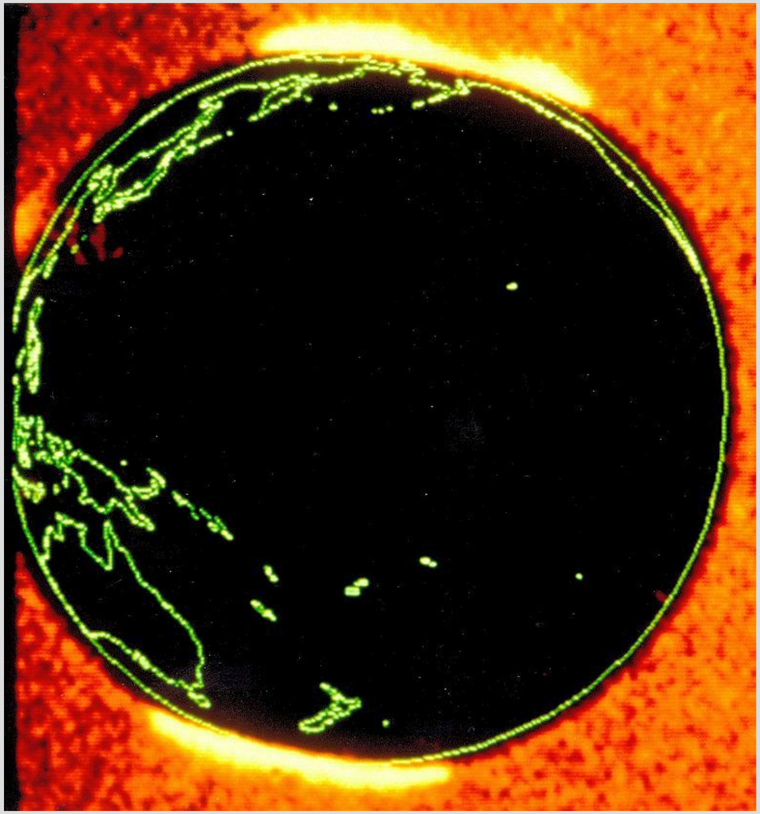


Foto från DMSP-satelliten

Auroral ovals

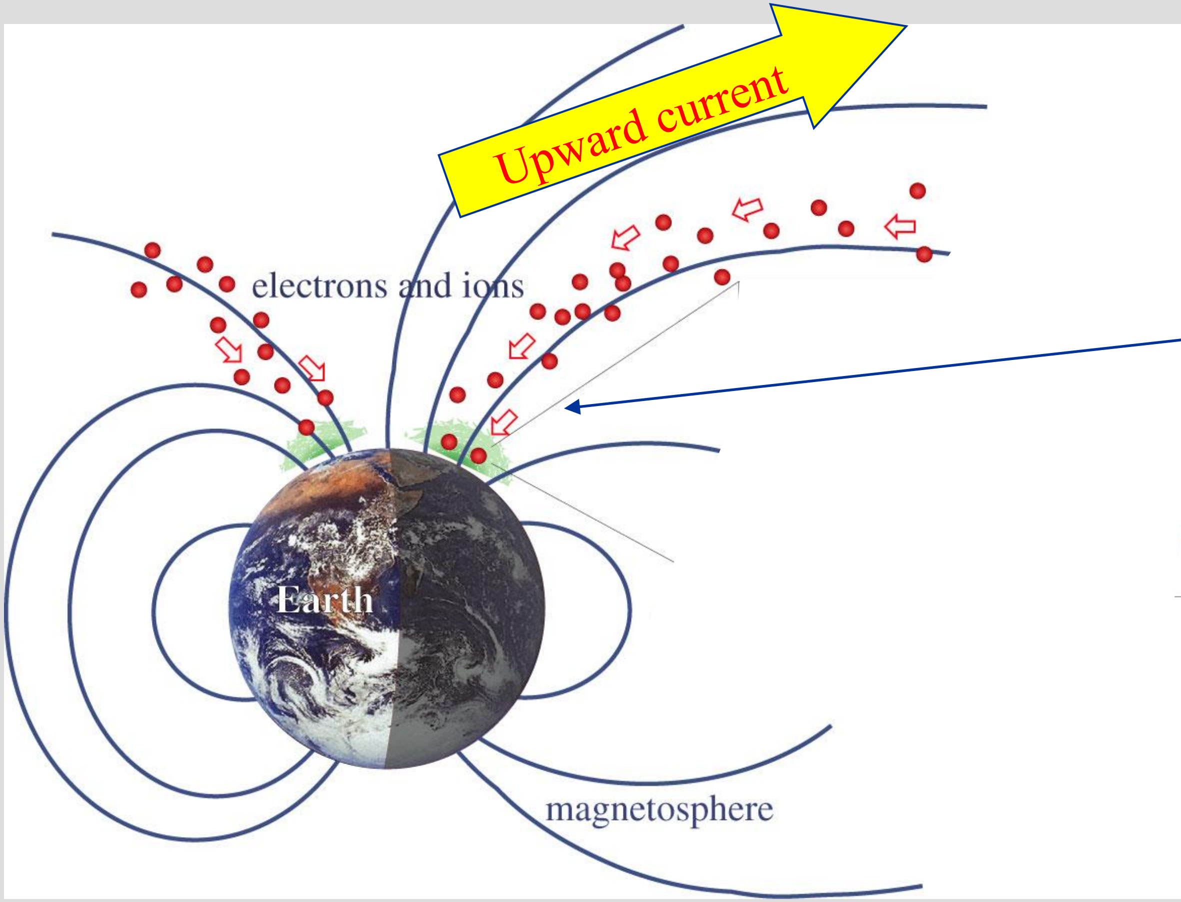


Polar



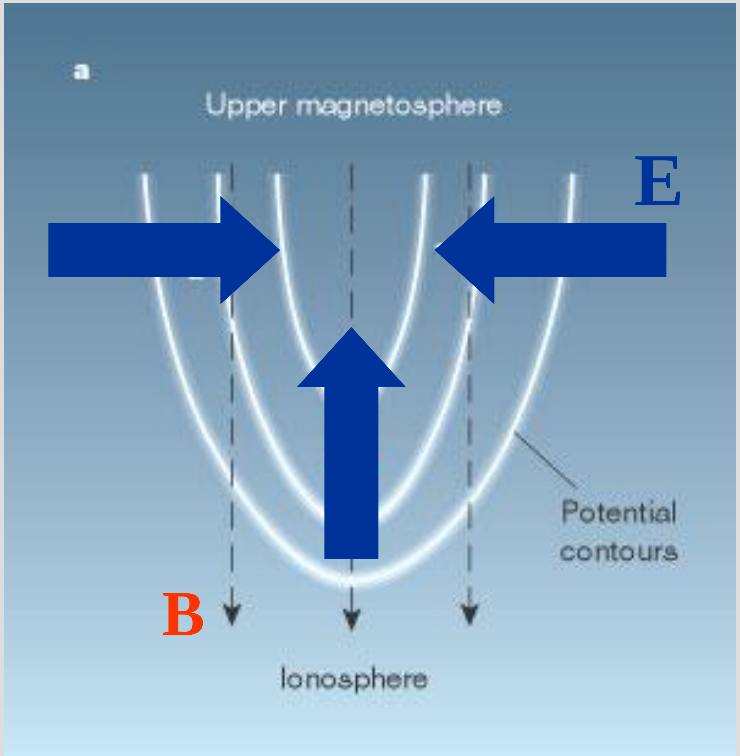
Dynamics Explorer

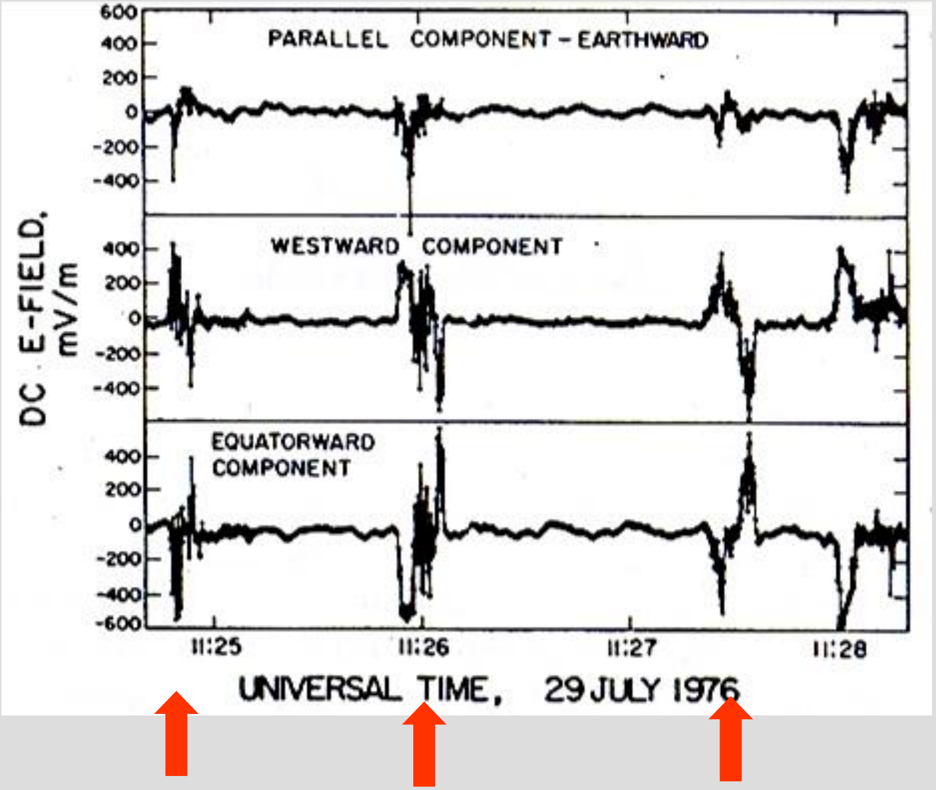
Why particle acceleration?



- The magnetosphere often seems to act as a current generator.
- The lower down you are on the field line, the more particles have been reflected by the magnetic mirror.
- At low altitudes there are not enough electrons to carry the current.

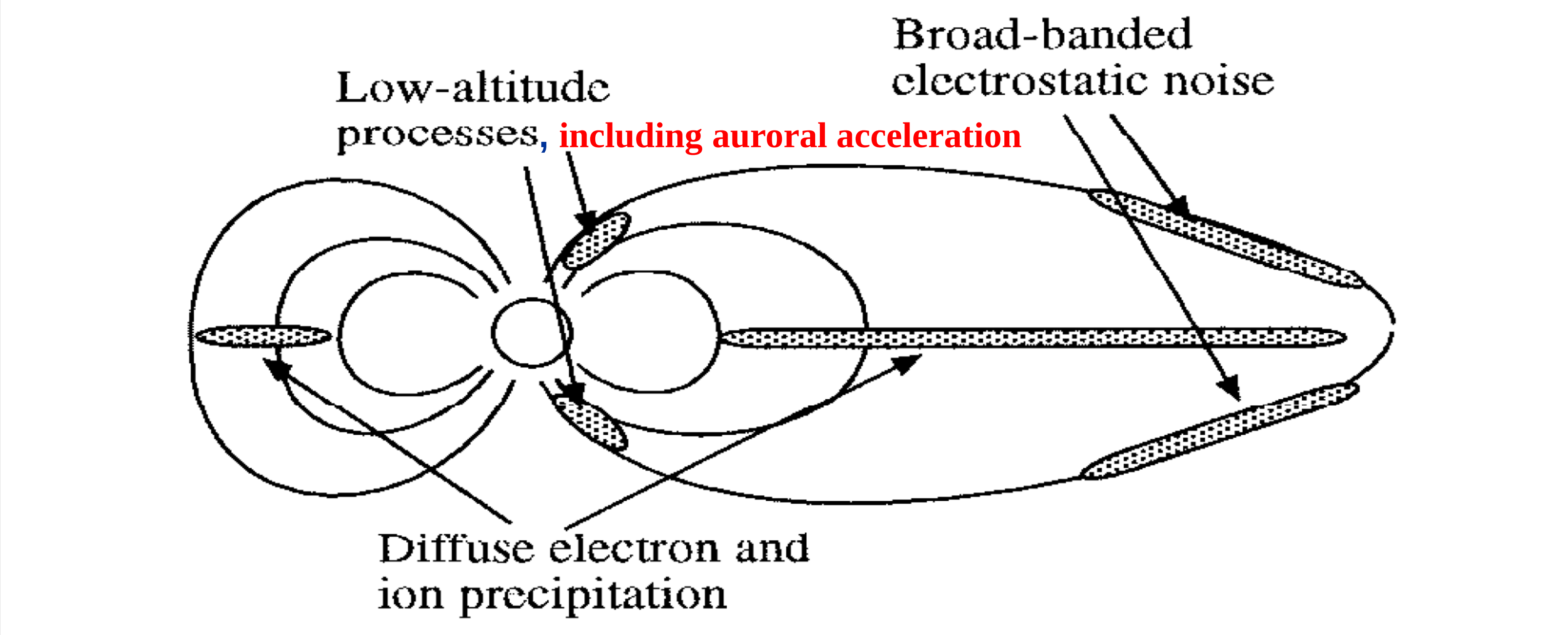
Satellite signatures of U potential





Measurements made by the ISEE satellite (Mozer et al., 1977)

Acceleration regions



Auroral acceleration region typically situated at altitude of 1-3 R_E

Jupiter aurora

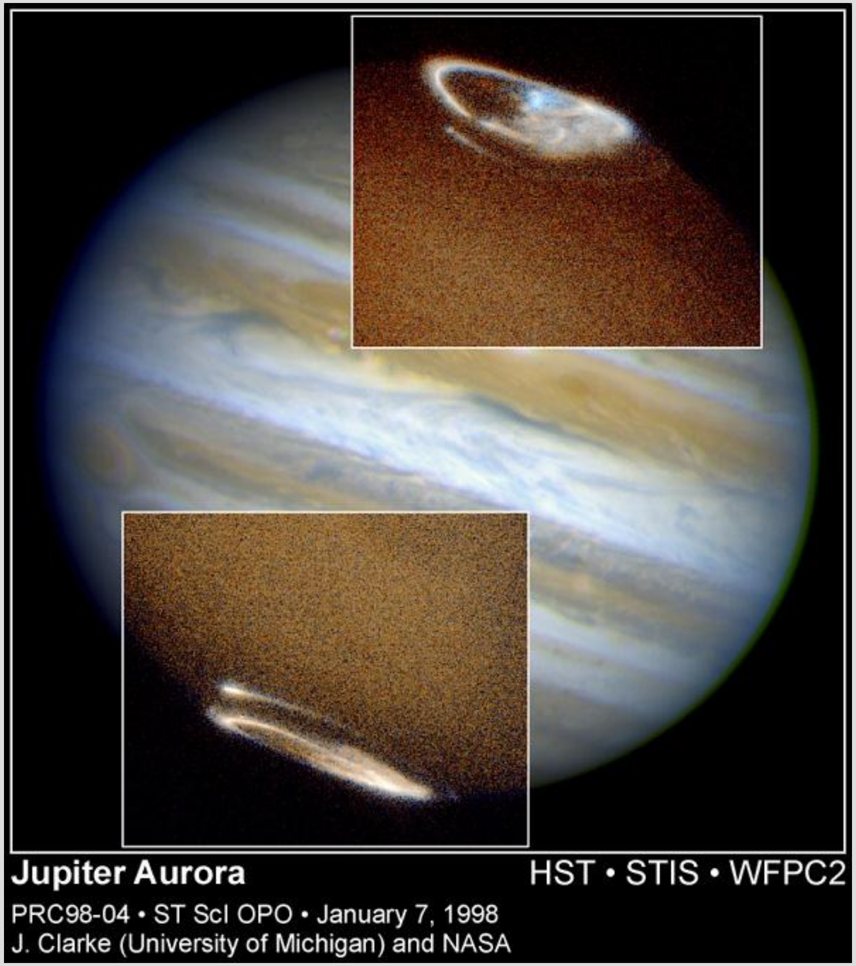
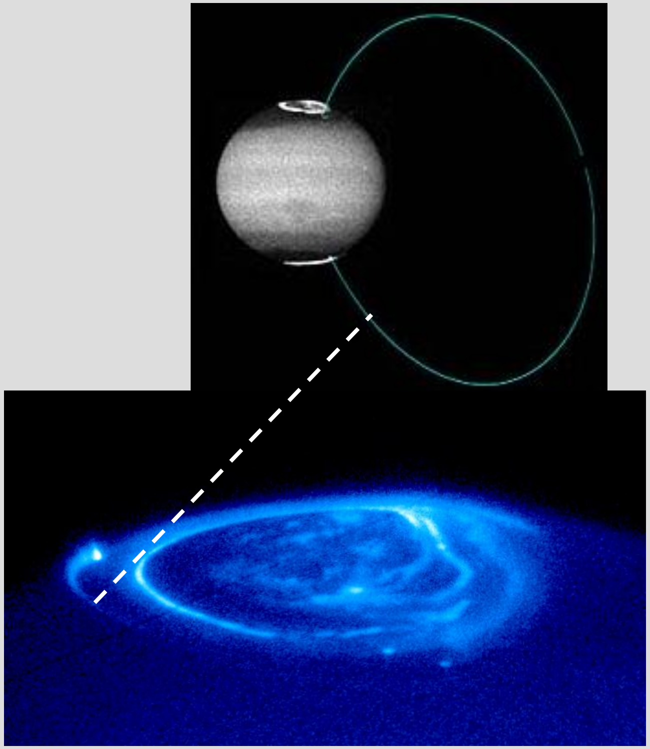


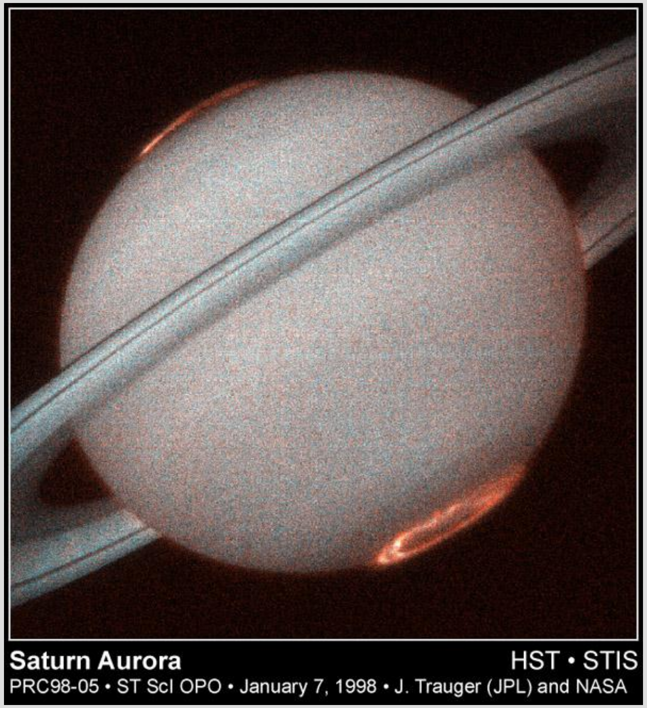
Foto från Hubble Space Telescope

- Jupiter's aurora has a power of ~1000 TW *(compare Earth: ~100 GW, nuclear power plant: ~1 GW)*
- Note the "extra" oval on Io's flux tube!



Aurora of the other planets

Saturn



Saturnus' aurora: not noticeably different from Jupiter's, but much weaker. (Total power about the same as Earth's aurora.)

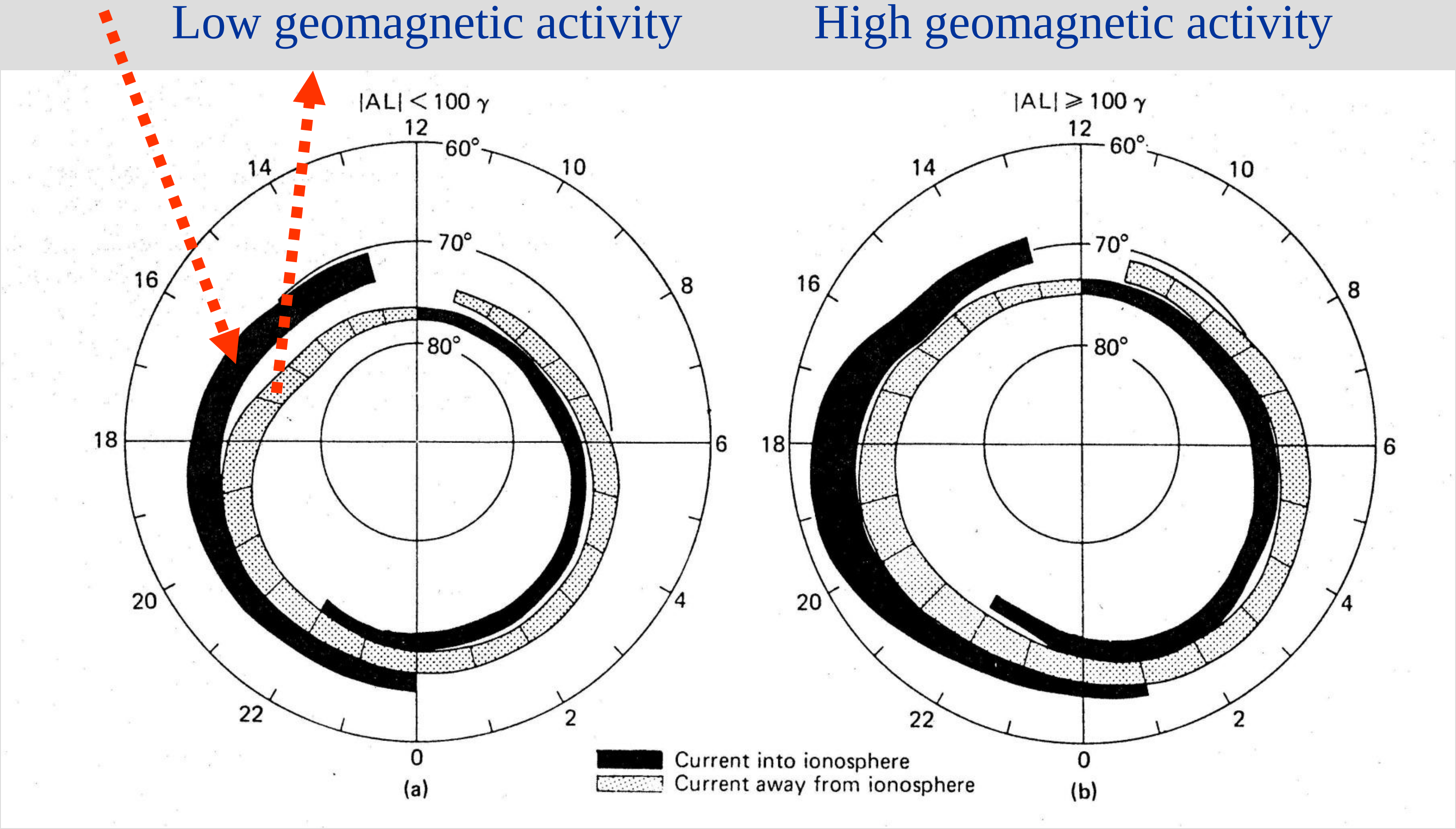
Uranus: *Auora detected in UV. Probably associated with Uranus' ring current/radiotion belts and not very dynamic.*

Neptunus: *weak UV aurora detected.*

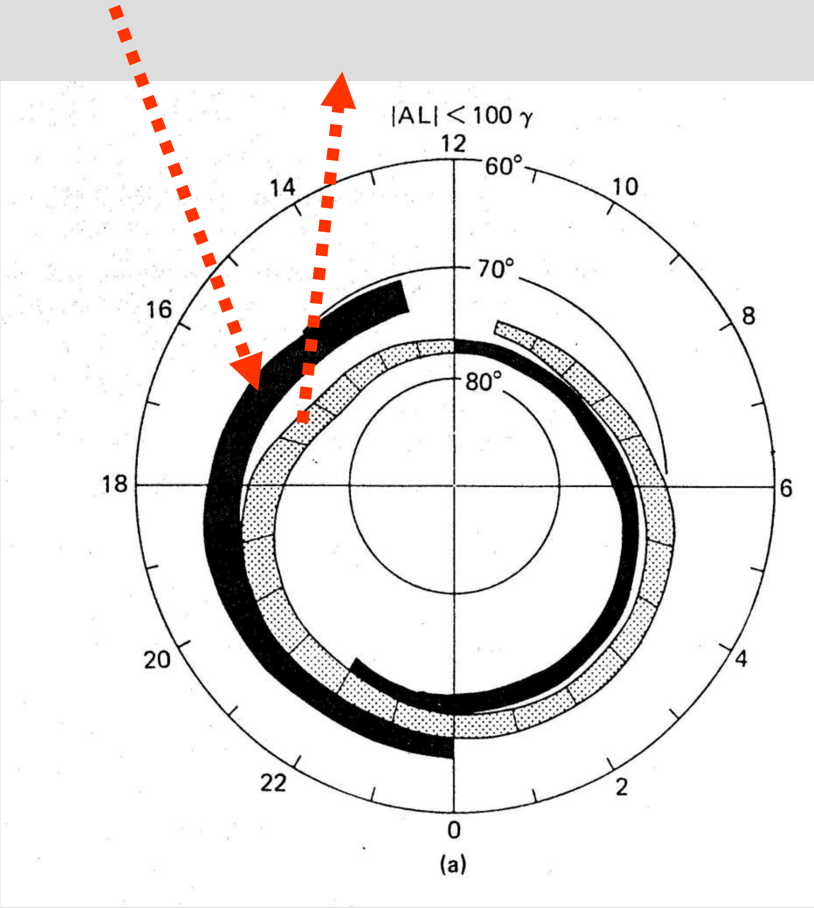
Mars, Venus: *No aurora.*

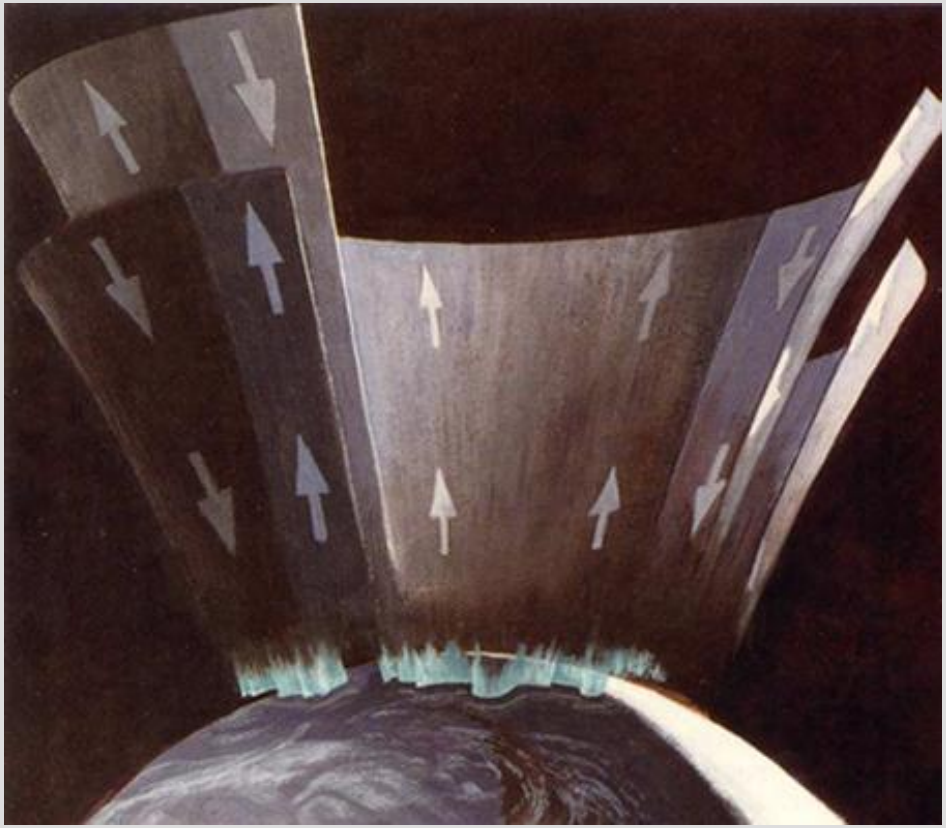
Birkeland currents in the auroral oval

Low geomagnetic activity High geomagnetic activity

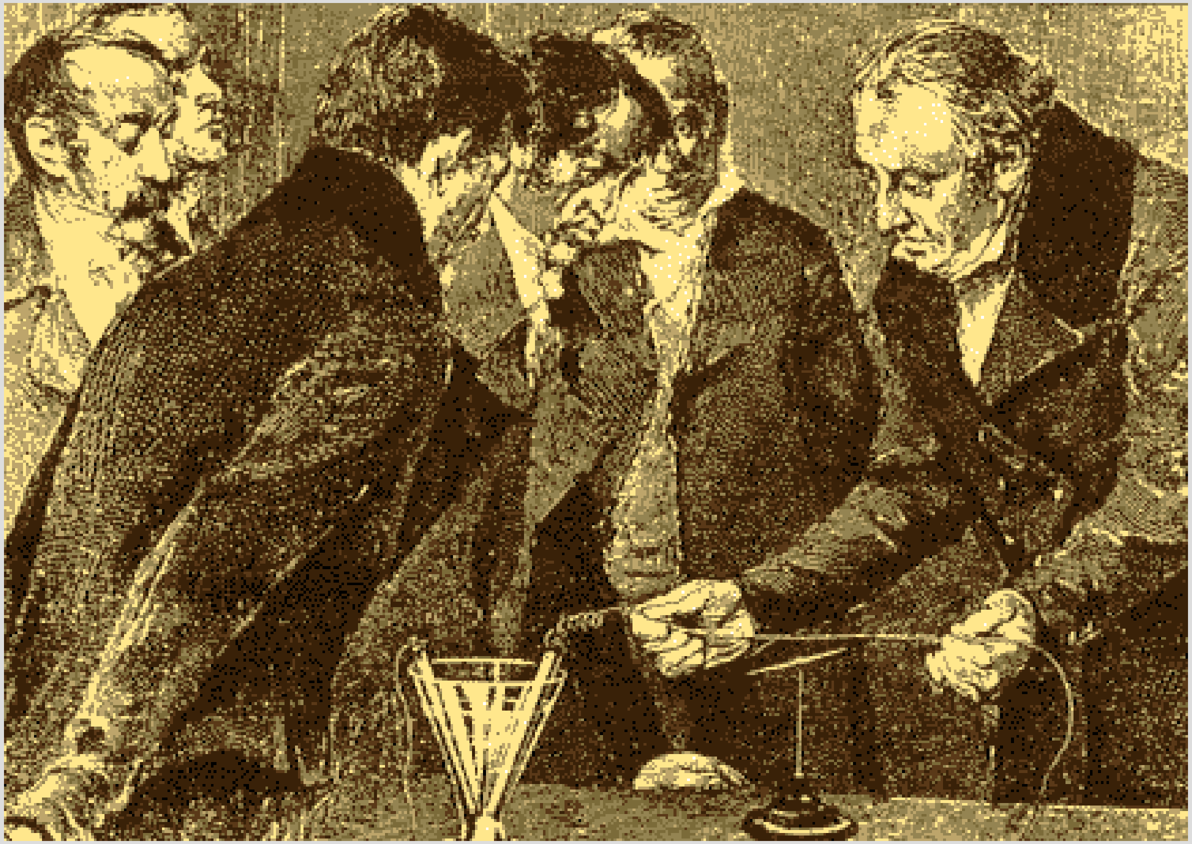


Birkeland currents in the auroral oval

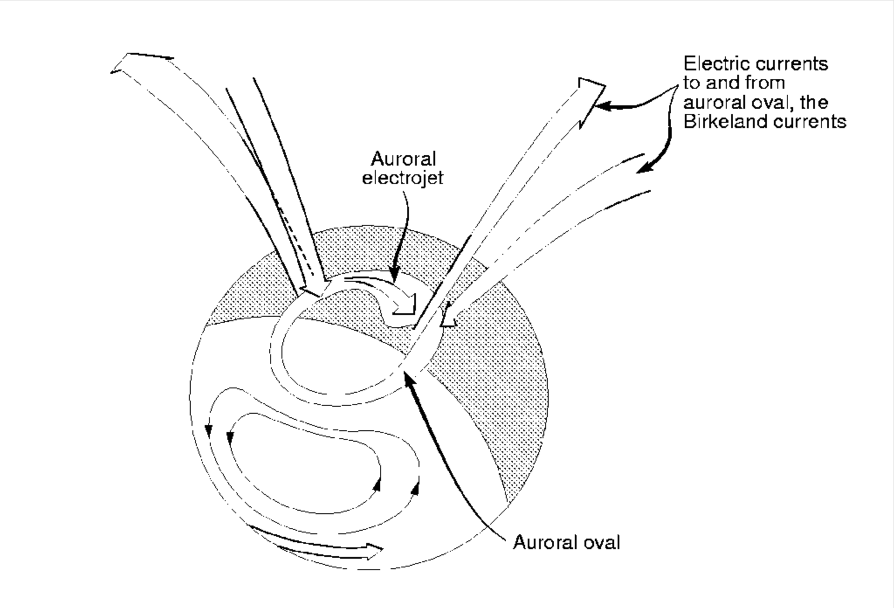




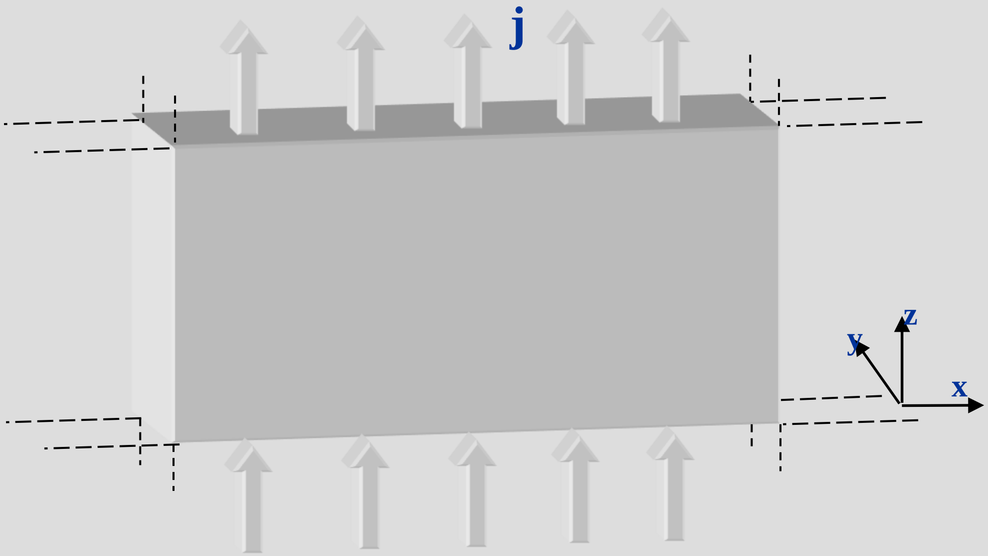
How can you measure currents in space?



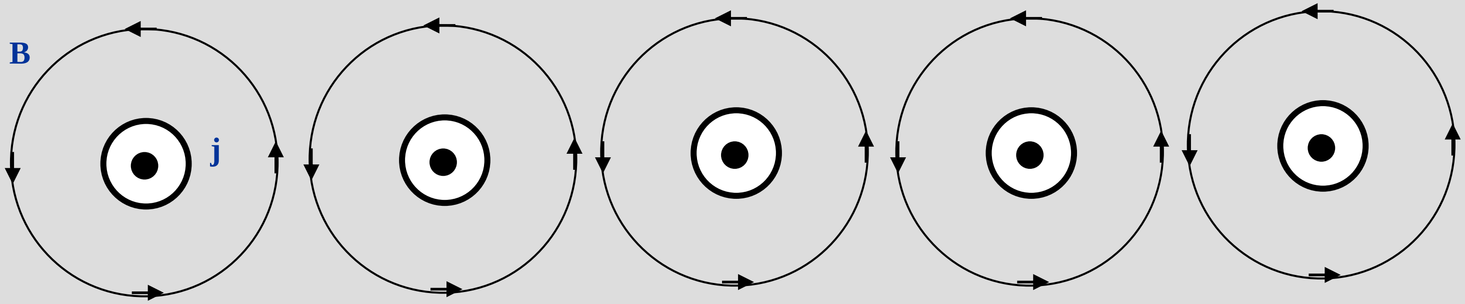
Current sheet approximation



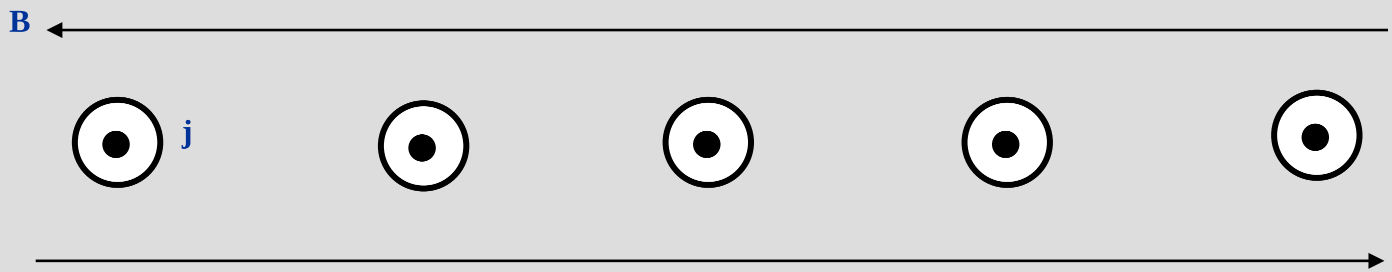
Approximate currents by thin current sheets with infinite size in the x- och z-directions.



Current sheet approximation

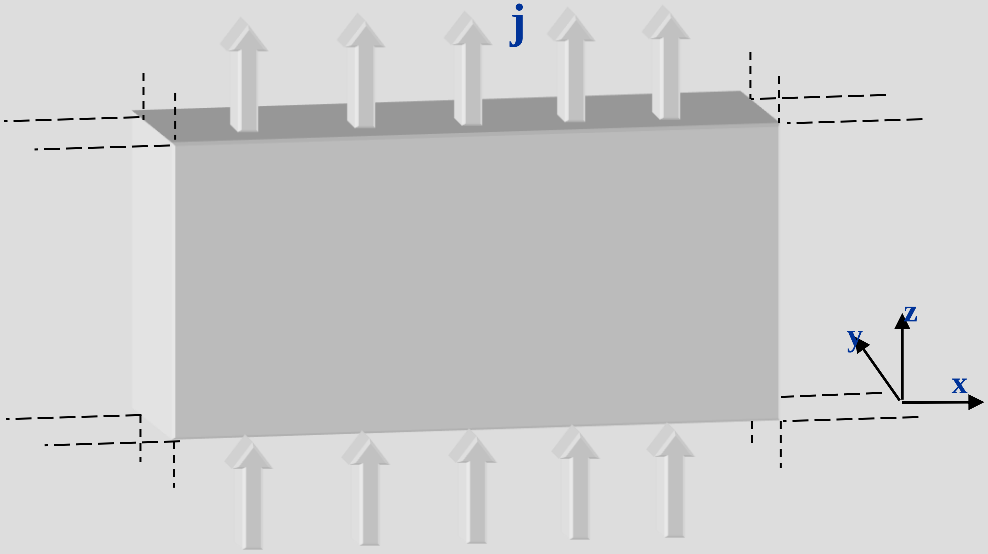


What will the magnetic field around such a current configuration be? Start by approximating with line currents to get a qualitative picture.



The closer you place the line currents, the more the magnetic fields between the line currents will cancel

Current sheet approximation and Ampére's law



$$\left(\frac{\partial B_z}{\partial y}-\frac{\partial B_y}{\partial z},\ \frac{\partial B_x}{\partial z}-\frac{\partial B_z}{\partial x},\ \frac{\partial B_y}{\partial x}-\frac{\partial B_x}{\partial y}\right)=\mu_0\left(j_x,\ j_y,\ j_z\right)$$

But $\frac{\partial}{\partial x}=0$ and $\frac{\partial}{\partial z}=0$

$$\left(\frac{\partial B_z}{\partial y},\ 0,\ -\frac{\partial B_x}{\partial y}\right)=\mu_0\left(0,\ 0,\ j_z\right)$$

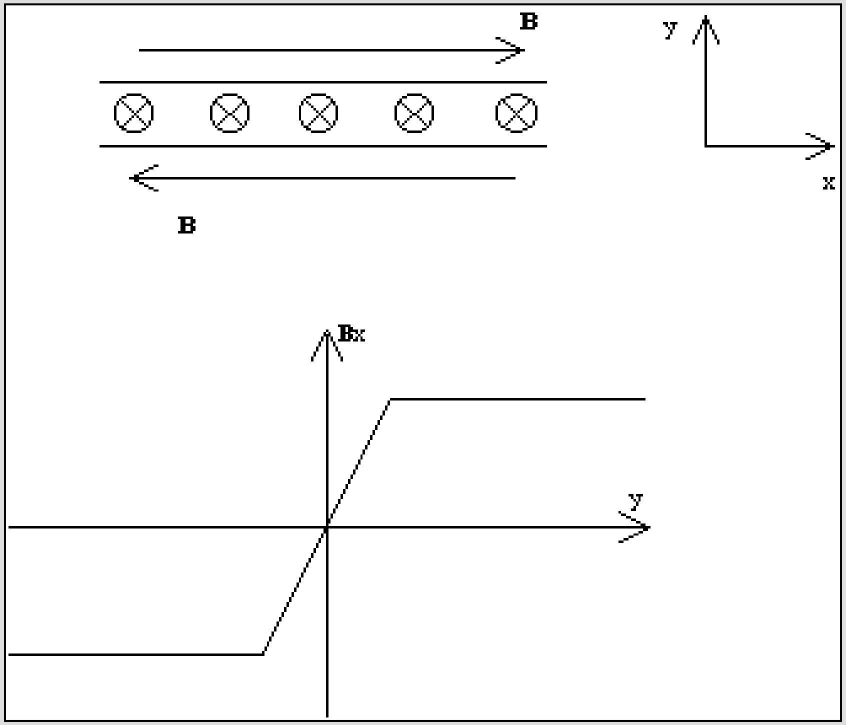
eller

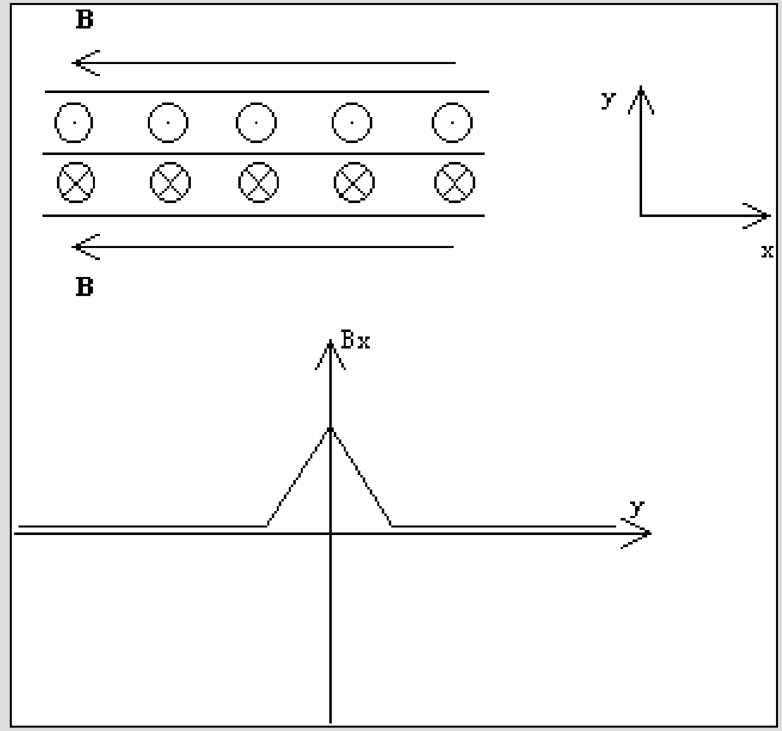
Ampére's law (no time dependence):

$$\nabla\times\mathbf{B}=\mu_0\mathbf{j}$$

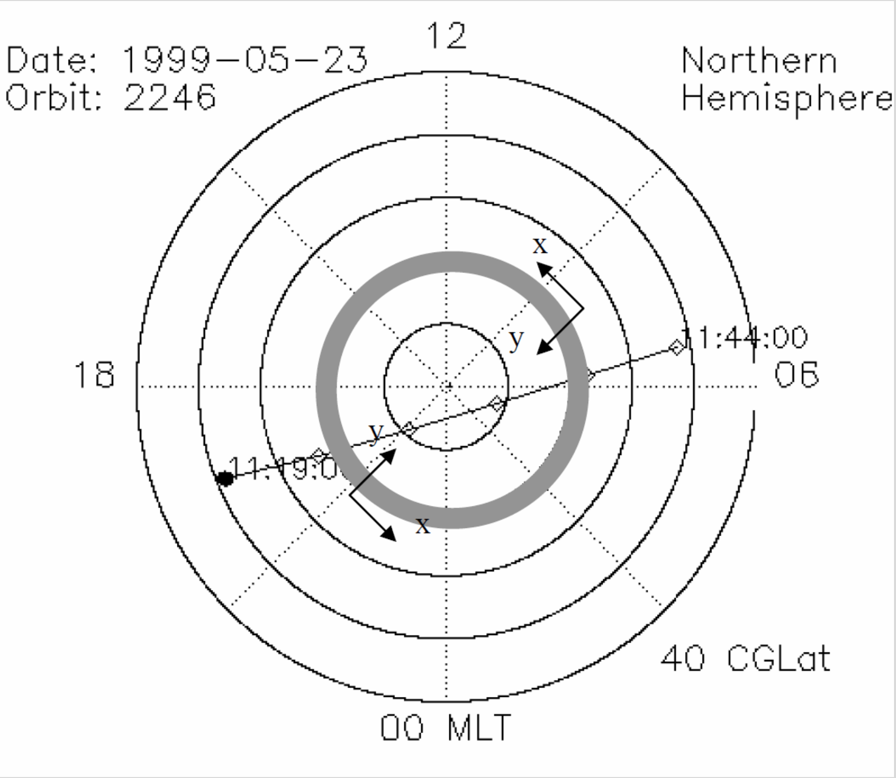
$$j_z=-\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

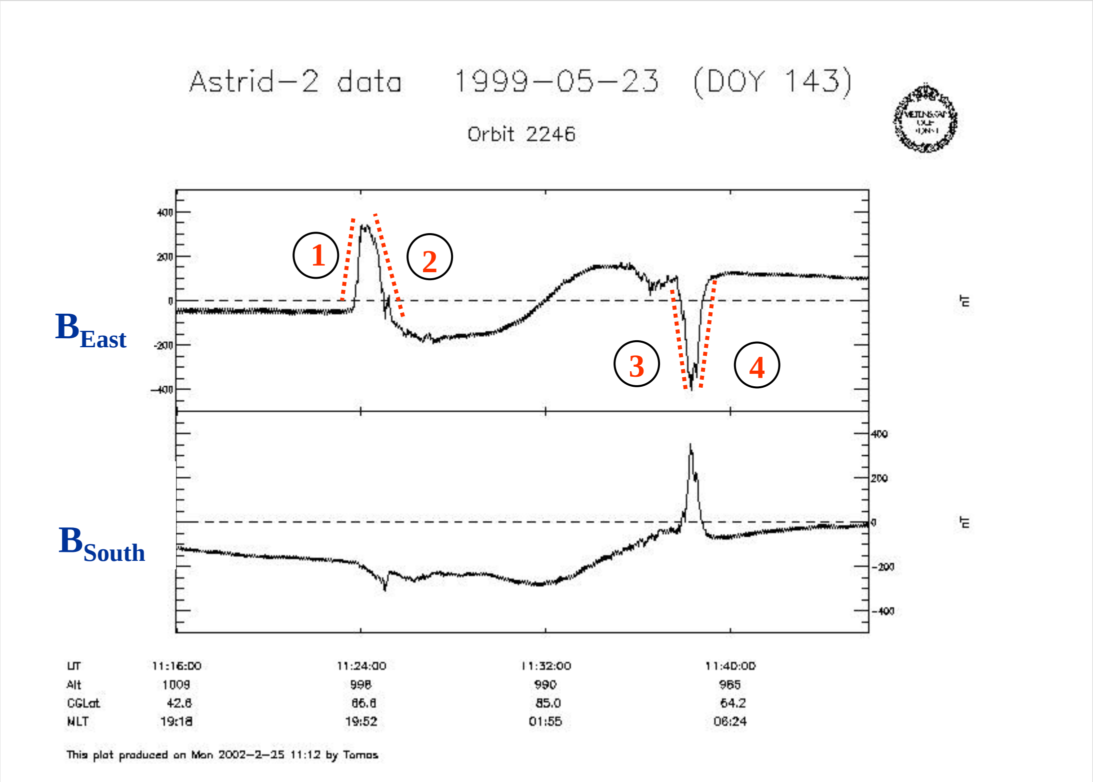
Current sheet - example





$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$





What is the direction of the current in current sheet 1?

$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

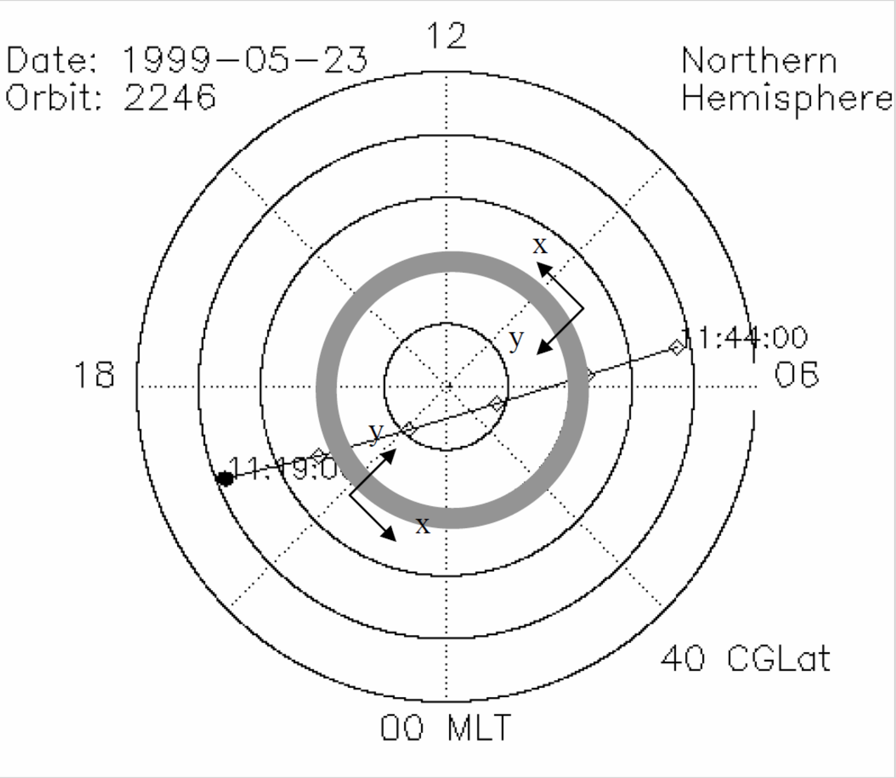
$$\frac{\partial B_x}{\partial y} = \frac{\partial B_{East}}{\partial y} > 0$$

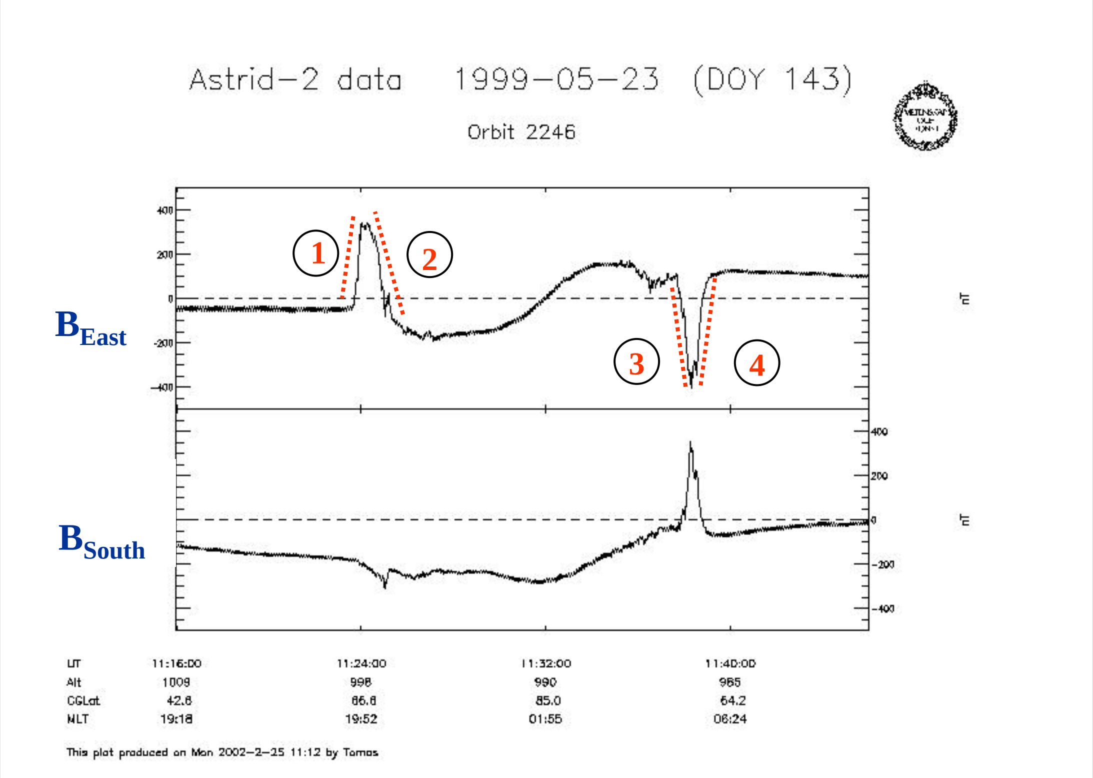
$$\Rightarrow$$

$$j_z < 0$$

Blue

Into the ionosphere

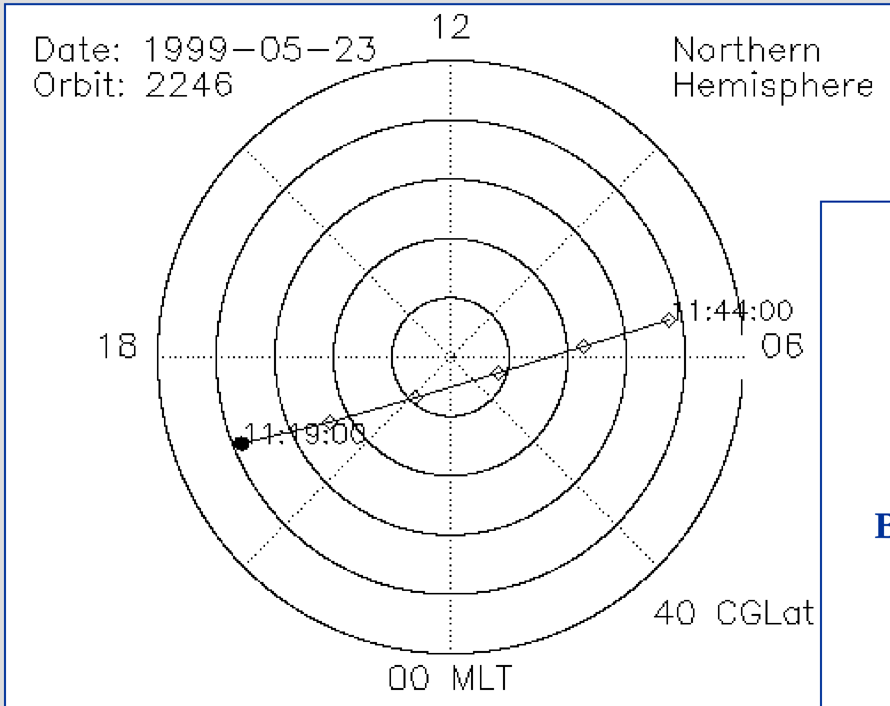


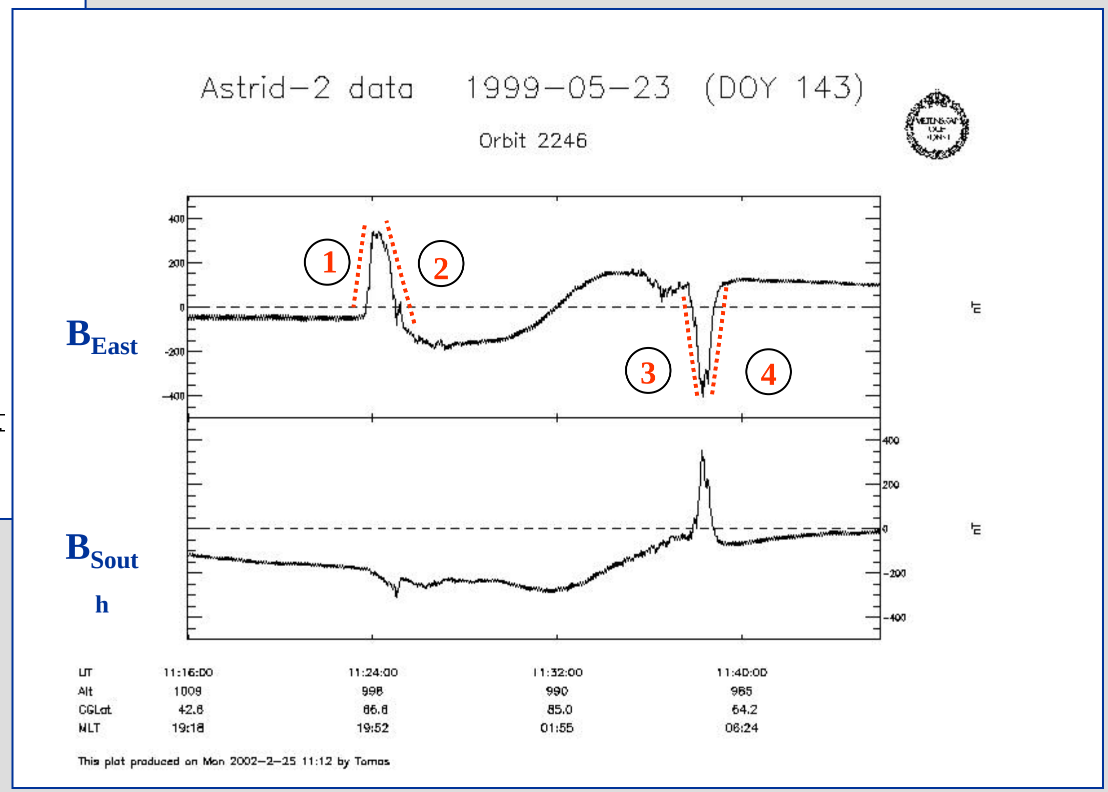


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

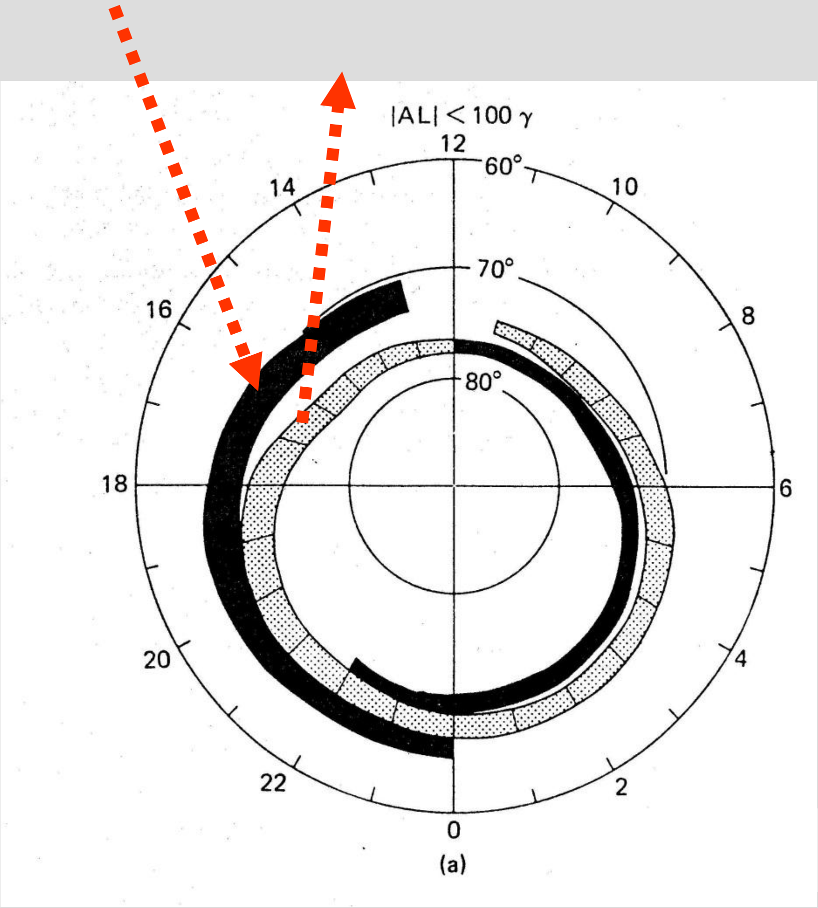
1)	$\frac{\partial B_x}{\partial y} > 0$	$\Rightarrow$	$j_z < 0$	Into the ionosphere
2)	$\frac{\partial B_x}{\partial y} < 0$	$\Rightarrow$	$j_z > 0$	Out of the ionosphere
3)	$\frac{\partial B_x}{\partial y} > 0$	$\Rightarrow$	$j_z < 0$	Into the ionosphere
4)	$\frac{\partial B_x}{\partial y} < 0$	$\Rightarrow$	$j_z > 0$	Out of the ionosphere

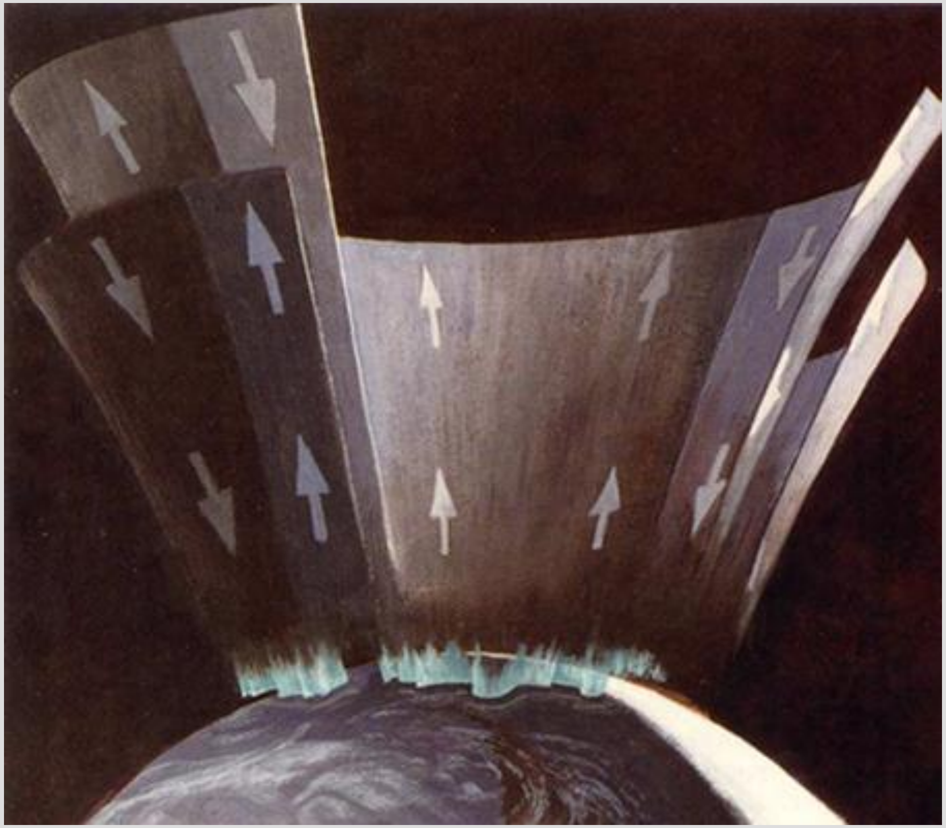
Astrid-2 data





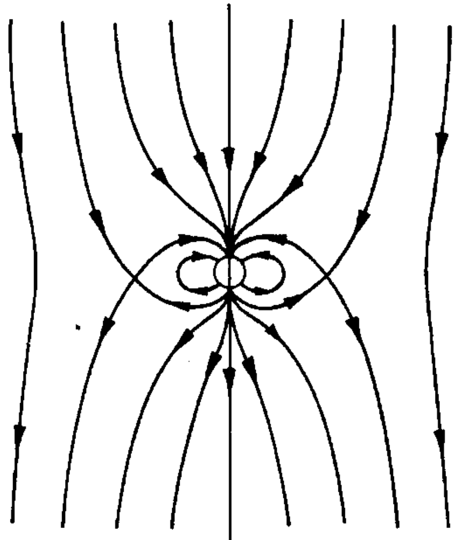
Birkeland currents in the auroral oval





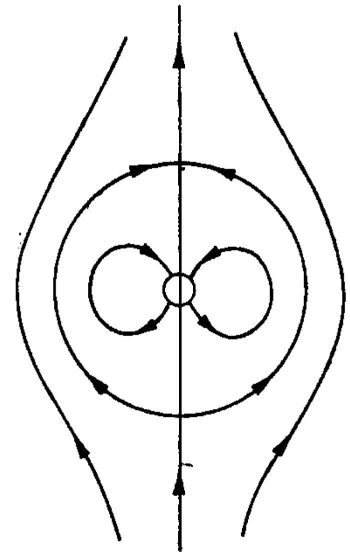
Magnetospheric dynamics

open magnetosphere



(b)

closed magnetosphere



(a)

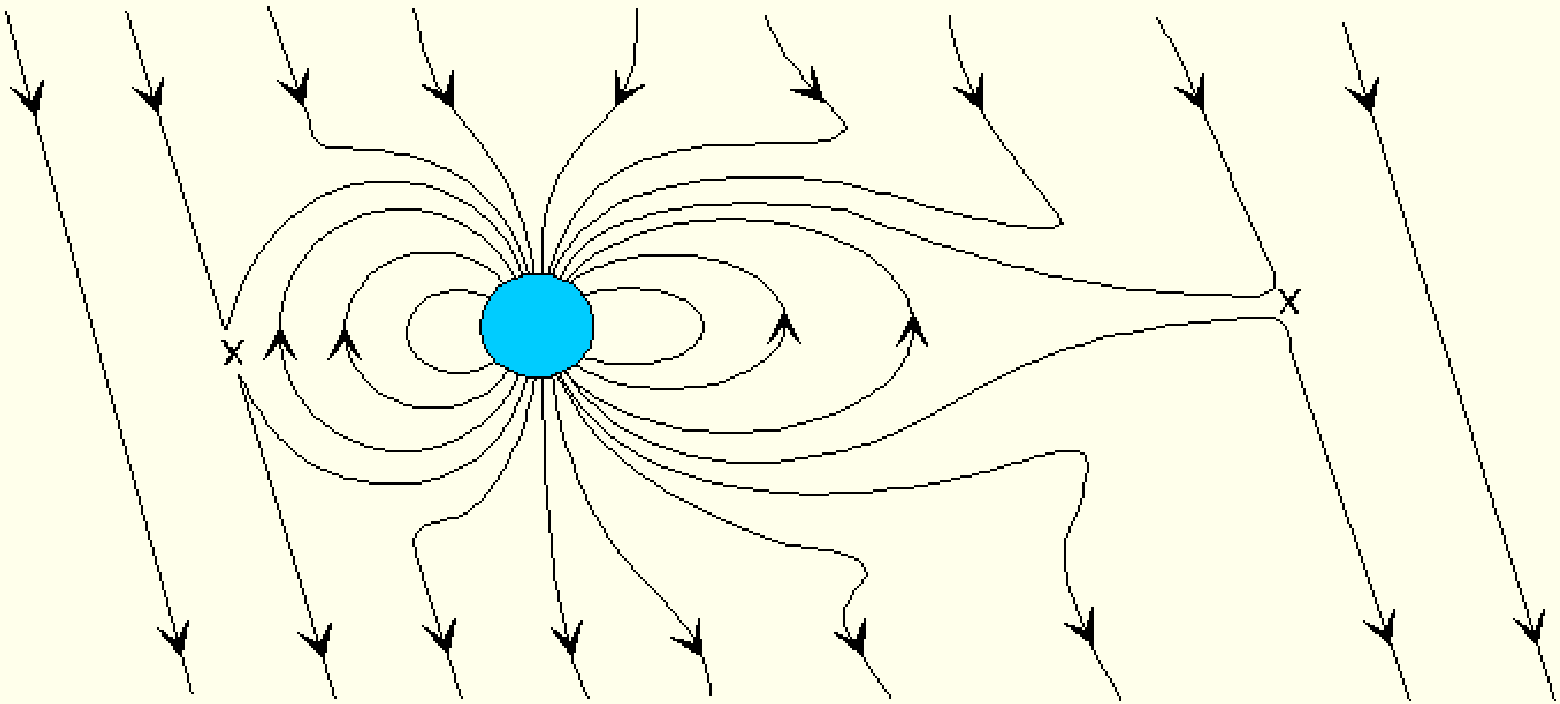
southward

Interplanetary magnetic field (IMF)

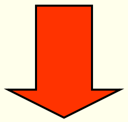
northward

Magnetospheric dynamics

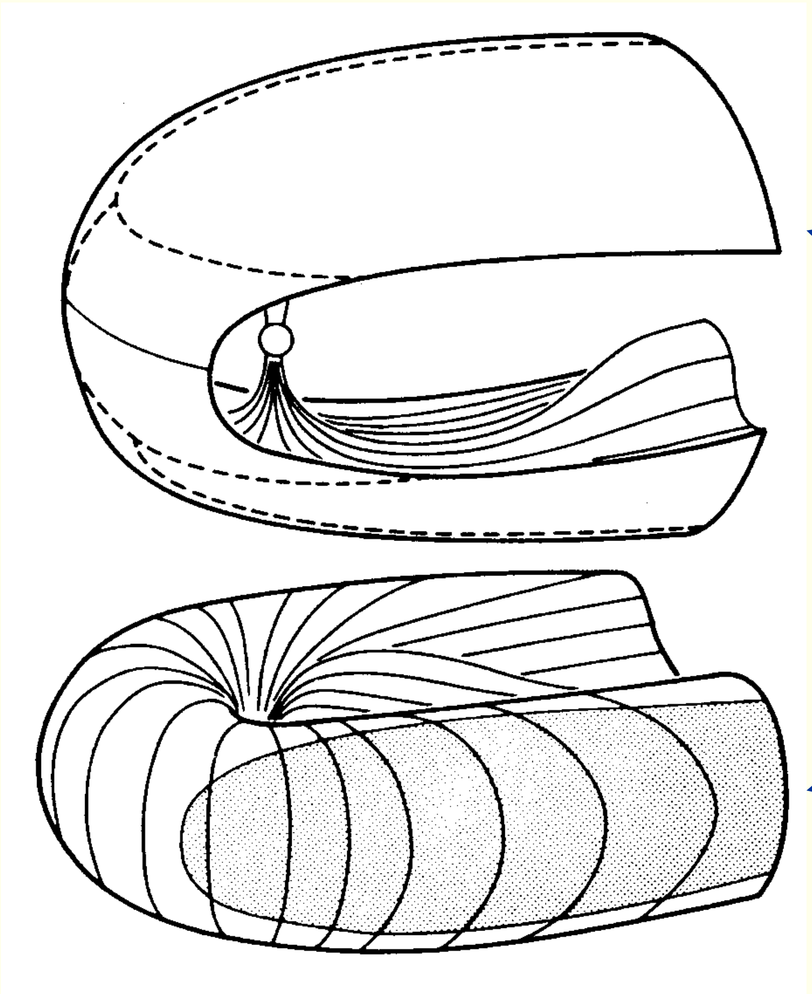
open magnetosphere



Southward IMF



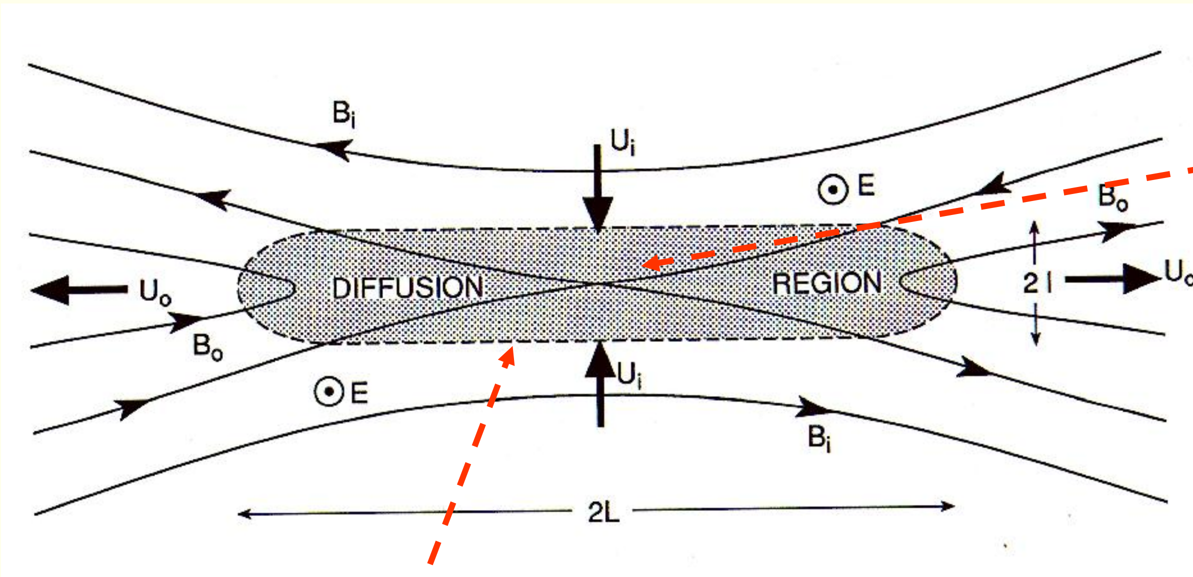
Magnetospheric topology



Open field lines

Closed field lines

Reconnection



In 'diffusion region':

$R_m = \mu_0 \sigma l v \sim 1$

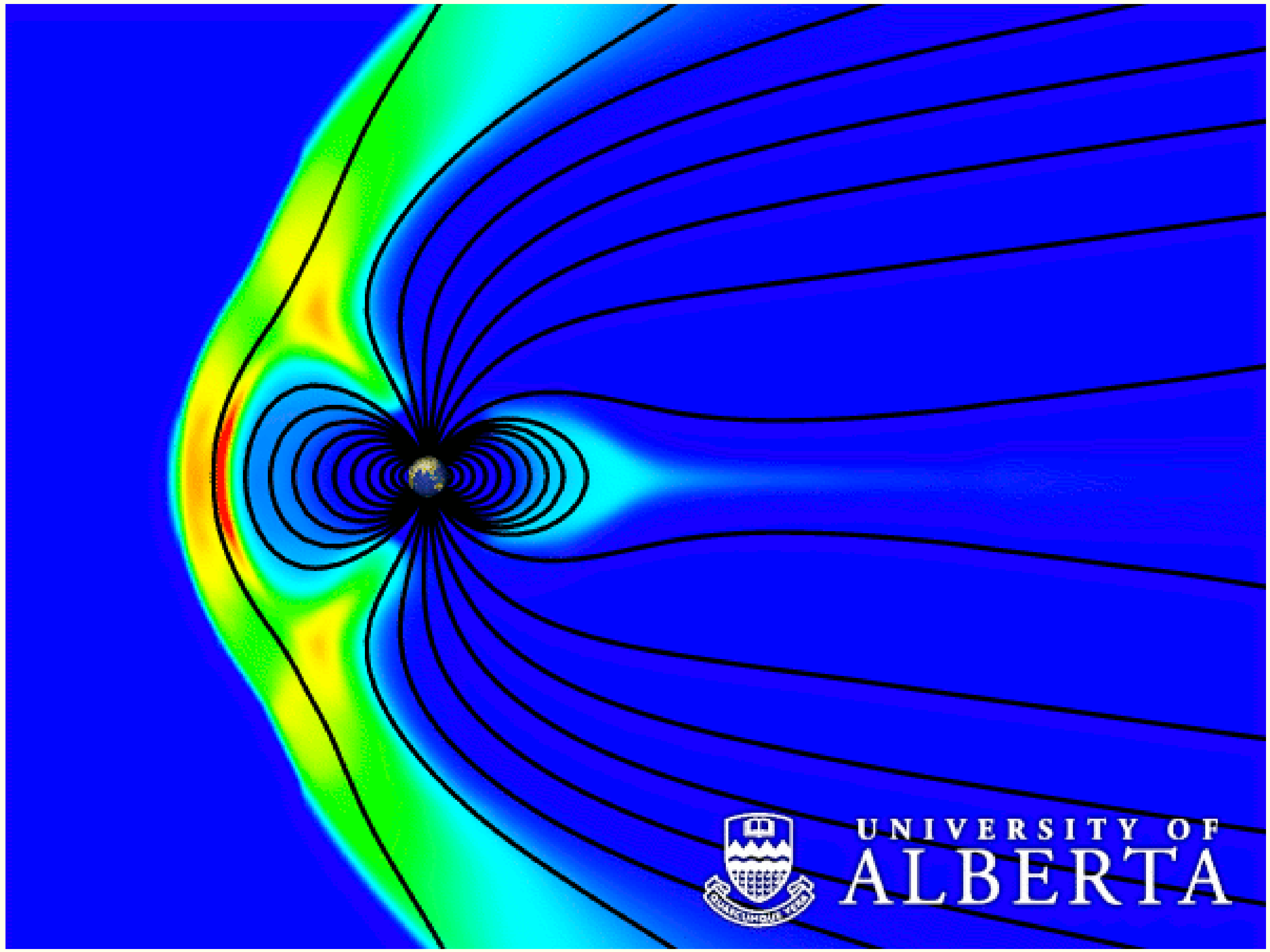
Thus: condition for frozen-in magnetic field breaks down.

A second condition is that there are two regions of magnetic field pointing in *opposite* direction:

- Field lines are "cut" and can be re-connected to other field lines
- **Magnetic energy is transformed into kinetic energy ($U_o >> U_i$)**
- **Plasma from different field lines can mix**

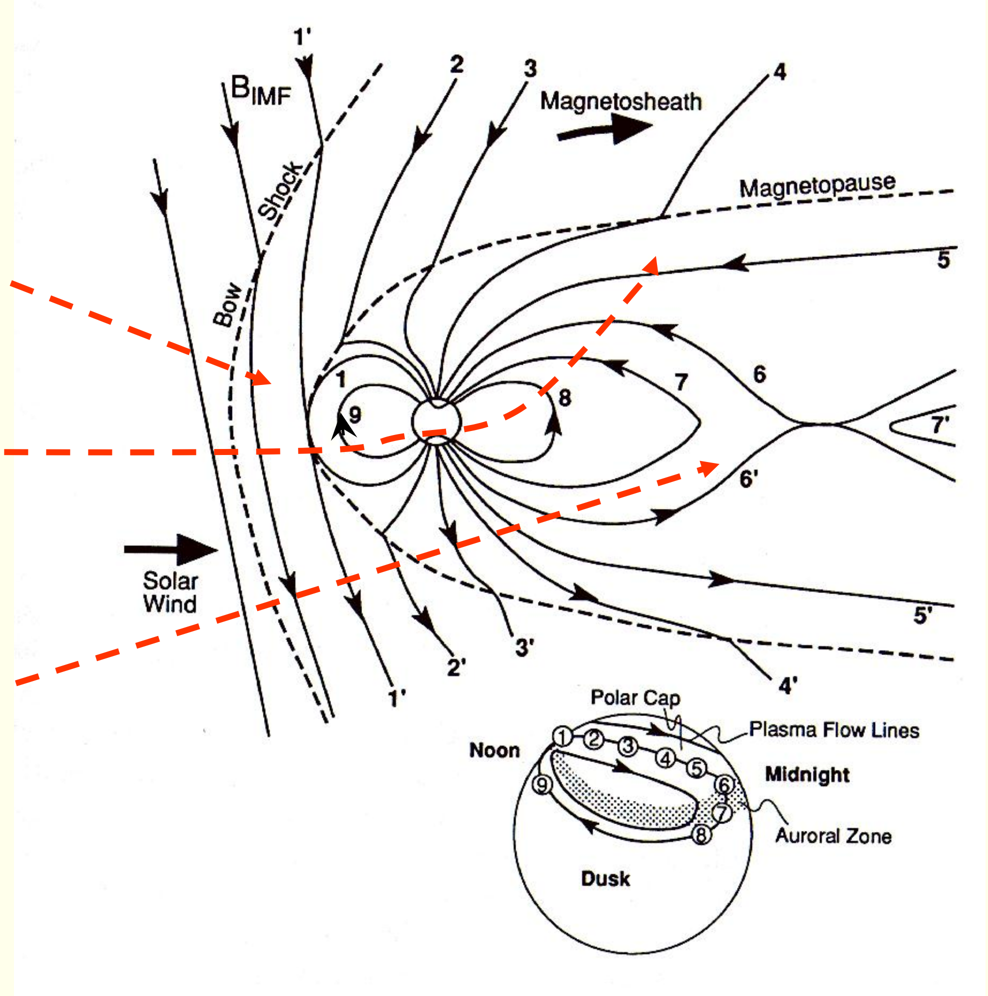
Reconnection and plasma convection

Solar wind

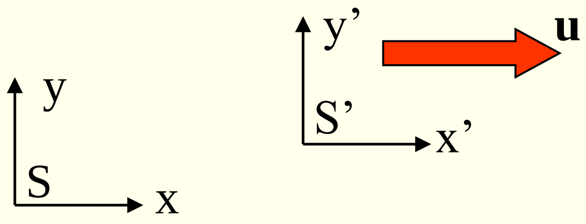


Reconnection och plasma convection

- Reconnection on the dayside "re-connects" the solar wind magnetic field and the geomagnetic field
- In this way the plasma convection in the outer magnetosphere is driven
- In the night side a second reconnection region drives the convection in the inner magnetosphere.
  The reconnection also heats the plasmasheet plasma.



Field transformations (relativistic)



Relativistic transformations (perpendicular to the velocity $\mathbf{u}$*):*

$$\mathbf{E}' = \frac{\mathbf{E} + \mathbf{u} \times \mathbf{B}}{\sqrt{1 - u^2/c^2}}$$

$$\mathbf{B}' = \frac{\mathbf{B} - (\mathbf{u}/c^2) \times \mathbf{E}}{\sqrt{1 - u^2/c^2}}$$

For $u << c$*:*

$$\mathbf{E}' = \mathbf{E} + \mathbf{u} \times \mathbf{B}$$

$$\mathbf{E} = \mathbf{E}' - \mathbf{u} \times \mathbf{B}$$

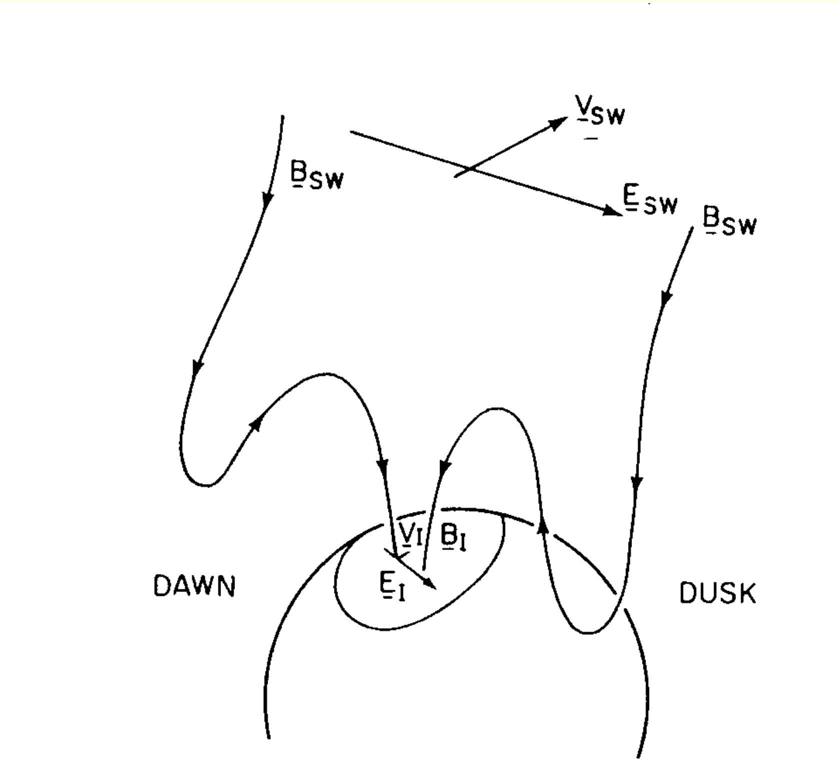
induced electric field

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 1



The solar wind generates an electric field

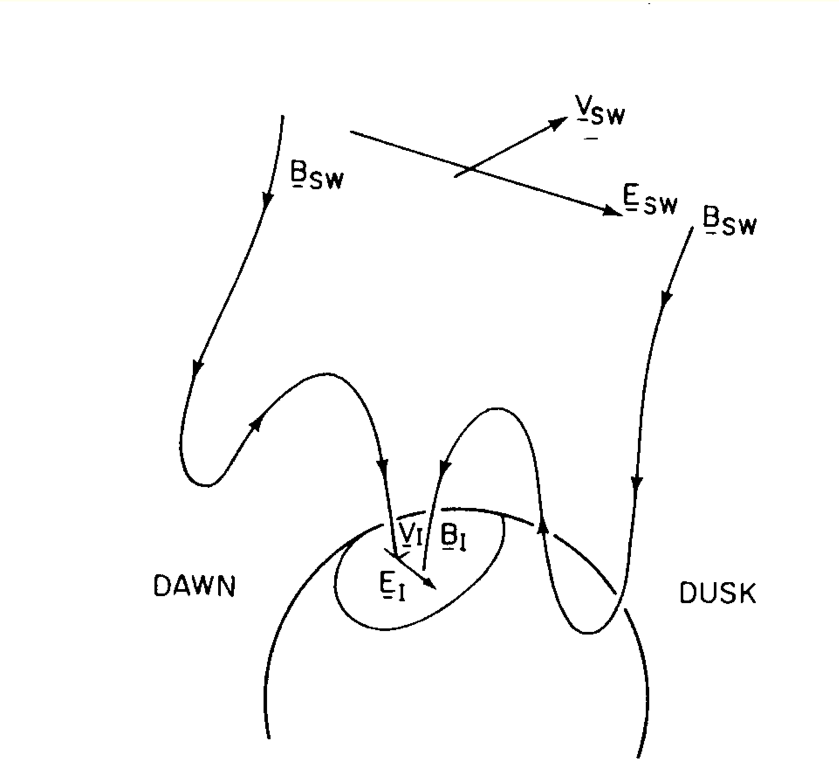
$$\mathbf{E}_{SW} = -\,\mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

which maps down to the ionosphere, since the field lines are very good conductors

Magnetospheric dynamics

open magnetosphere

Viewpoint 2



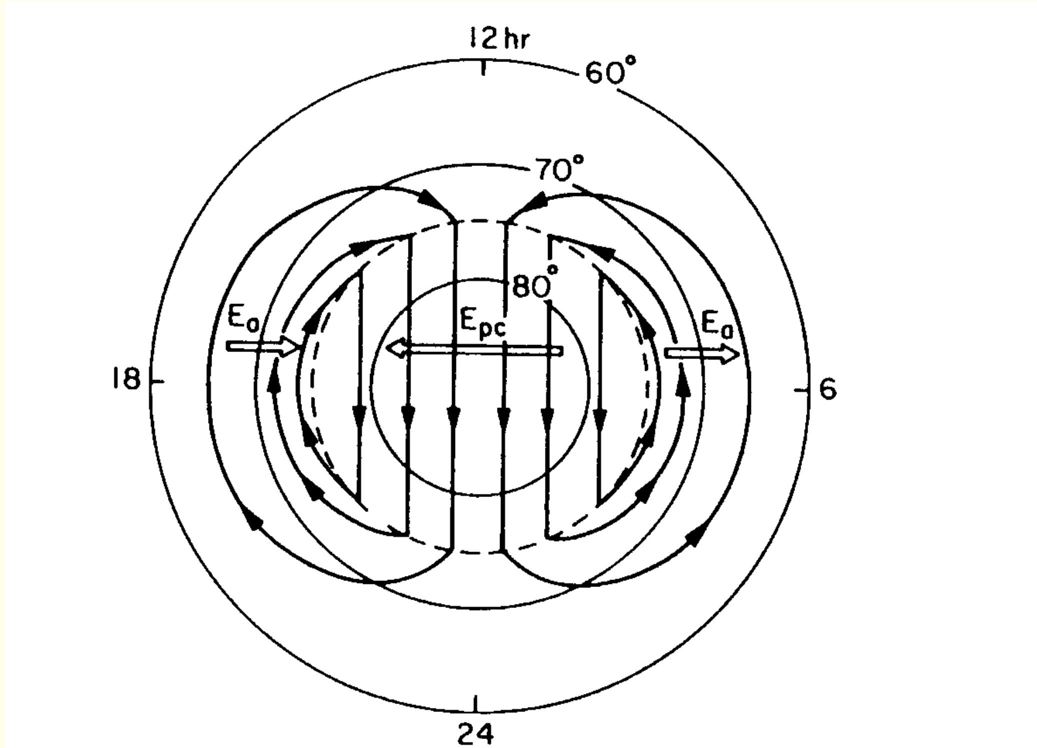
The solar wind magnetic field draws the ionospheric plasma with it, since the field is frozen into the plasma. This motion induces an ionospheric electric field

$$\mathbf{E}_I = -\mathbf{v}_I \times \mathbf{B}_I$$

Magnetospheric dynamics

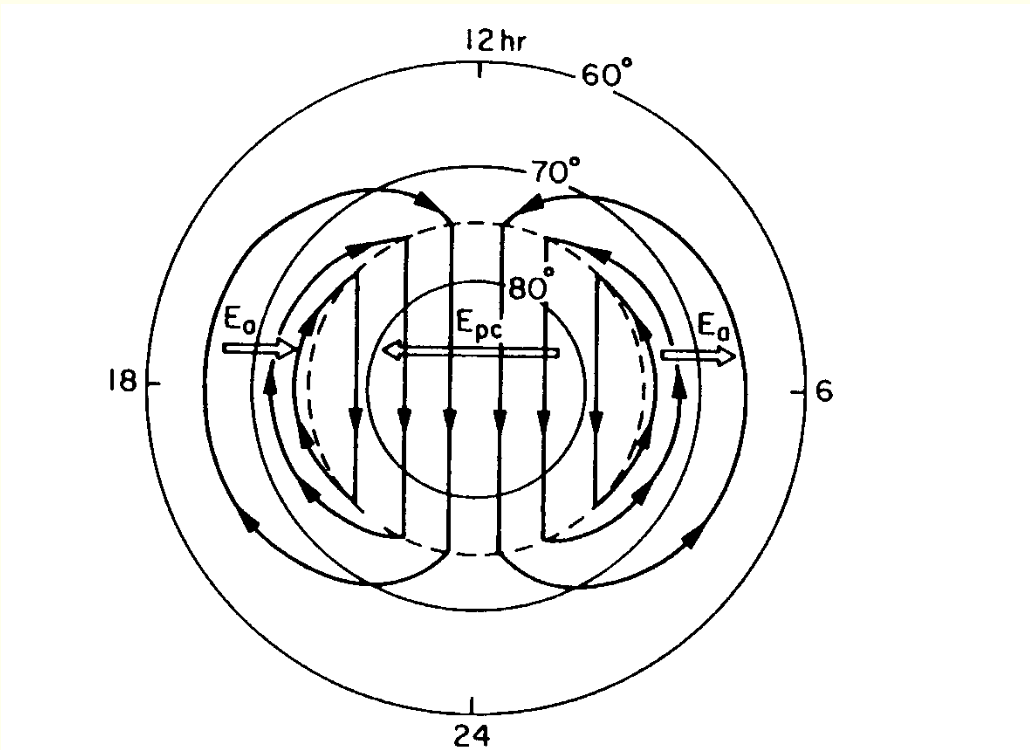
Plasma convection in the ionosphere

The electric field ”propagates” to the ionosphere, since the field lines are good conductors, and thus equipotentials



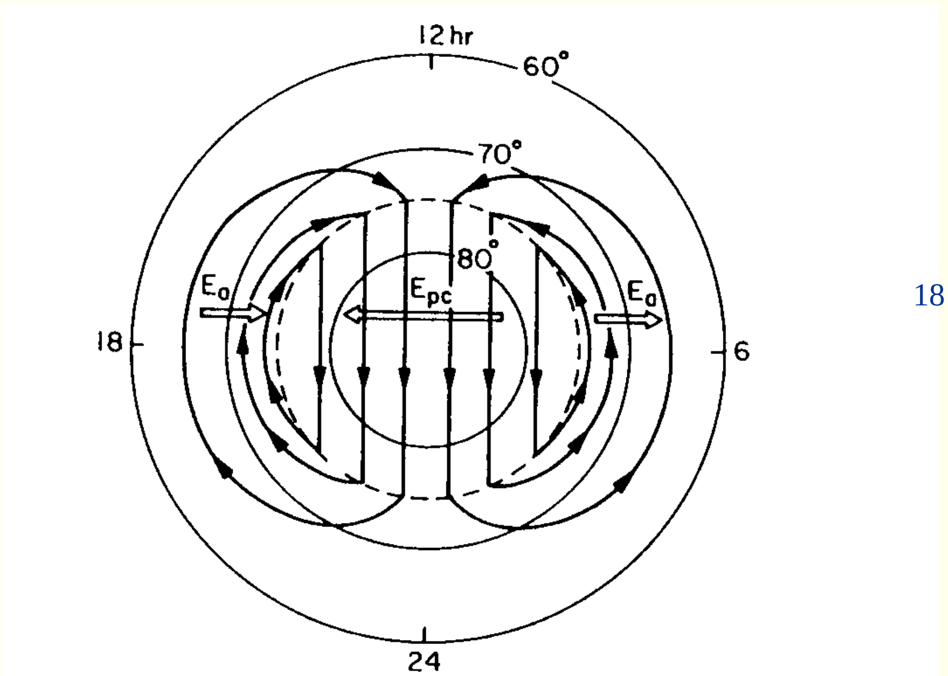
Do you recognize this pattern?

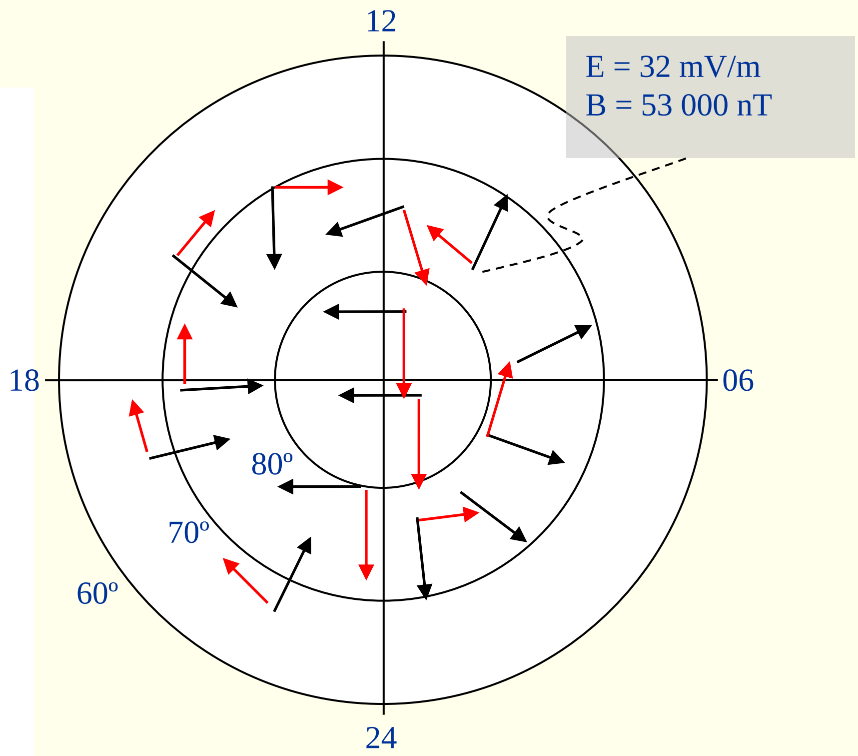
Plasma convection in the ionosphere



Do you recognize this pattern?

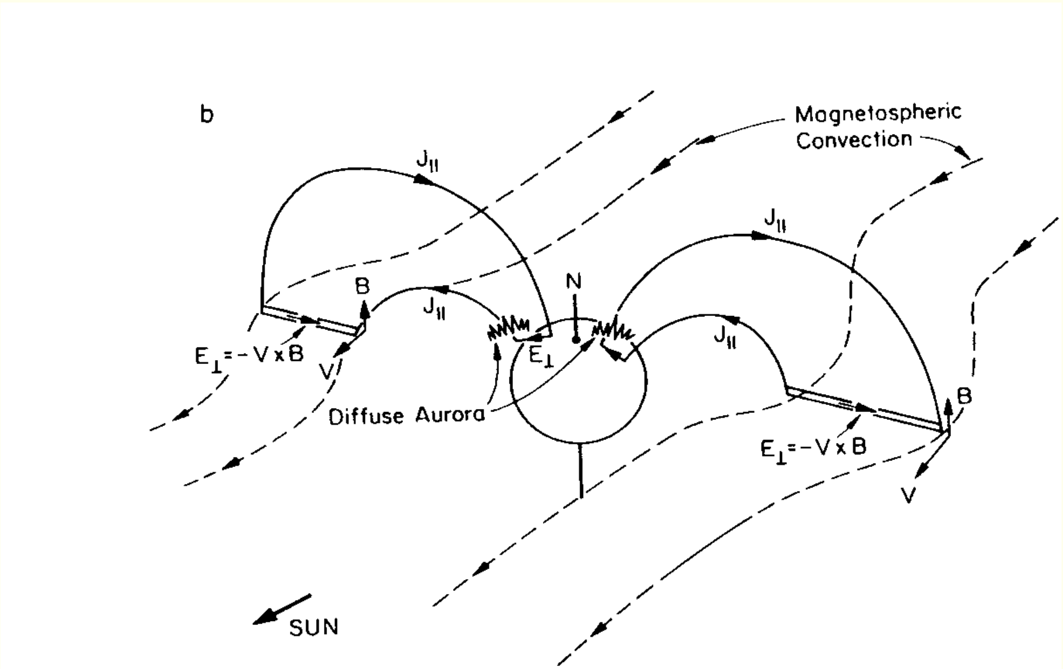
Plasma convection in the ionosphere





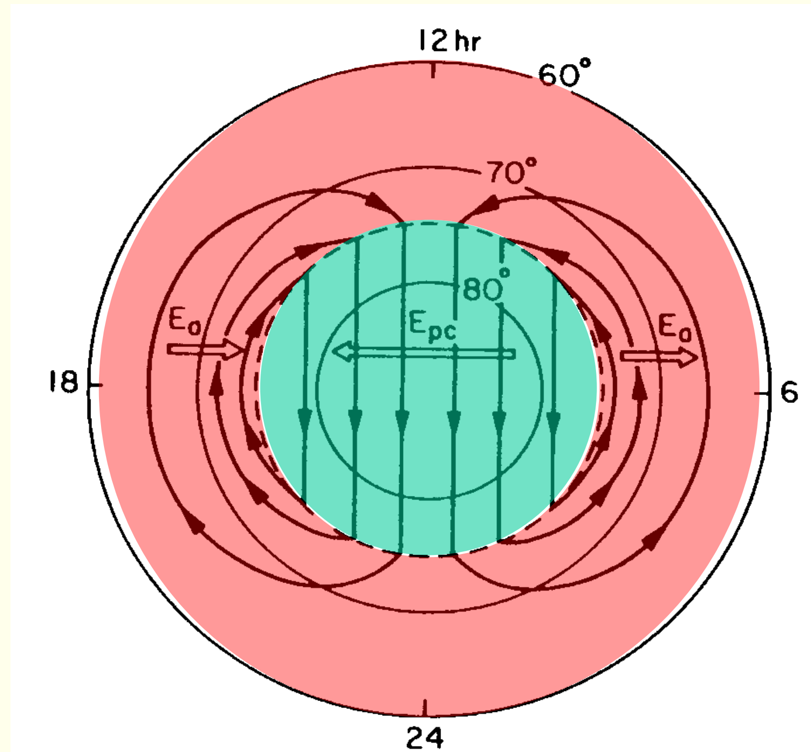
Static, large-scale MI-coupling

Magnetospheric and ionospheric convection



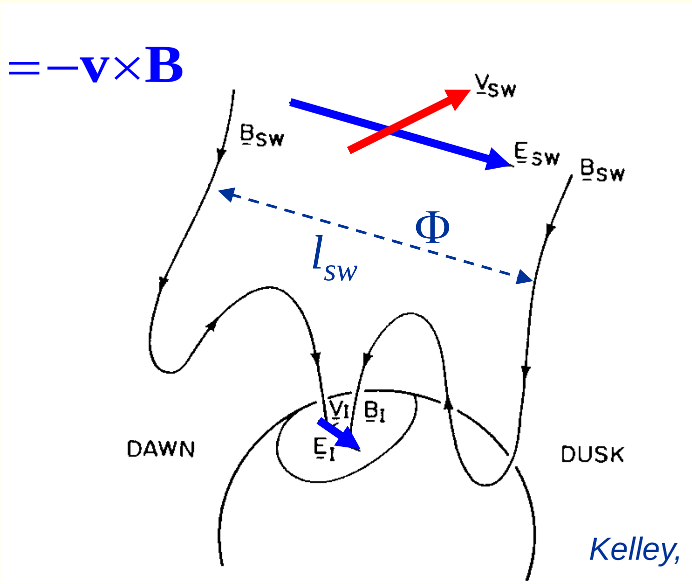
Kelley, 1989

Ionospheric convection

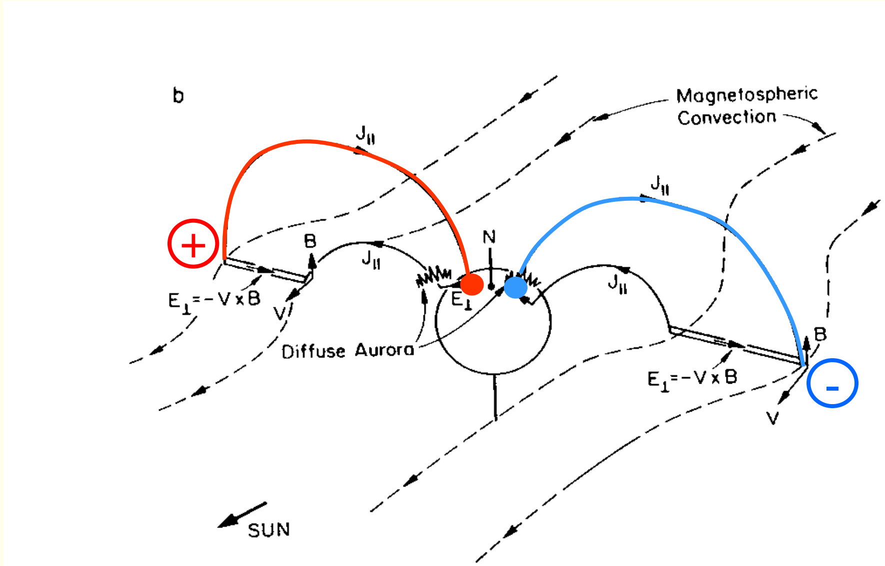


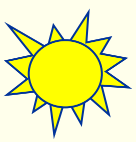
Magnetospheric plasma convection

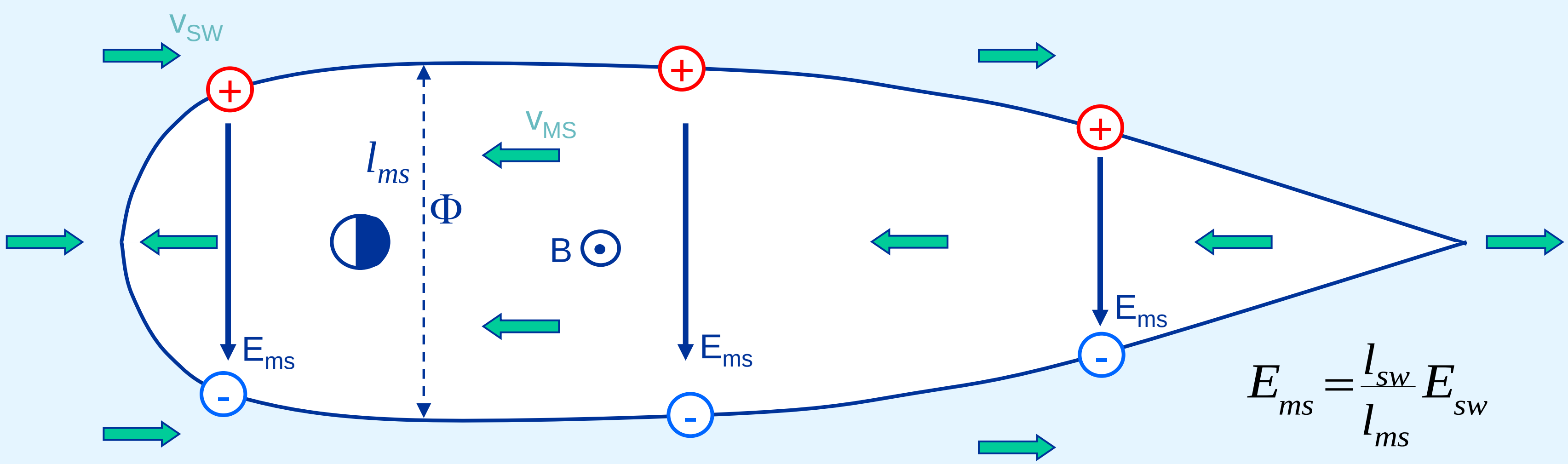
$$\mathbf{E}_{sw} = -\mathbf{v} \times \mathbf{B}$$



Kelley, 1989

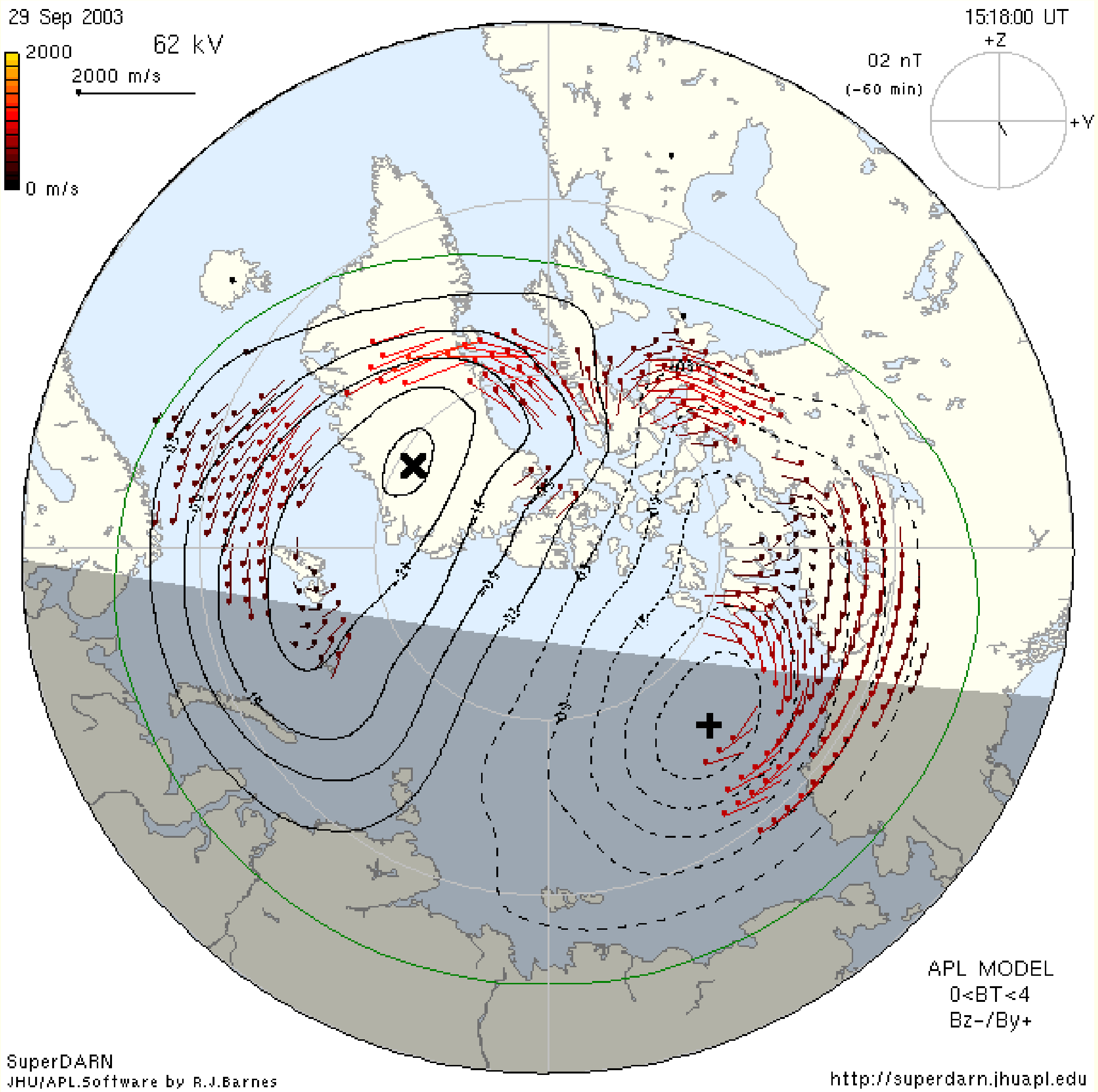






$$E_{ms} = \frac{l_{sw}}{l_{ms}} E_{sw}$$

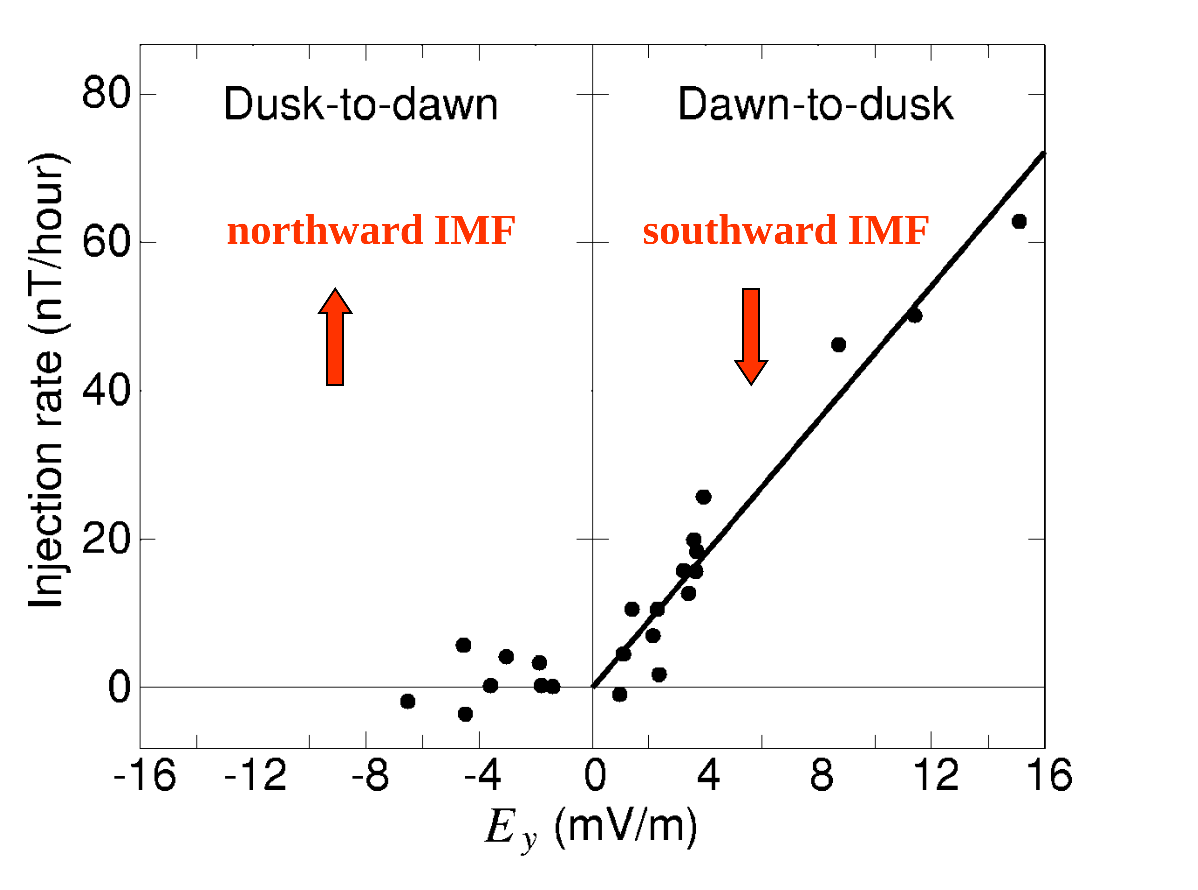
Measurements of plasma convection in the magnetosphere



Magnetospheric dynamics

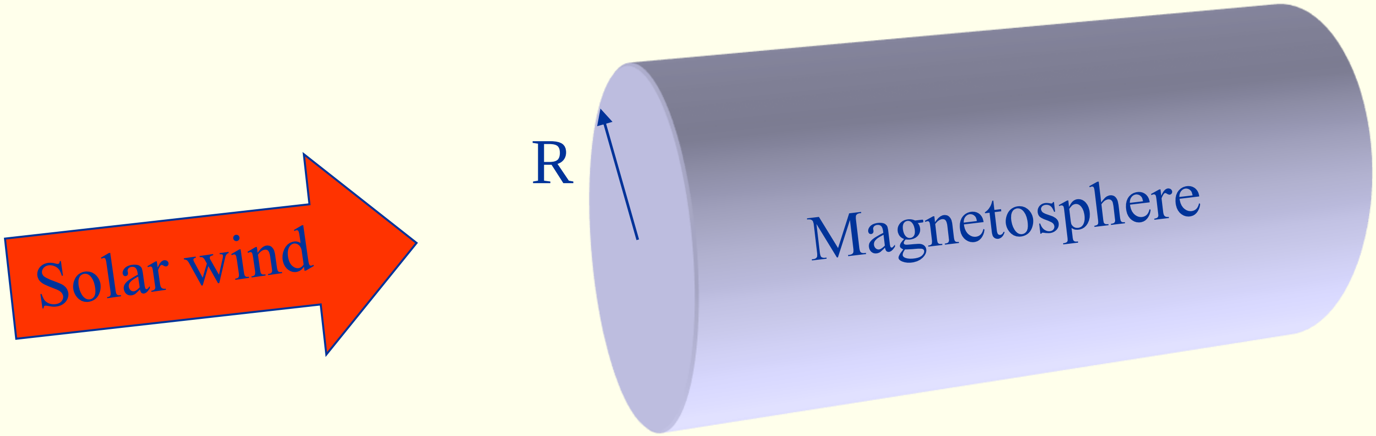
Energy input

Plasma convection in the magnetosphere



- Solar wind generates electric field $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$.
- Depending on direction of B, sign of E changes
- Energy input only for open magnetosphere
- The magneto-sphere works like a diode!

Energy budget (1)



$W_{kin} = \rho v^2/2 = 0.63 \cdot 10^{-9}\ Jm^{-3}$

$W_{term} = n_e k_b T_e = 1.4 \cdot 10^{-11}\ Jm^{-3}$

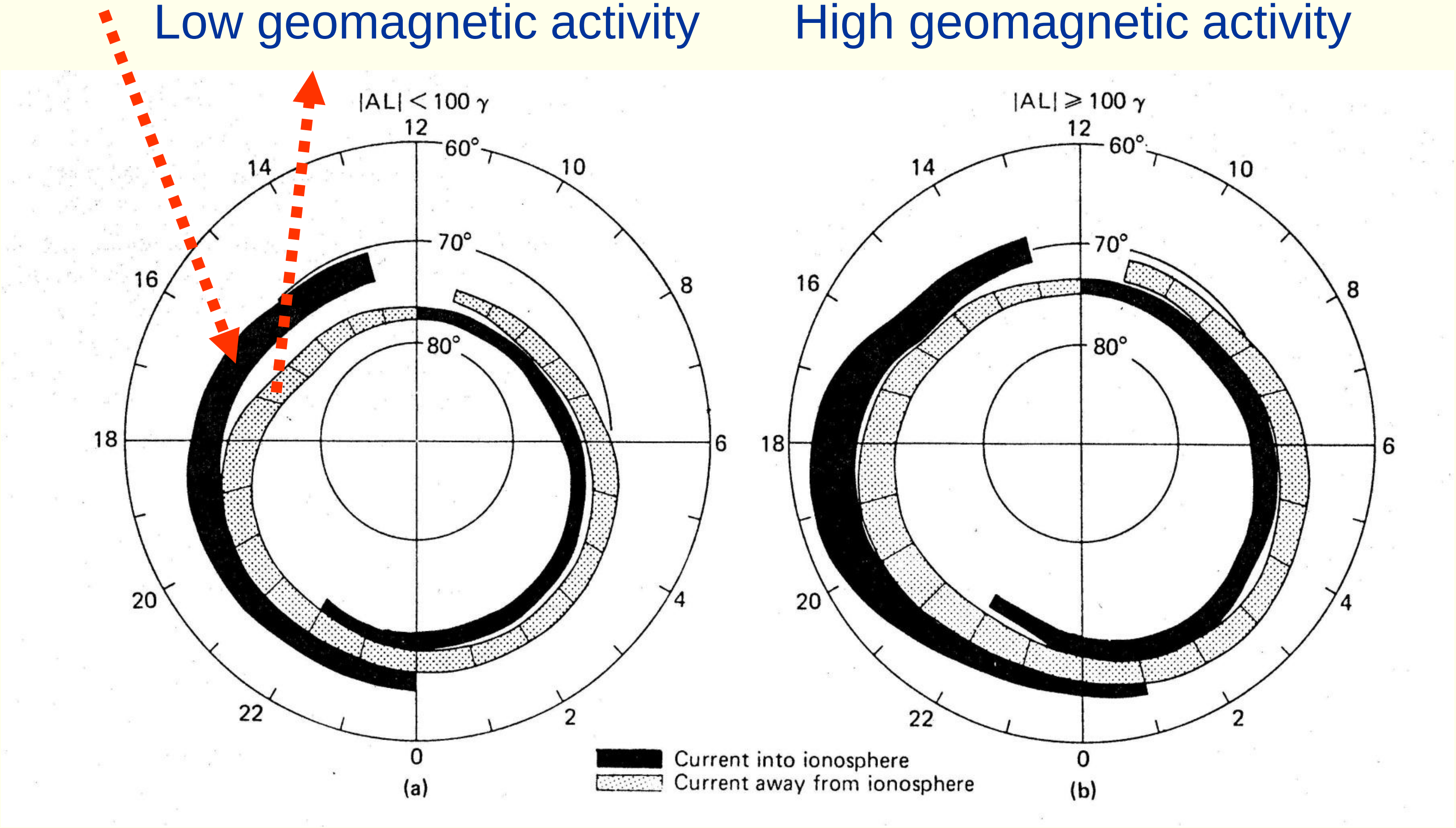
$A = \pi R^2 = \pi(10R_E)^2$

$\Phi_{kin} = v_{SW} W_{kin} = 0.2 \cdot 10^{-3}\ Wm^{-2}$

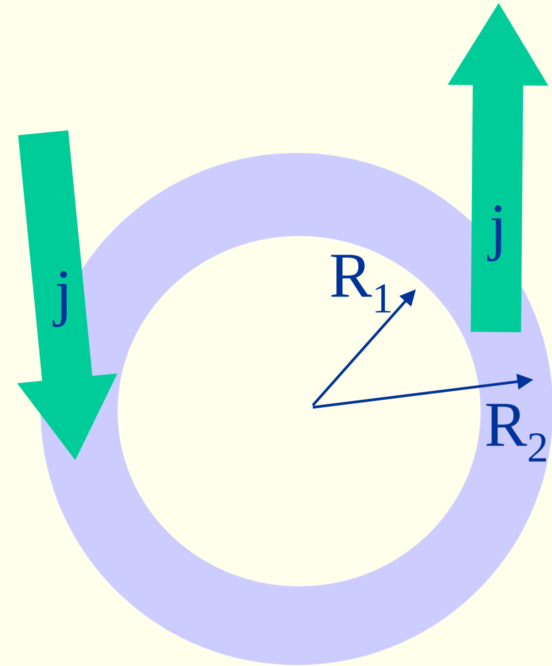
$$\mathbf{P_{sw} = \Phi_{kin} A = 3 \cdot 10^{12}\ W}$$

Birkeland currents in the auroral oval

Low geomagnetic activity   High geomagnetic activity



Energy budget (2)



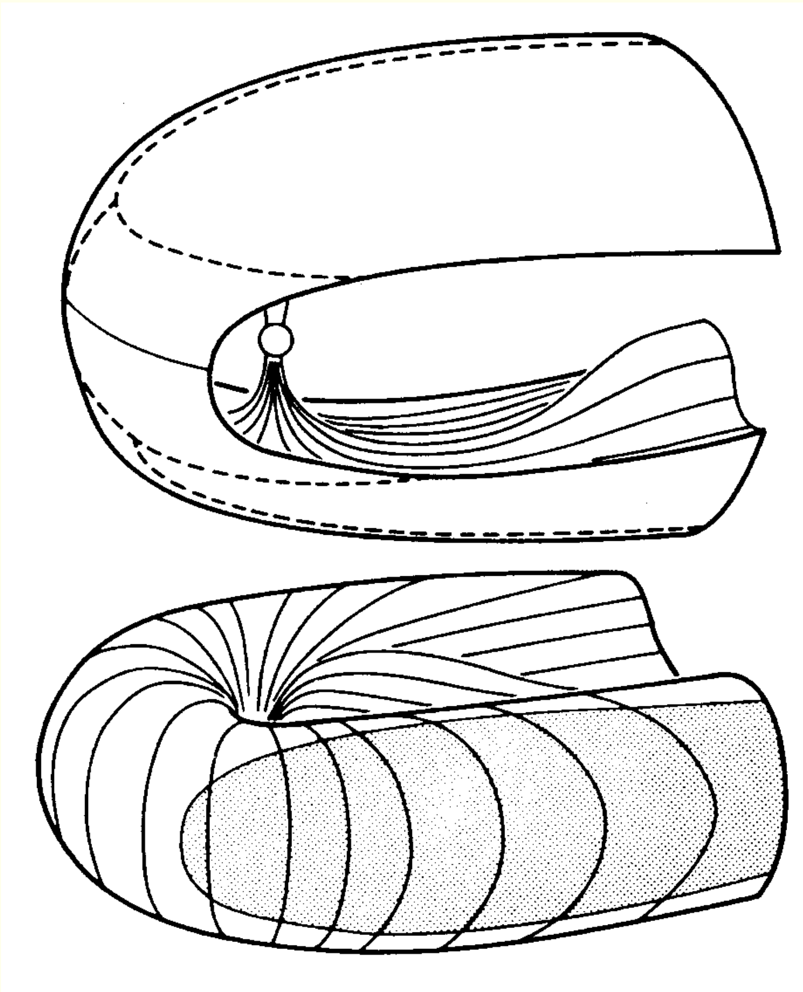
$A = \pi(R_2^2 - R_1^{2)} = 2 \cdot 10^{13}\ \mathrm{m}^2$

$I = jA/2 = ½ \cdot 0.1 \cdot 10^{-6}\ \mathrm{Am}^{-2} \cdot 2 \cdot 10^{13}\ \mathrm{m}^2$
$= 10\ \mathrm{MA}$

U = ?

P = UI = ?

Magnetospheric topology



Open field lines

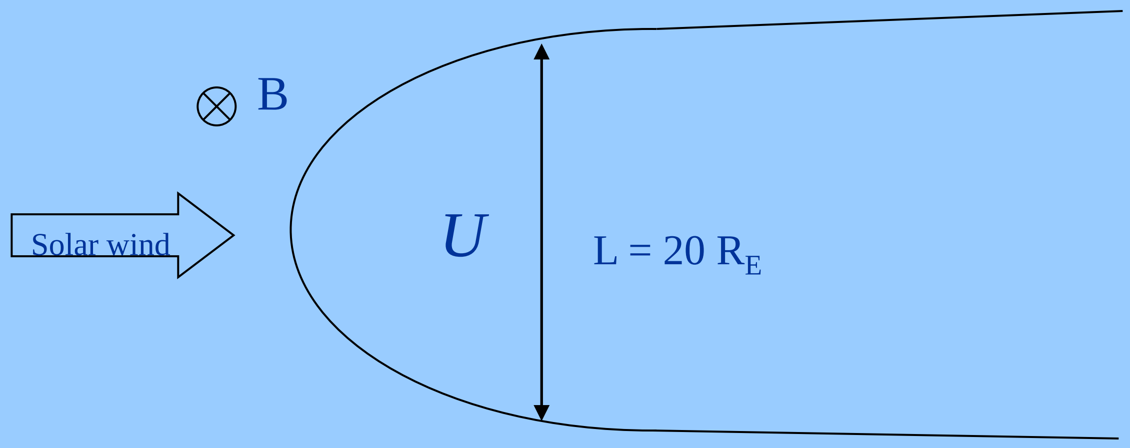
Closed field lines

What is the potential drop over the magnetosphere?

$$\mathbf{E} = -\mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

$$v_{SW} = 300 \text{ km/s}$$

$$B_{SW} = 5 \text{ nT}$$



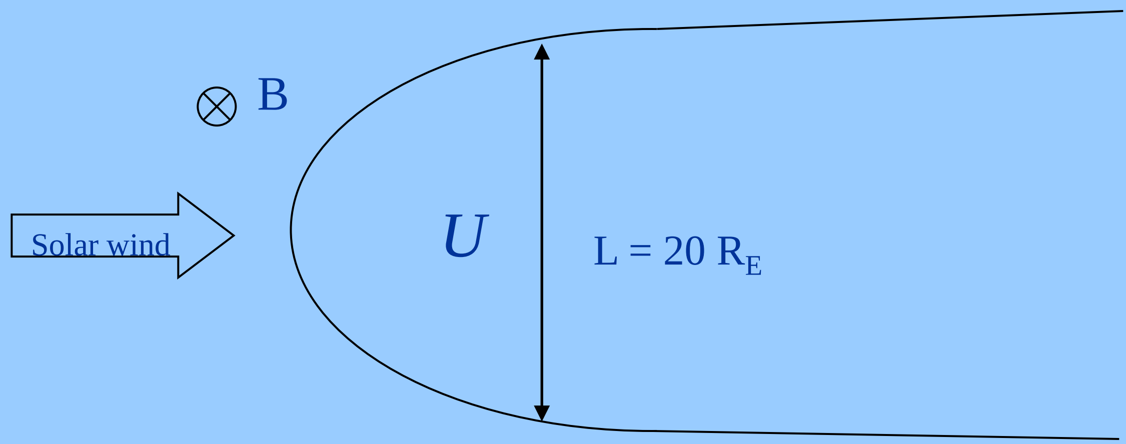
Blue	2 kV	Yellow	20 kV
Red	200 kV	Green	2 MV

What is the potential drop over the magnetosphere?

$$\mathbf{E} = -\mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

$$v_{SW} = 300 \text{ km/s}$$

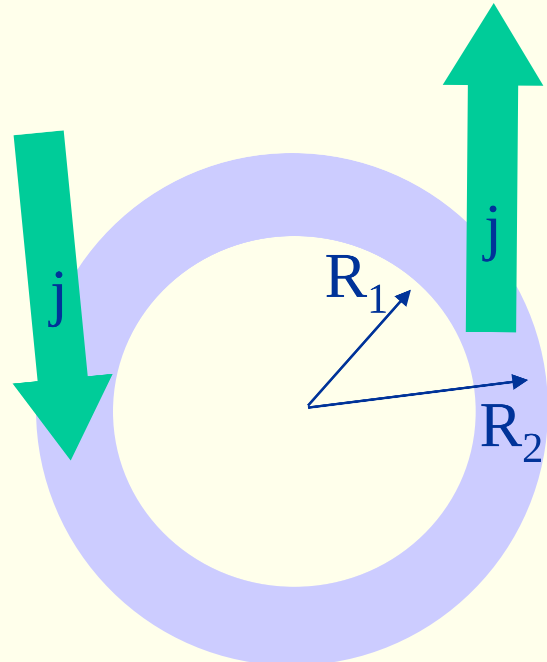
$$B_{SW} = 5 \text{ nT}$$



$$U = v_{SW} B_{SW} L = 300 \cdot 10^3 \cdot 5 \cdot 10^{-9} \cdot 20 \cdot 6378 \cdot 10^3 = 190 \text{ kV}$$

Red 200 kV

Energy budget (2)



Auroral oval

$U = 200$ kV

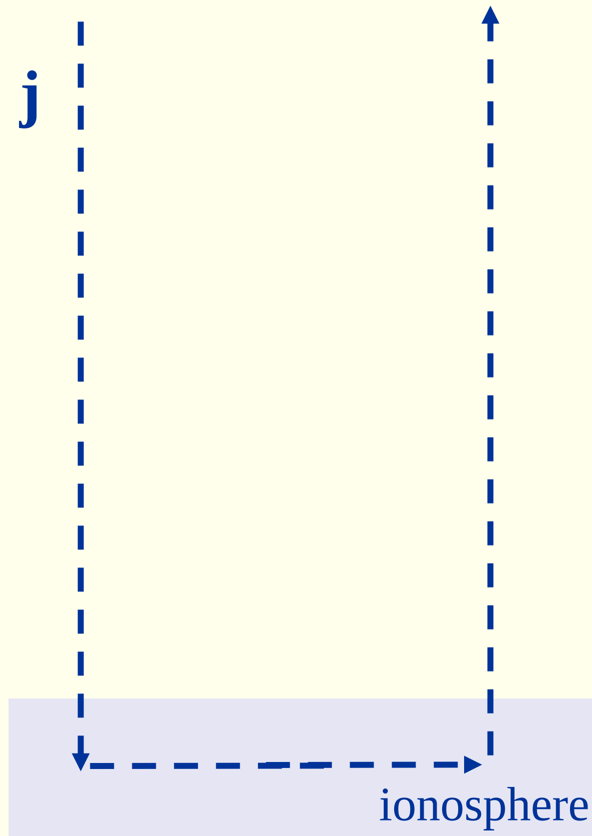
$A = \pi(R_2^2 - R_1^2) = 2{\cdot}10^{13}$ m^3

$I = jA/2 = ½{\cdot}0.1{\cdot}10^{-6}$ Am$^{-2} \cdot 2{\cdot}10^{13}$ m$^2 = 10$ MA

P = UI = $2{\cdot}10^{11}$ W = *6% of P_{SW}*

Geomagnetic activity, definition

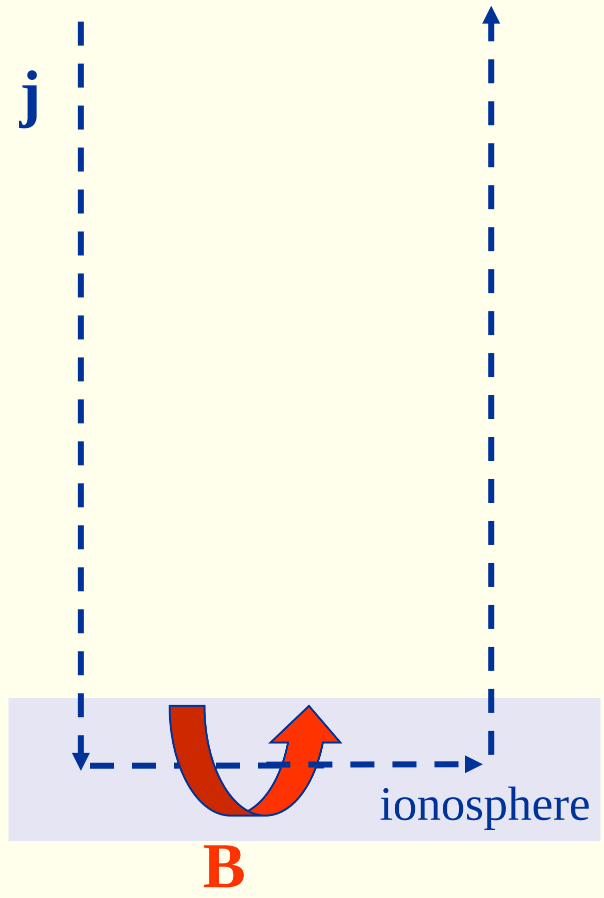
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.



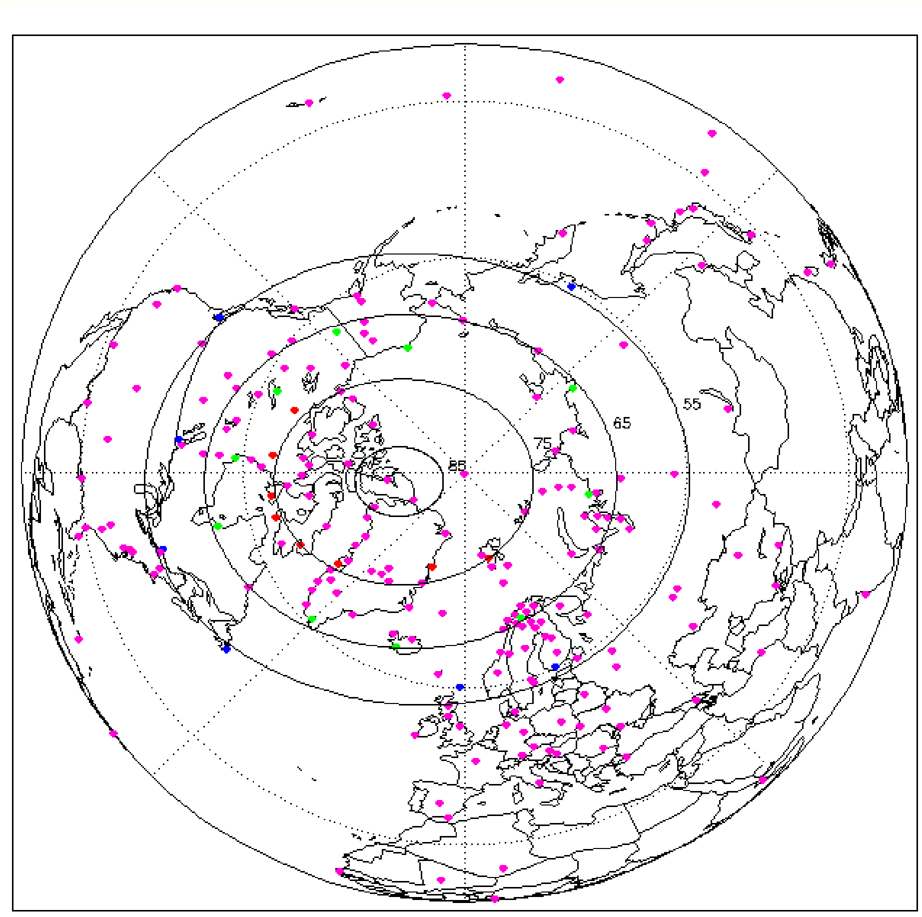
How can you observe these changing currents on Earth?

Geomagnetic activity, definition

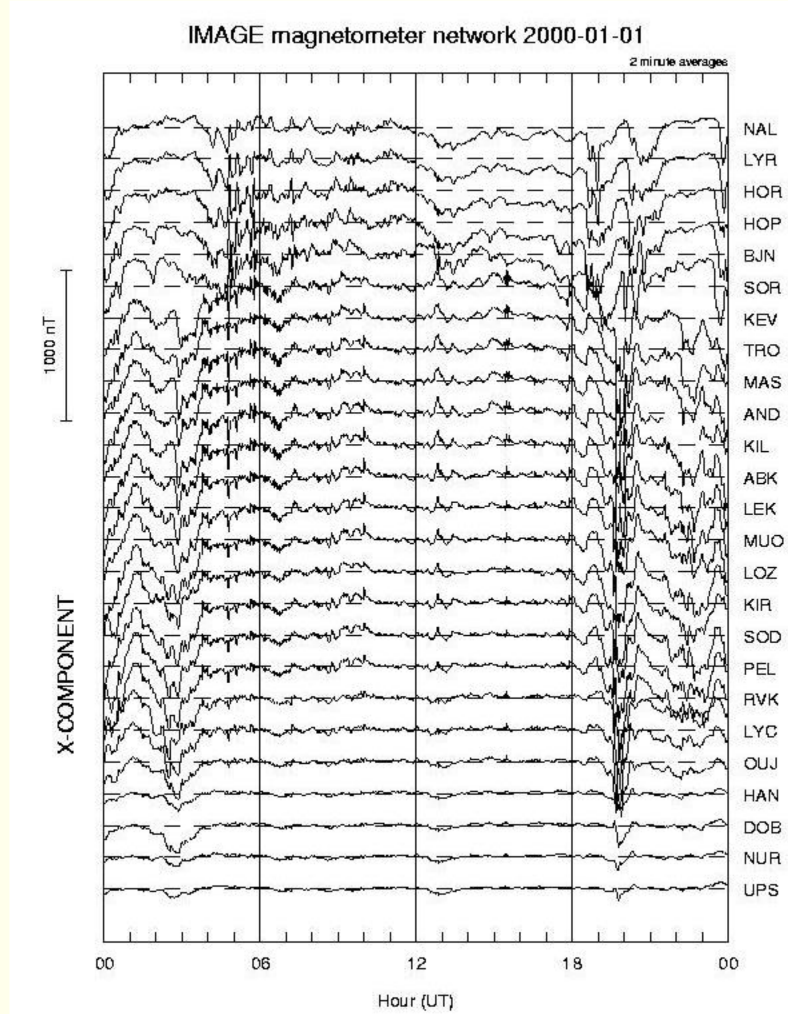
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.
- The variations are observed by geomagnetic observatories



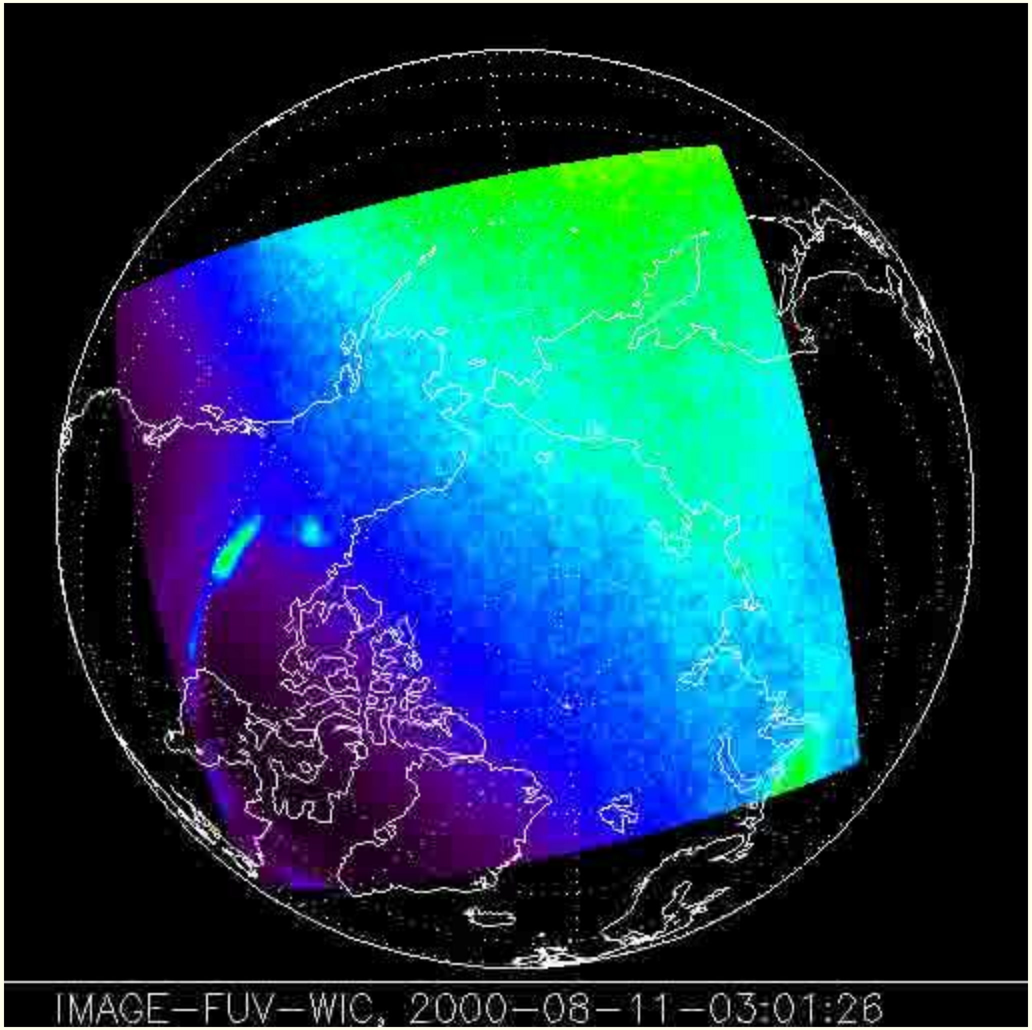
Magnetic observatories



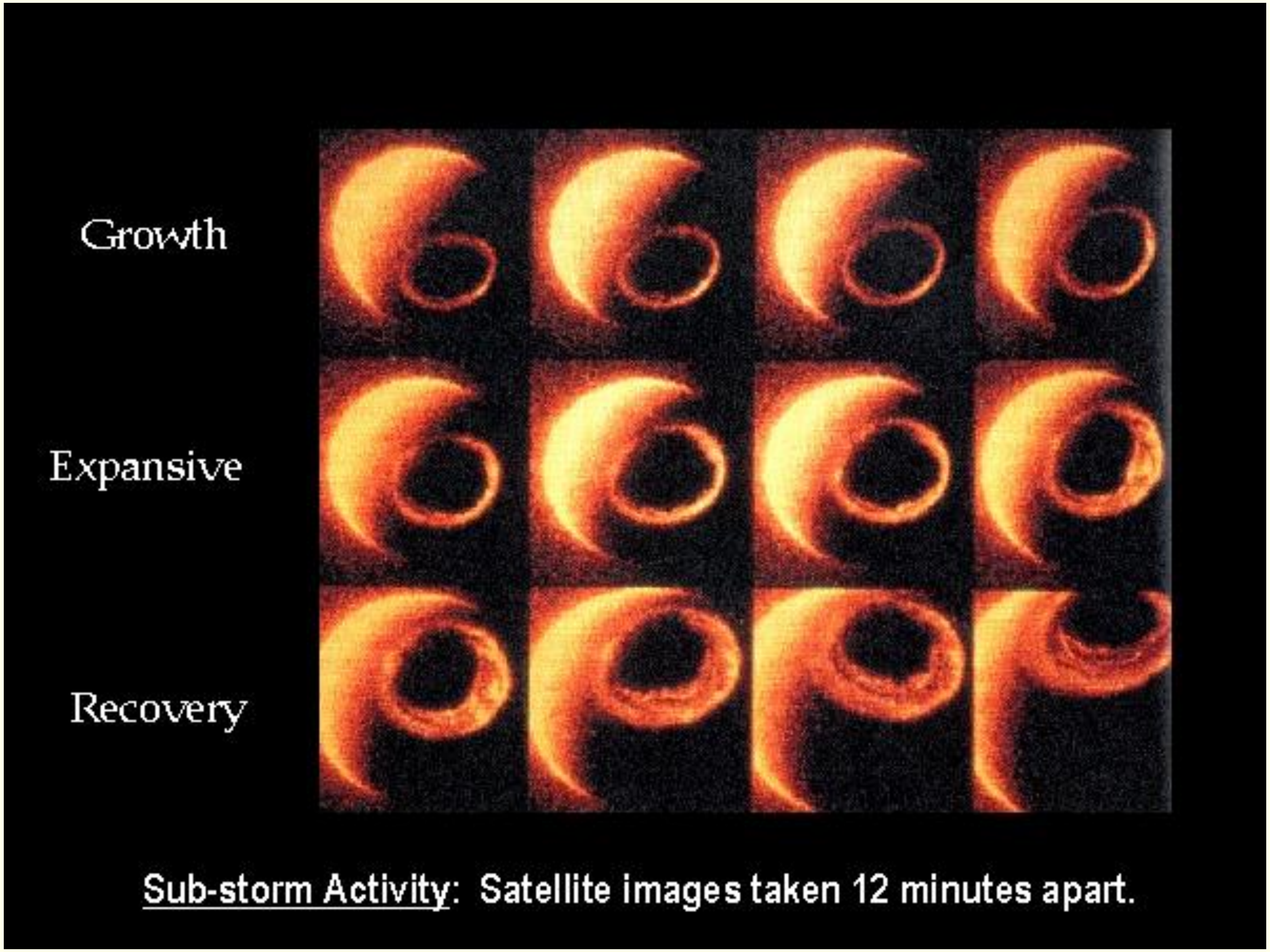
Magnetogram



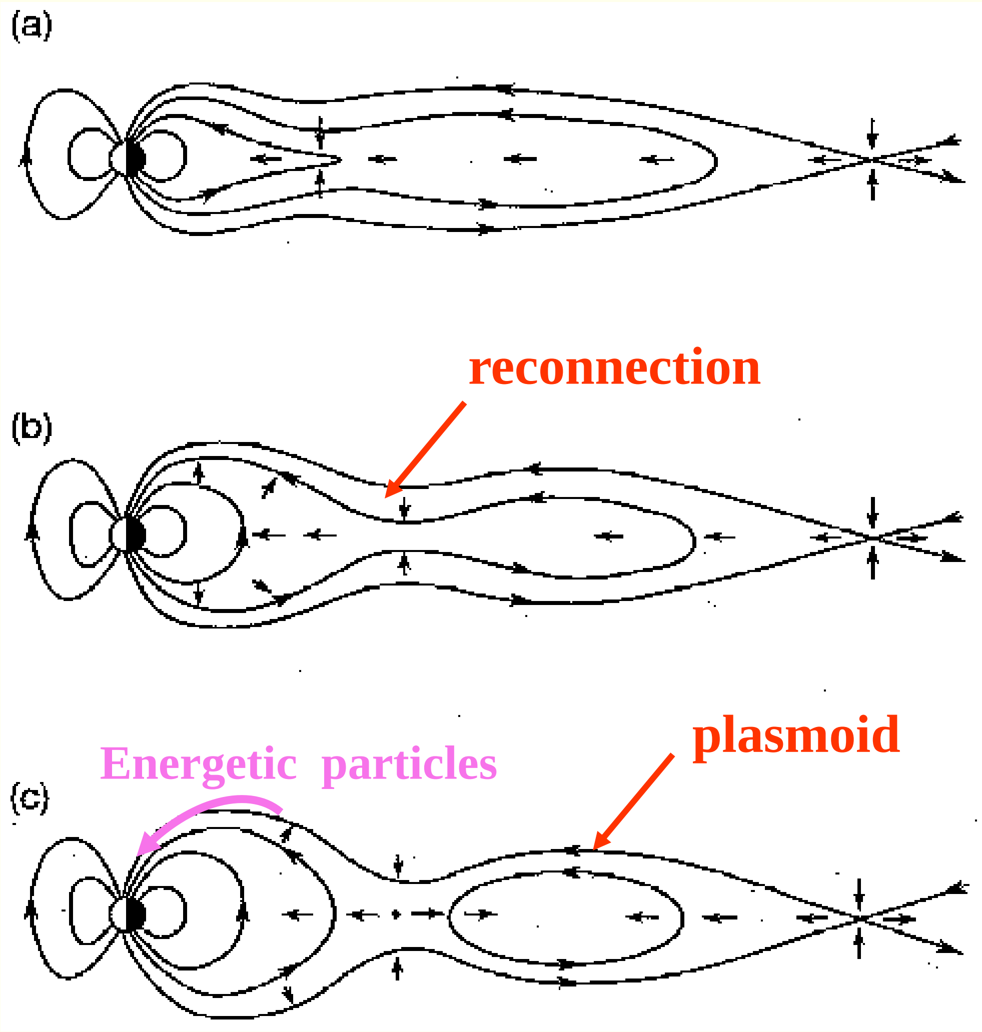
Aurora during substorm



Aurora during substorm

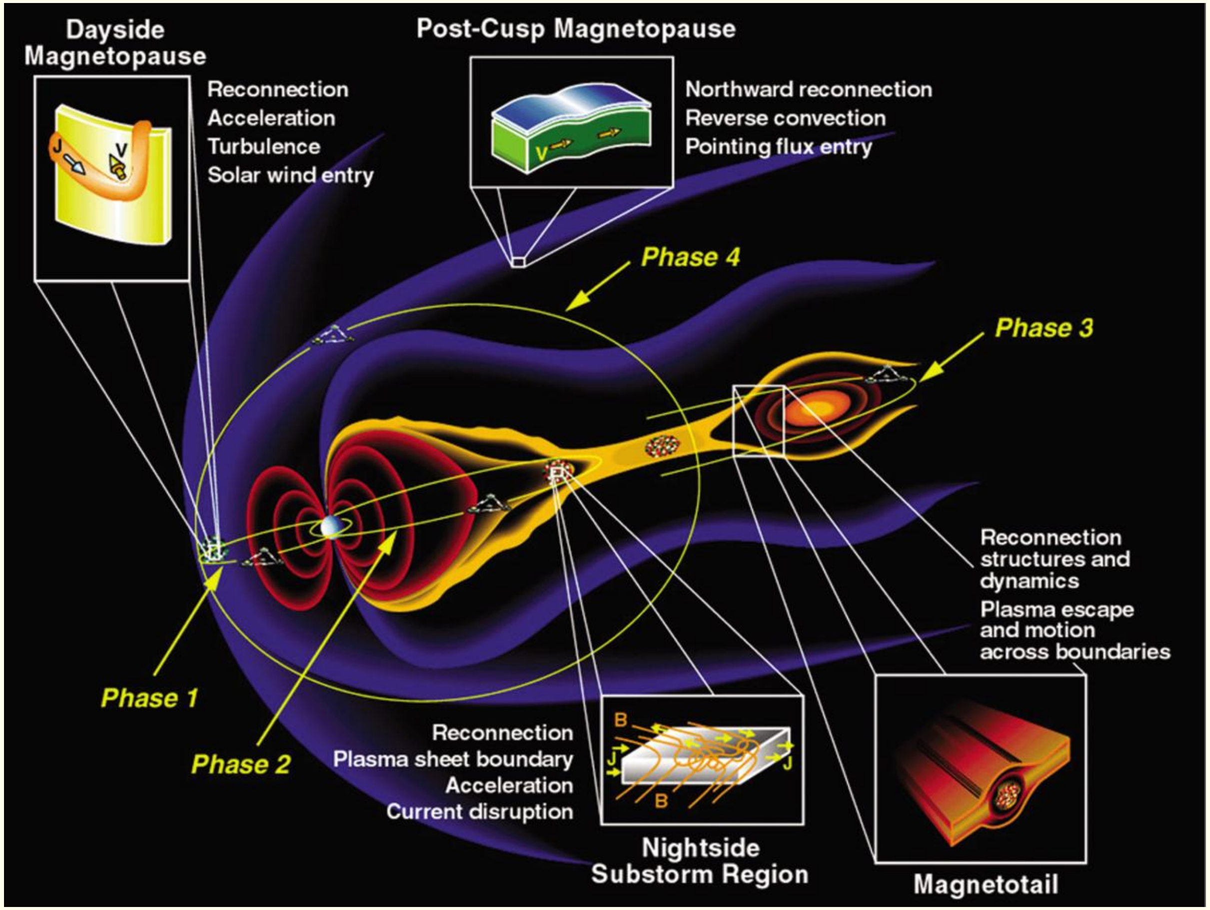


Substorms - magnetosphere



- **GROWTH PHASE**: When IMF southward, energy is pumped into magnetostail and is stored as megnetic energy
- **ONSET:** After a certain time (~1 h) the magnetostail goes unstable and "snaps" due to fast reconnection.
- **EXPANSION/MAIN PHASE**: Close to Earth the magnetosphere returns to dipole-like cinfiguration. Plasma is energized and injected into the inner parts of the magnetosphere.
- **RECOVERY PHASE**: In the outer parts of the magnetotail a *plasmoid* is ejected. The magnetosphere returns to its ground state.

Substorms - magnetosphere



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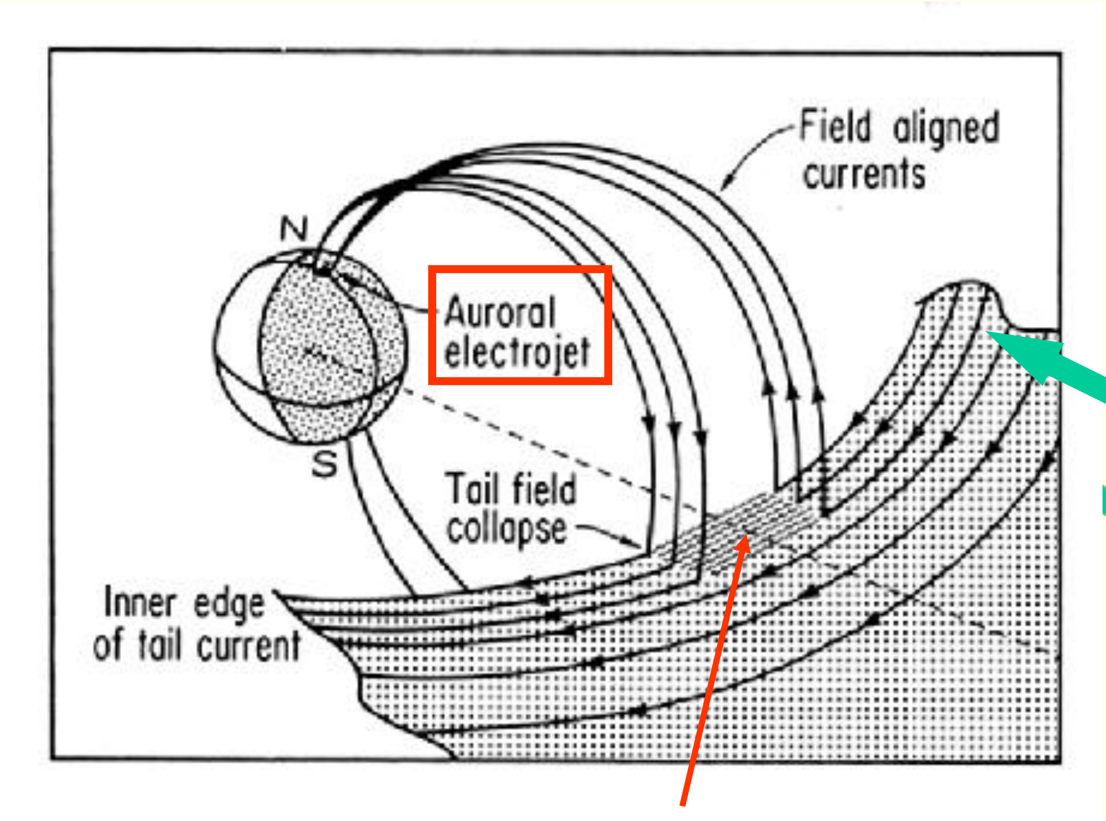
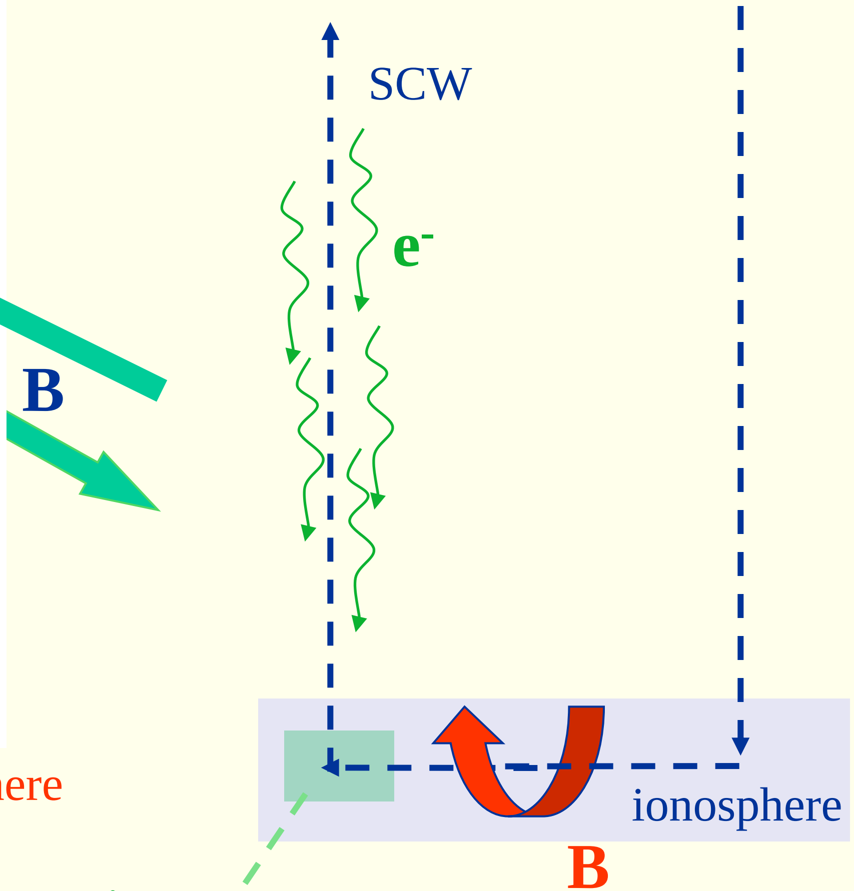
Substorm Current Wedge (SCW)

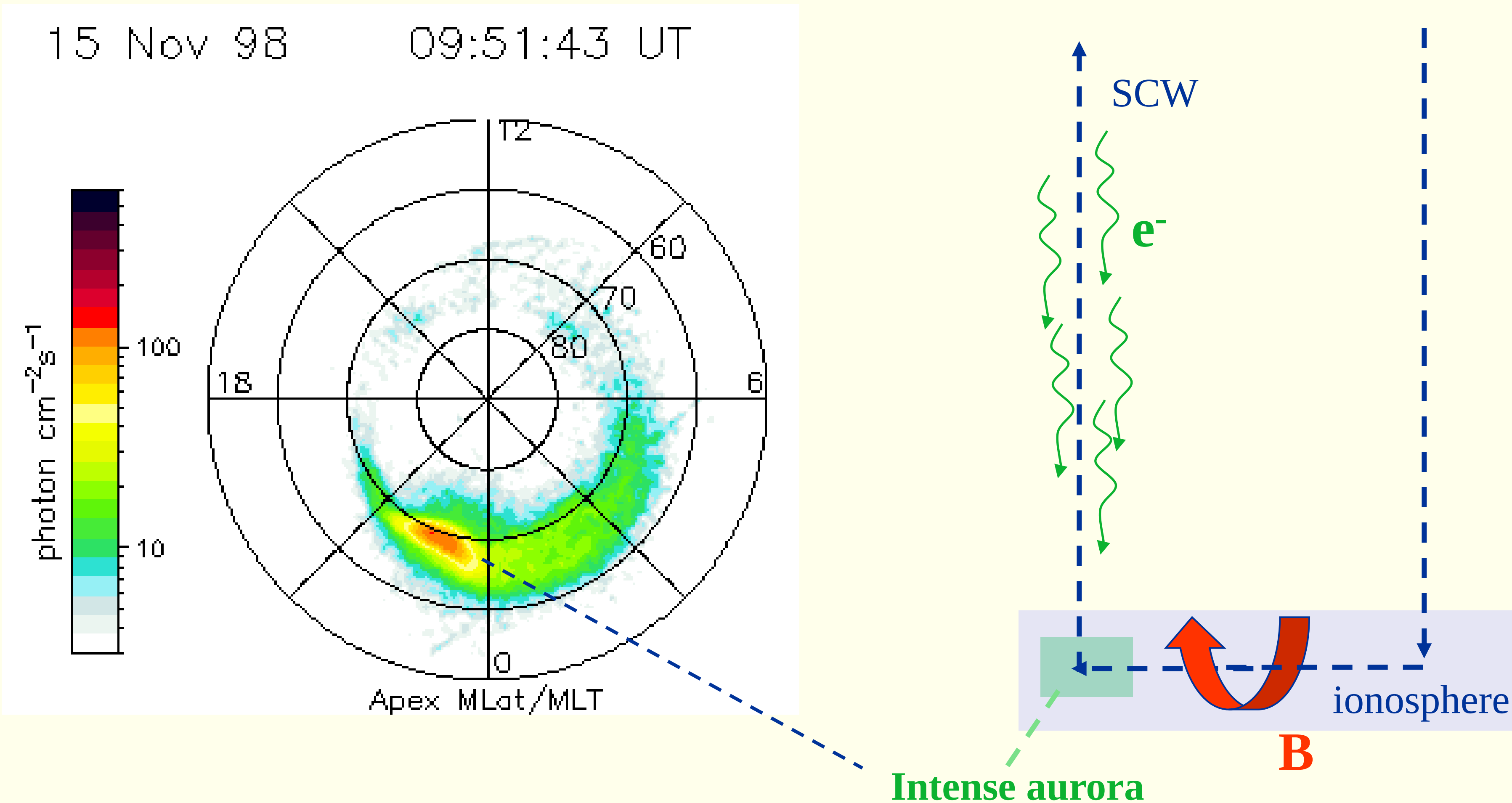


Due to reconnection processes the resistivity increases here ⇒

Current takes another direction – through the ionosphere!

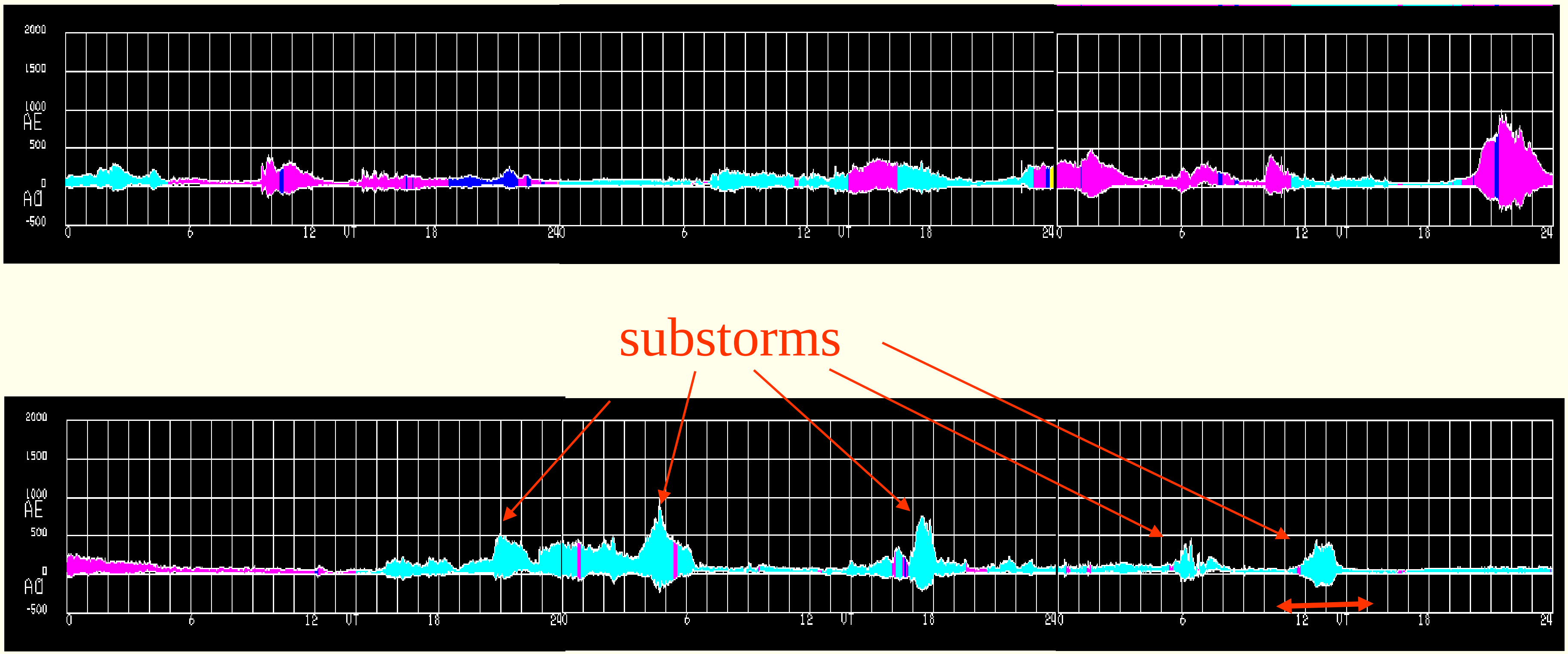


Substorm Current Wedge (SCW)



Auroral Electrojet (AE) index

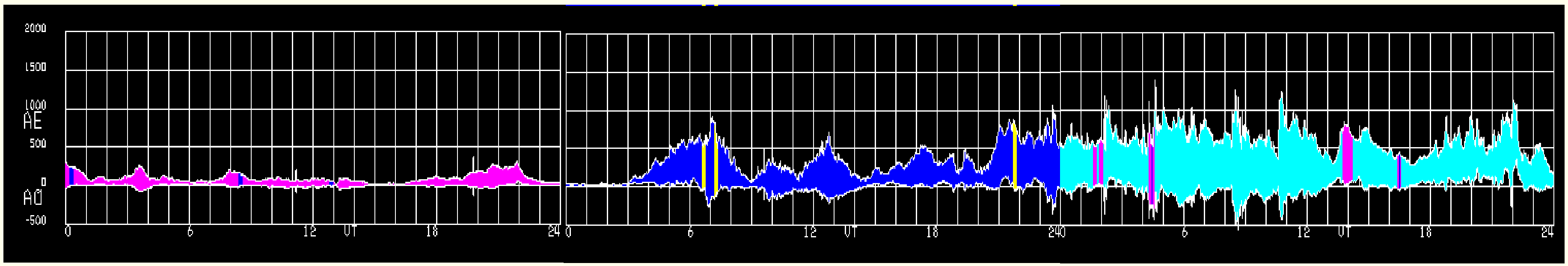
The AE index Measures the strength of the substorm current wedge (SCW), by using the information from several magnetic observatories.

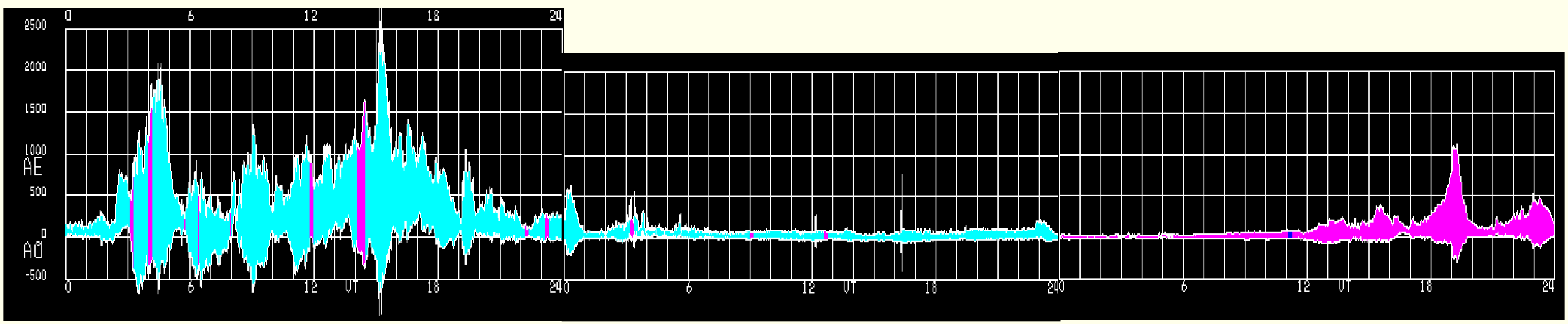


~1 – 3 h

Geomagnetic storms

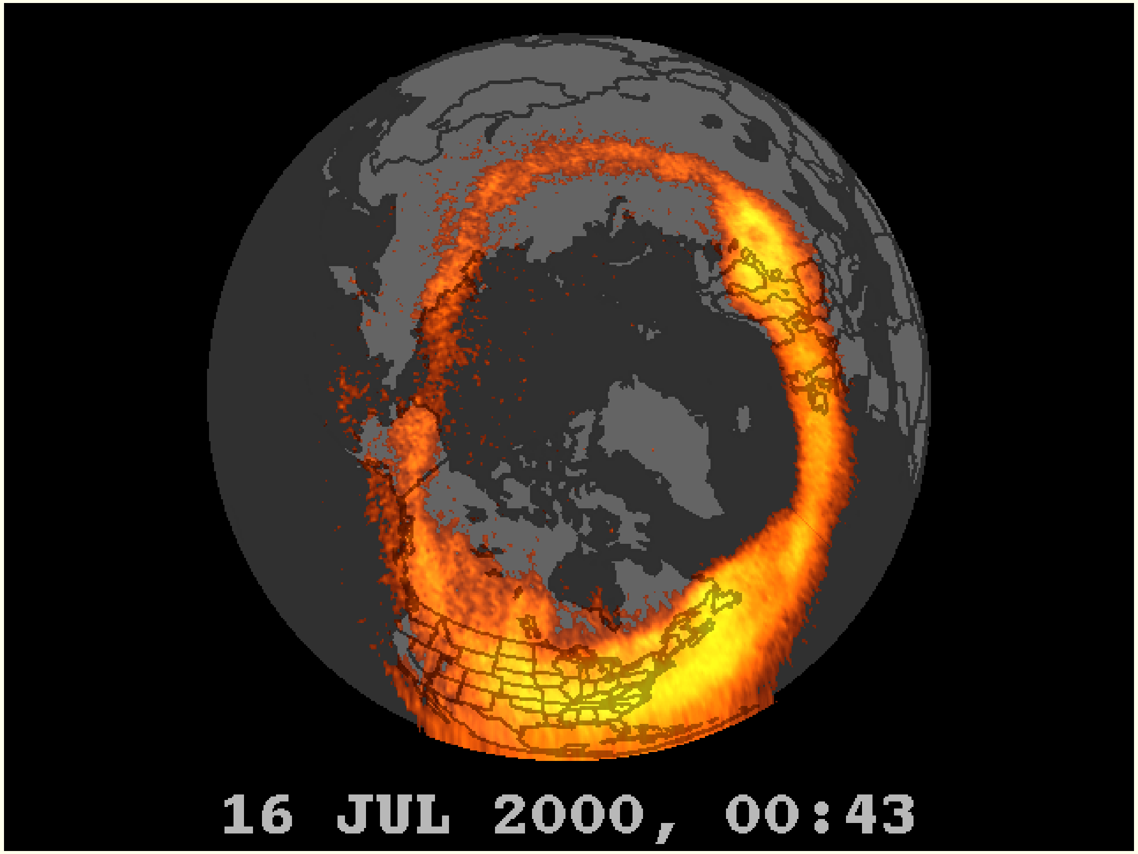
Geomagnetic storms are extended periods with southward interplanetary magnetic field (IMF) and a large energy input into the magnetosphere.



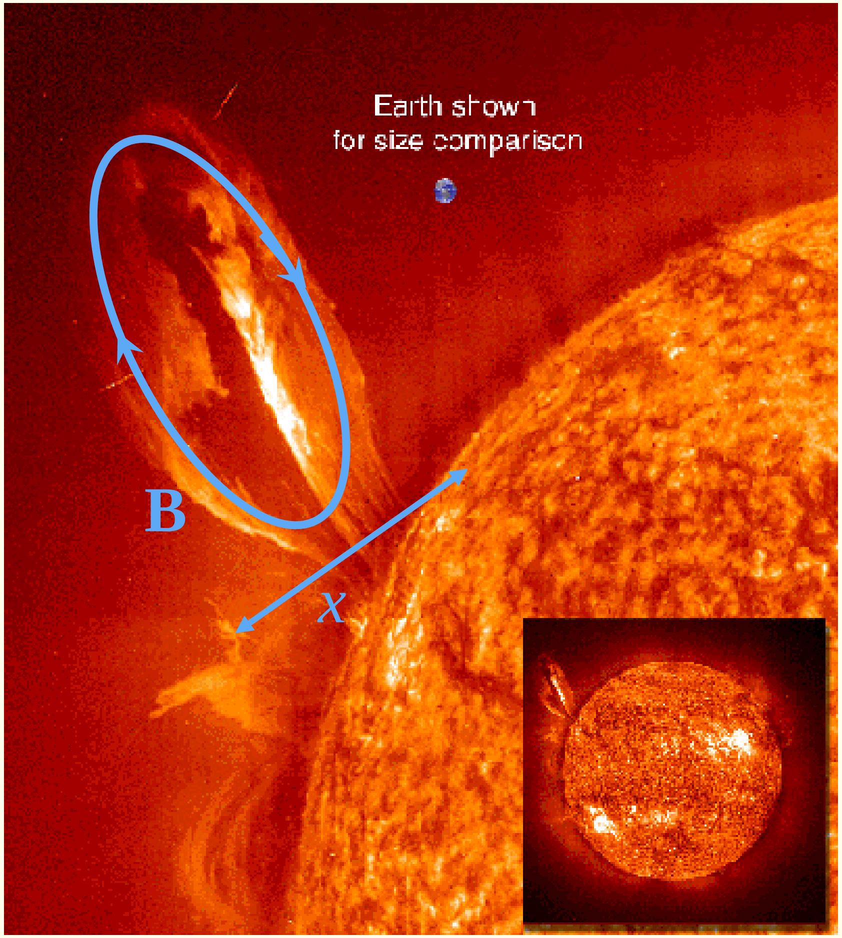


Geomagnetic storms

Auroral oval very extended

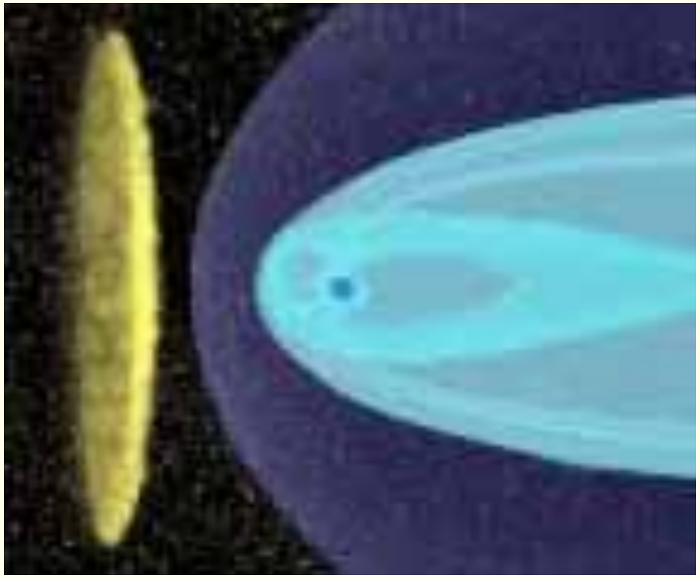


Geomagnetic storms and coronal mass ejections



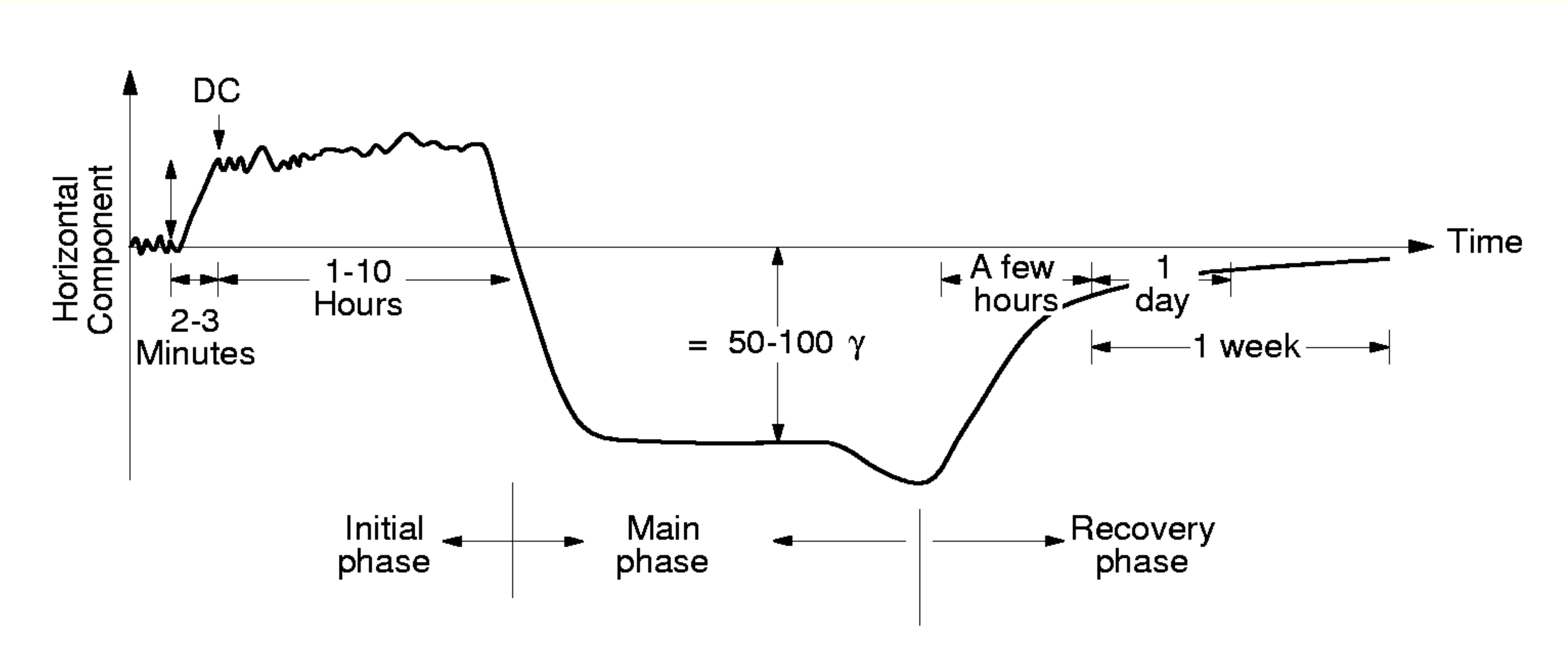
- Large geomagnetic storms are often associated with coronal mass ejections (CMEs)
- Because of their magnetic structure, they will give long periods with a constant IMF
- A typical time for a CME to pass Earth becomes $T = x/v \sim 10\ R_E/1000\ \mathrm{kms}^{-1} \sim 60$ h

What happens with the geomagnetic field when the CME hits the magnetosphere?

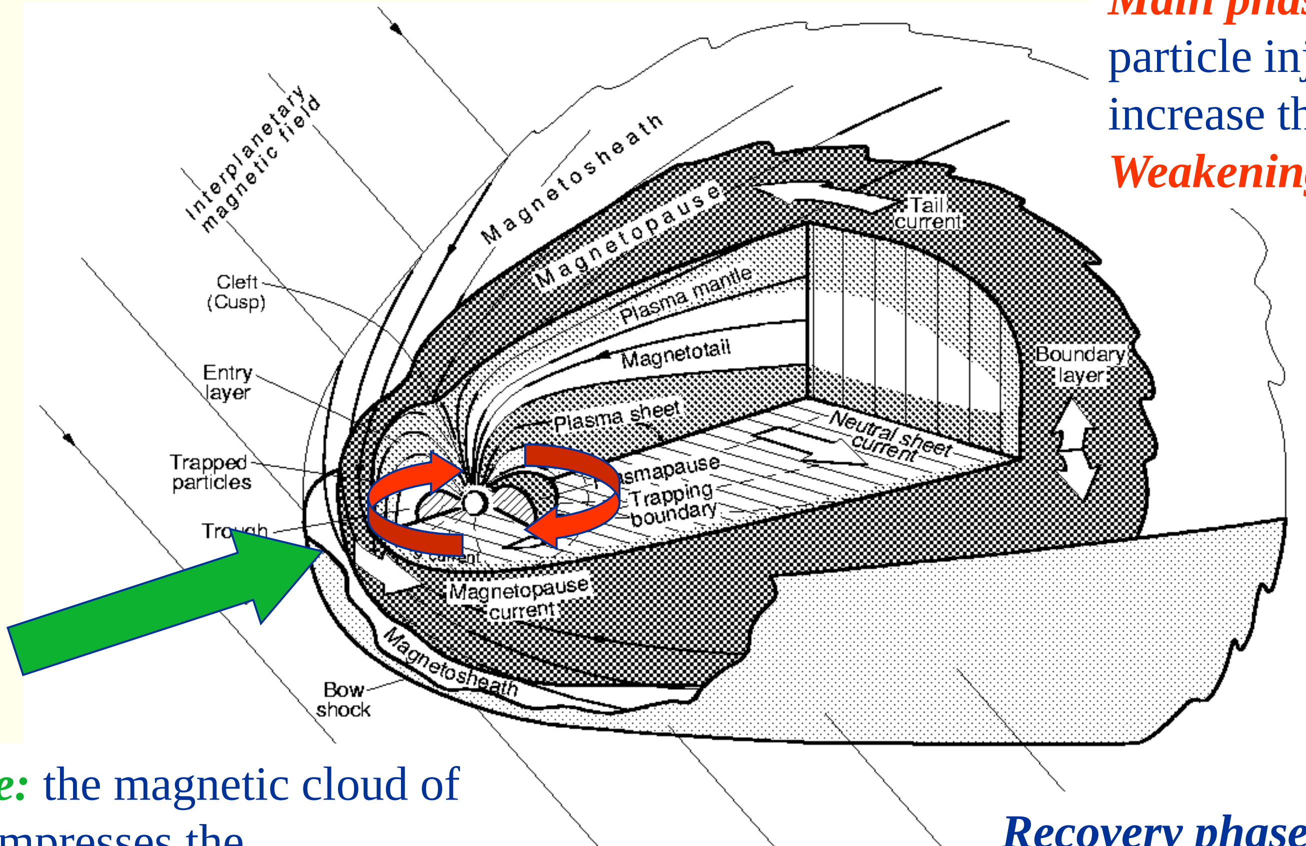


Geomagnetic storms - phases

Magnetogram



Geomagnetic storms - phases

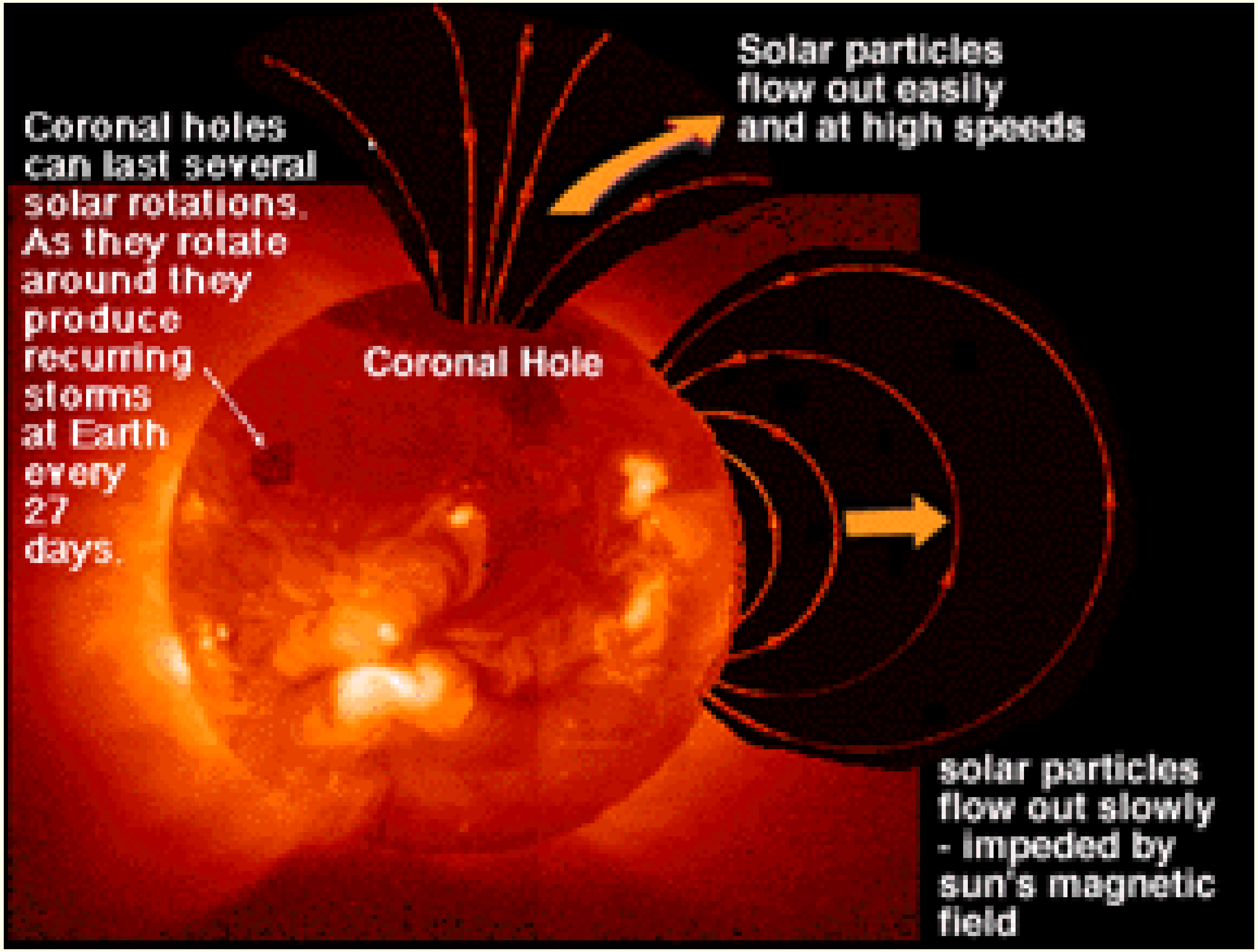


Main phase: Several particle injections increase the ring current.
Weakening of B

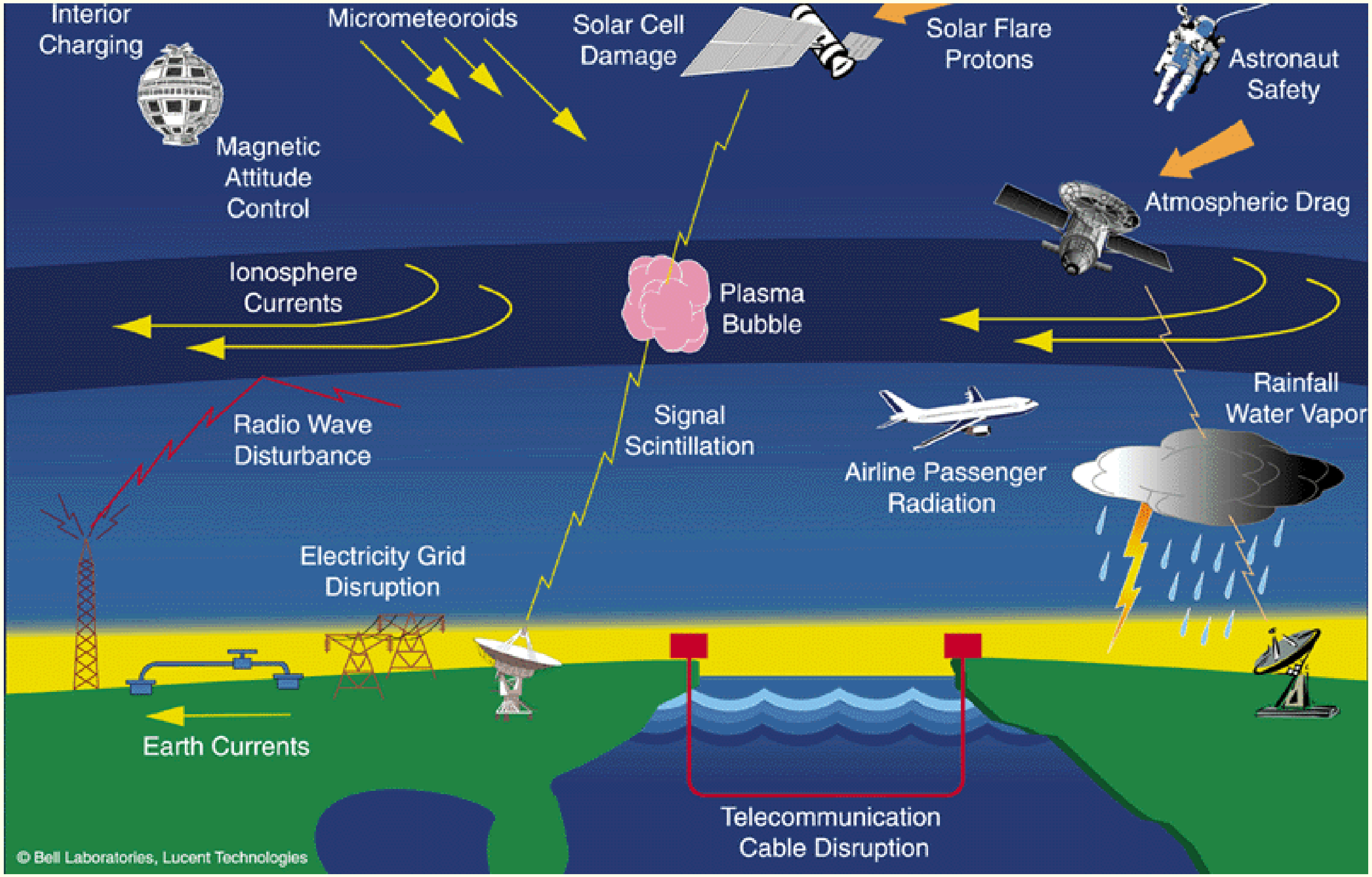
Initial phase: the magnetic cloud of the CME compresses the geomagnetic field.
Increase of B

Recovery phase: ring current returns to normal strength.
Recovery of B

Periodic geomagnetic activity

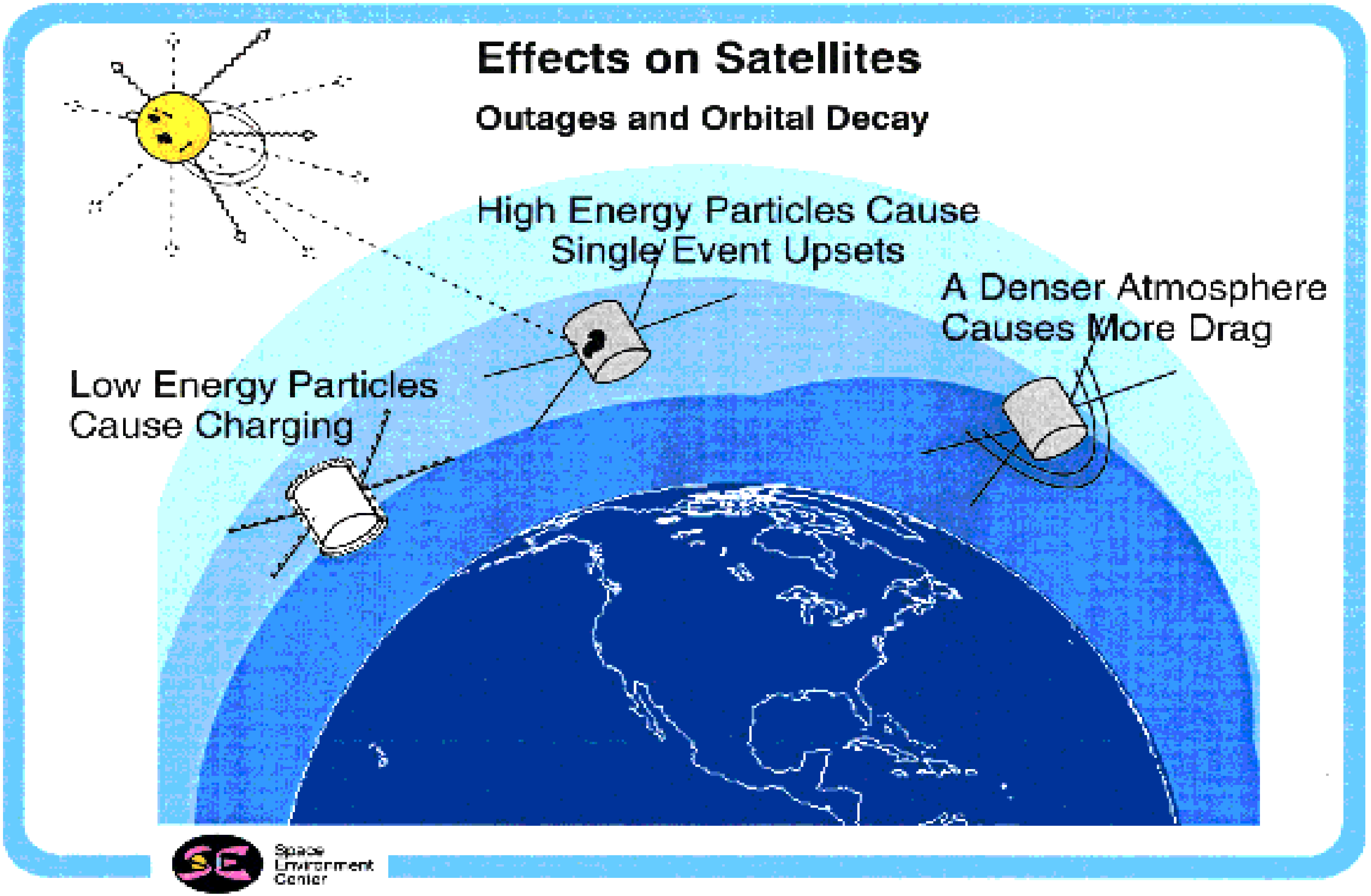


Space weather: consequences of solar and geomagnetic activity



"conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health."

US National Space Weather Programme

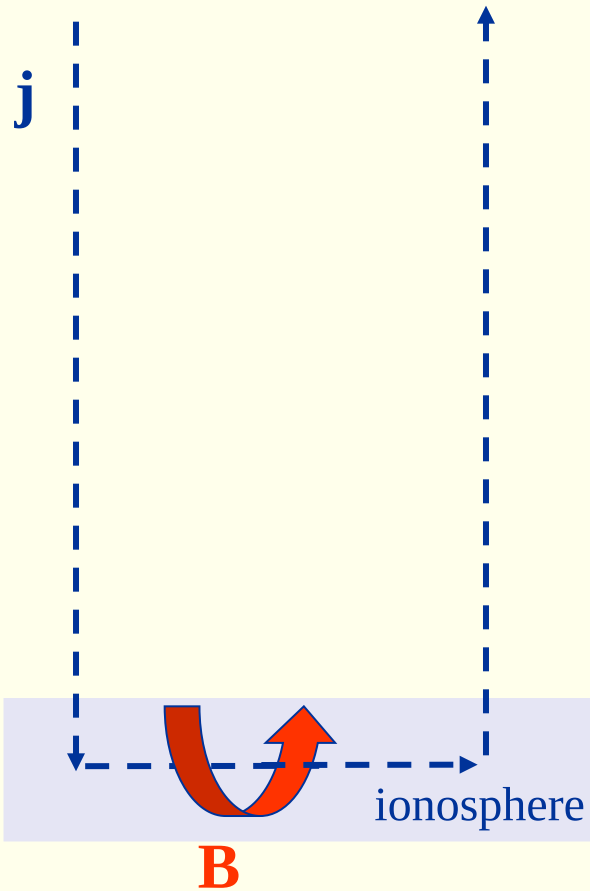

Effects on Satellites
Outages and Orbital Decay
High Energy Particles Cause
Single Event Upsets
A Denser Atmosphere
Causes More Drag
Low Energy Particles
Cause Charging
Space
Environment
Center

Damage To Solar Panels

Satellite power budgets can be very tight so degradation in solar panel performance is a serious issue.

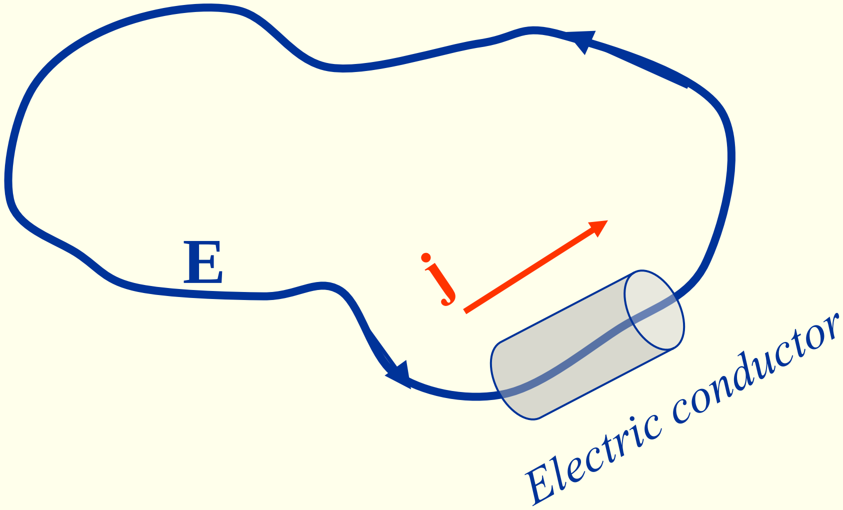
The damage is done by energetic particles which penetrate the surface of the panel and deposit a significant amount of energy inside the solar cells. This displaces the atoms within the cells and causes a loss in efficiency.

GIC – Geomagnetically Induced Currents



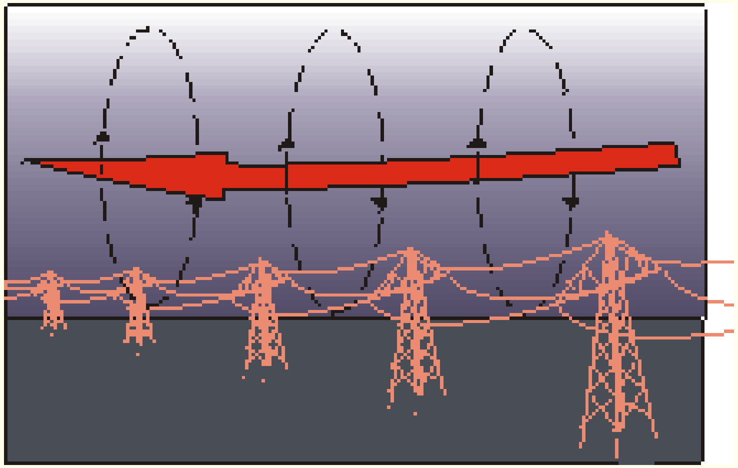
$$\frac{\partial B}{\partial t} = -\nabla \times \mathbf{E}$$

Faraday's law



GIC – Geomagnetically Induced Currents

Can damage electric power grids

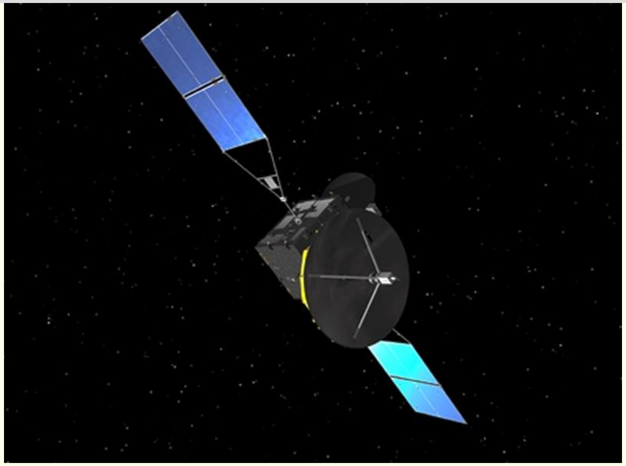


Induced currents is pipelines increase corrosion.

Highly energetic particles

- Particles in the radiation belts.
- Particles from solar activity (solar flares, CME)
- Cosmic radiation

Danger to astronauts



Disturb or damage electronics on satellites and aeoreplanes.

Increase the rate of ionization in lower D region and thus increases absorption of radio waves.

Space weather on the internet

www.spaceweather.com

www.swpc.noaa.gov/SWN (Space Weather Prediction Centre)

What is cosmic radiation?

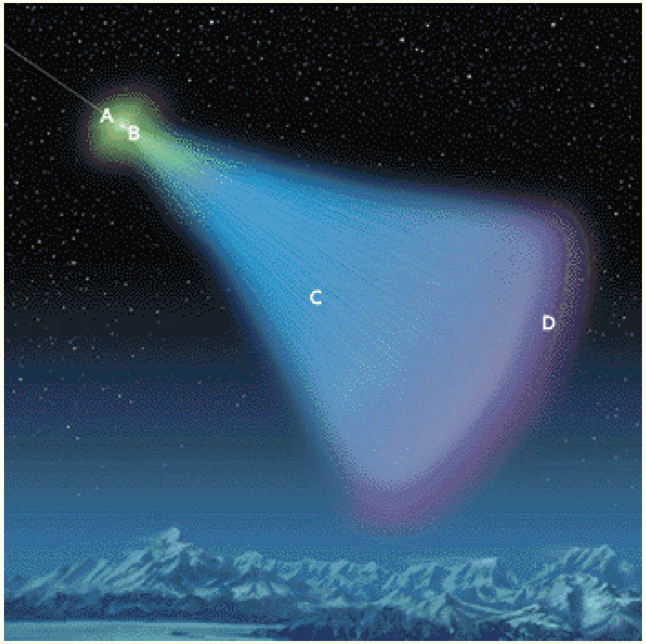
Cosmic rays (= cosmic radiation)

Primary cosmic radiation

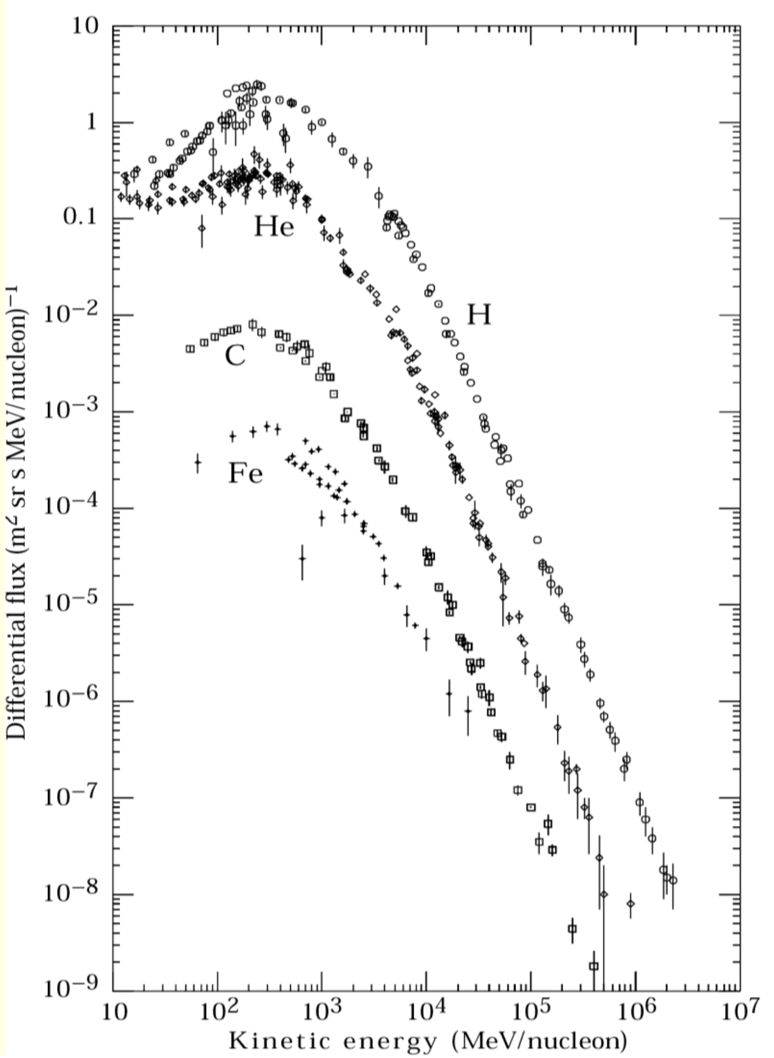
Extremely energetic particles ($>10^8$ eV)

- Galactic cosmic rays
- Solar 'cosmic rays' (Solar Energetic Particles)

Secondary cosmic radiation



Composition and spectrum of galactic cosmic radiation

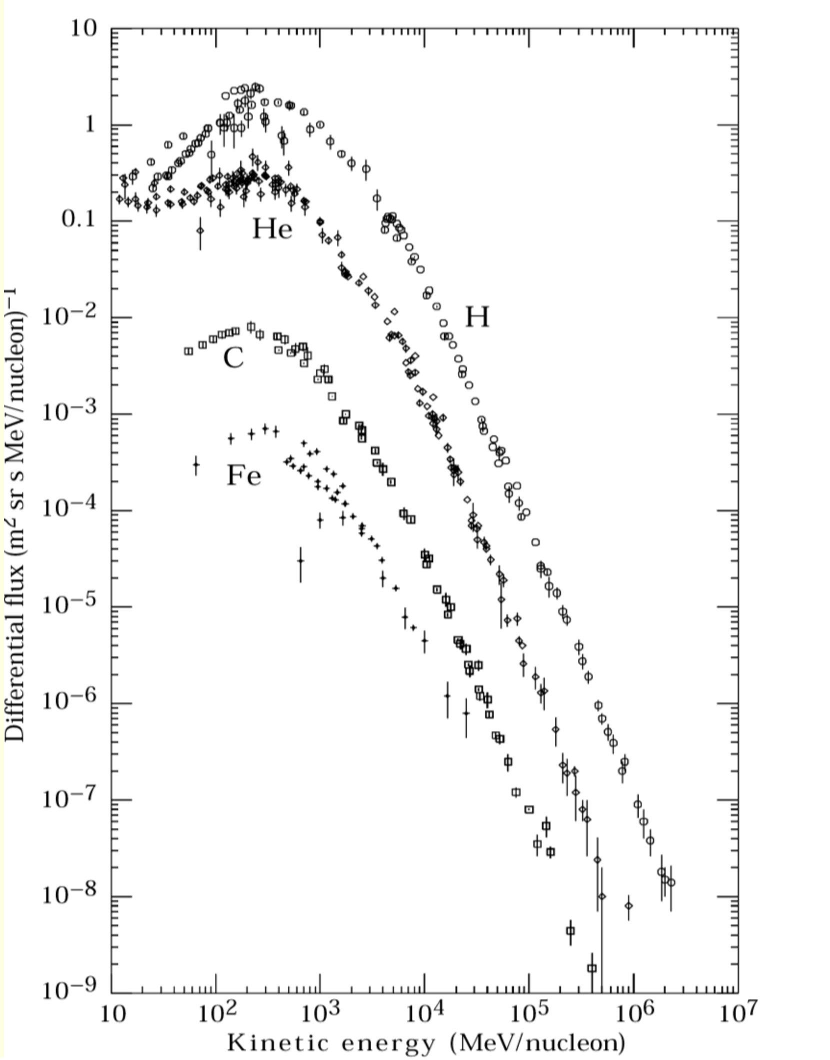


Simpson, 1983.

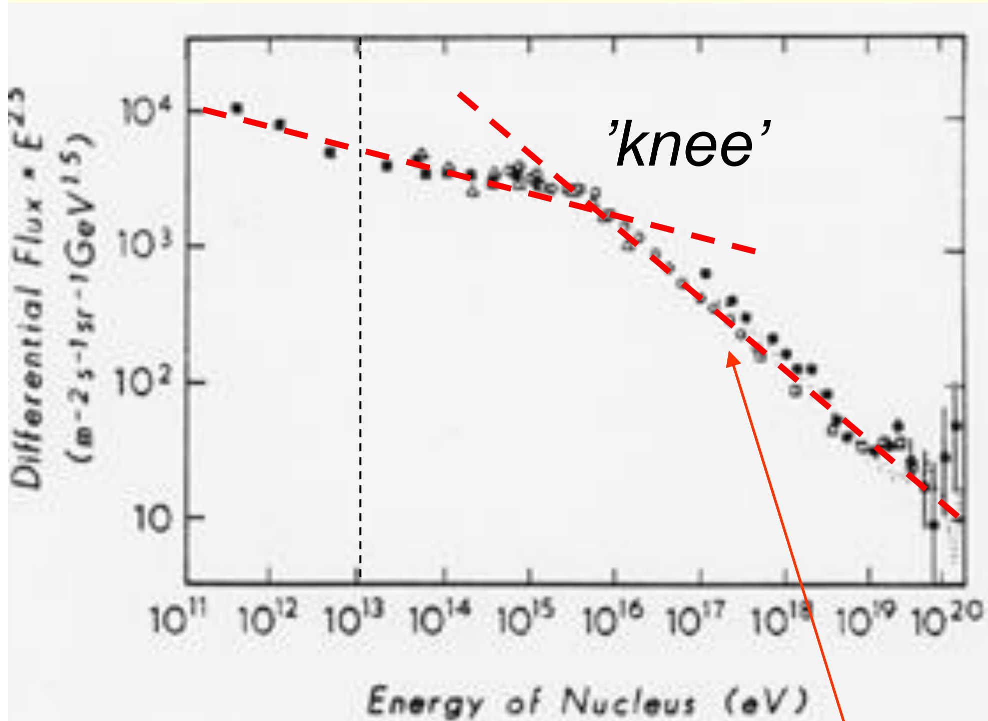
83 % protons
13 % alpha particles
3 % electrons
1 % other nuclei

All cosmic ray particles are fully ionized

Spectrum of galactic cosmic radiation

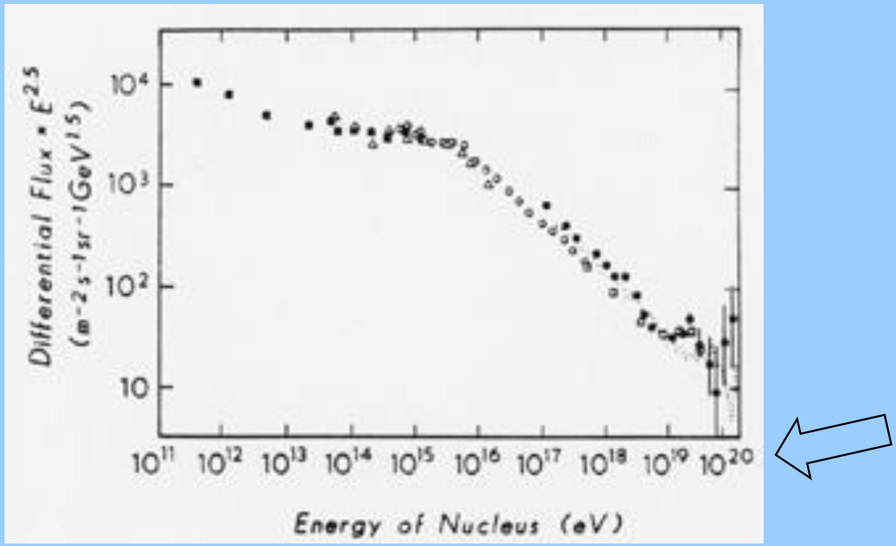


Simpson, 1983.



Ultra-energetic cosmic radiation.
Origin unknown. Extragalactic???

How much kinetic energy is there in a 10^{20} eV cosmic ray particle?



Blue	Energy of a mosquito moving at 10 km/h
Yellow	Energy of a tennis ball moving at 100 km/h
Red	Energy of a car moving at 10 km/h

How much kinetic energy is there in a 10^{20} eV cosmic ray particle?

10^{20} eV = $10^{20} \cdot 1.6 \cdot 10^{-19}$ J = 16 J

A mosquito weighs about 5 mg. 10 km/h ≈ 2.8 m/s ⇒

$$\frac{mv^2}{2} = \frac{5 \cdot 10^{-6} \cdot (10/3.6)^2}{2} = 2 \cdot 10^{-5} \text{ J}$$

A tennis ball weighs about 50 g. 100 km/h ≈ 28 m/s ⇒

$$\frac{mv^2}{2} = \frac{0.05 \cdot (100/3.6)^2}{2} = 19 \text{ J}$$

A car weighs about 1 ton. 10 km/h ≈ 3 m/s ⇒

$$\frac{mv^2}{2} = \frac{1000 \cdot (10/3.6)^2}{2} = 39 \text{ kJ}$$

Yellow

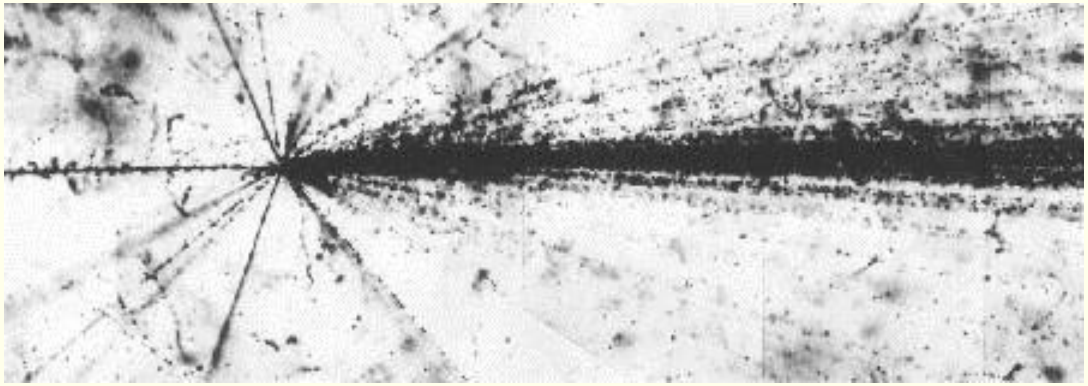
Tennis ball moving at 100 km/h

Cosmic radiation

Primary cosmic radiation

*Extremely energetic particles (>**10^8 eV**) which originate outside of the solar system.*

83 % protons
13 % alpha particles
3 % electrons
1 % other nuclei



Secondary cosmic radiation

- Starts at about 55 km altitude.
- Created by collisions between primary cosmic radiation and the atmosphere.
- Maximum ("*Pfotzer maximum*") at approx. 20 km altitude.
- Contains mostly protons, neutrons and mesons

Pfotzer maximum

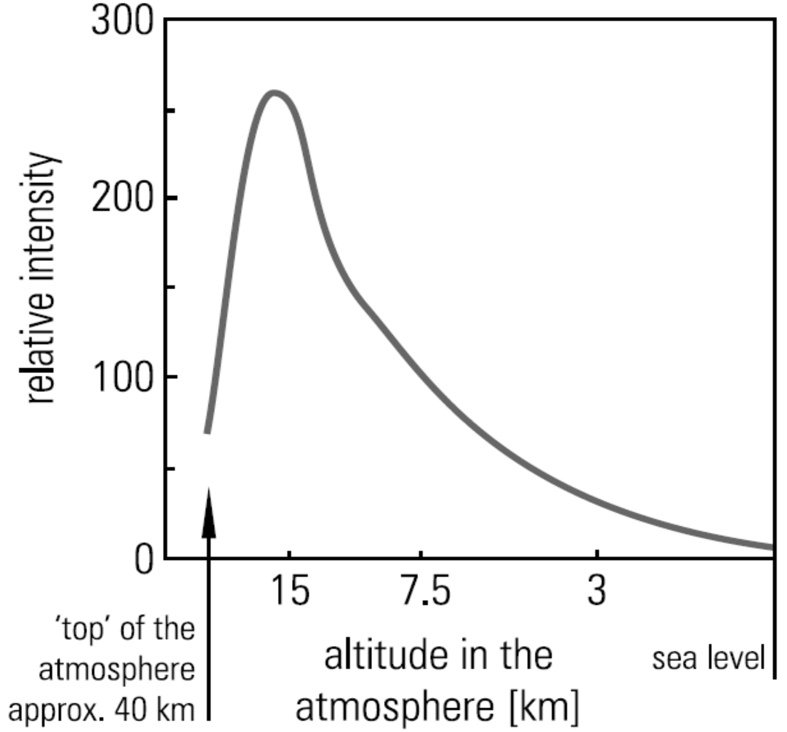
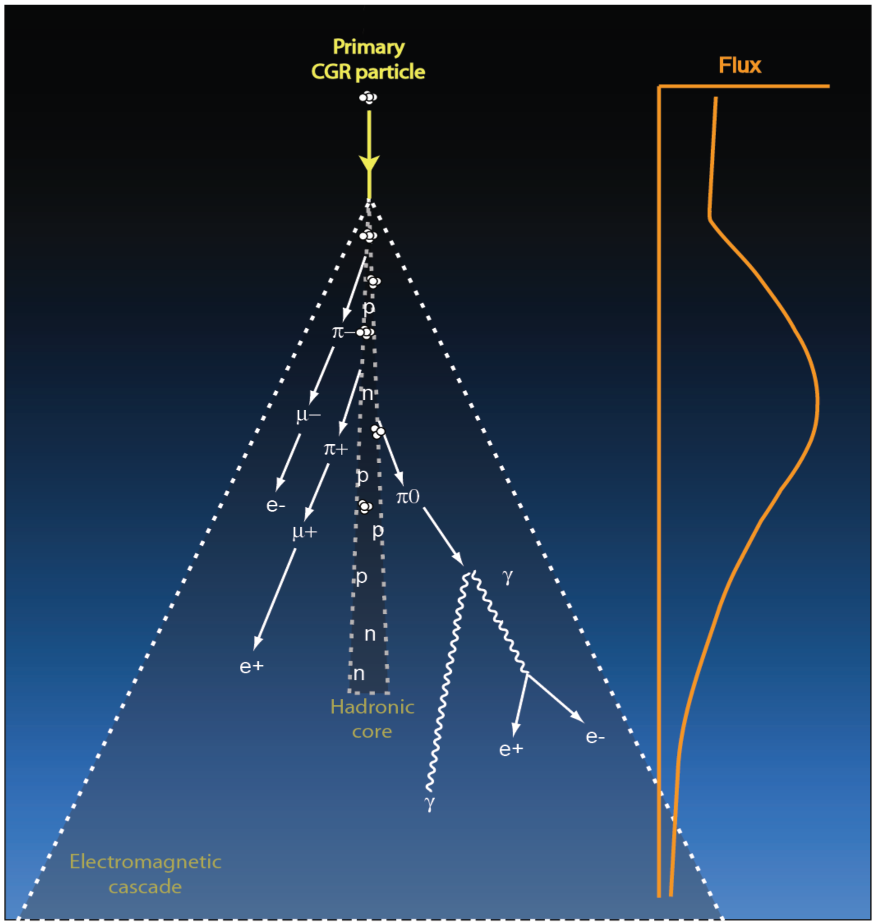
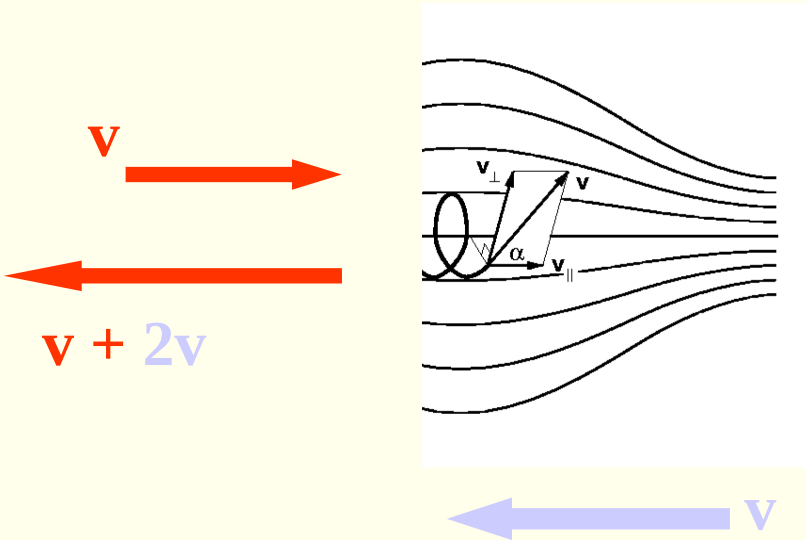


Fig. 1.12
Intensity profile of cosmic particles in the atmosphere

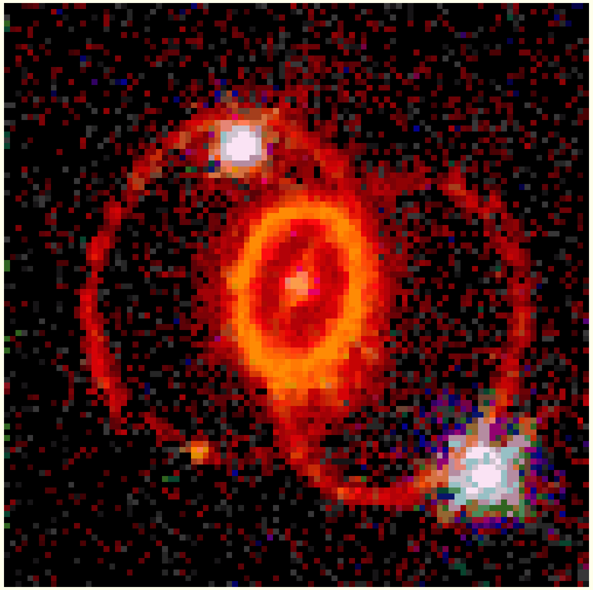


Origin of galactic cosmic radiation

Two main theories

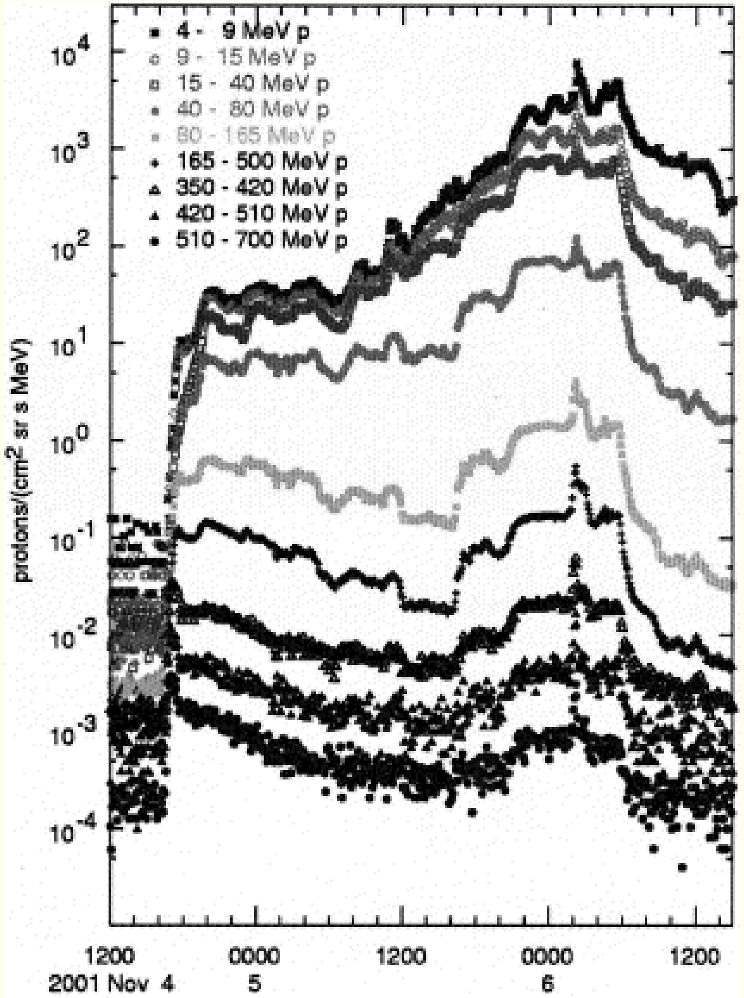


Fermi acceleration by two magnetic mirrors in motion



Shock waves from supernova explosion

Solar Energetic Particles (SEP)



- Associated with solar flares or coronal mass ejections
- Energies of tens of keV to GeV

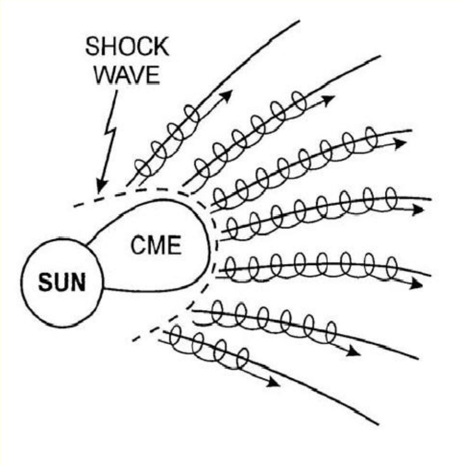


Figure 22: Time profiles of the strong SEP proton flux event of November 4, The peak at the time of shock passage is clearly defined early on November 6, even at proton energies as high as 510 – 700 MeV. From Reames (2004).

Neutron albedo

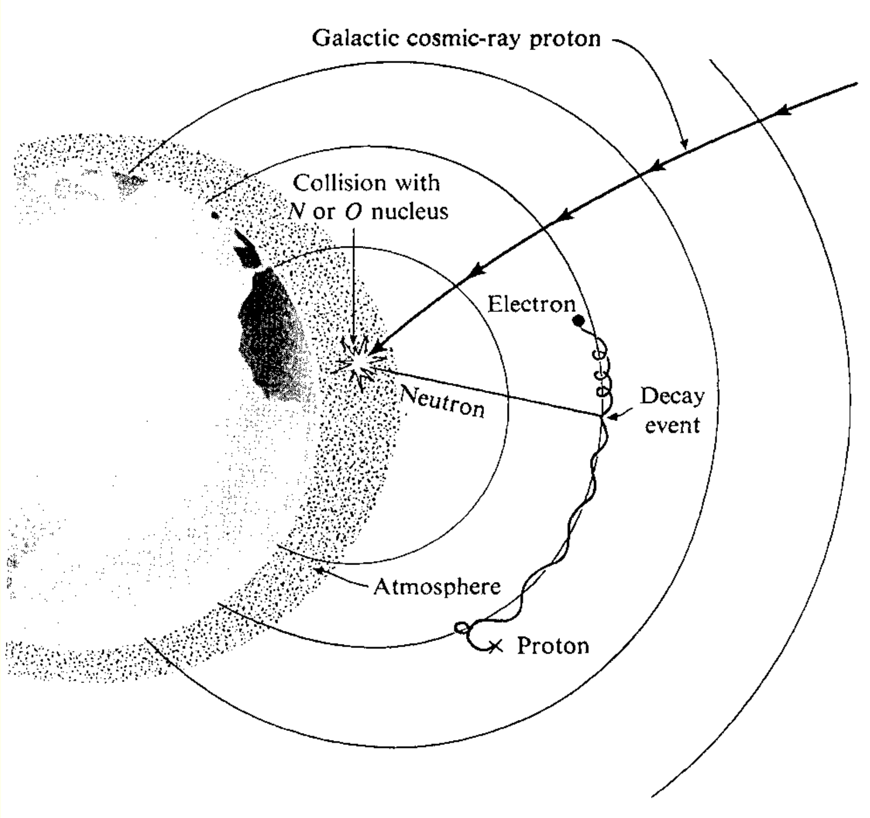


Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

Among these are neutrons, that are not affected by the magnetic field. They decay, soom eof them when they happen to be in the radiation belts. The resulting protons and electrons are trapped in the radiation belts.

This contribution to the radiation belts are called the ***neutron albedo***.

Relativistic dynamics

Relativistic momentum

$$\mathbf{p} = \frac{m\mathbf{v}}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma m\mathbf{v}$$

$$\gamma \equiv \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Relativistic energy

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma mc^2$$

Relation between energy and momentum

$$E^2 = p^2c^2 + m^2c^4$$

Relativistic dynamics

Rest energy

$$E = mc^2$$

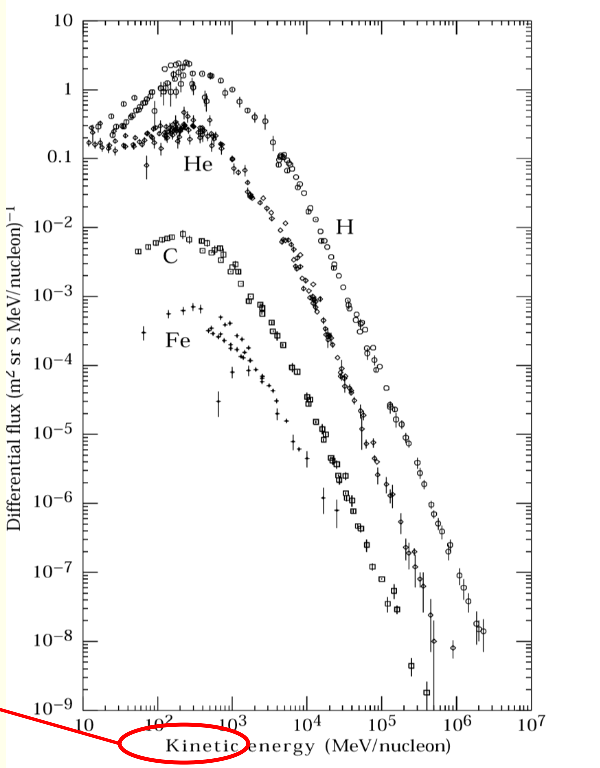
Kinetic energy

$$E_{kin} = E - mc^2 = mc^2(\gamma - 1)$$

Rest energy of electron : 512 keV ~ 0.5 MeV

Rest energy of proton: 939 MeV ~ 1 GeV

!!!



24.1: Major components of the primary cosmic radiation (from Ref. 1).

Relativistic gyro radius

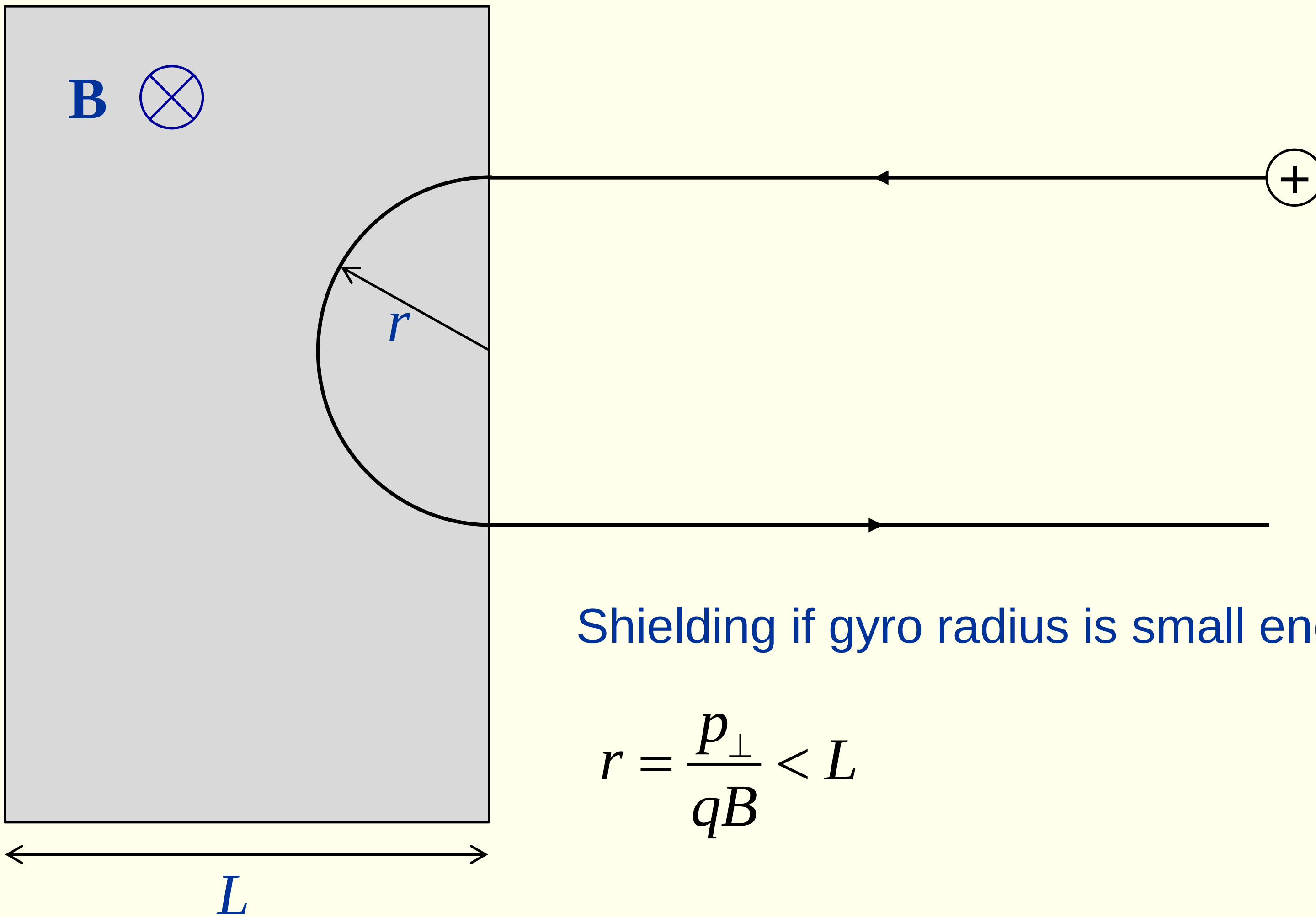
Non-relativistic gyro radius

$$r_L = \frac{mv_\perp}{qB} = \frac{p_\perp}{qB}$$

Relativistic gyro radius

$$r_L = \frac{p_{rel,\perp}}{qB} = \gamma \frac{mv_\perp}{qB}$$

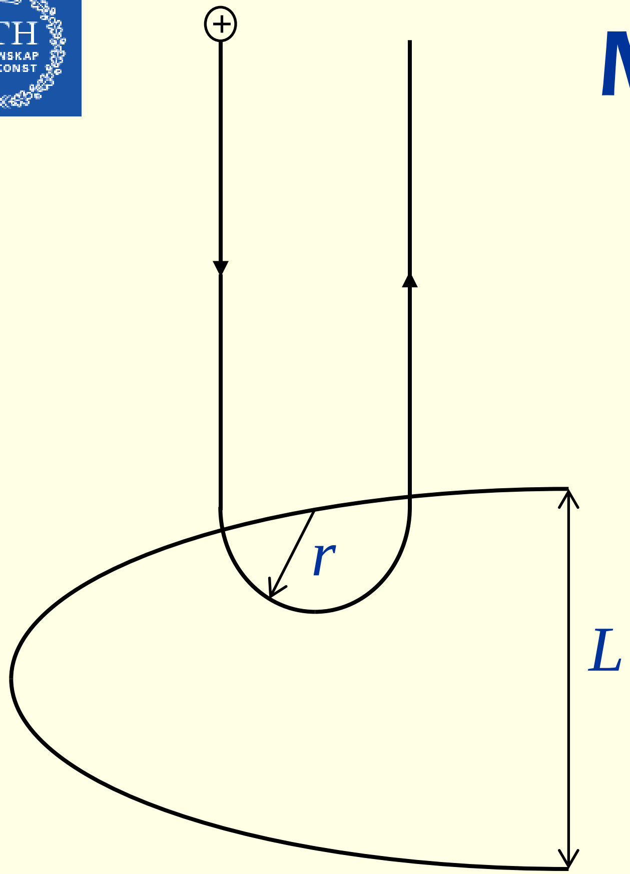
Magnetic shielding



Shielding if gyro radius is small enough

$$r = \frac{p_\perp}{qB} < L$$

Magnetic shielding of magnetosphere



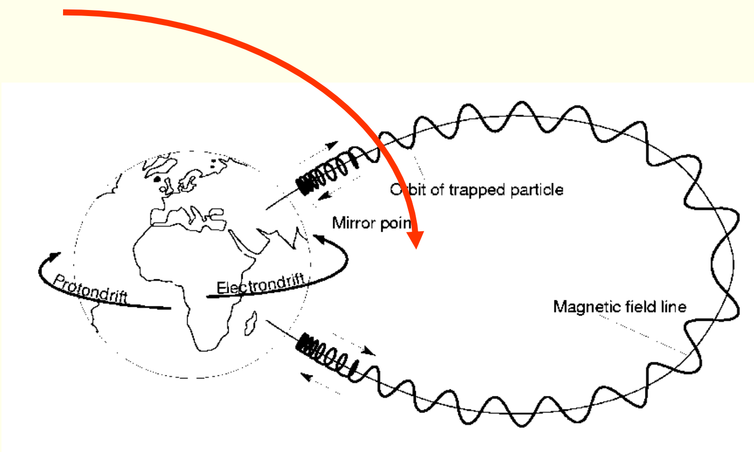
Shielding if

$$r = \frac{p_\perp}{qB} < L$$

What will be the maximum energy of cosmic ray particles that will be shielded?

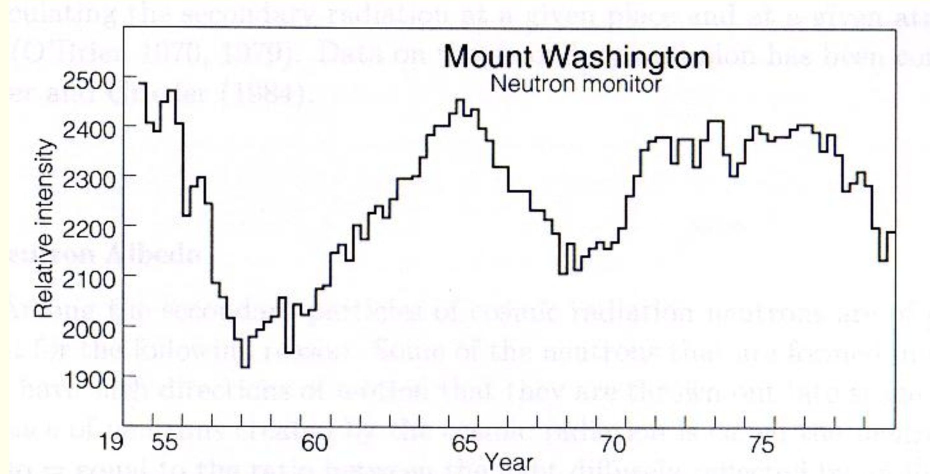
Effect of magnetic field

- Cosmic radiation is affected by magnetic field, as all he smaller the gyro radius, the more difficult it is for the particle to reach Earth.



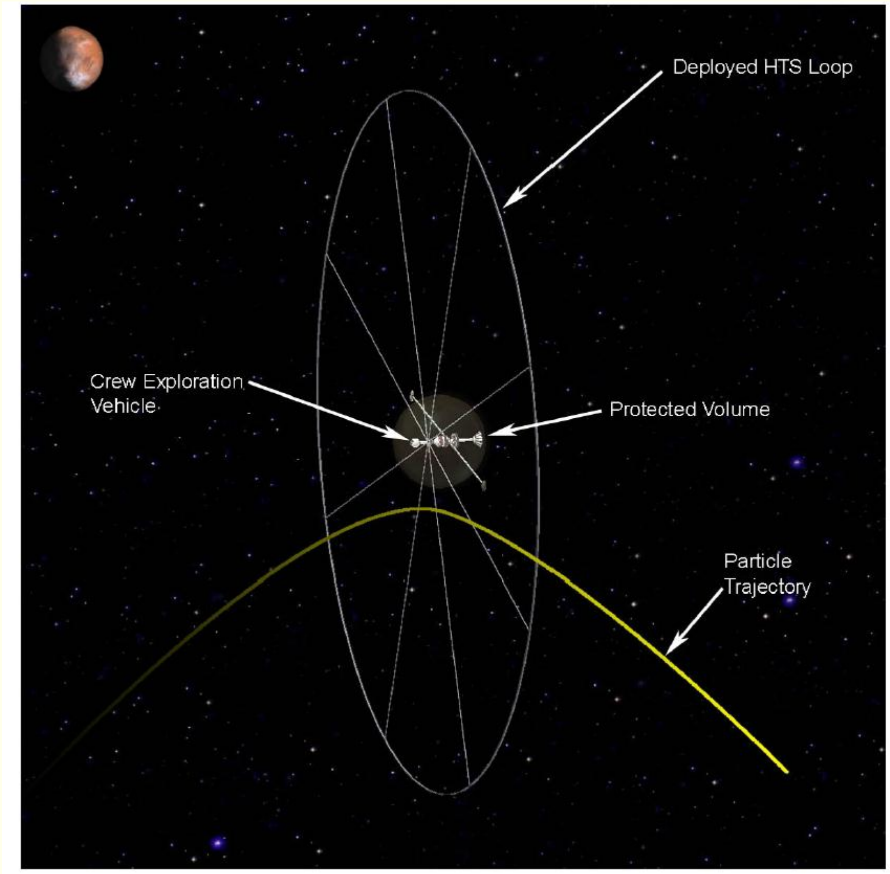
- Gyro radius is r = p/(eZB). Define rigidity:

$$P = pc/(eZ)$$



- Temporal variations:
  - –27 days (IMF, solar rotation)
  - –11 years (IMF, solar cycle)

Artificial magnetic shielding of spacecraft



Last Minute!

Last Minute!

- What was the most important thing of today's lecture? Why?
- What was the most unclear or difficult thing of today's lecture, and why?
- Other comments