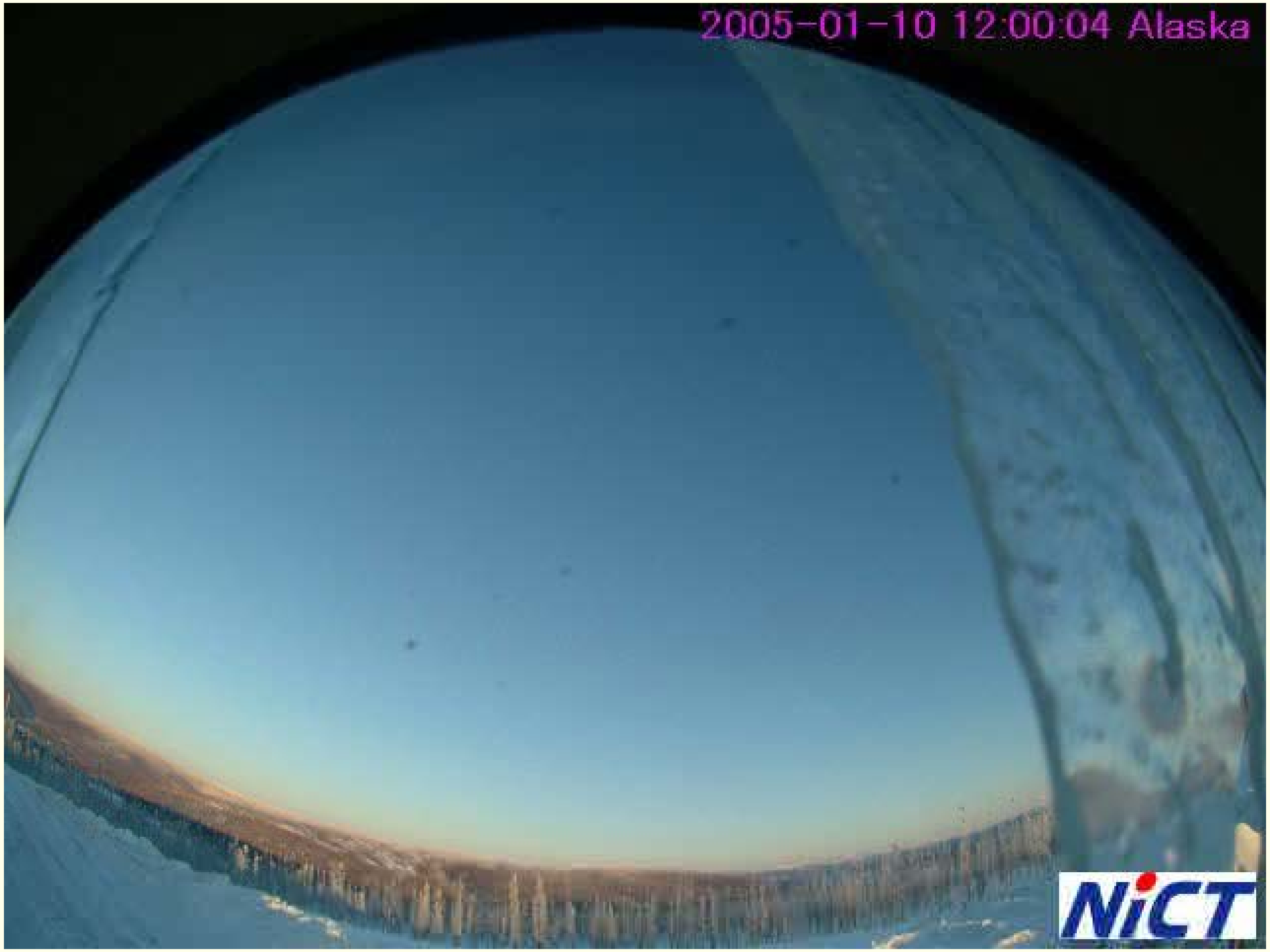
Last lecture (7)

- Particle motion in magnetosphere
- Aurora

Today's lecture (8)

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

The aurora

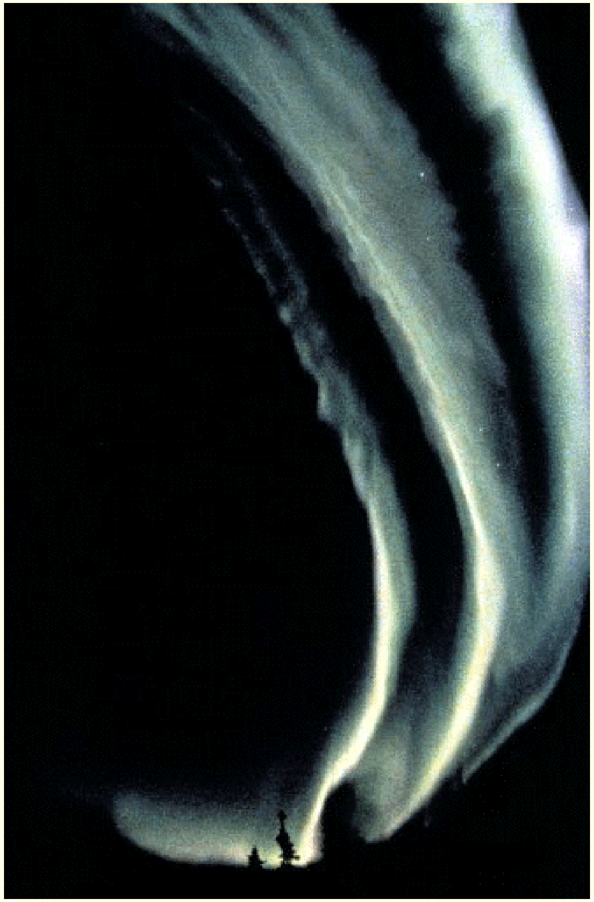


The aurora

The aurora

The aurora

Homogenous auroral arcs

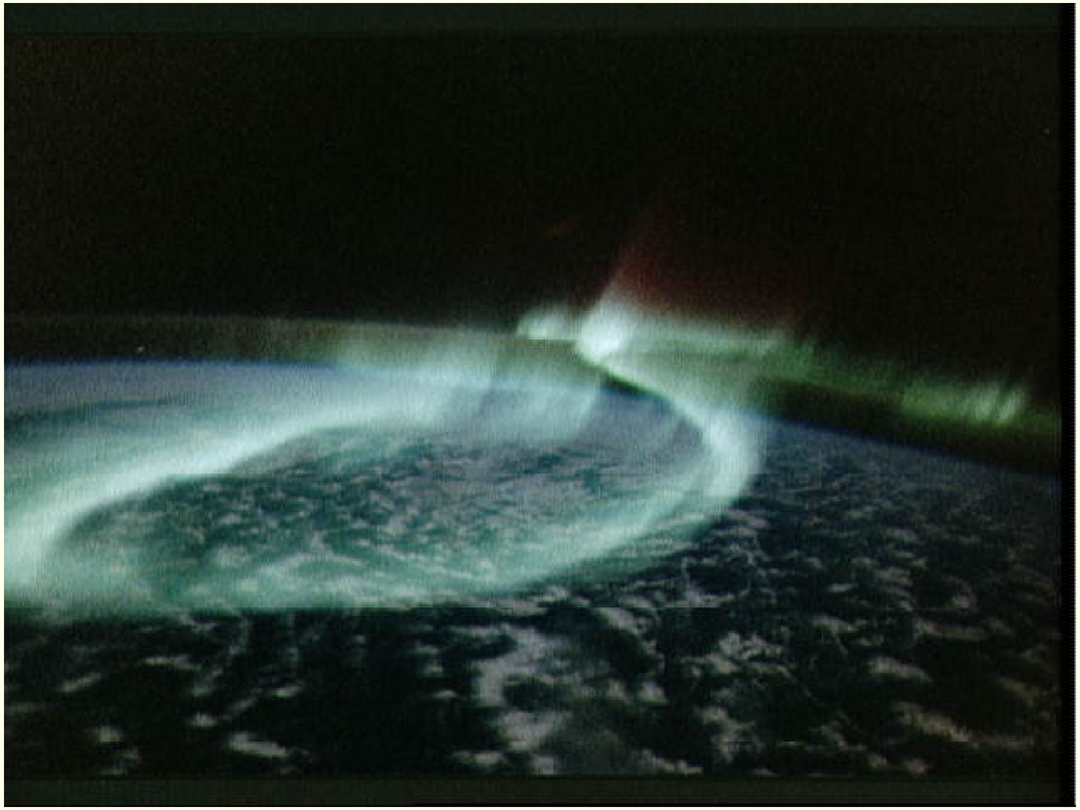


Rays, curtains

Rays are formed in the direction of the local magnetic field.

Drapes develop from homogenous arcs, often when they increase in intensity.

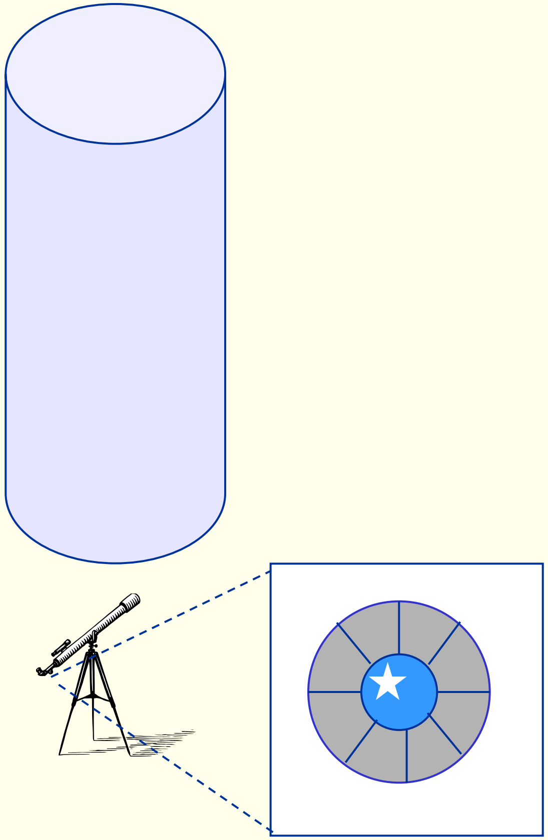
Auroral spirals



Develop when arcs become unstable

Auroral corona

Geometric effect of perspective when you look towards magnetic zenith. Compare the figure.



Aurora - altitude

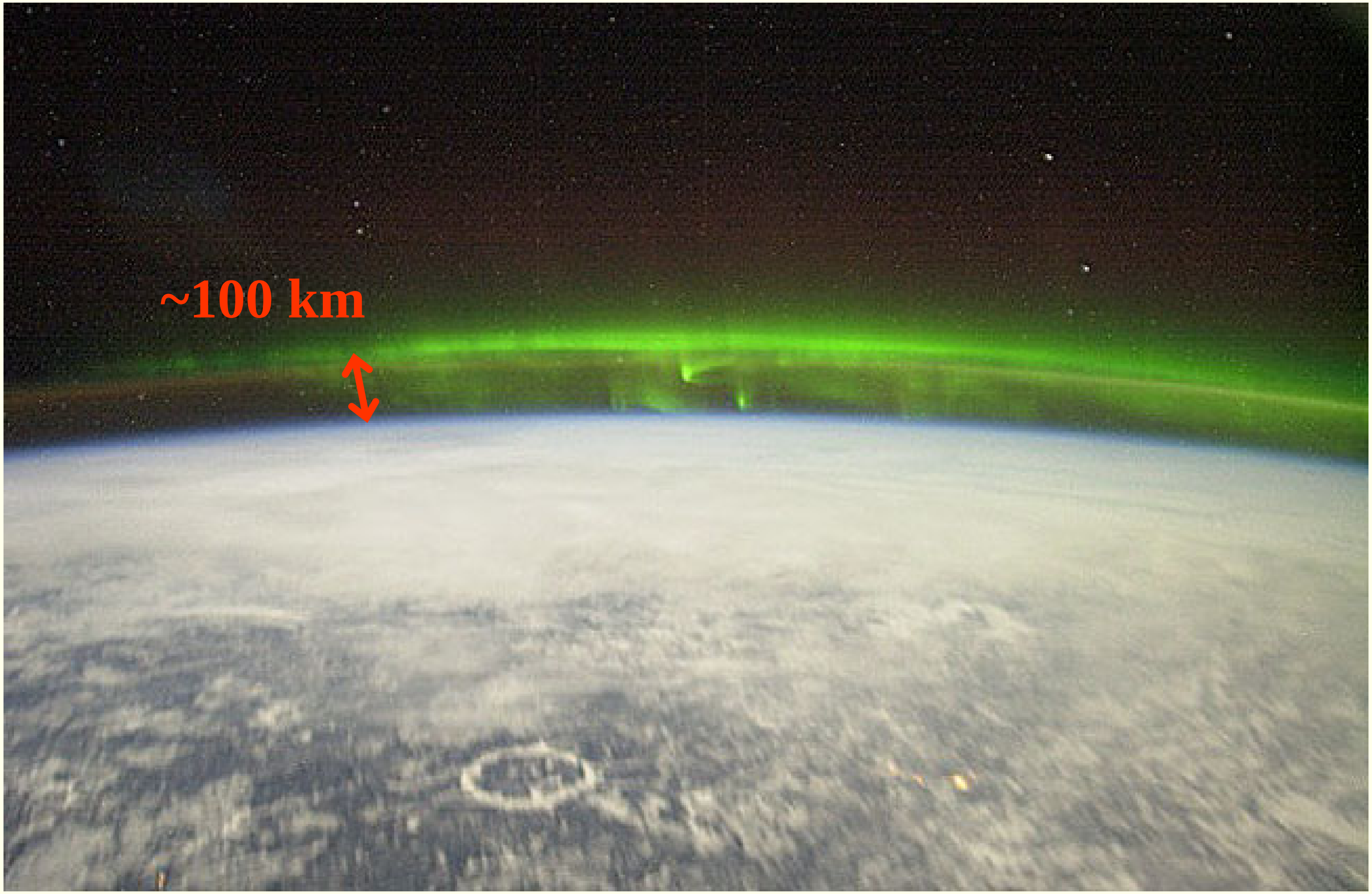


Foto from International Space Station

Early notions

Woodcut from Böhmen 1570.

Anders Celsius documented that compass needles where strongly affected during auroral activity in 1733.

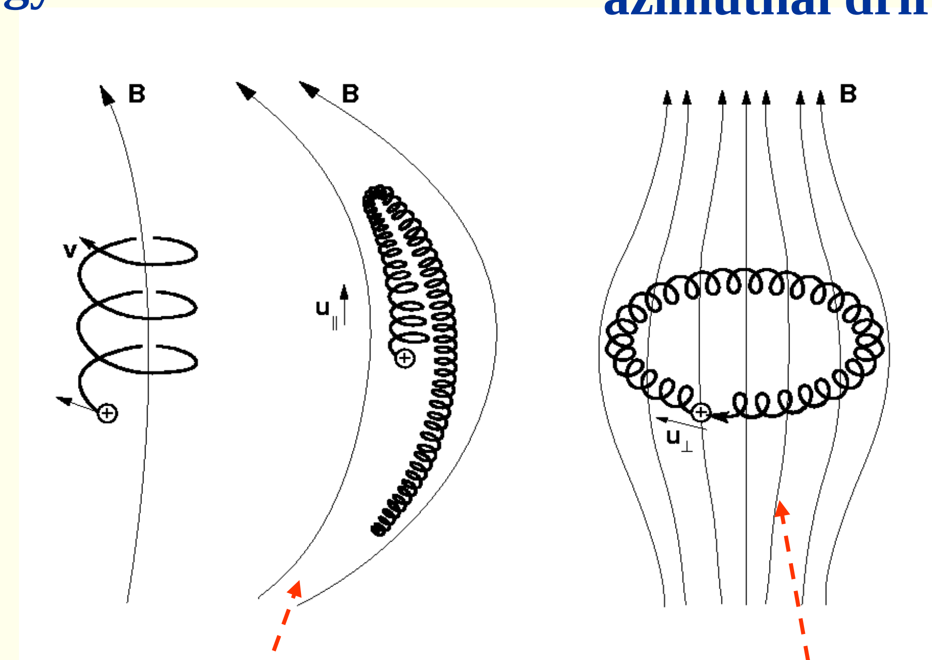
What causes the aurora?

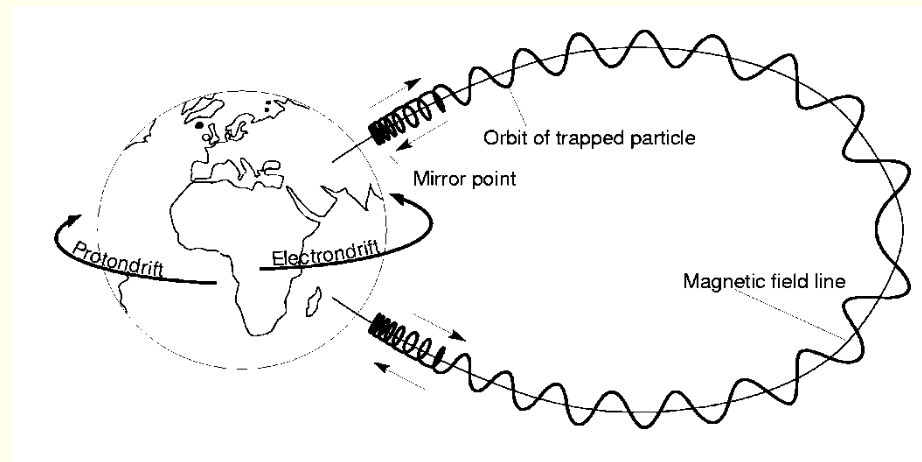
Particle motion in geomagnetic field

longitudinal oscillation

gyration

azimuthal drift

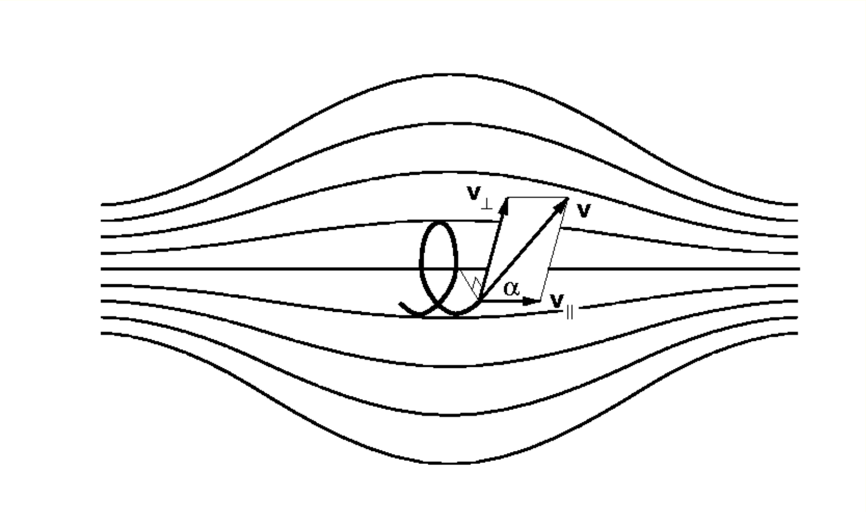




Magnetic mirror

grad B drift

Magnetic mirror



$mv^2/2$ constant (energy conservation) →

$$\frac{\sin^2\alpha}{B} = konst$$

particle turns when α = 90° →

$$B_{turn} = B/\sin^2\alpha$$

If maximal B-field is B_{max} a particle with pitch angle α can only be turned around if

$$B_{turn} = B/\sin^2\alpha \le B_{max}$$ →

$$\alpha > \alpha_{lc} = \arcsin\sqrt{B/B_{max}}$$

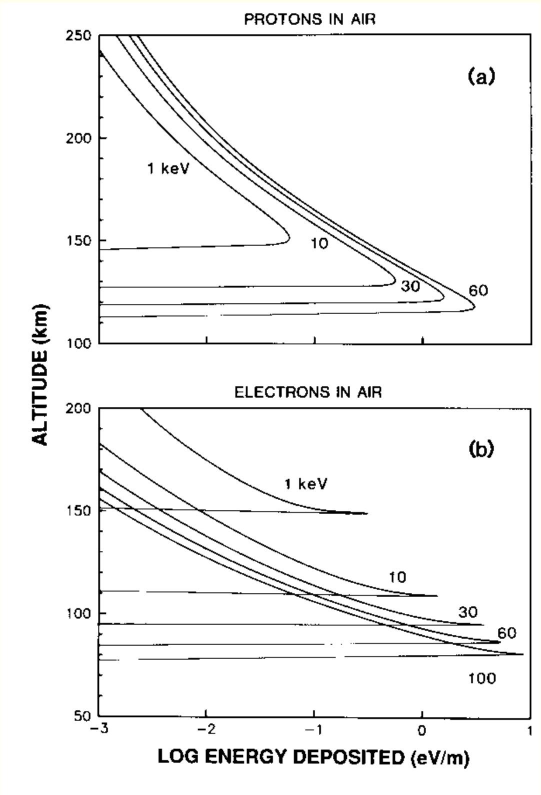
The magnetic moment μ is an ***adiabatic invariant***.

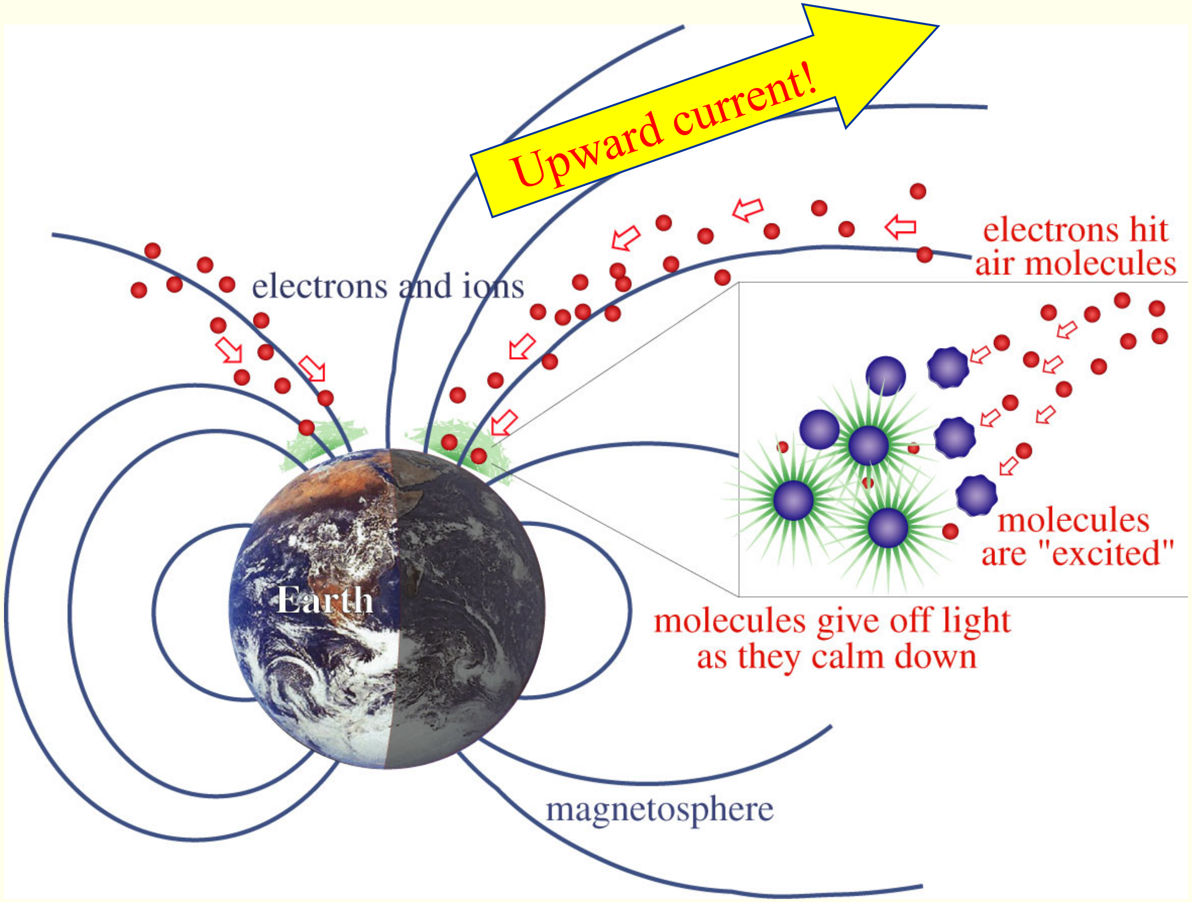
$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2\sin^2\alpha}{2B}$$

Particles in ***loss cone*** :

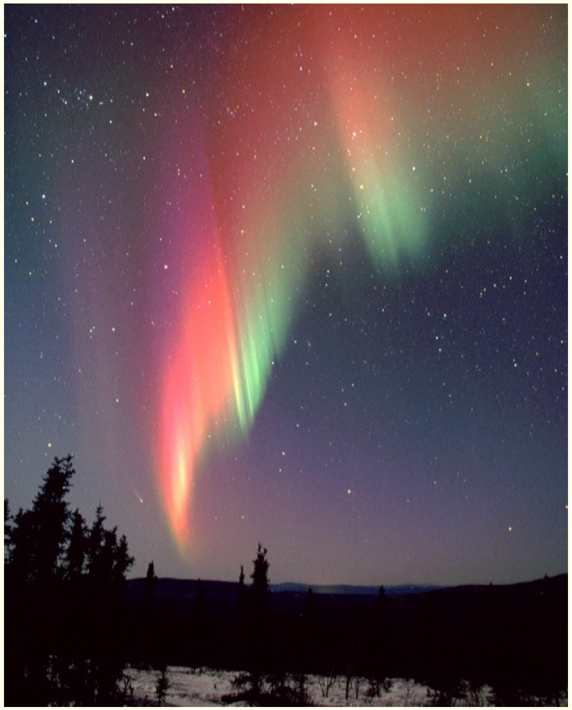
$$\alpha < \alpha_{lc}$$

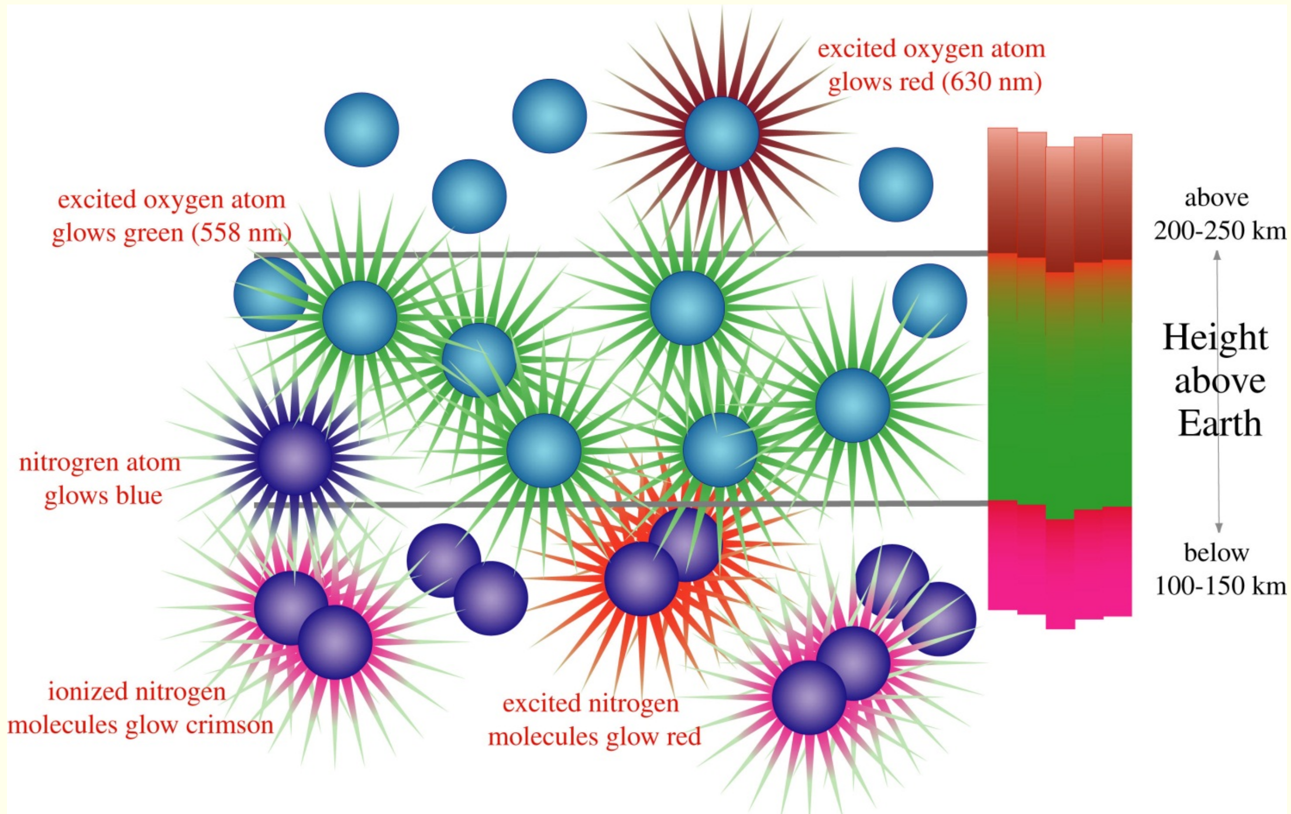
Collisions - emissions





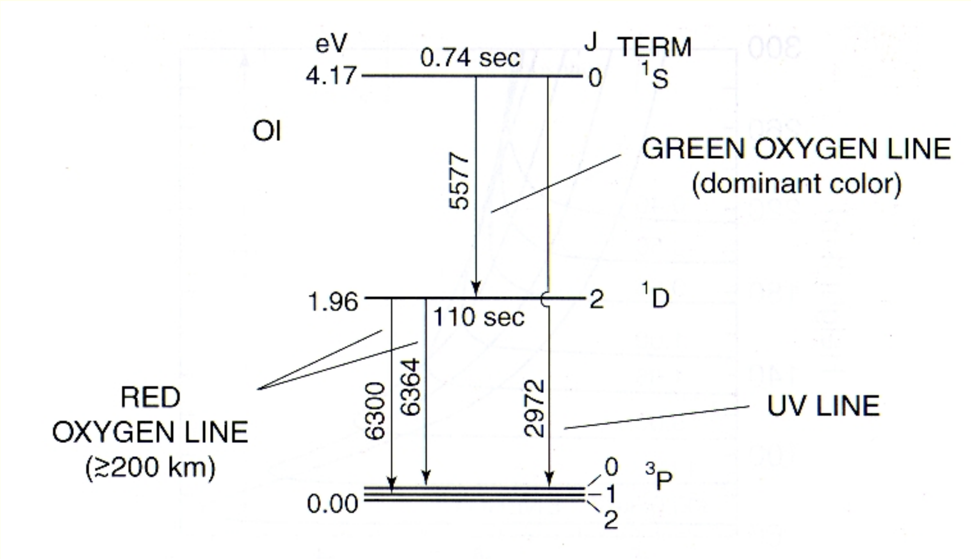
Emissions

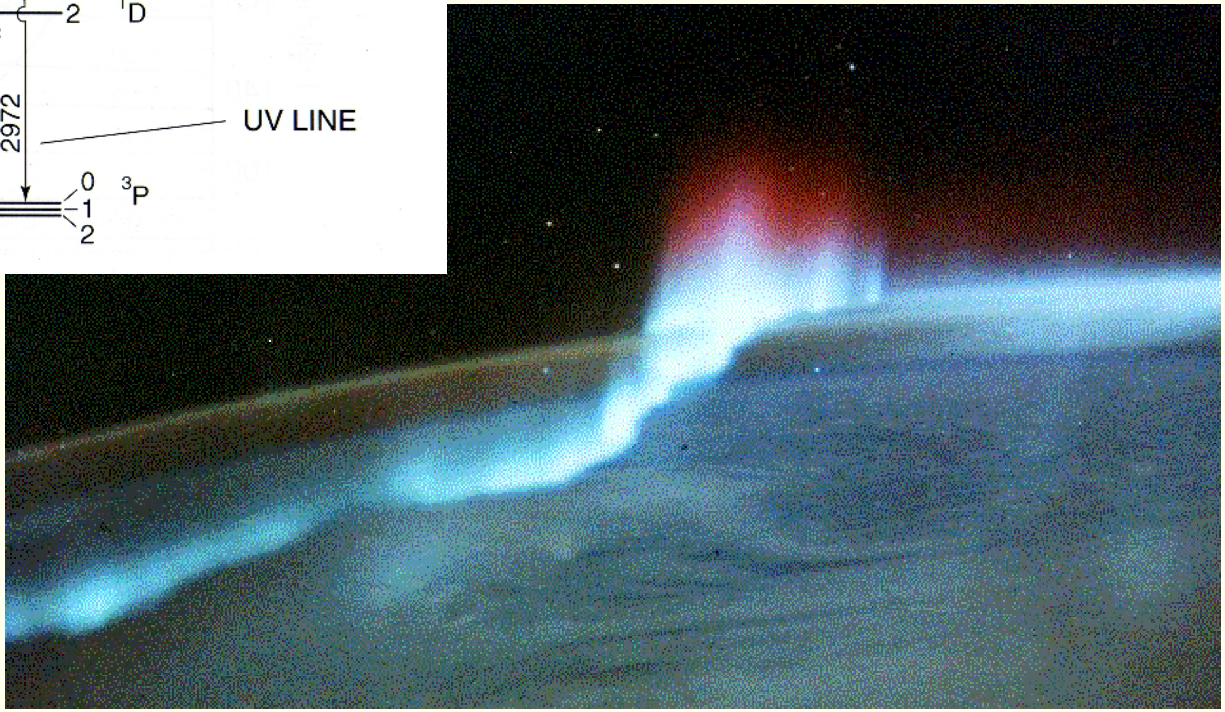




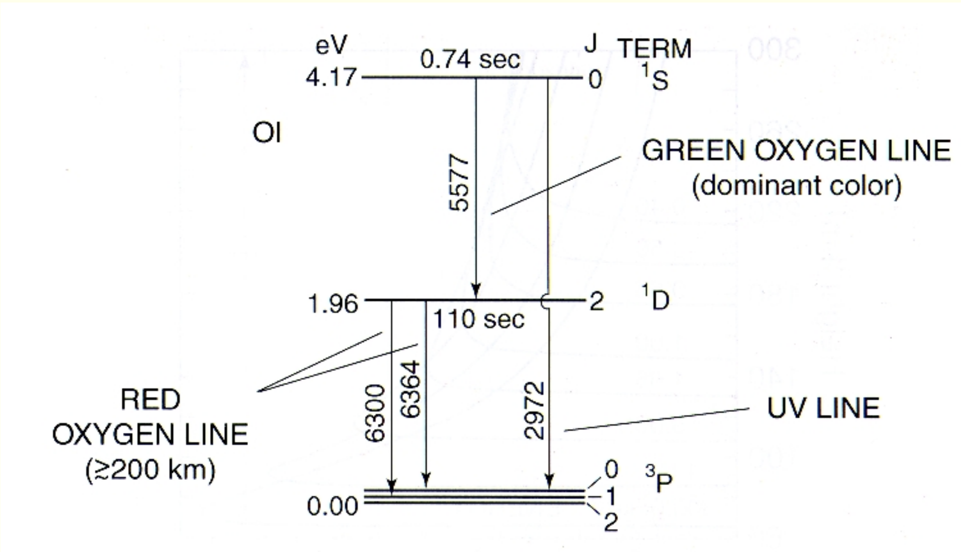
excited oxygen atom
glows red (630 nm)
excited oxygen atom
glows green (558 nm)
nitrogren atom
glows blue
ionized nitrogen
molecules glow crimson
excited nitrogen
molecules glow red
above
200-250 km
Height
above
Earth
below
100-150 km

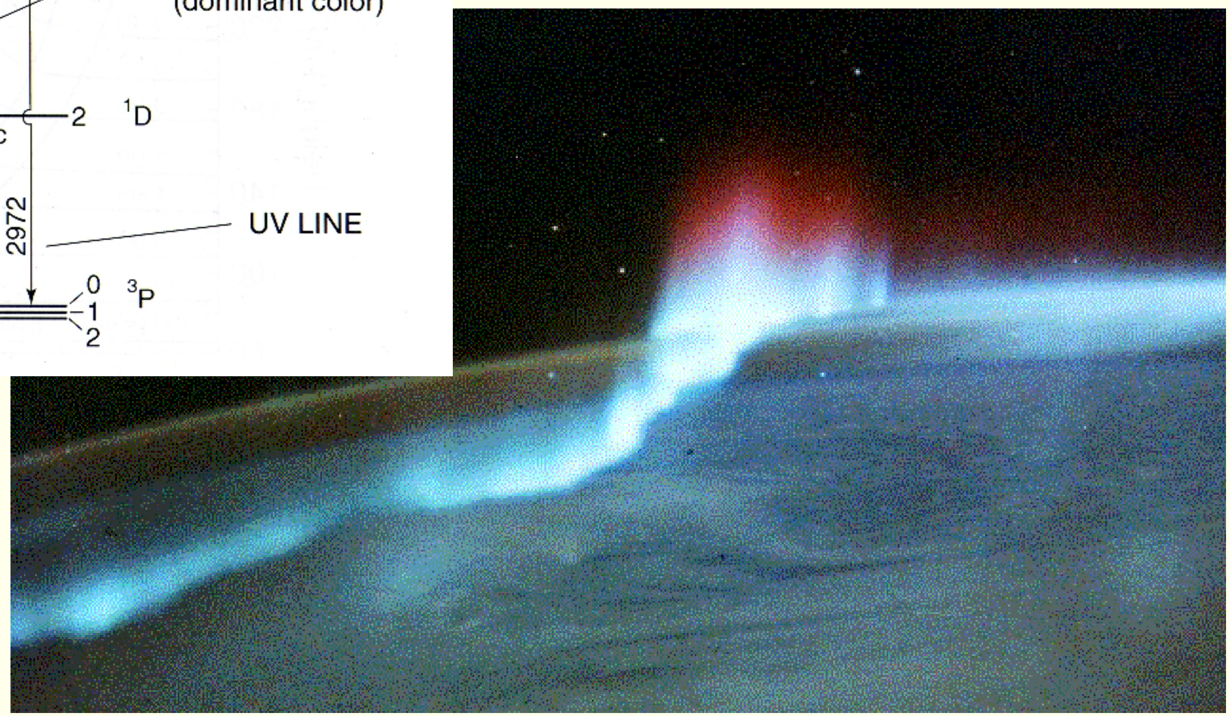
Oxygen emissions



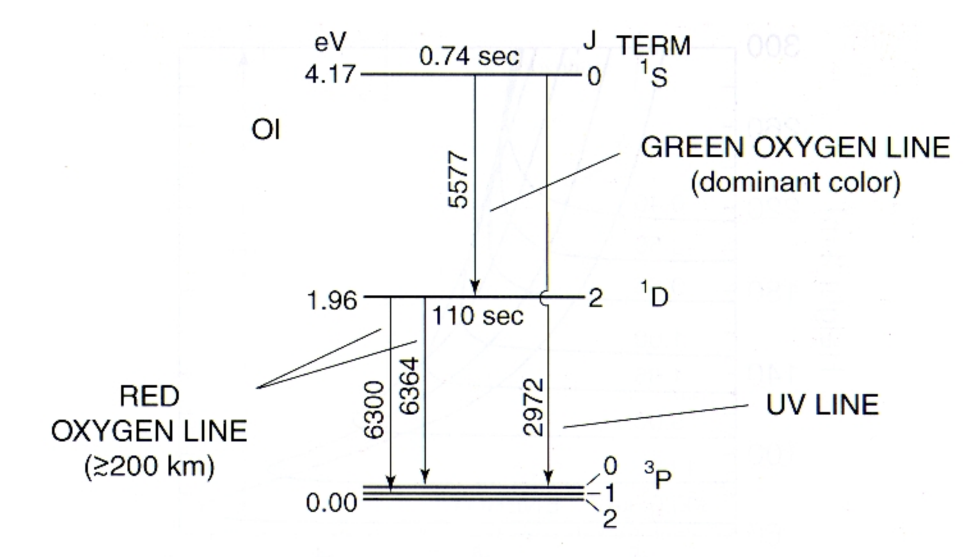


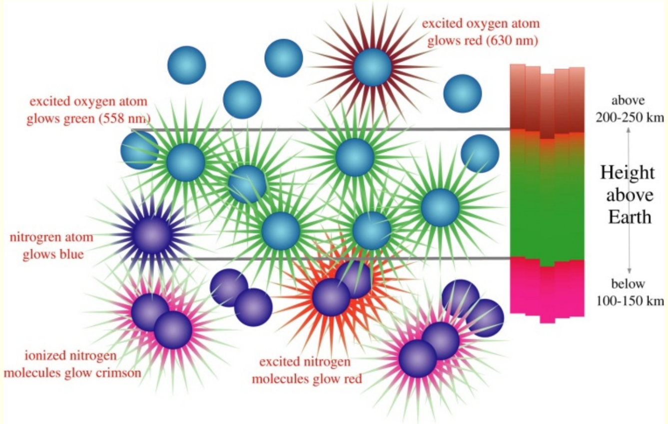
Why is there no red emissions at lower altitude?

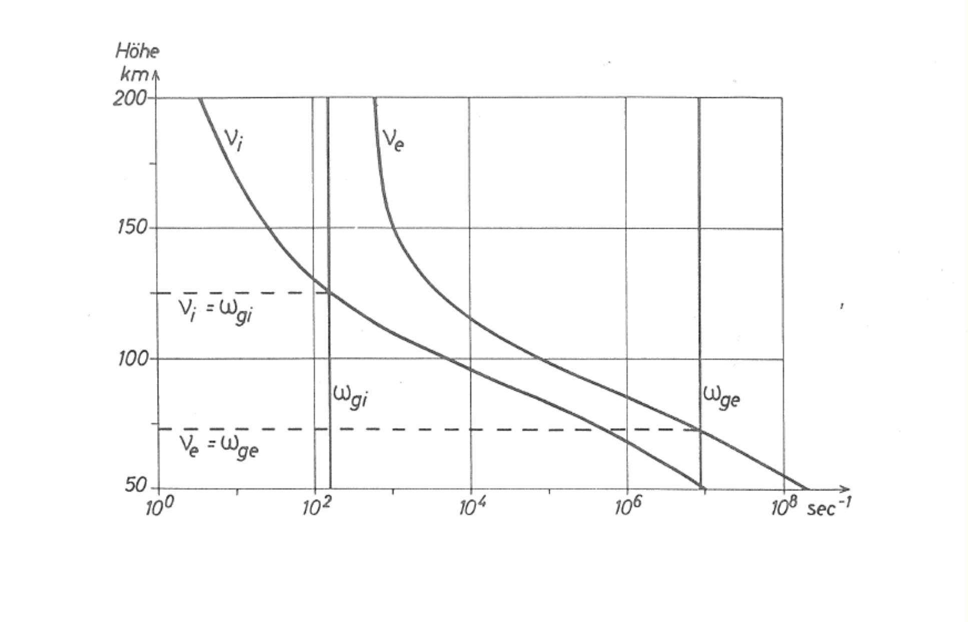




Oxygen emissions







The red emission line is suppressed by collisions at lower altitudes due the its long transition time. (When an excited atom collides with another atom, is is de-excited without any emission.)

Larger scales

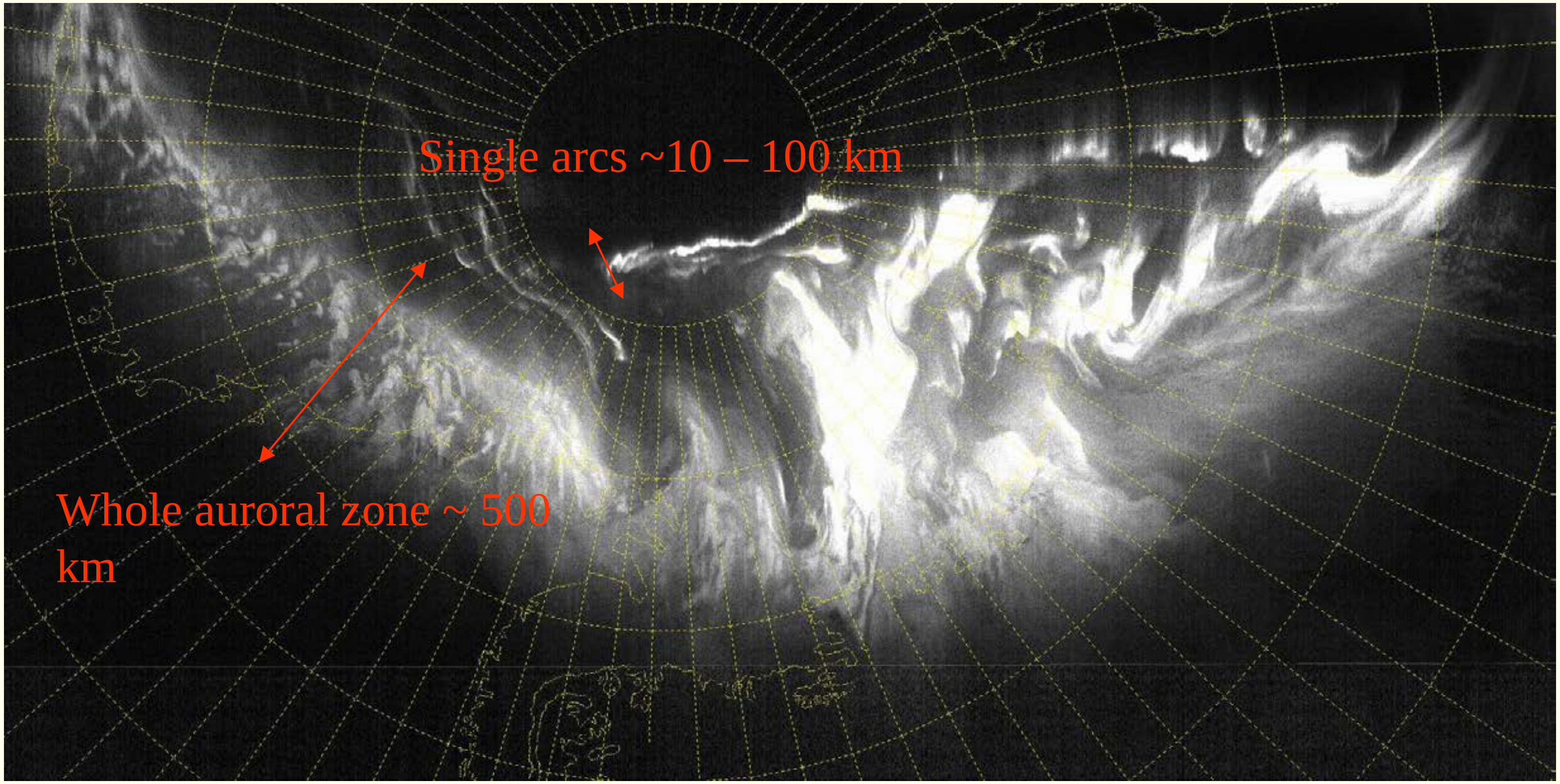
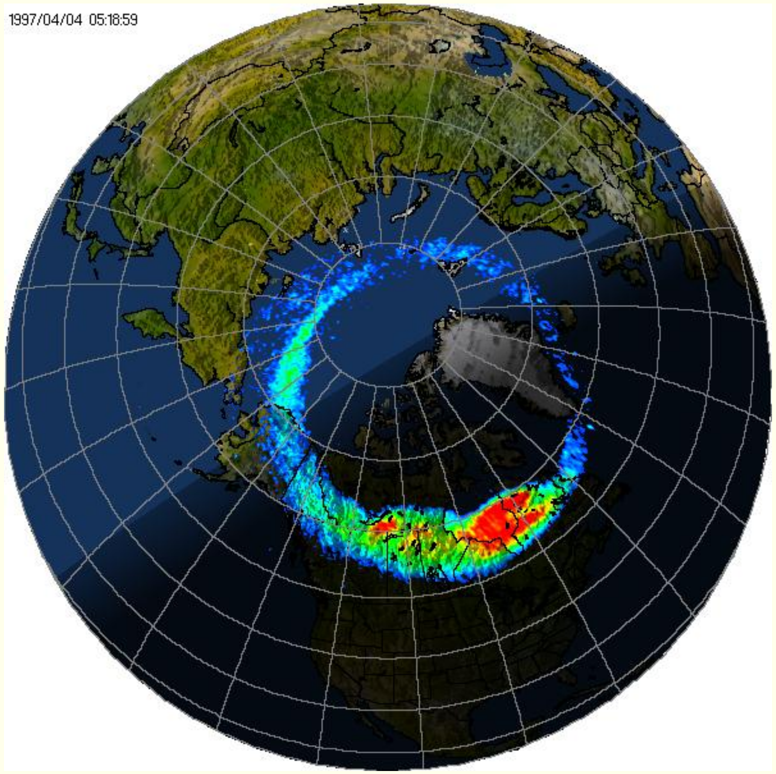
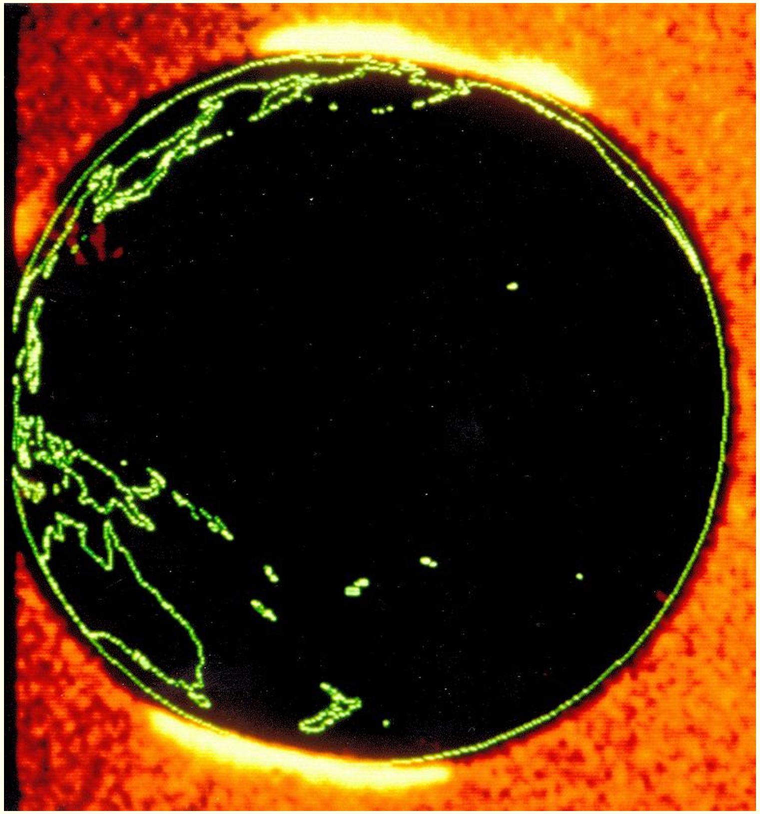


Foto från DMSP-satelliten

Auroral ovals



Polar

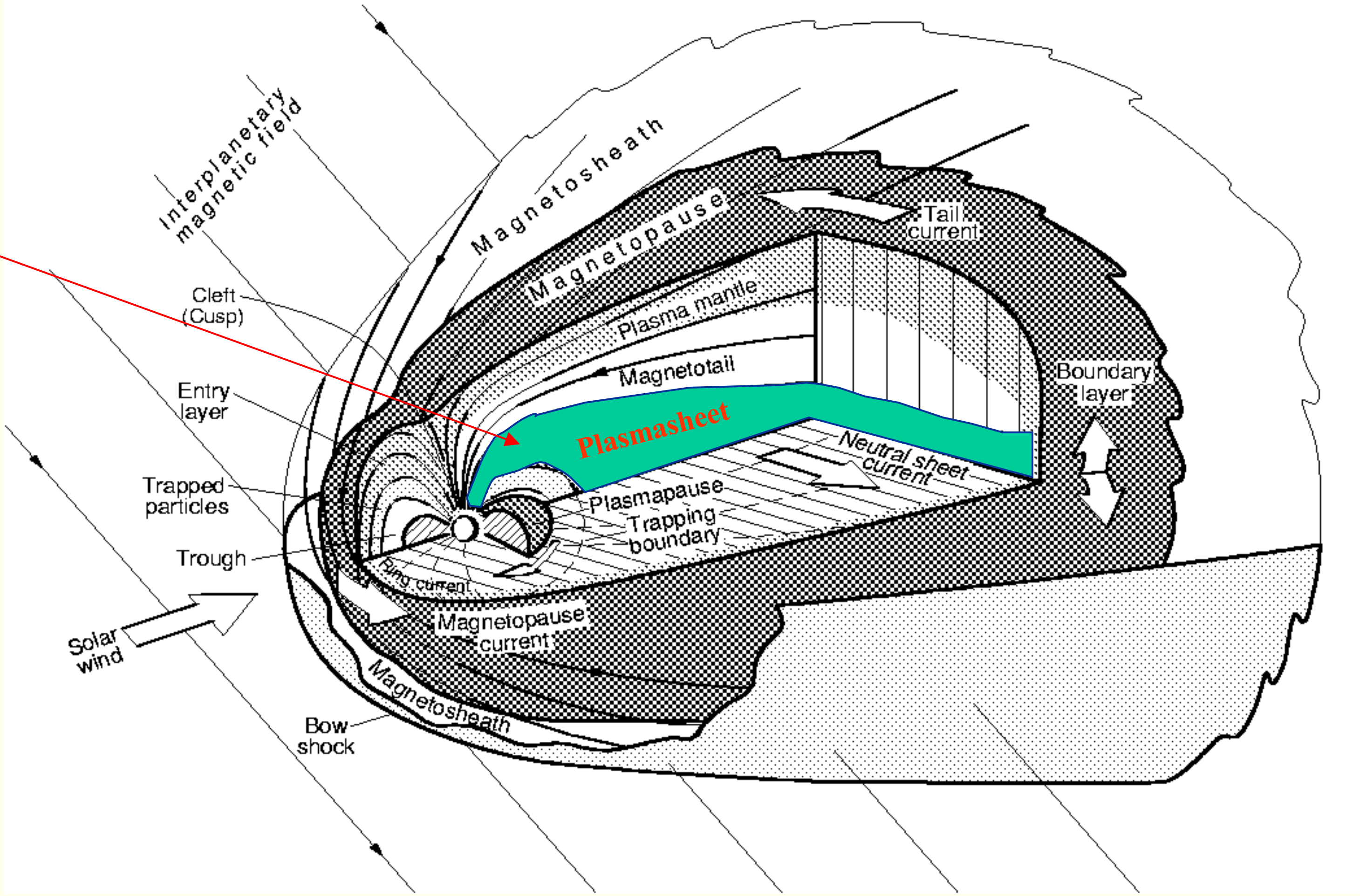


Dynamics Explorer

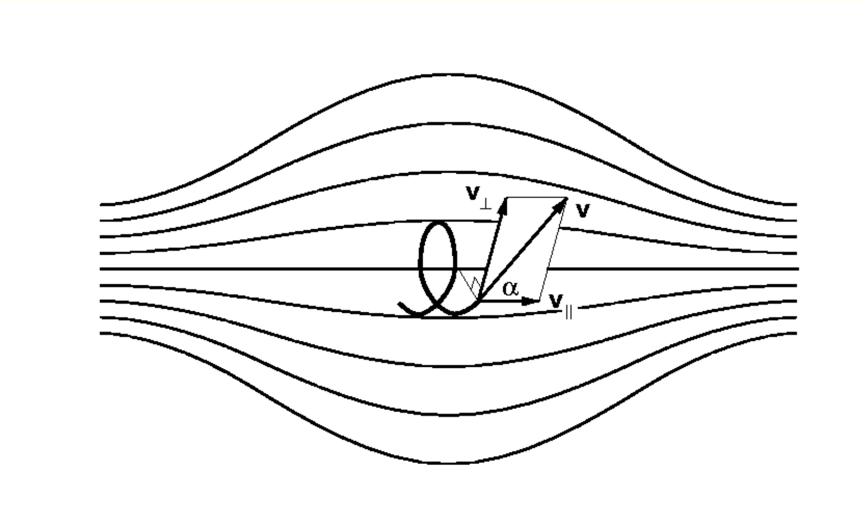
The auroral oval is the projection of the plasmasheet onto the atmosphere

Mystery!

The particles in the plasmasheet do not have high enough energy to create aurora visible to the eye.



Magnetic mirror



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Particles in ***loss cone*** :

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The magnetic moment μ is an ***adiabatic invariant***.

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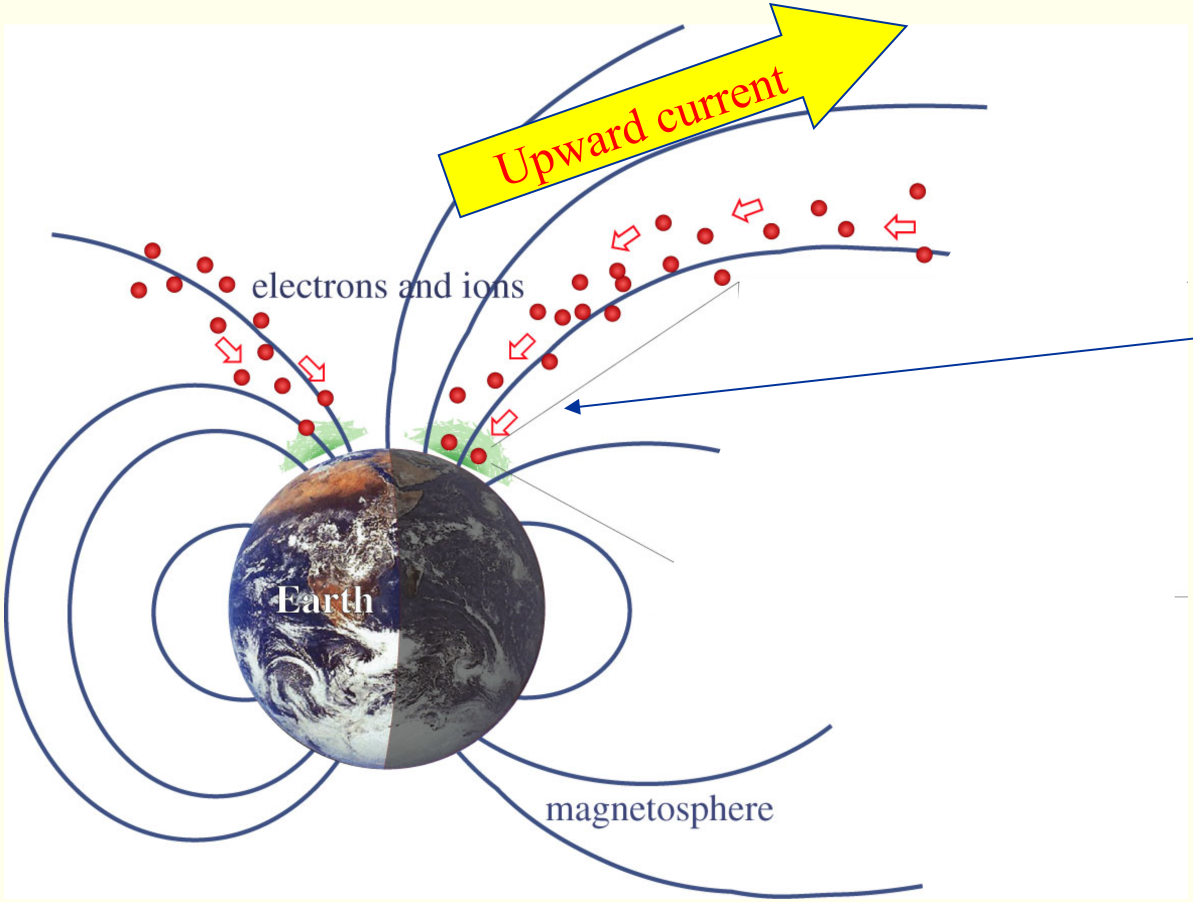
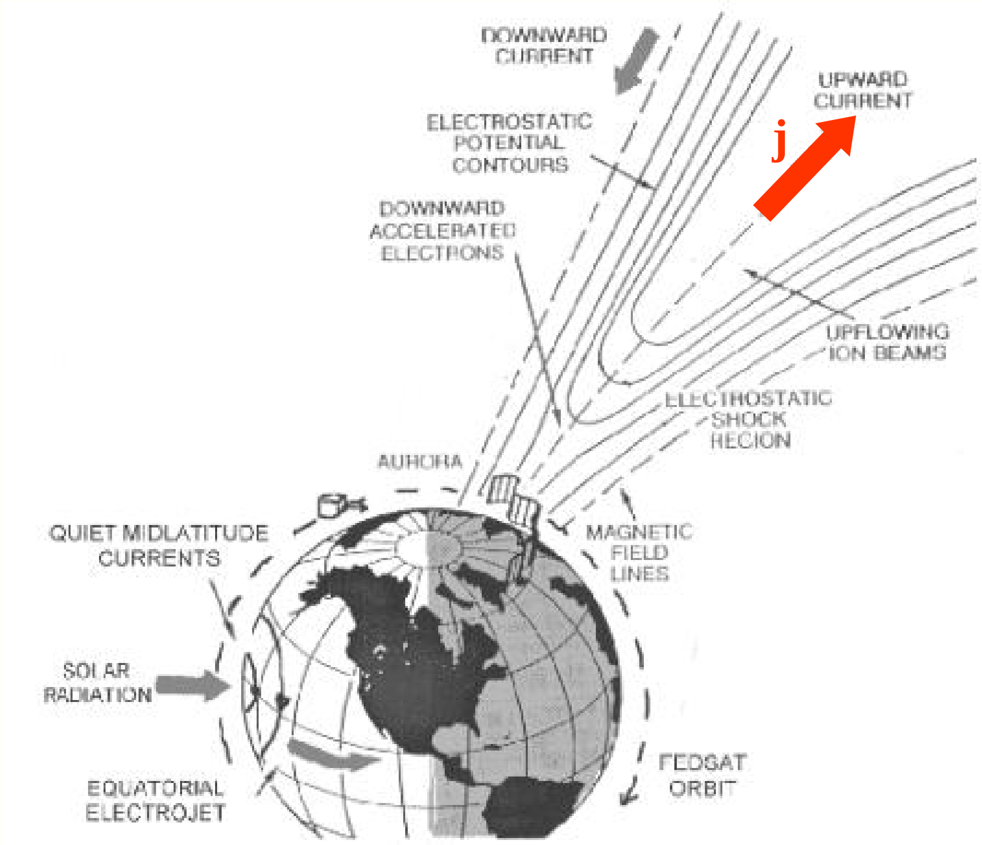
Why particle acceleration?



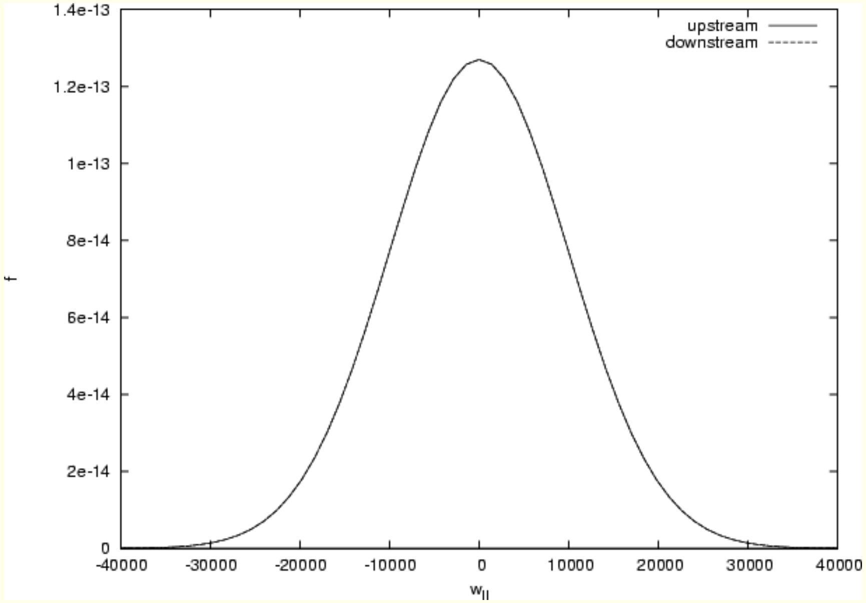
- The magnetosphere often seems to act as a current generator.
- The lower down you are on the field line, the more particles have been reflected by the magnetic mirror.
- At low altitudes there are not enough electrons to carry the current.

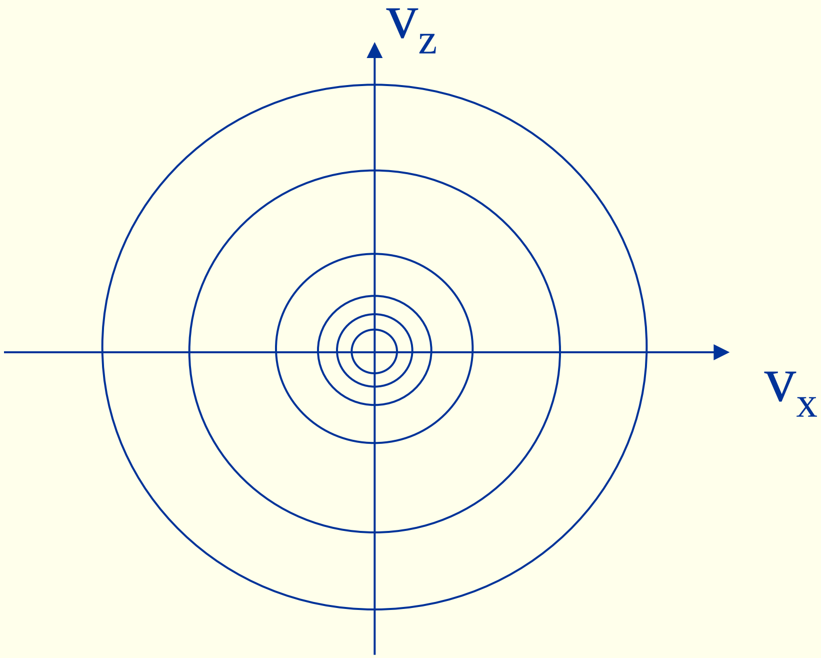
Why particle acceleration?



- Electrons are accelerated downwards by upward E-field.
- This increases the pitch-angle of the electrons, and more electrons can reach the ionosphere, where the current can be closed.

Distribution function

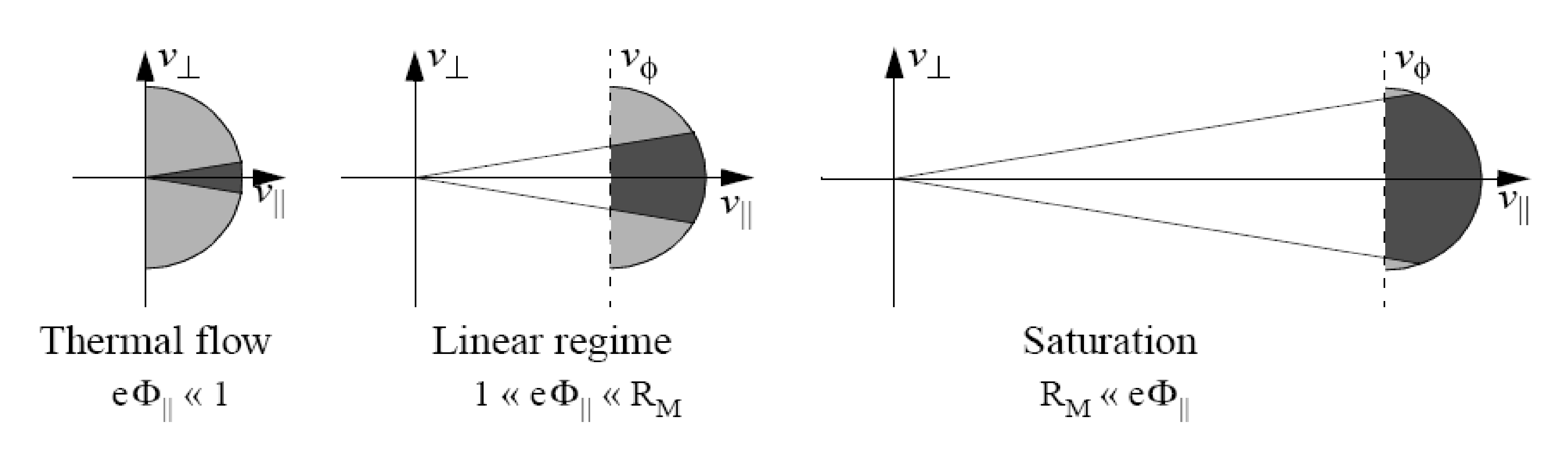




Example:
Maxwellian distribution

$$f = \frac{n}{\sqrt{(2\pi RT)^3}} \exp\left(-\frac{m(v_x^2 + v_y^2 + v_z^2)}{2kT}\right)$$

Why particle acceleration?



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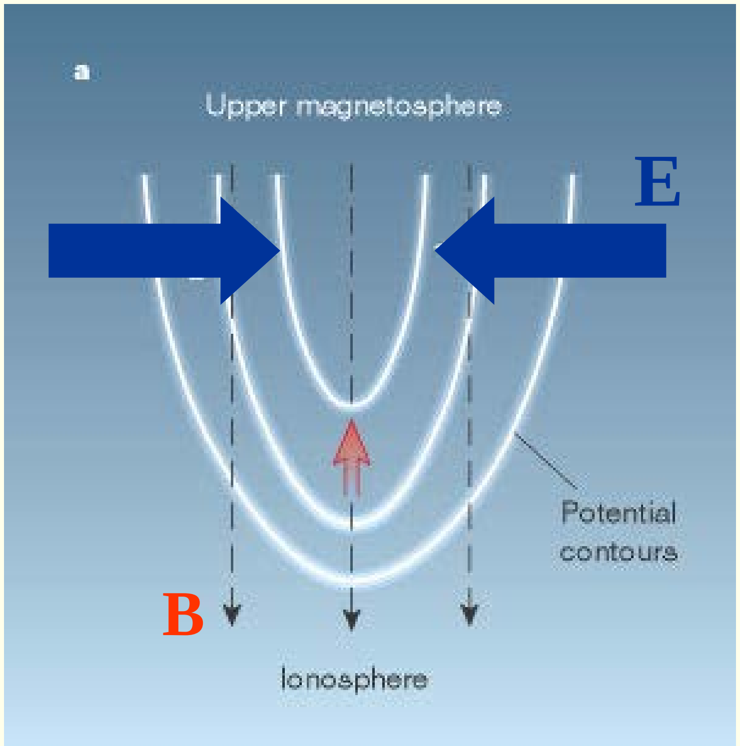
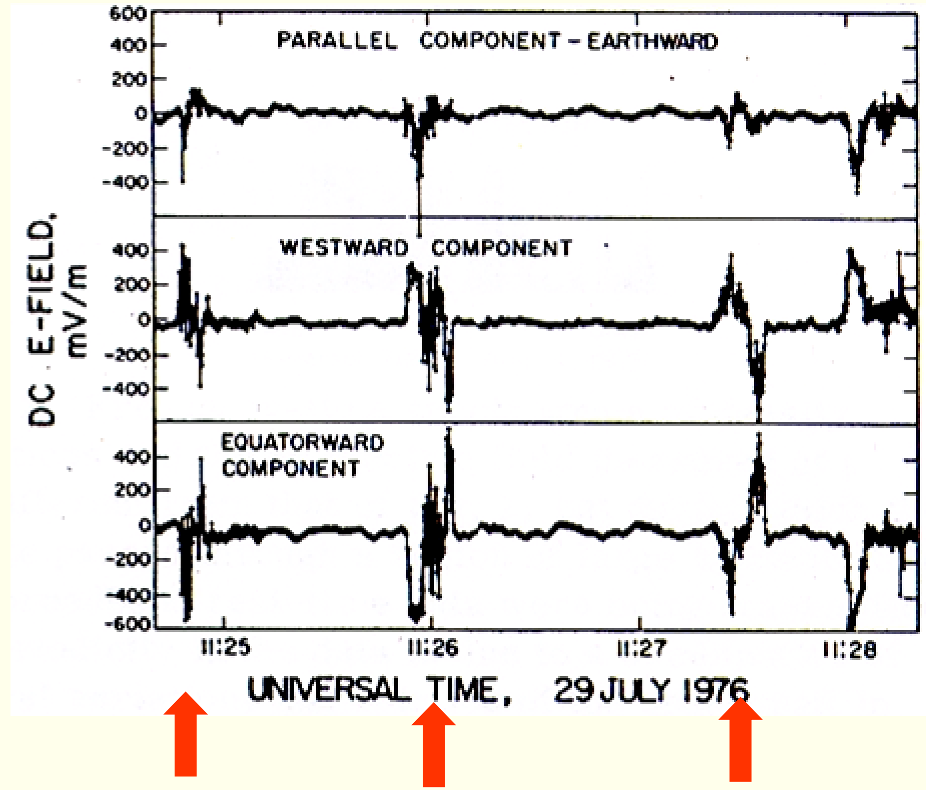
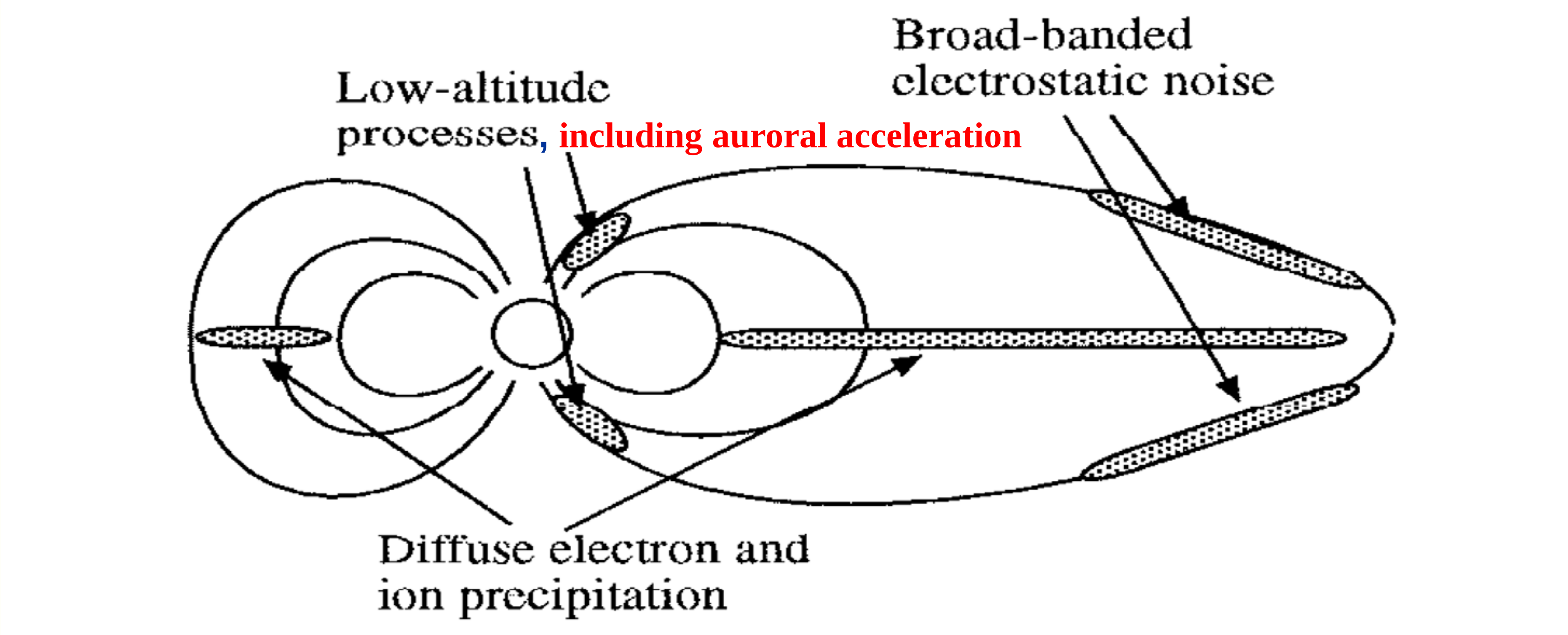
Satellite signatures of U potential





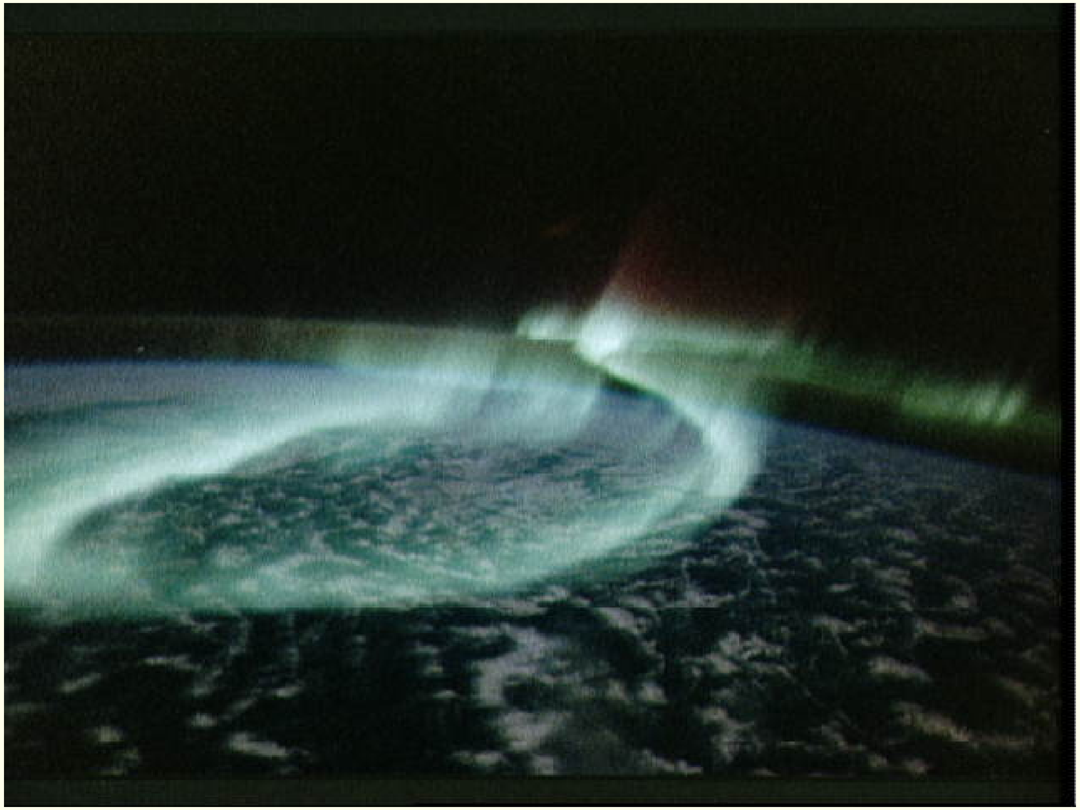
Measurements made by the ISEE satellite (Mozer et al., 1977)

Acceleration regions



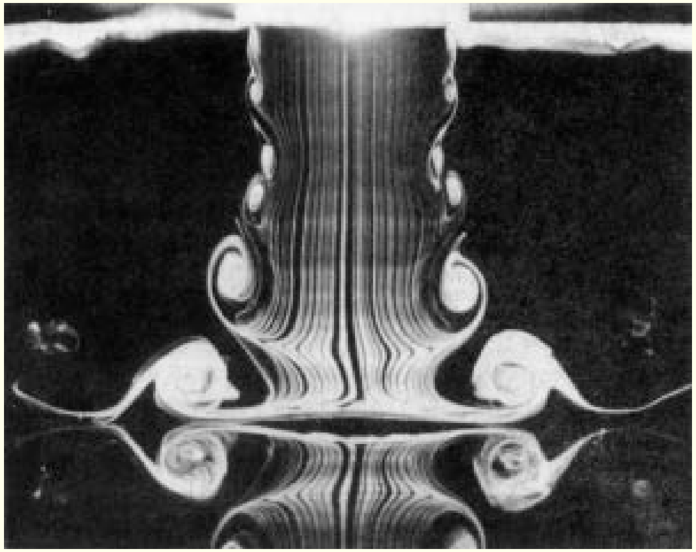
Auroral acceleration region typically situated at altitude of 1-3 R_E

Auroral spirals

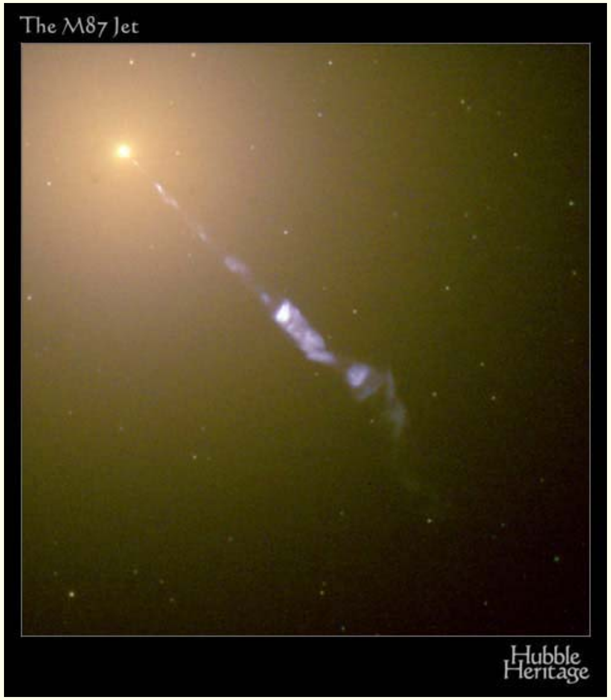


Develop when arcs become unstable

Kelvin-Helmholz-instability – a general phenomenon



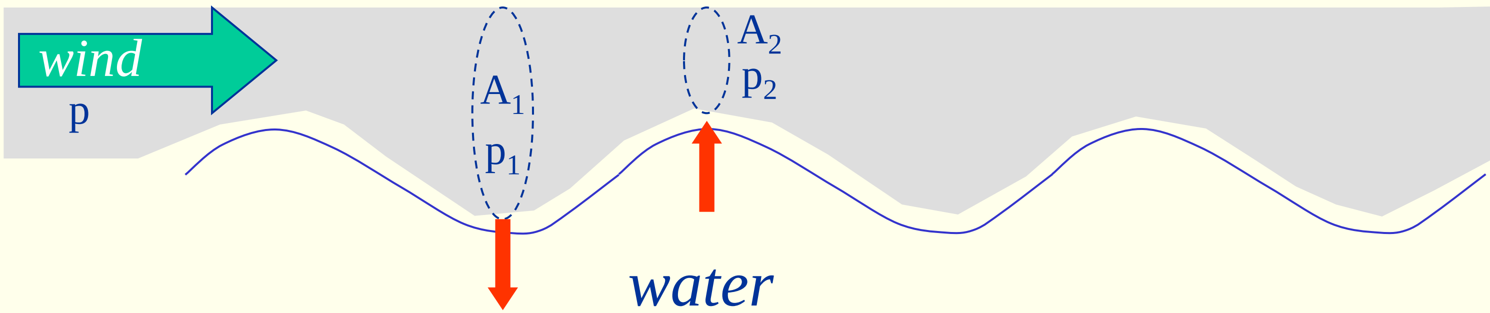
Aero- and fluid dynamics



Extragalactic jet (M87)

Cluds

Kelvin-Helmholz instability
Example: water waves



Continuity equation:

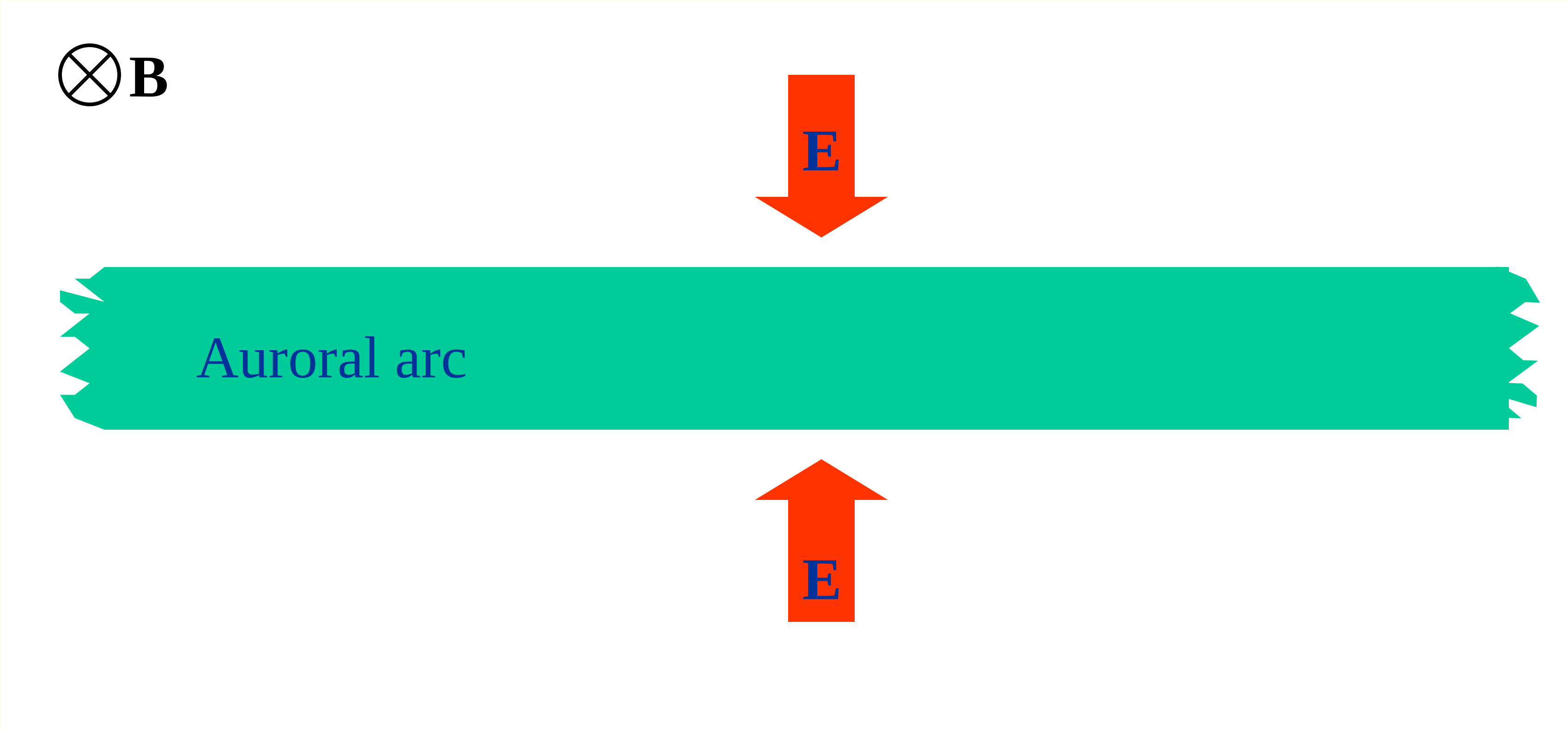
$$A_1 v_1 = A_2 v_2$$

Bernoulli's equation:

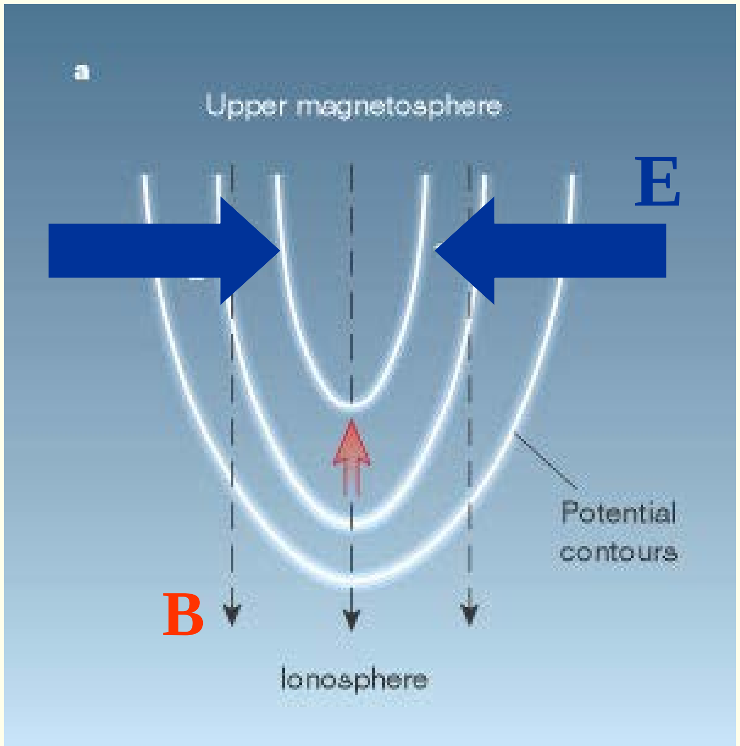
$$p_1 + \rho v_1^2 = p_2 + \rho v_2^2 = const.$$

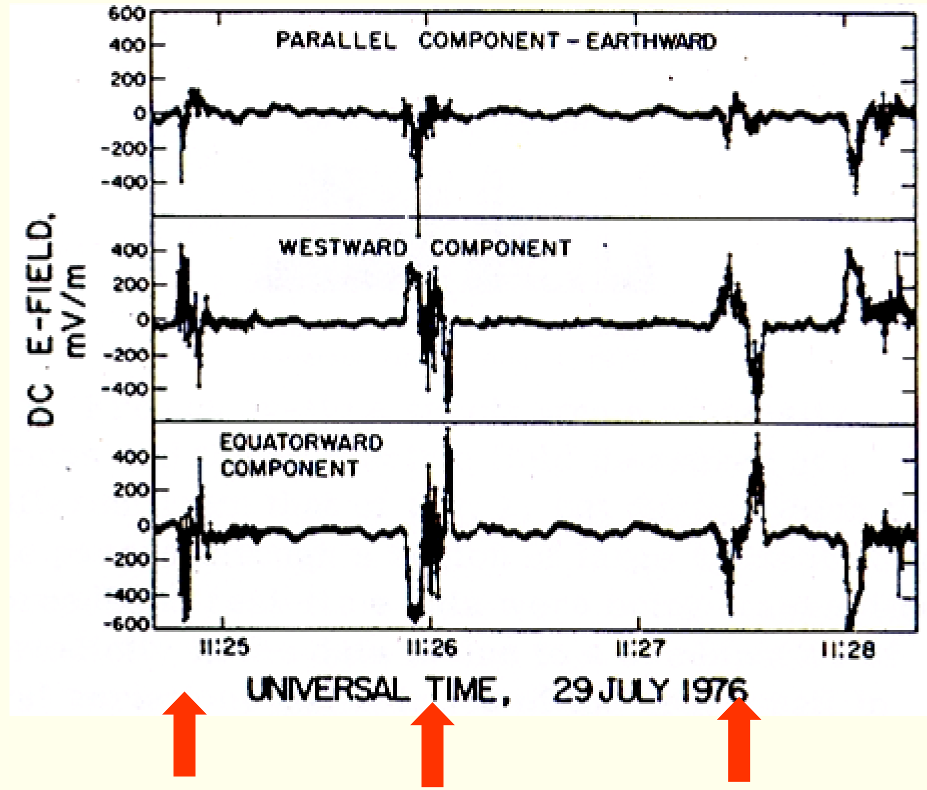
$$\because p_1 > p > p_2$$

Spirals – Kelvin-Helmholz instability



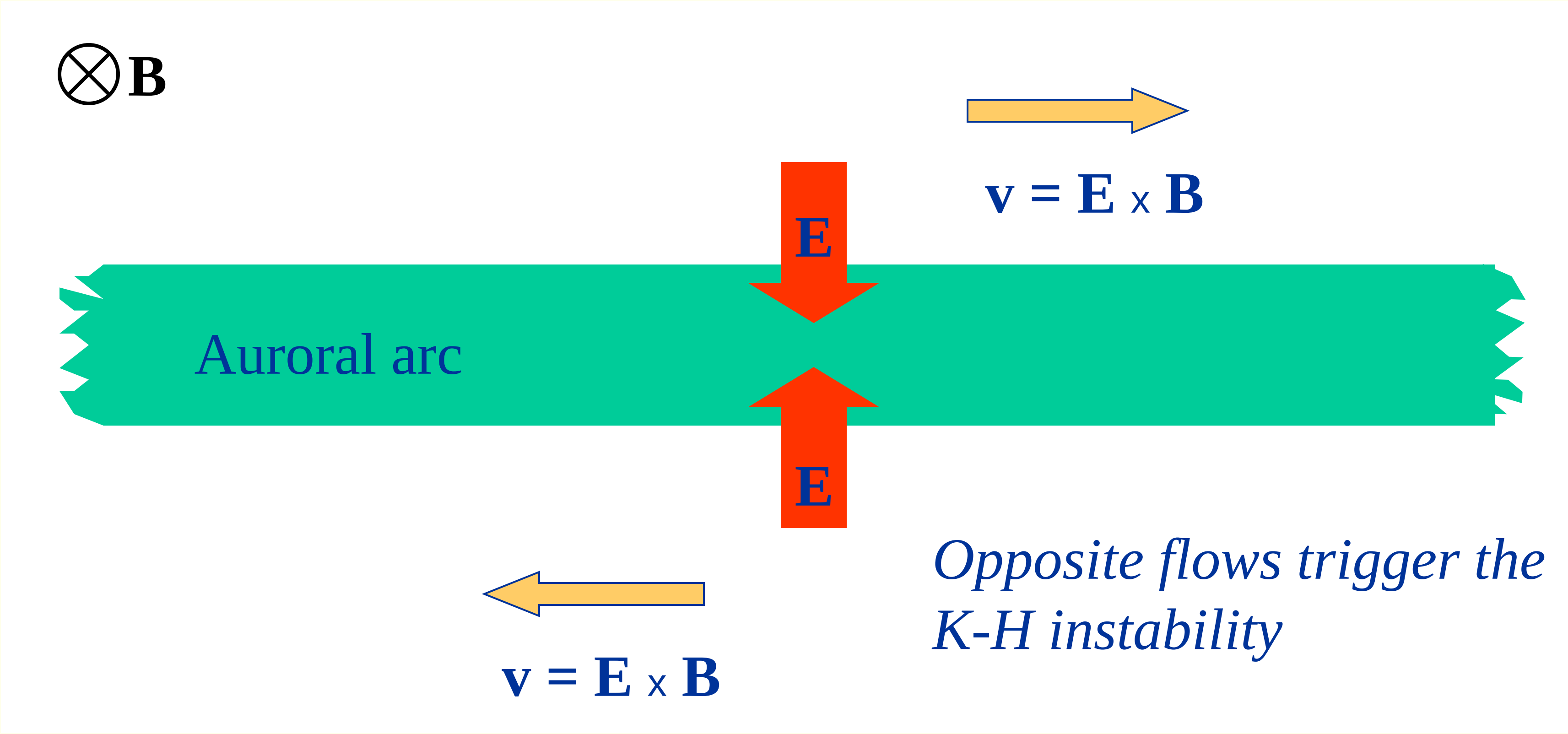
Satellite signatures of U potential



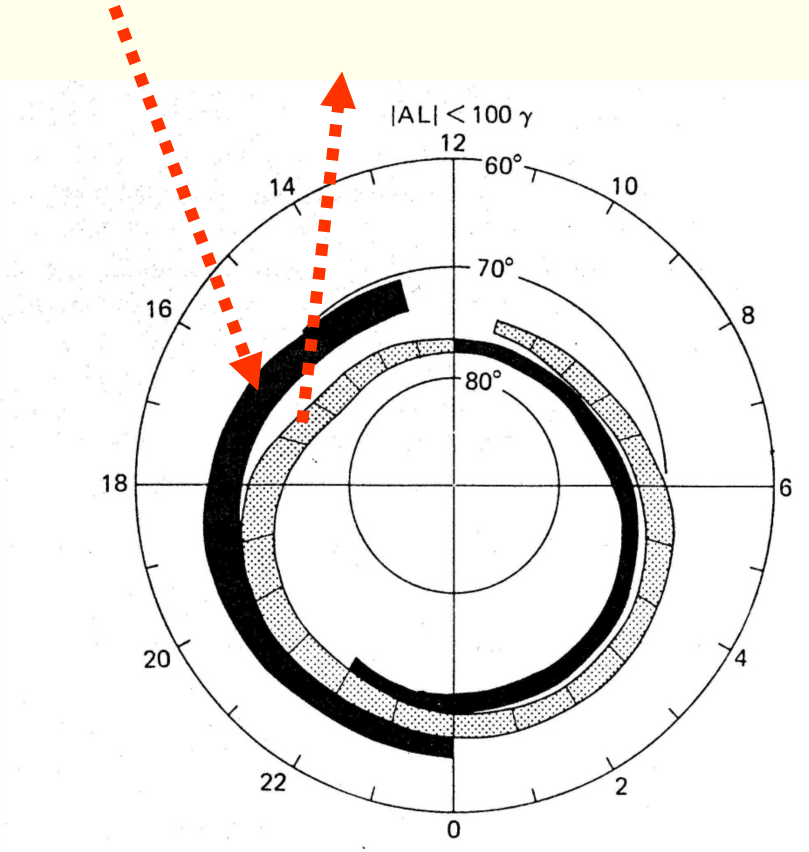


Measurements made by the ISEE satellite (Mozer et al., 1977)

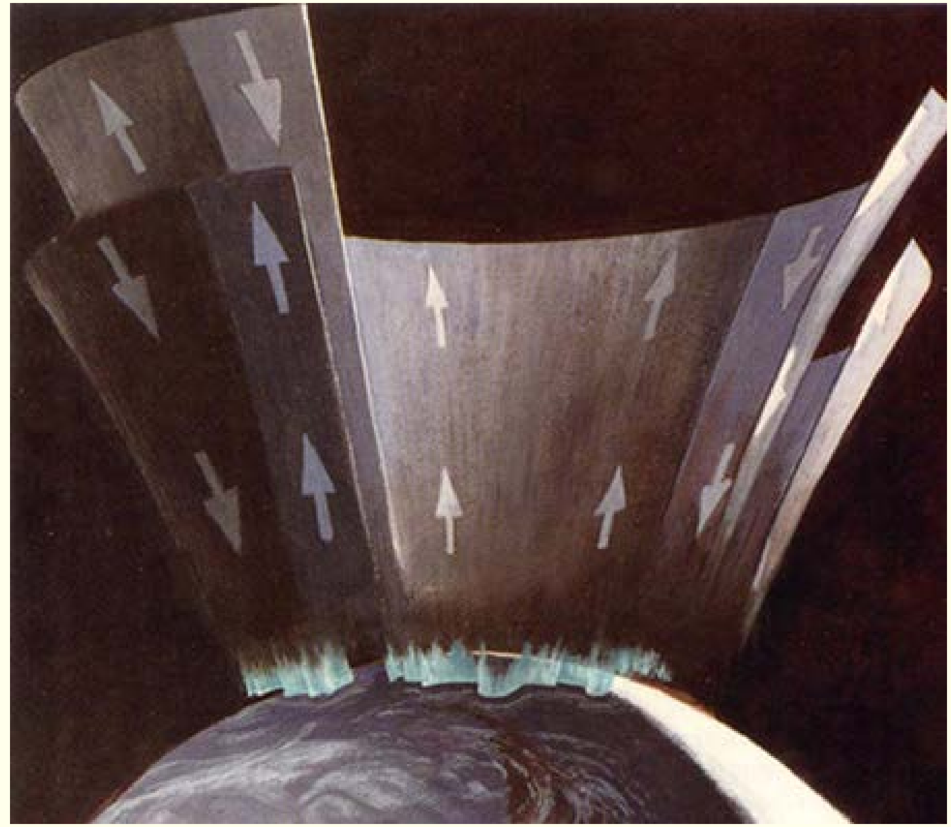
Spirals – Kelvin-Helmholz instability



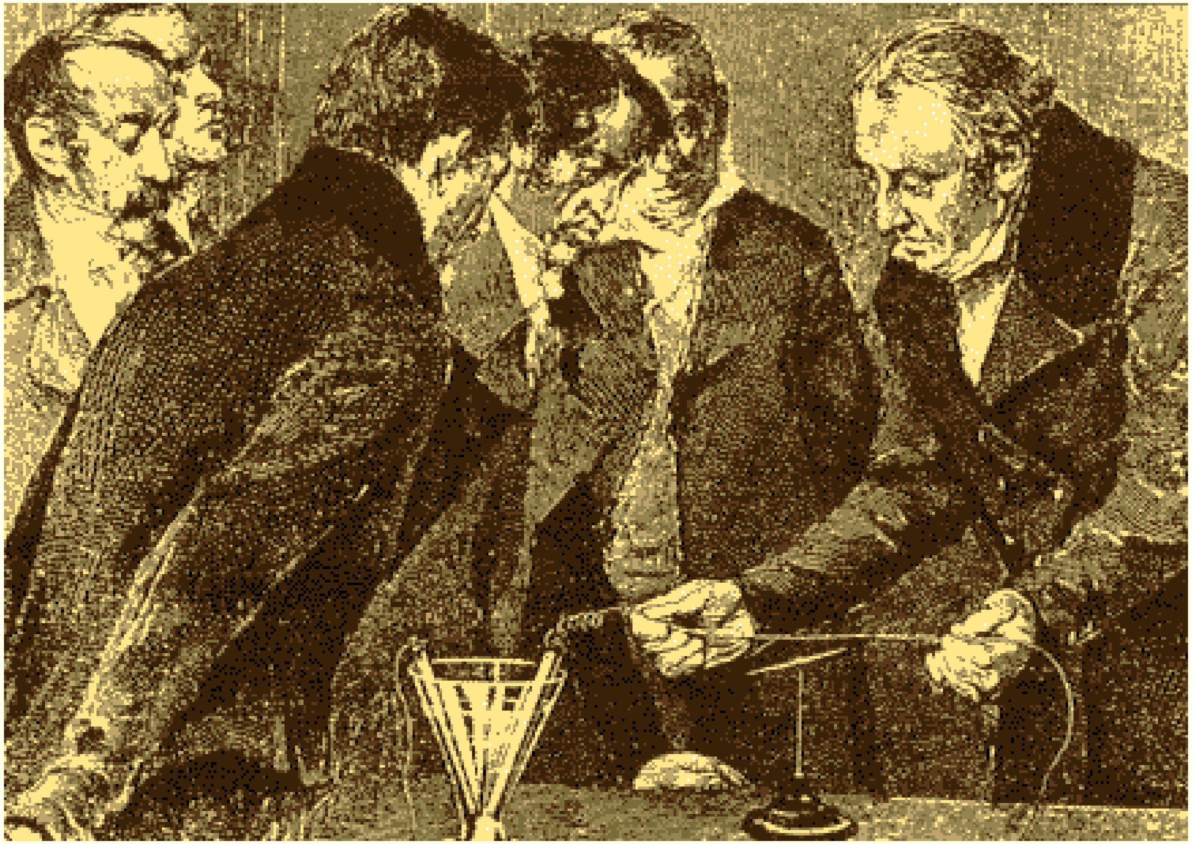
Birkeland currents in the auroral oval



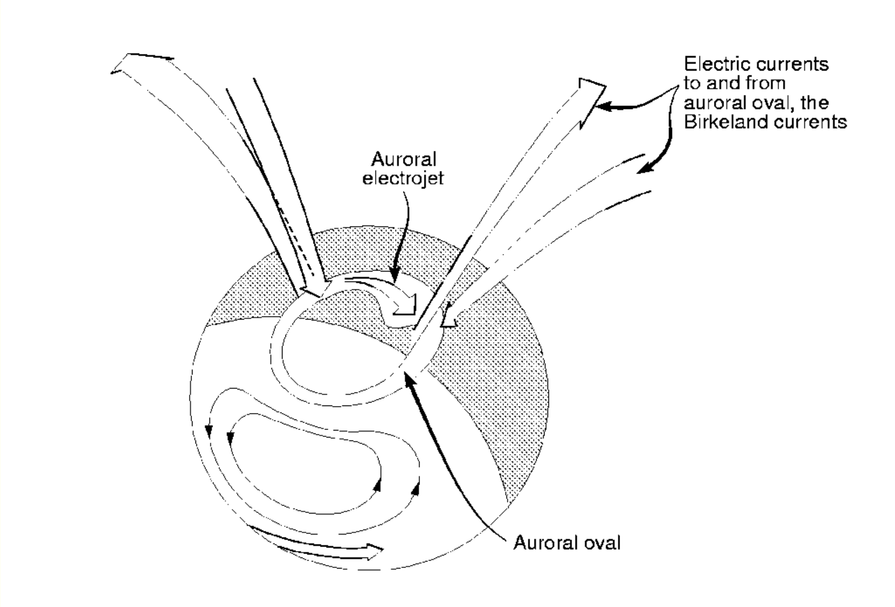
(a)



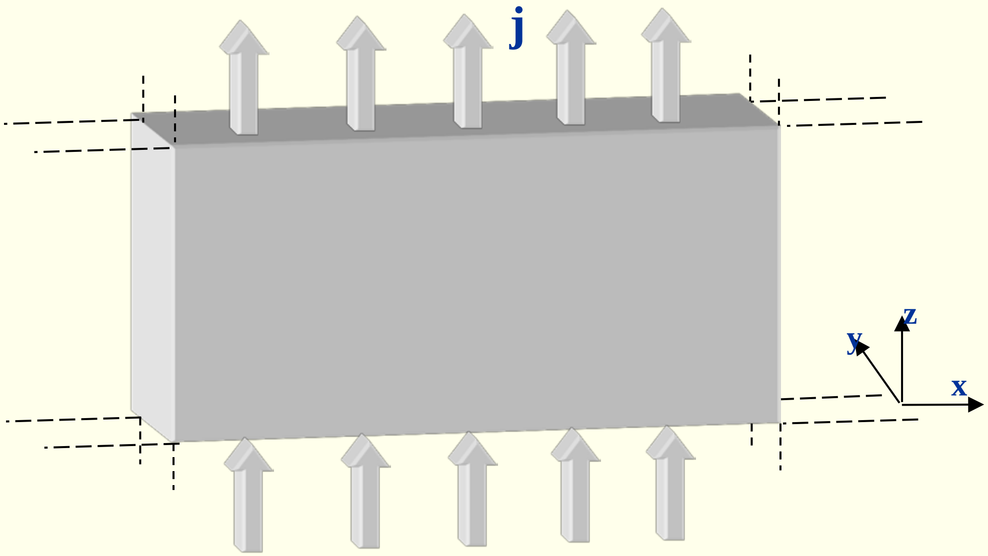
How can you measure currents in space?



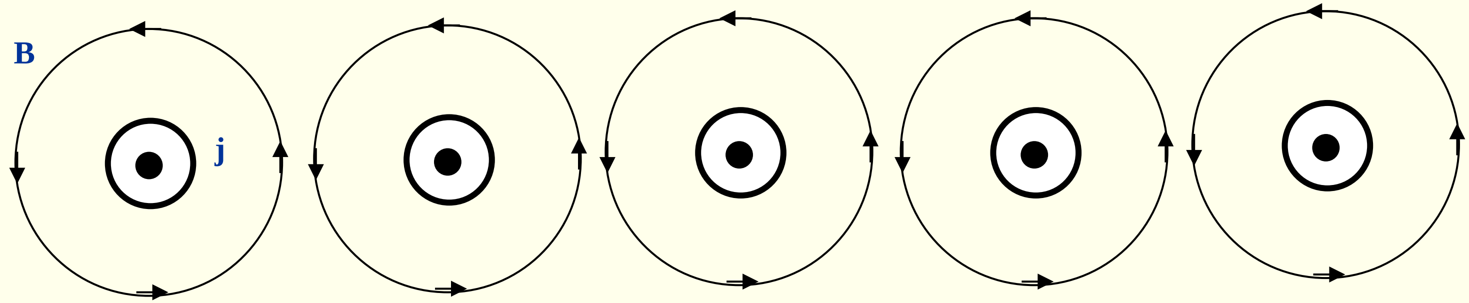
Current sheet approximation



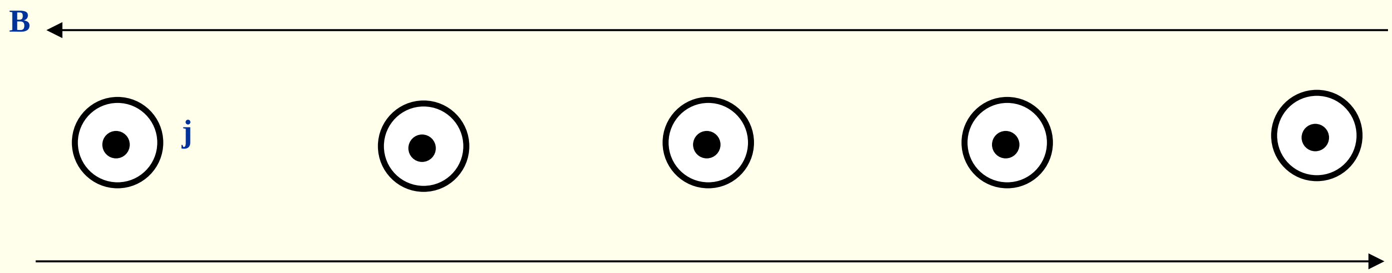
Approximate currents by thin current sheets with infinite size in the x- och z-directions.



Current sheet approximation

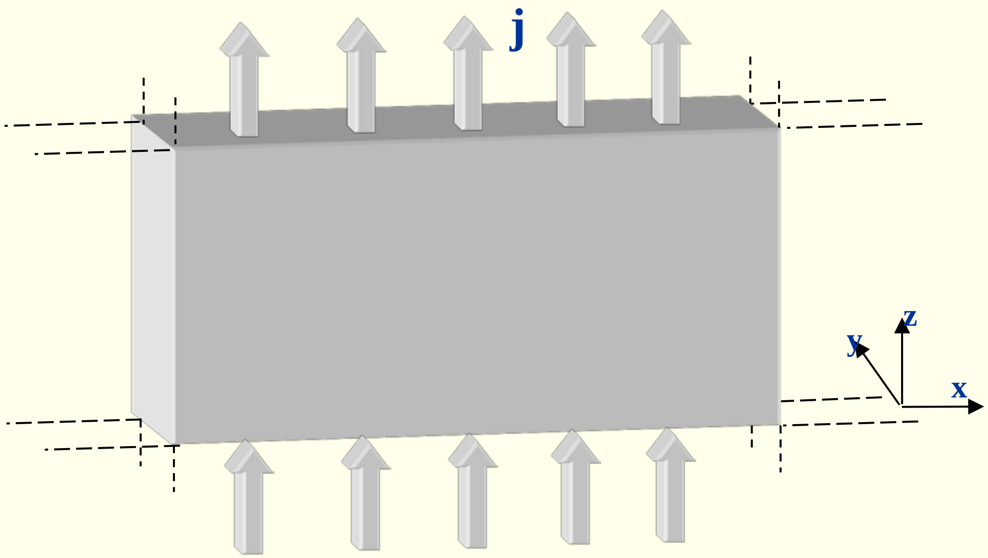


What will the magnetic field around such a current configuration be? Start by approximating with line currents to get a qualitative picture.



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 $\frac{\partial}{\partial z}=0$

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

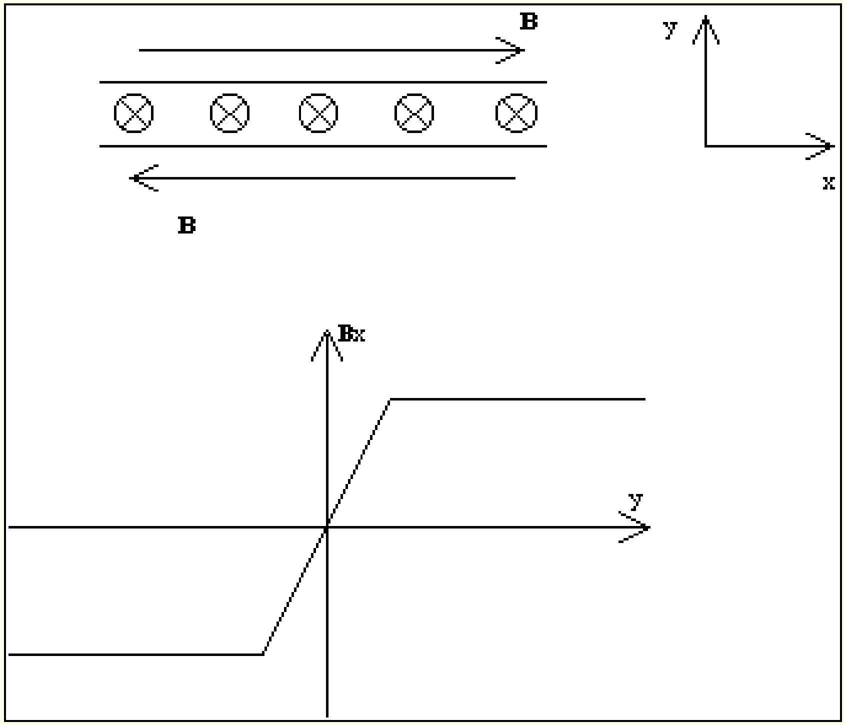
eller

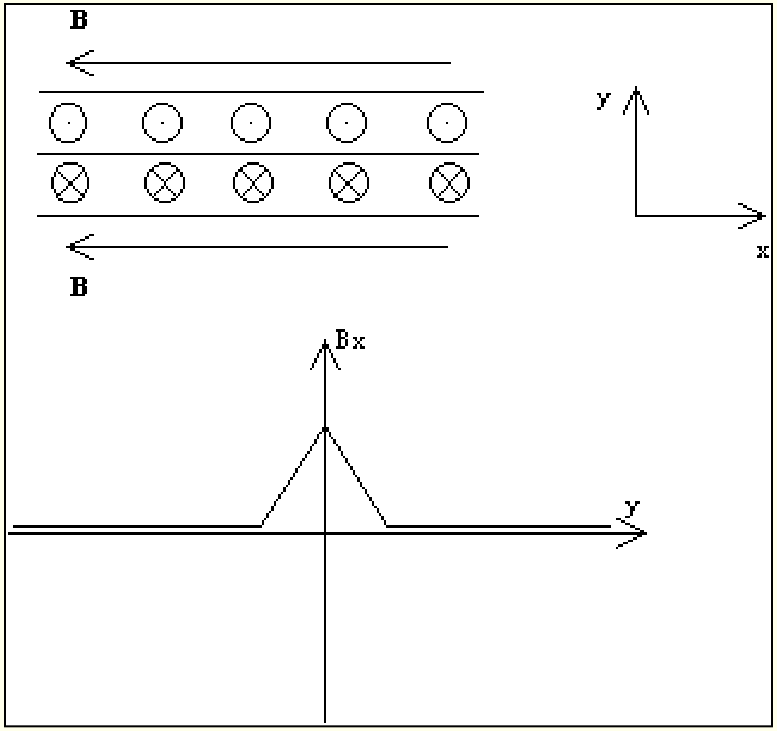
Ampére's law (no time dependence):

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

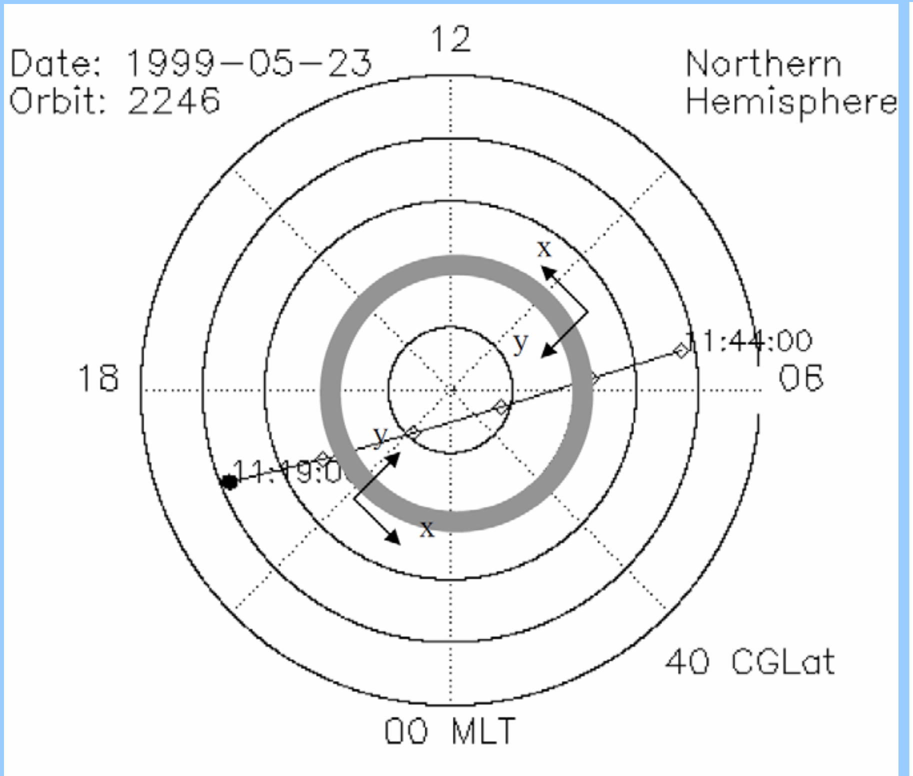
$$j_z=-\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

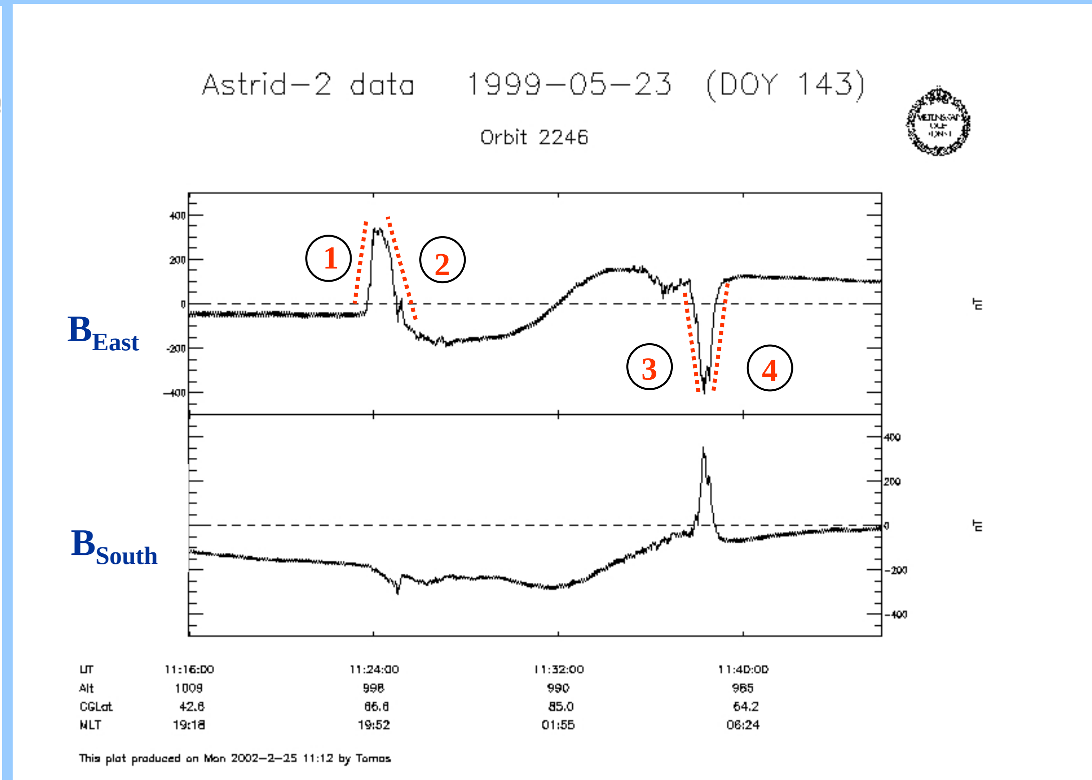
Current sheet - example





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

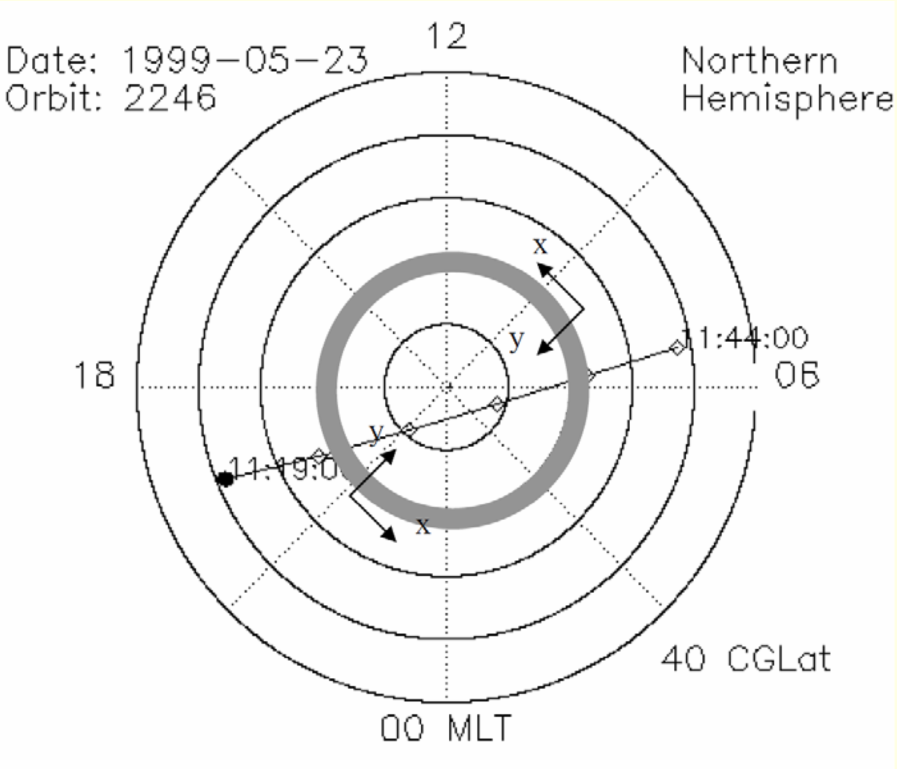


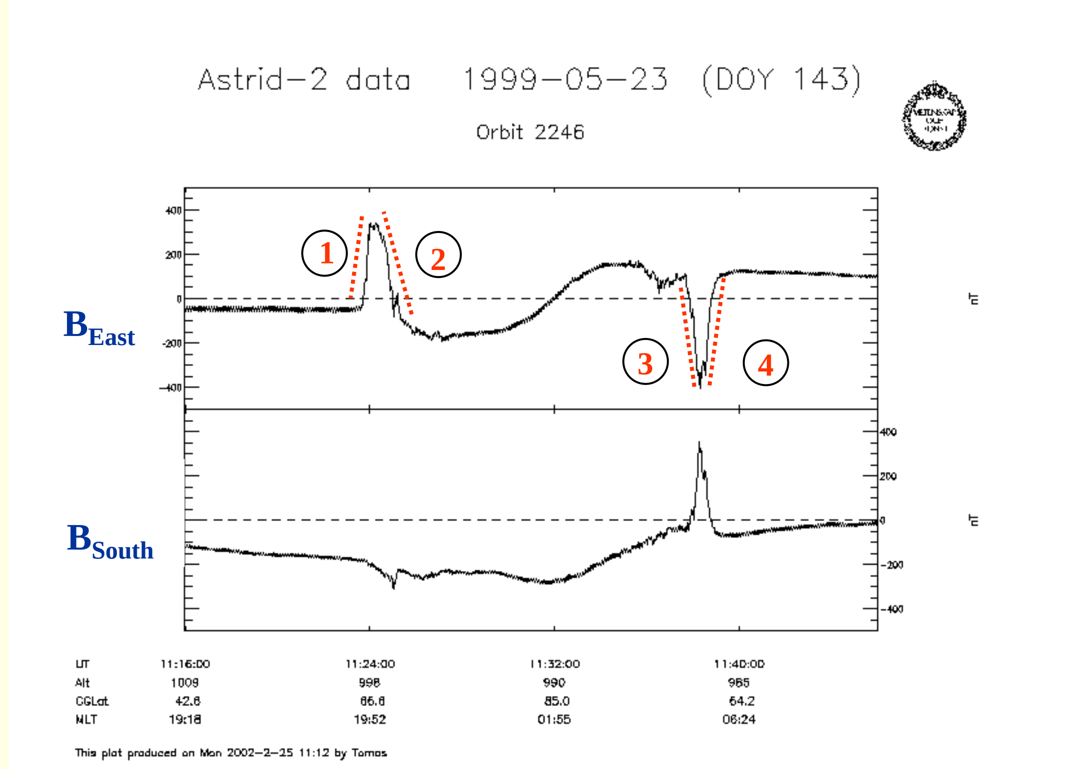


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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

Blue	Into the ionosphere
Red	Out of the ionosphere

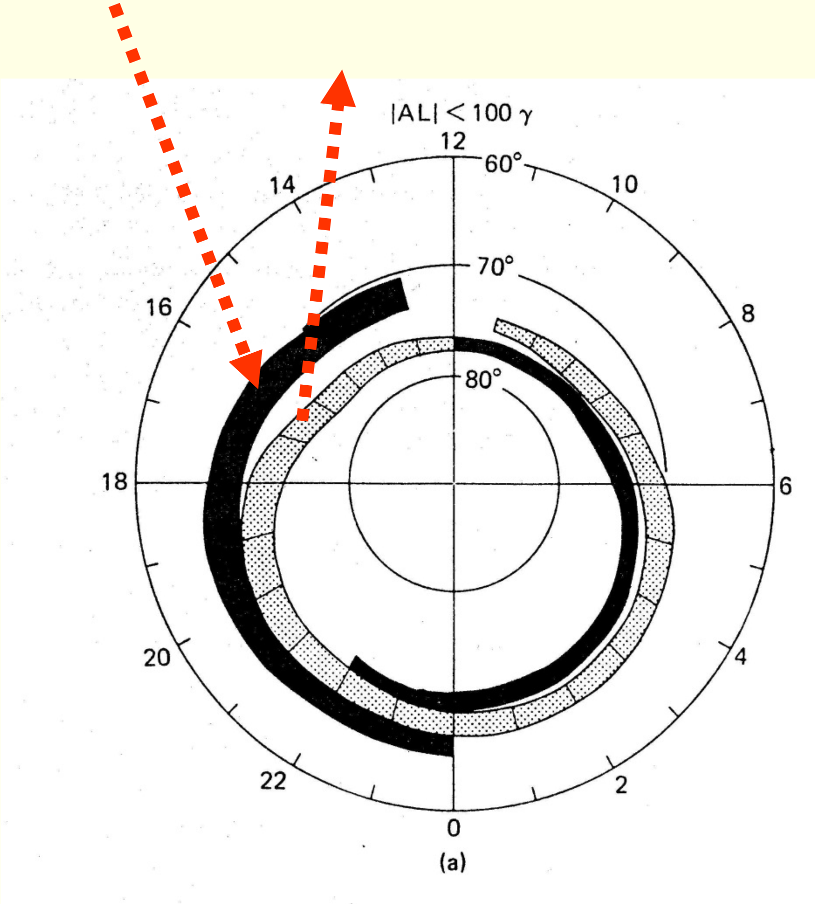


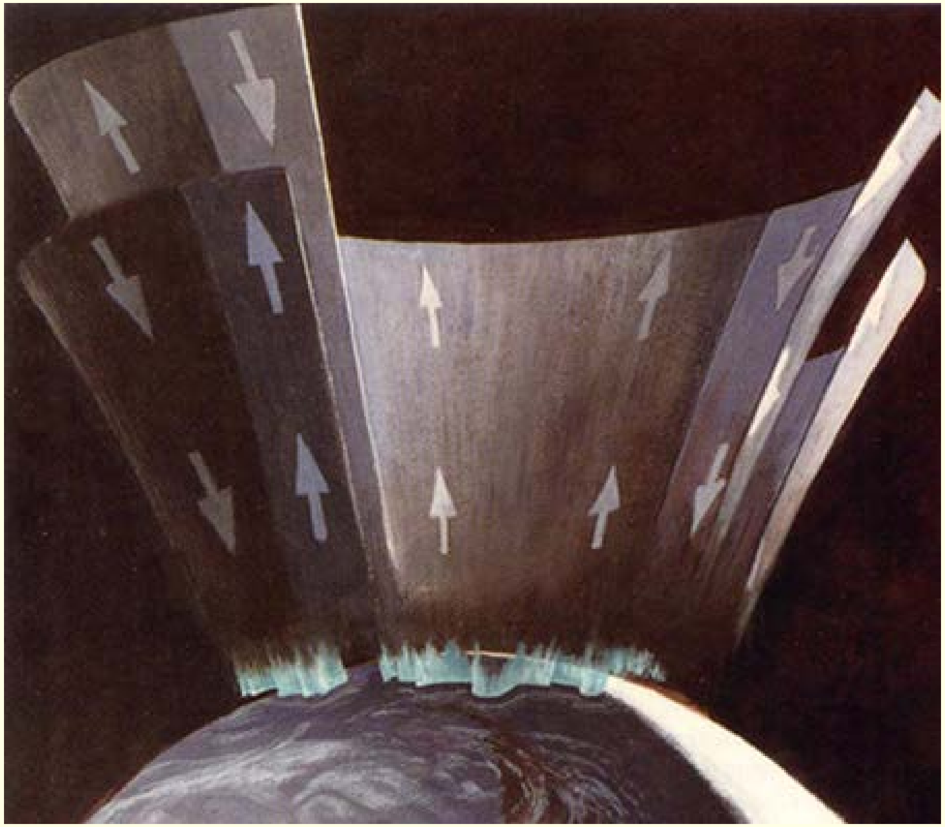


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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

Birkeland currents in the auroral oval

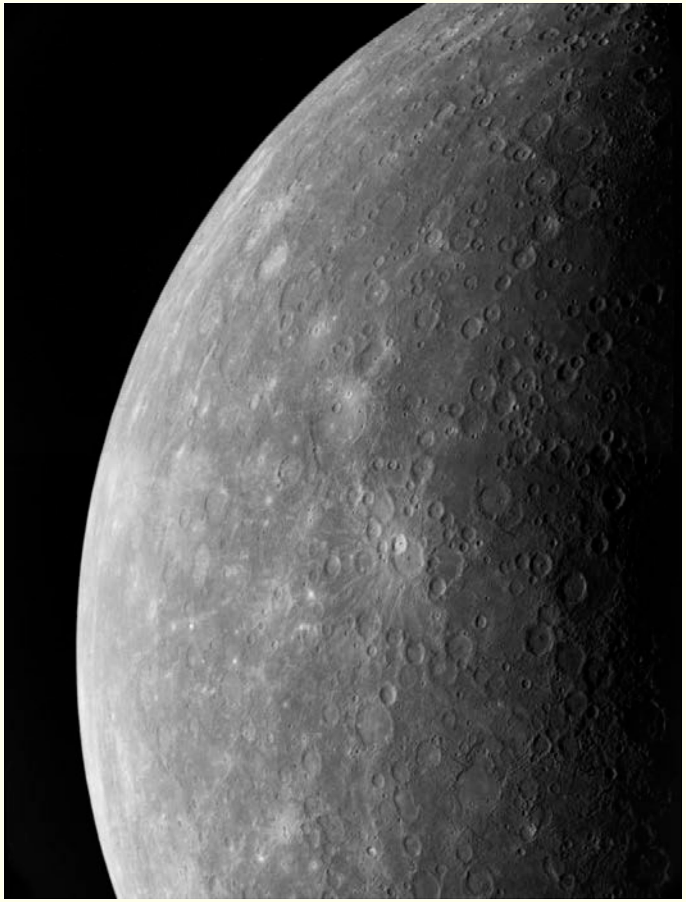




What do we need to have an aurora?

- Magnetic field (to guide the plasma particles towards the planet)
- Atmosphere (to create emissions)

Mercury



- No atmosphere
- X-ray aurora???
  Can possibly be created by electrons colliding directly with the planetary surface and lose their energy in one single collision.

Jupiter aurora

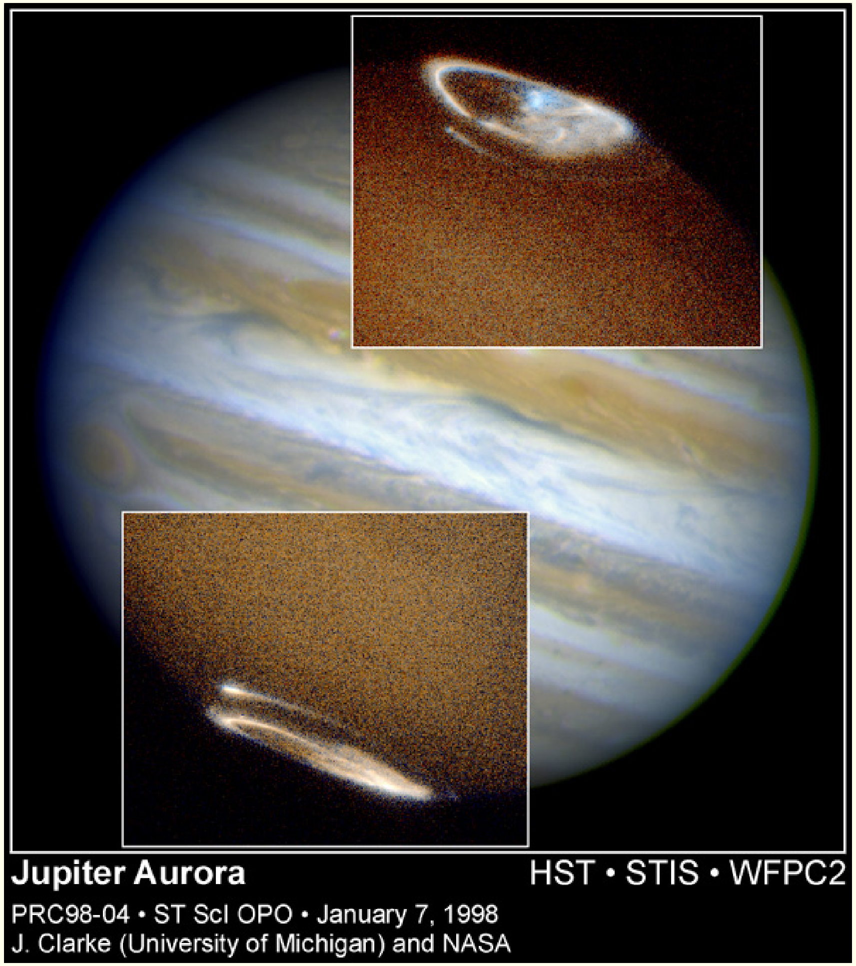
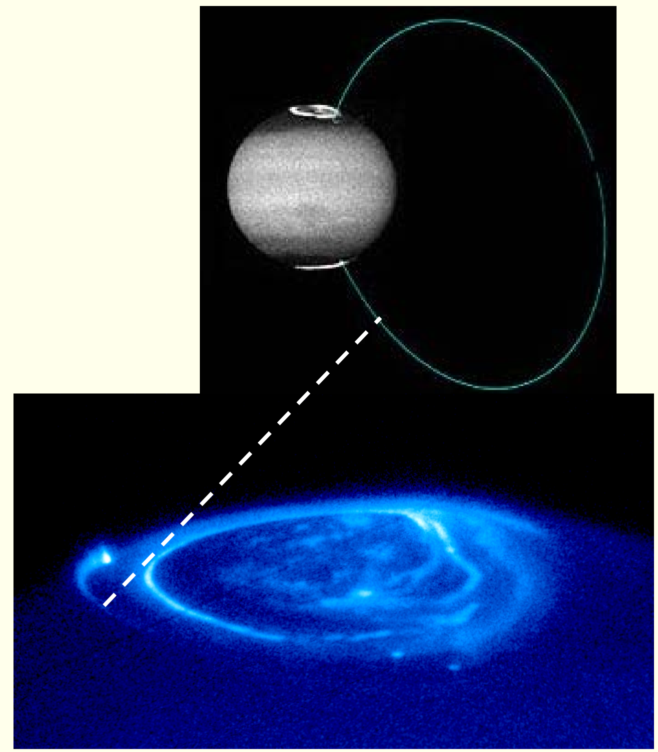


Foto från Hubble Space Telescope

- 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!



Jupiter and Io

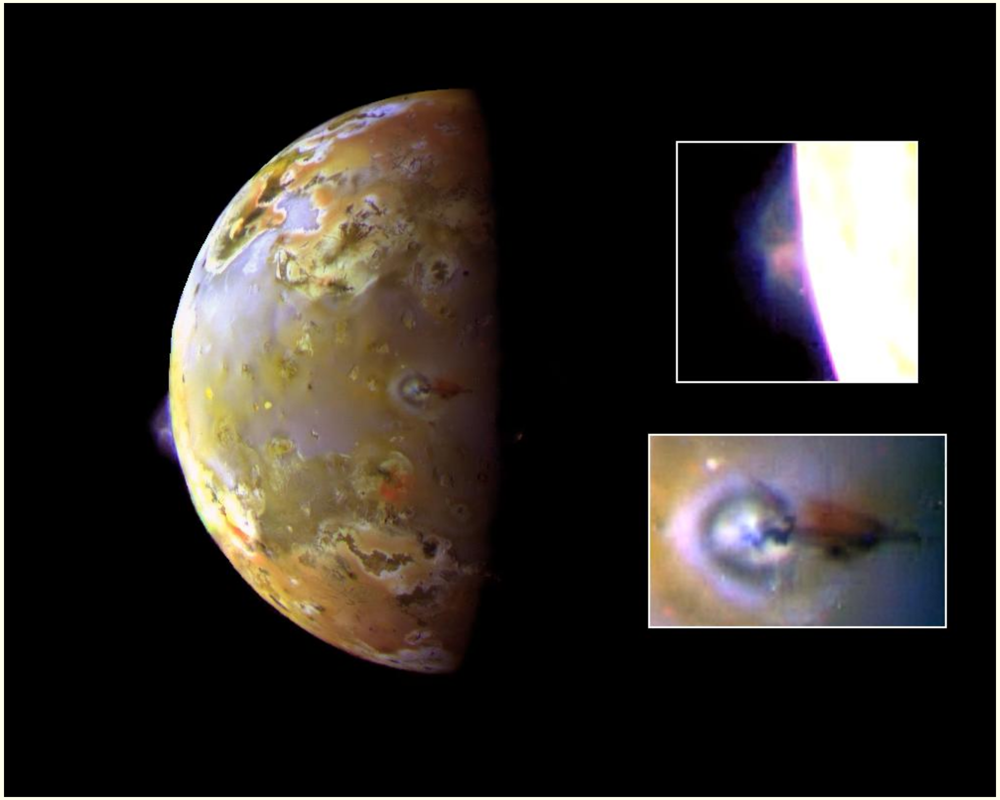
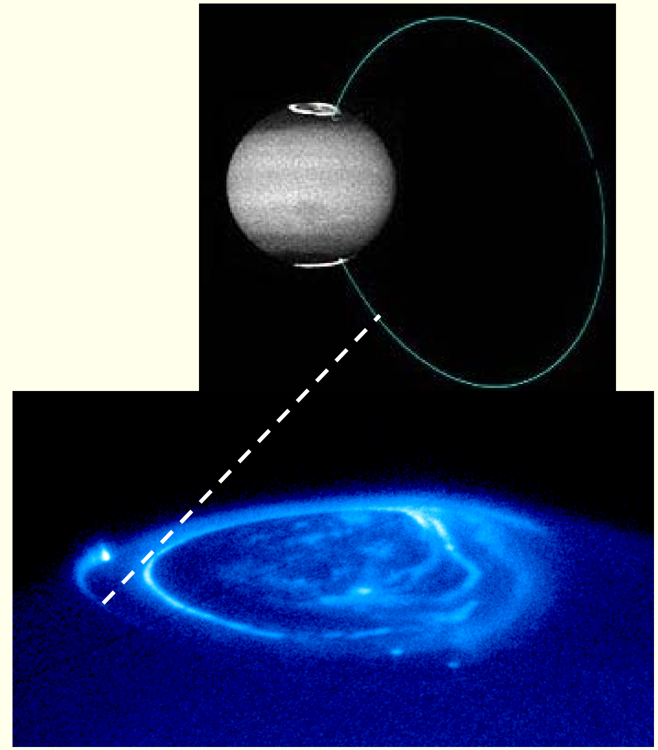


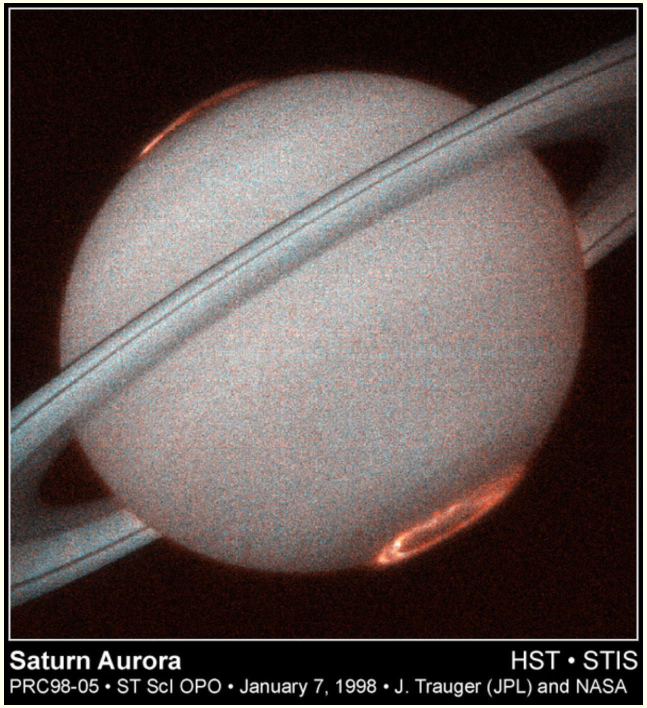
Photo from rymdsonden Galileo



The Jupiter moon Io is very volcanically active, and deposes large amounts of dust and gas in Jupiter's magnetosphere. This is ionized by the sunlight, and the charged plasma partícles follow Jupiter's magnetic field lines towards the atmosphere and cause auroral emissions.

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.*

Prerequisites for...

Life

- Energy source (sun)
- Atmosphere
- Magnetic field
- Water

Aurora

- Energy source (sun)
- Atmosphere
- Magnetic field

On space weather and viewing aurora

Some space weather sites

http://spaceweather.com/

http://www.esa-spaceweather.net/

http://sunearthday.nasa.gov/swac/

http://www.noaawatch.gov/themes/space.php

http://www.windows2universe.org/spaceweather/more_details.html

Kiruna

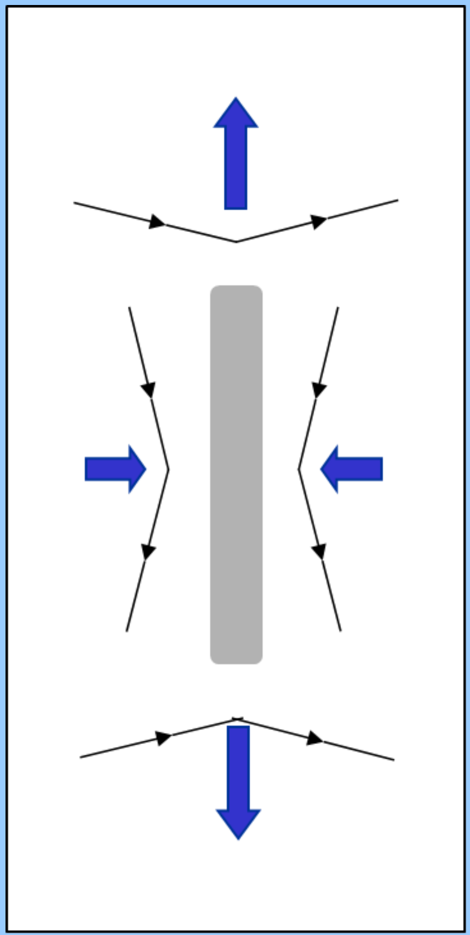
Kiruna all-sky camera:
http://www.irf.se/allsky/rtasc.php

http://sunearthday.nasa.gov/swac/tutorials/aur_kiruna.php

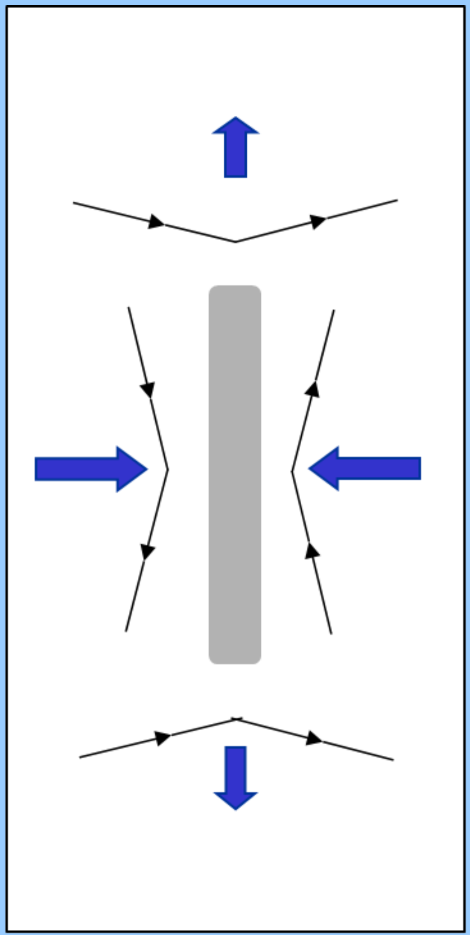
Forecasts:
http://flare.lund.irf.se/rwc/aurora/

http://www.irf.se/Observatory/?link[All-skycamera]=Aurora_sp_statistics

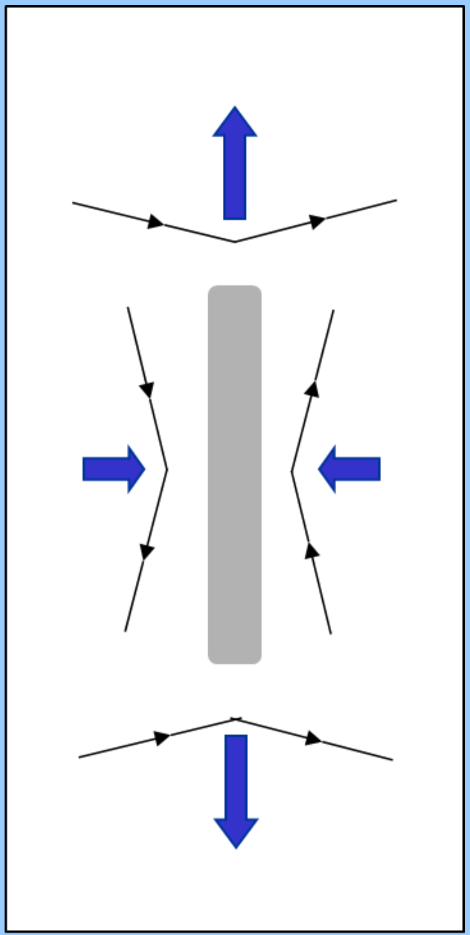
Magnetic reconnection



Green

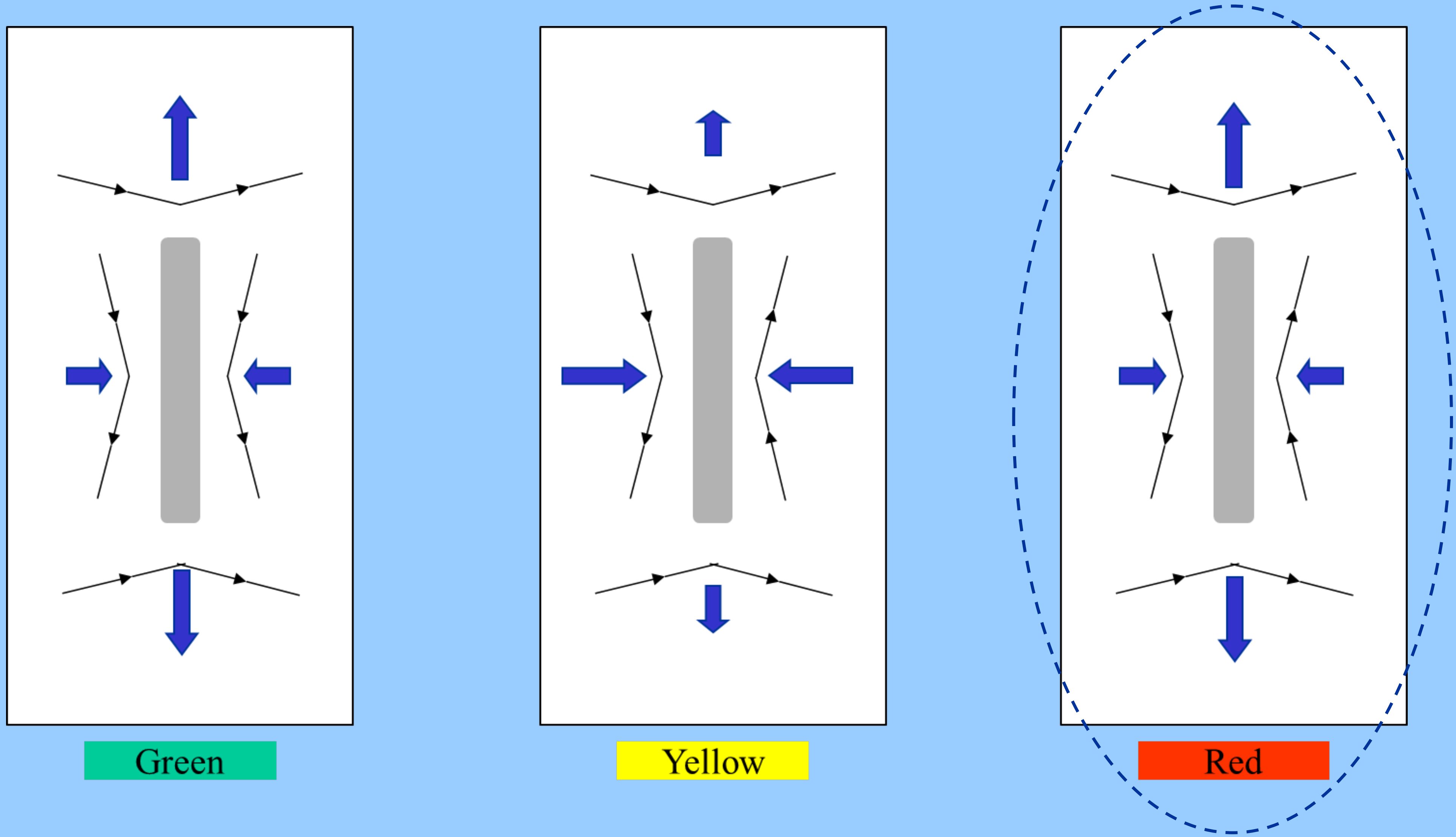


Yellow

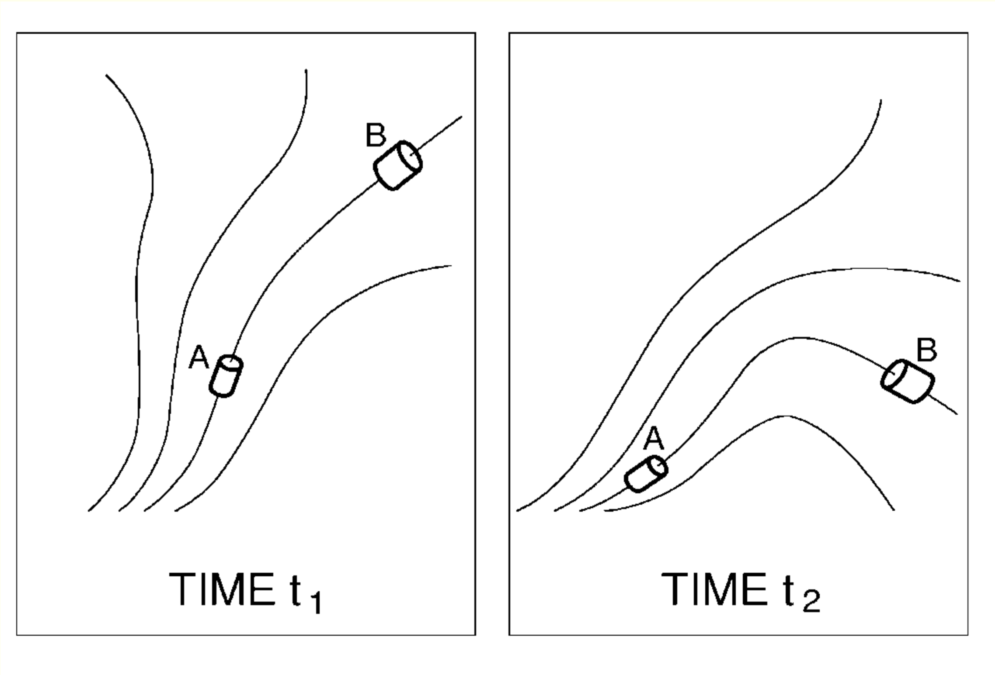


Red

Magnetic reconnection



Frozen in magnetic field lines



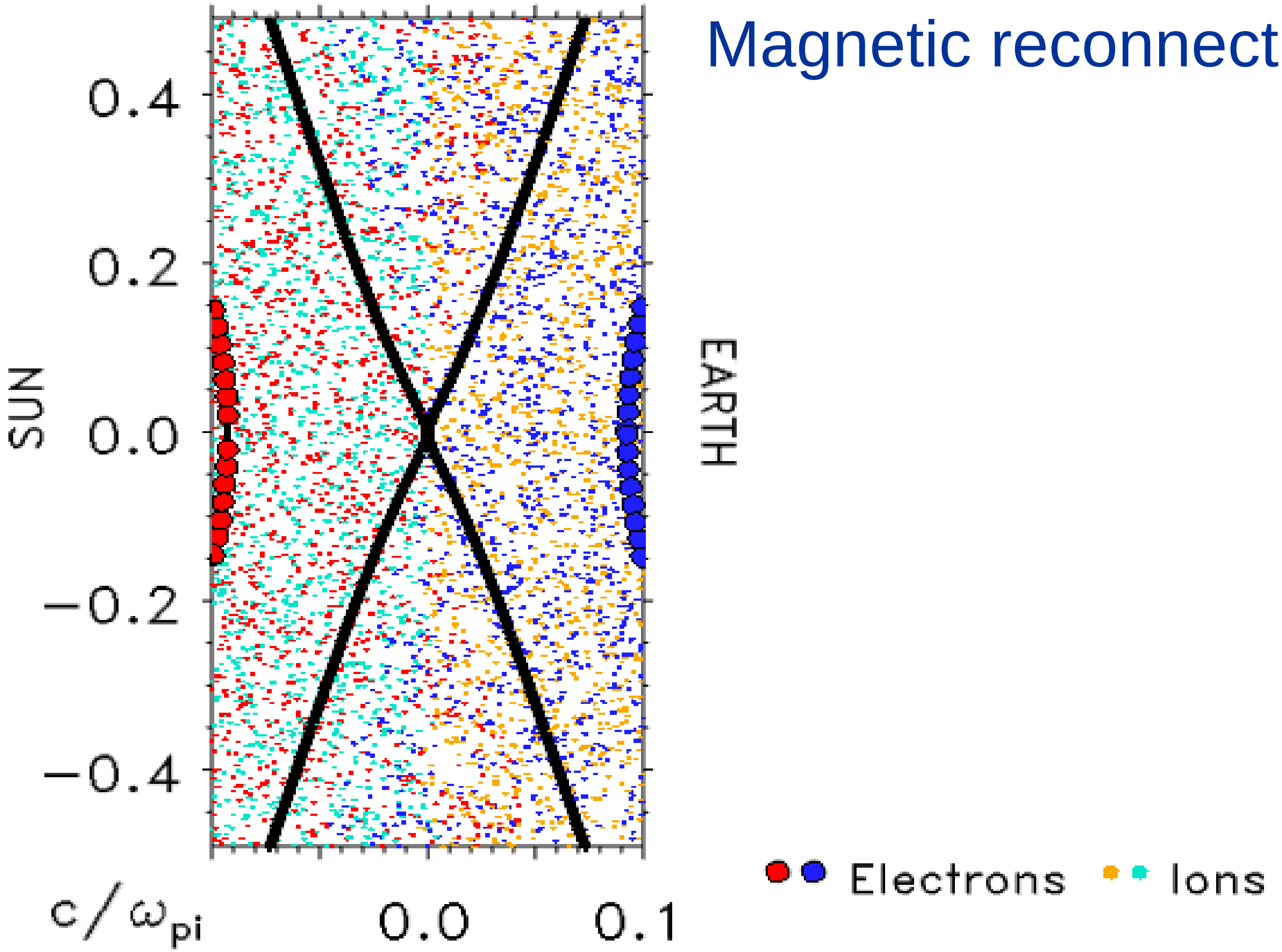
In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

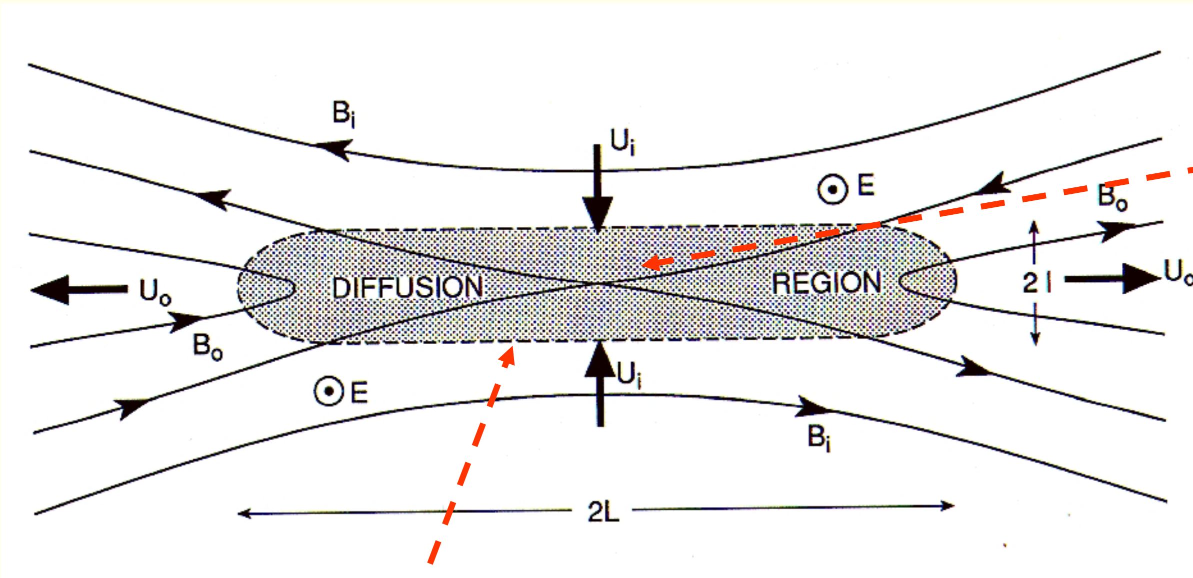
$$R_m = \mu_0 \sigma l_c v_c >> 1$$

An example of the collective behaviour of plasmas.

Magnetic reconnection



Reconnection



In 'diffusion region':

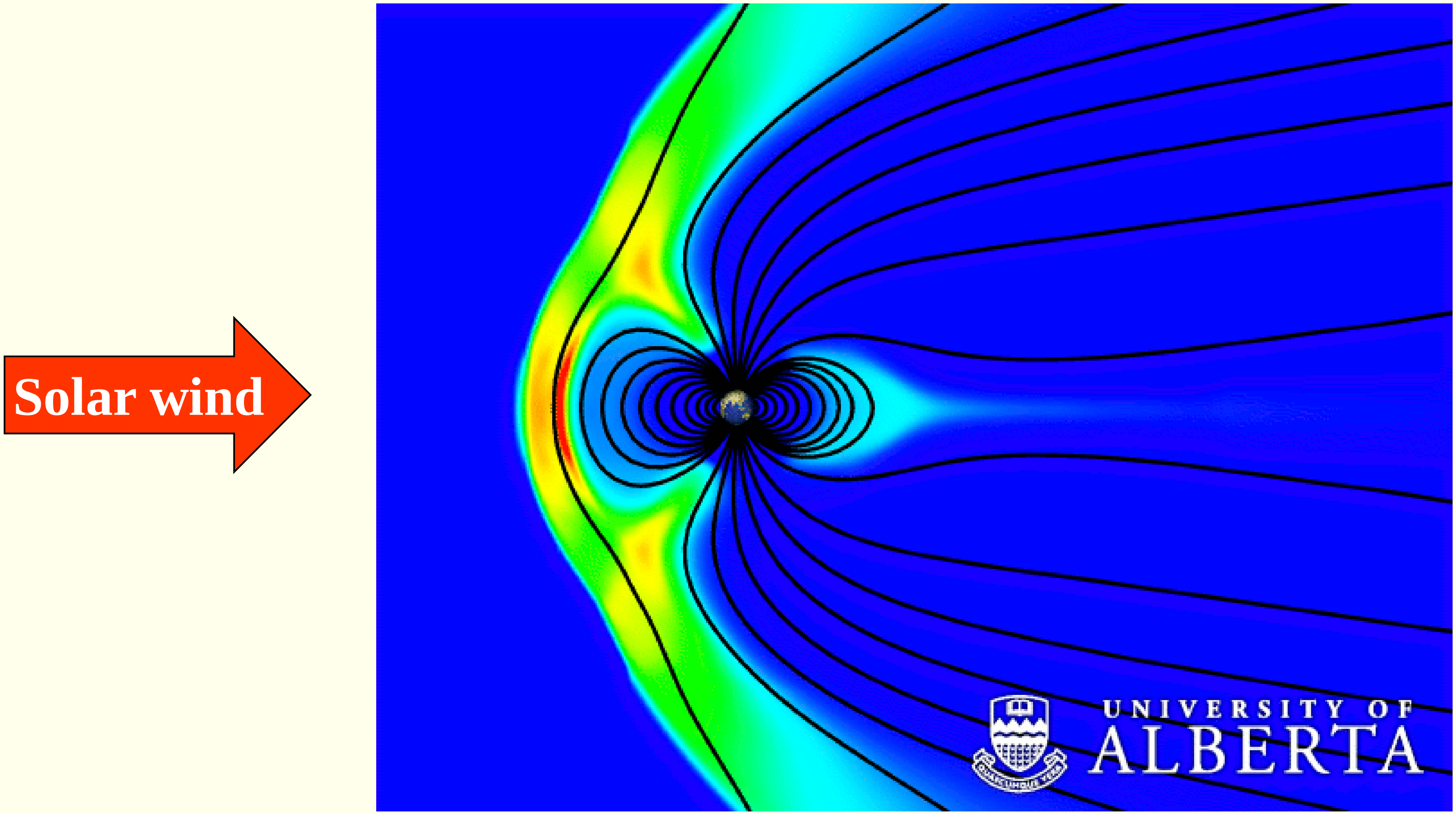
$R_m = \mu_0 \sigma l v \sim 1$

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:

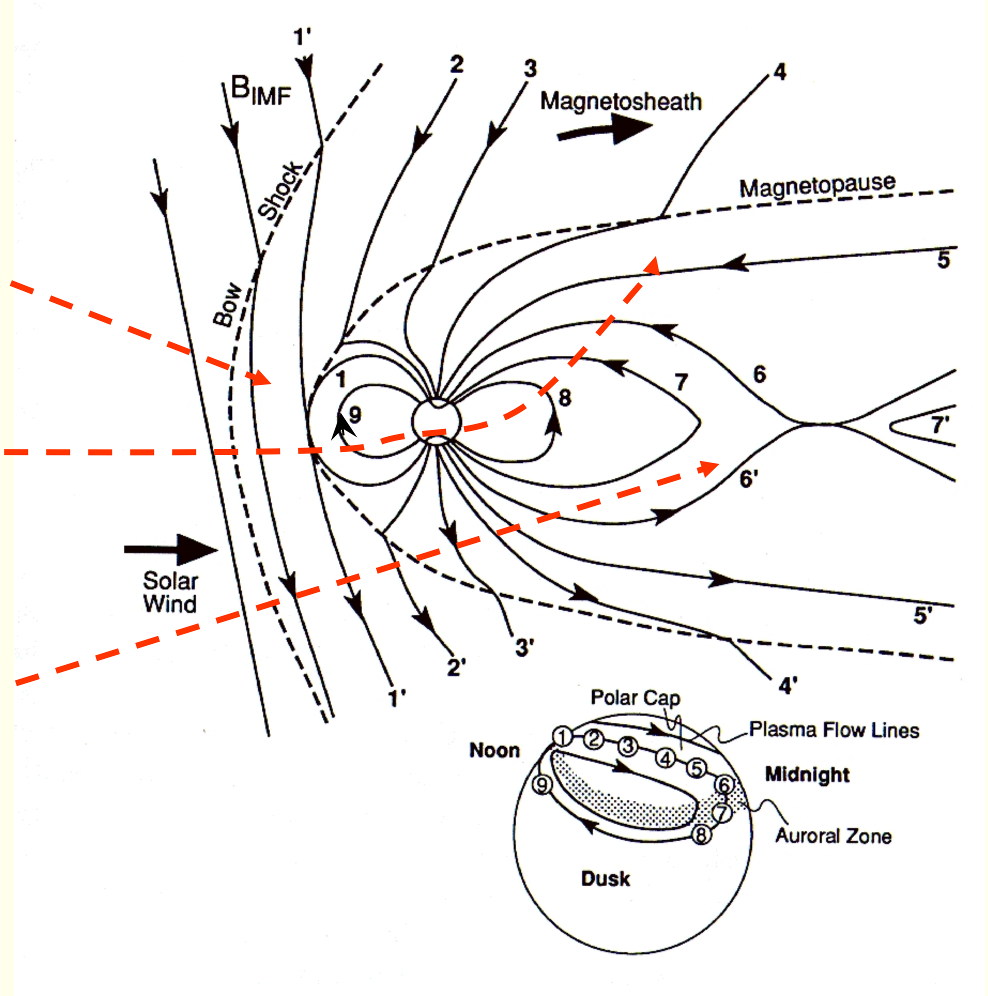
- Field lines are "cut" and can be re-connected to other field lines
- **Magnetic energy is transformed into kinetic energy ($U_o >> U_i$)**
- **Plasma from different field lines can mix**

Reconnection and plasma convection

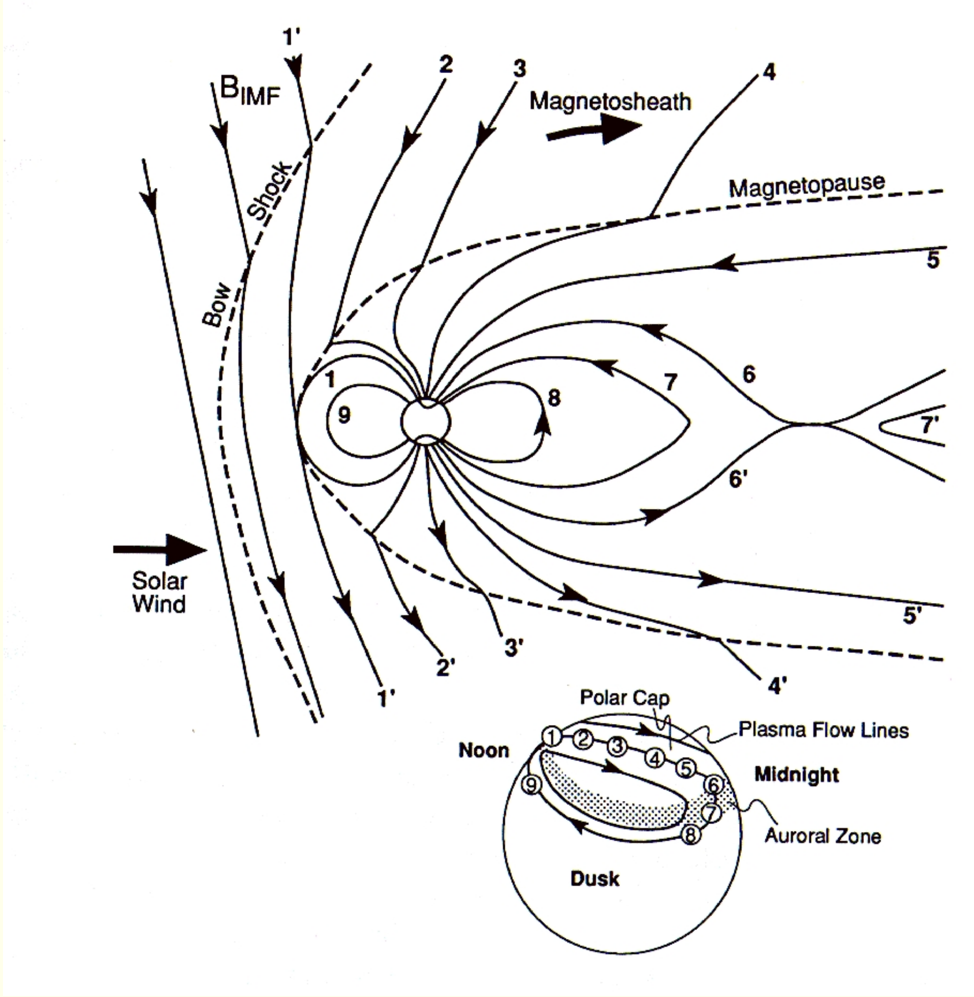


Reconnection och plasma convection

- 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.

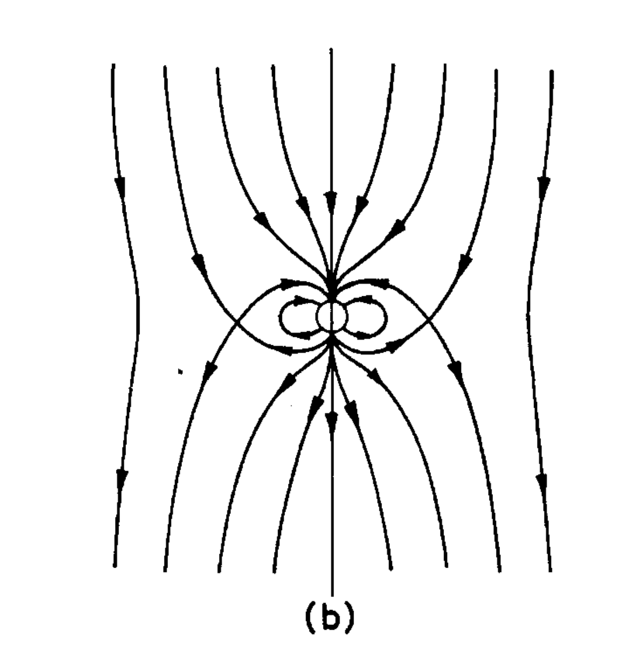


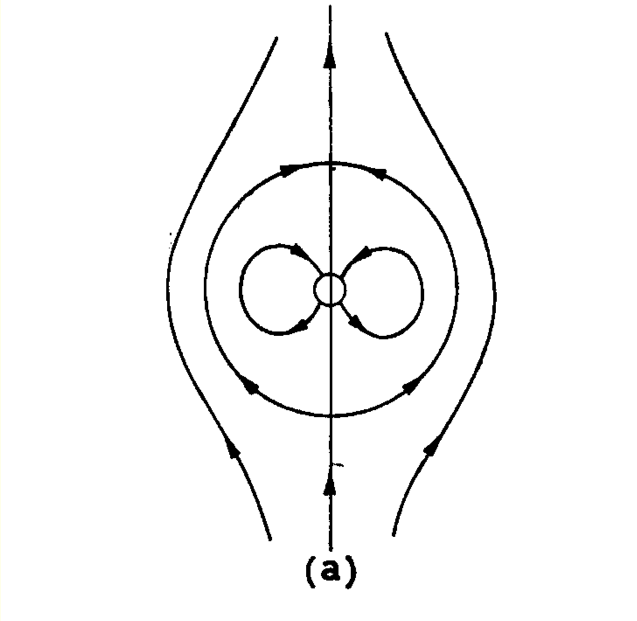
What happens if IMF is northward instead?



Magnetospheric dynamics

open magnetosphere ***closed magnetosphere***

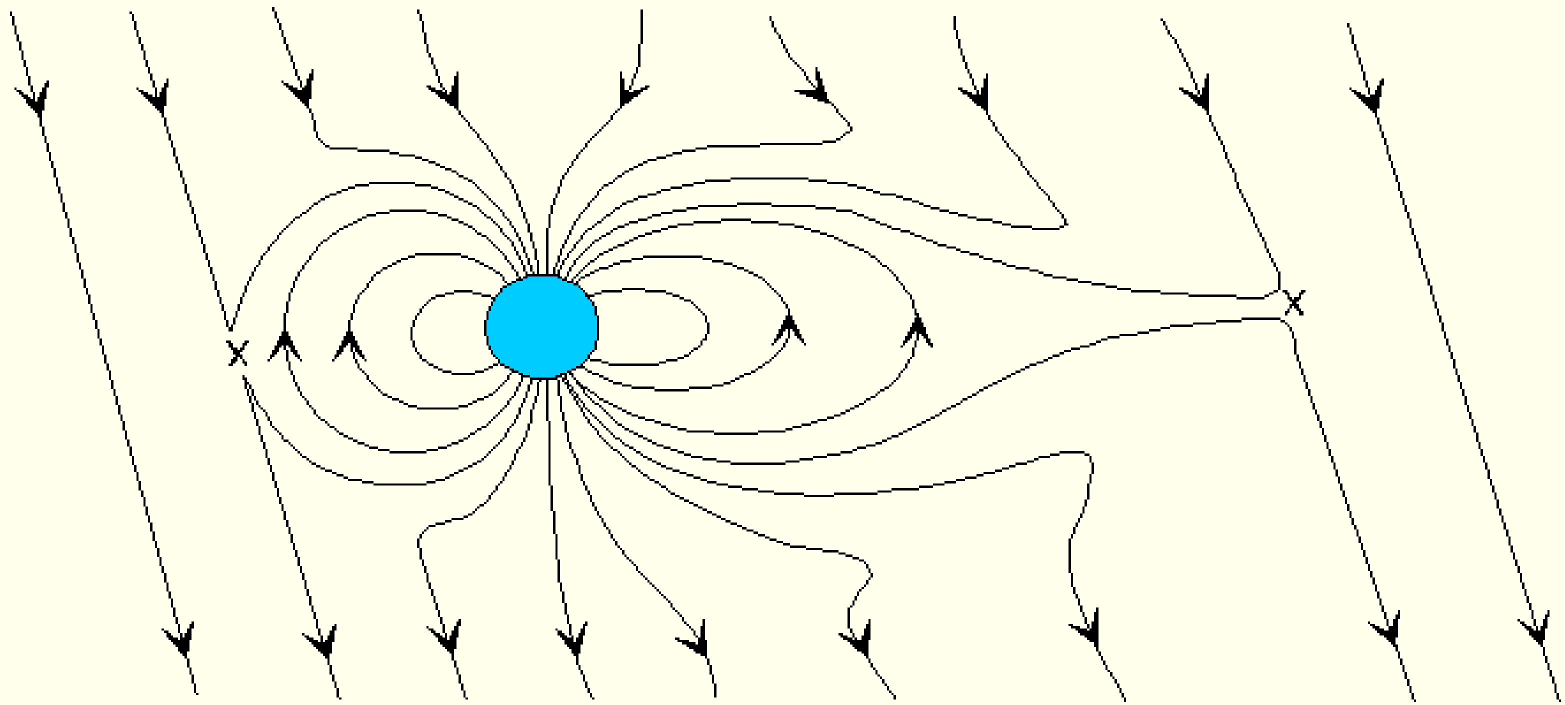




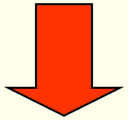
southward Interplanetary magnetic field (IMF) northward

Magnetospheric dynamics

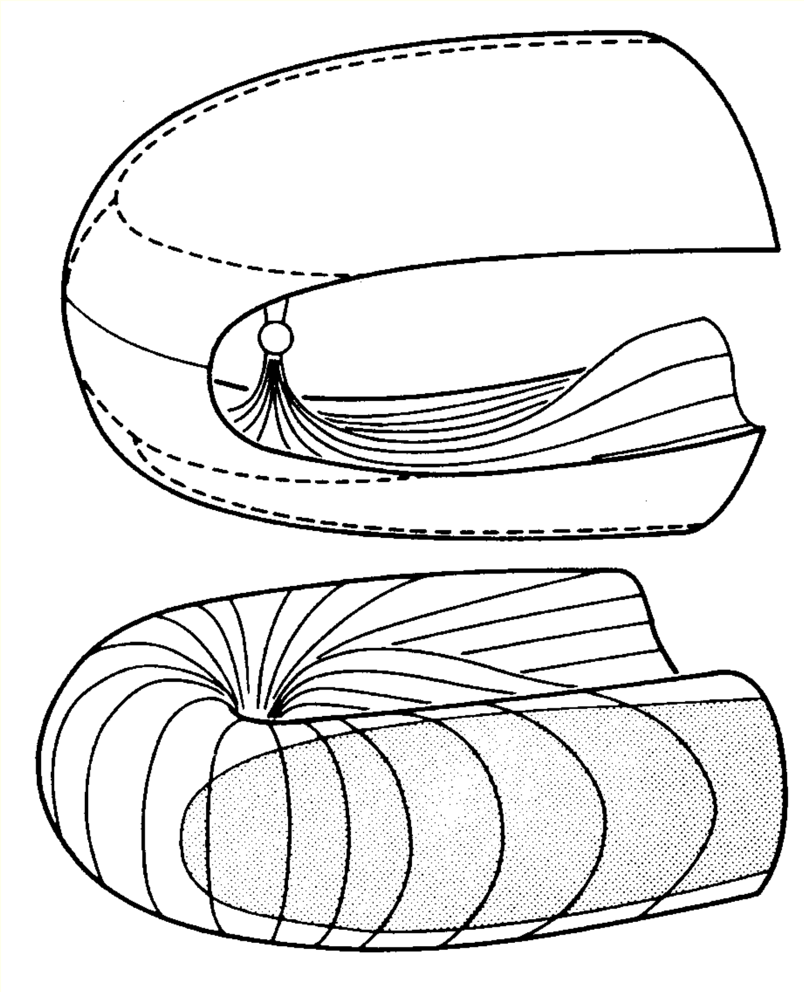
open magnetosphere



Southward IMF



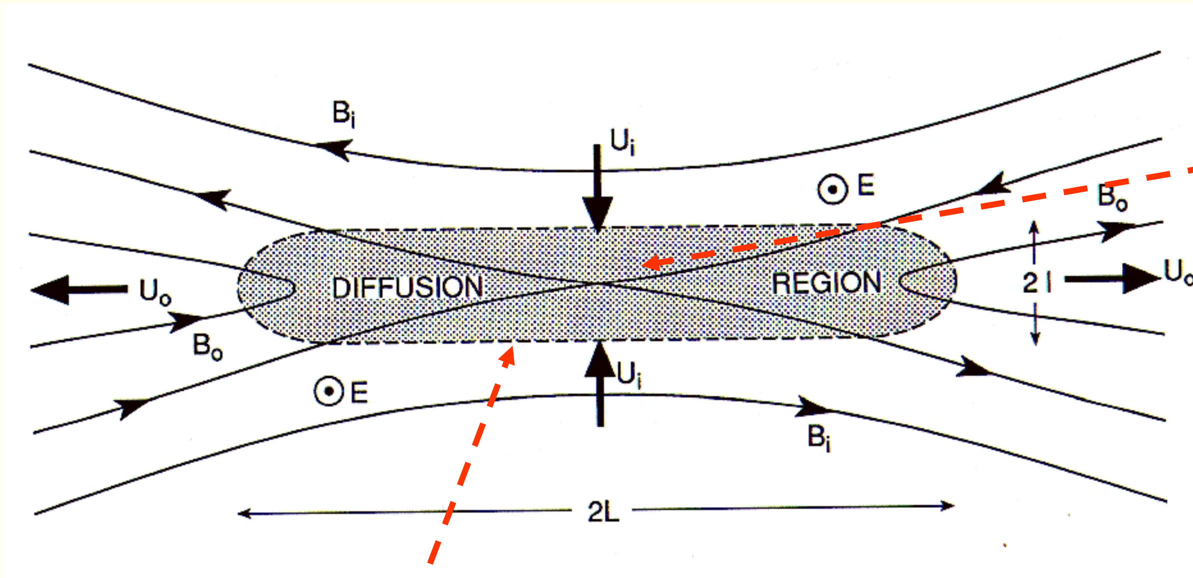
Magnetospheric topology



Open field lines

Closed field lines

Reconnection



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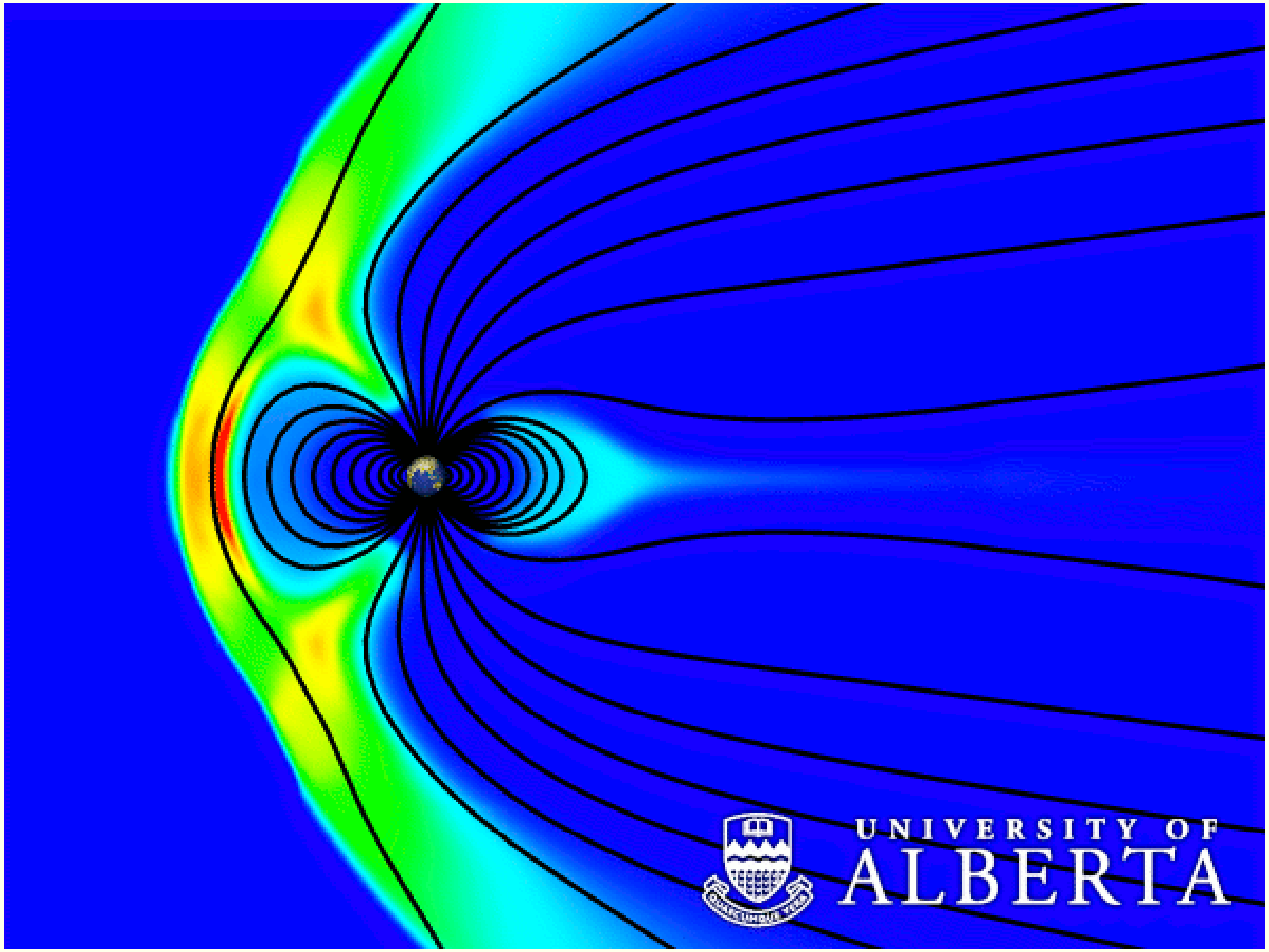
Reconnection and plasma convection

Solar wind



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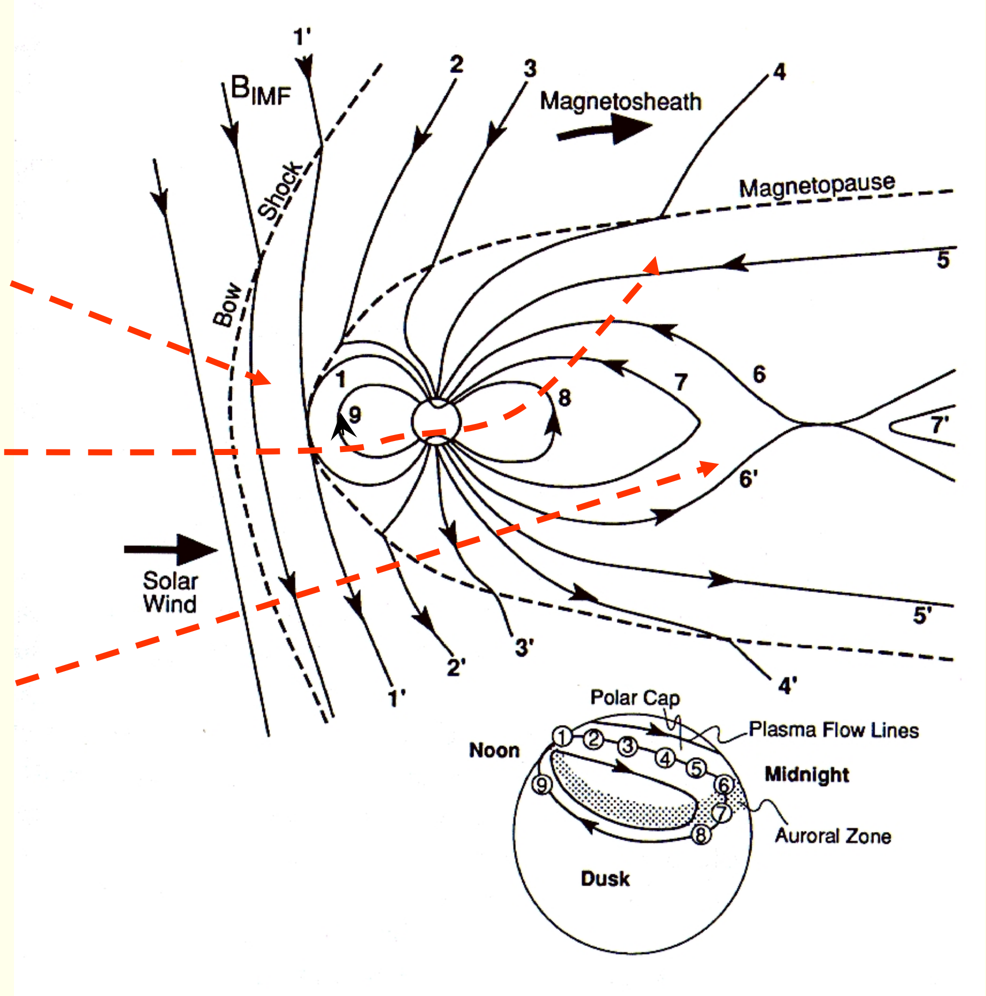
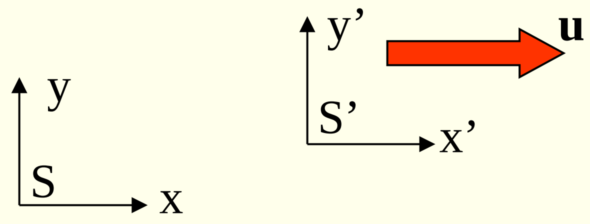


Field transformations (relativistic)



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

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

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

For $u << c$*:*

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

induced electric field

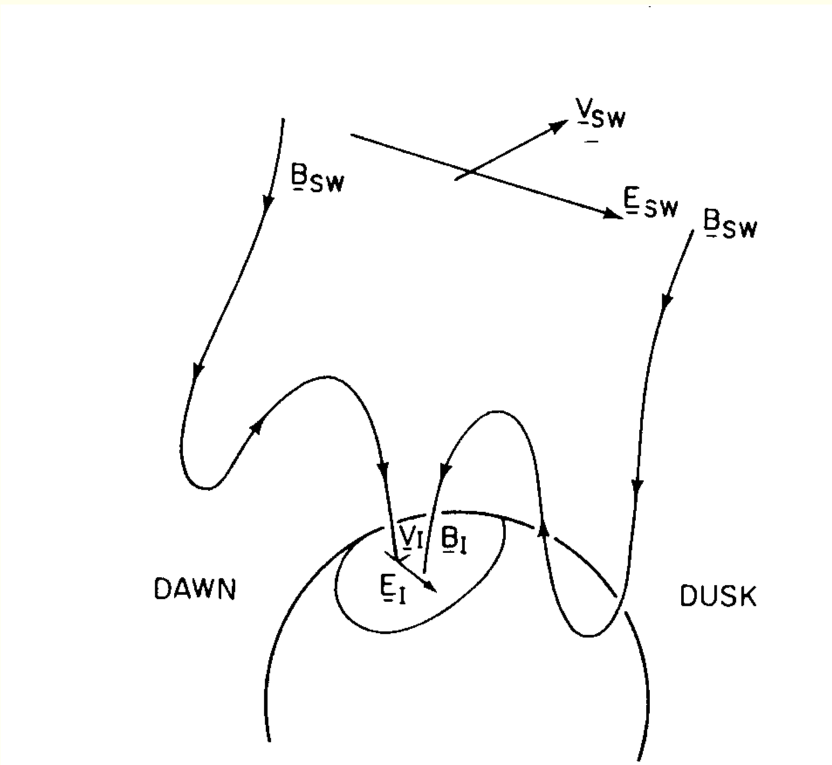
$$\mathbf{E} = \mathbf{E}' - \mathbf{u} \times \mathbf{B}$$

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 1



The solar wind generates an electric field

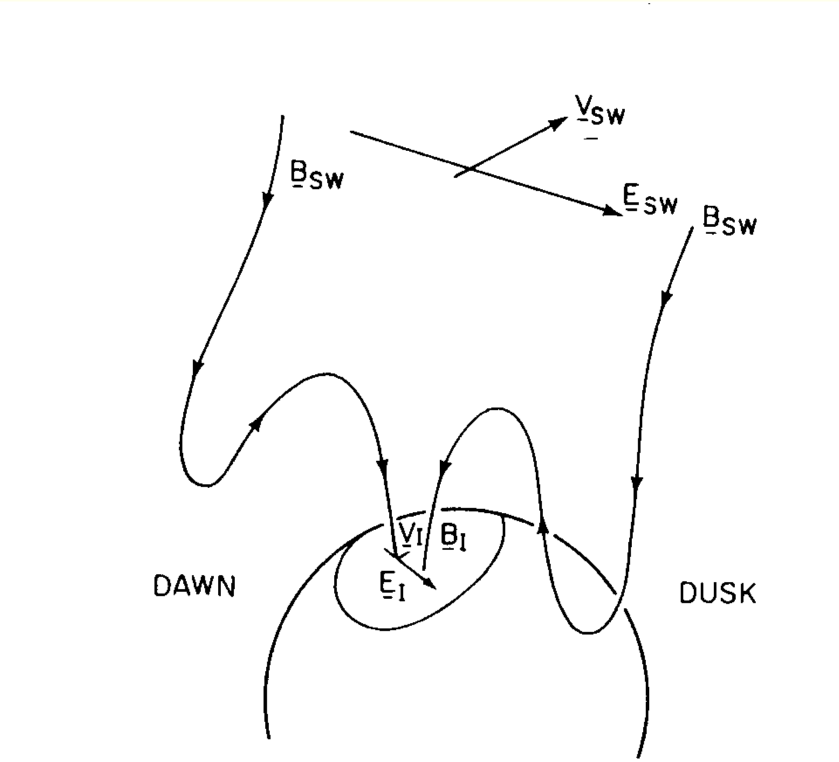
$$\mathbf{E}_{SW} = - \mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 2



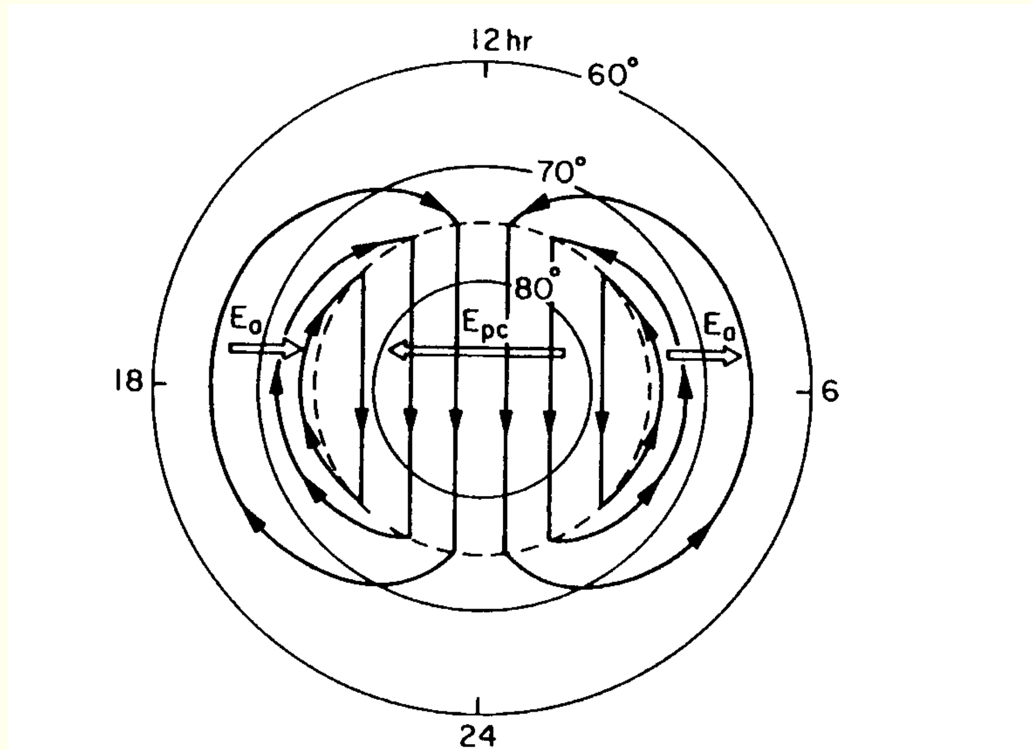
The solar wind magnetic field draws the ionospheric plasma with it, since the field is frozen into the plasma. This motion induces an ionospheric electric field

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

Magnetospheric dynamics

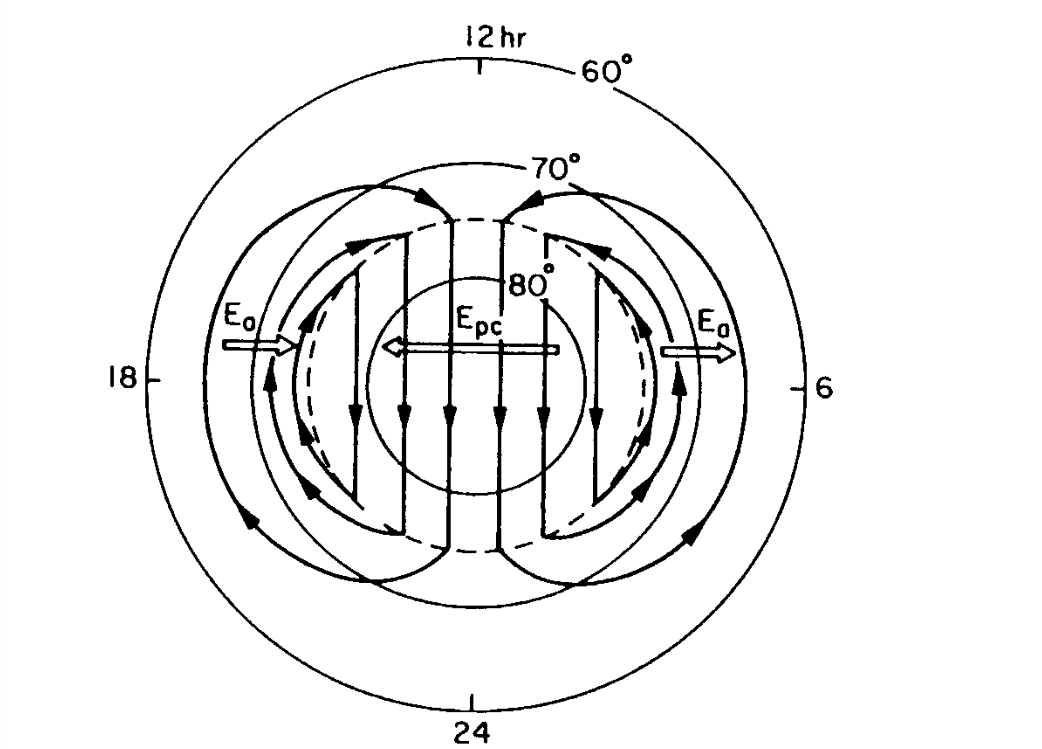
Plasma convection in the ionosphere

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



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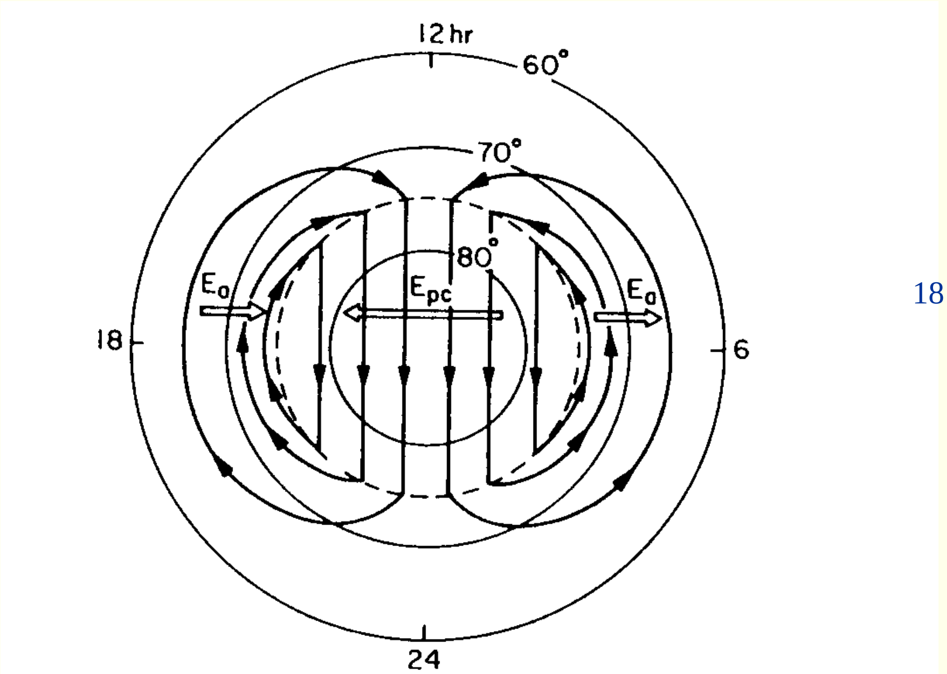
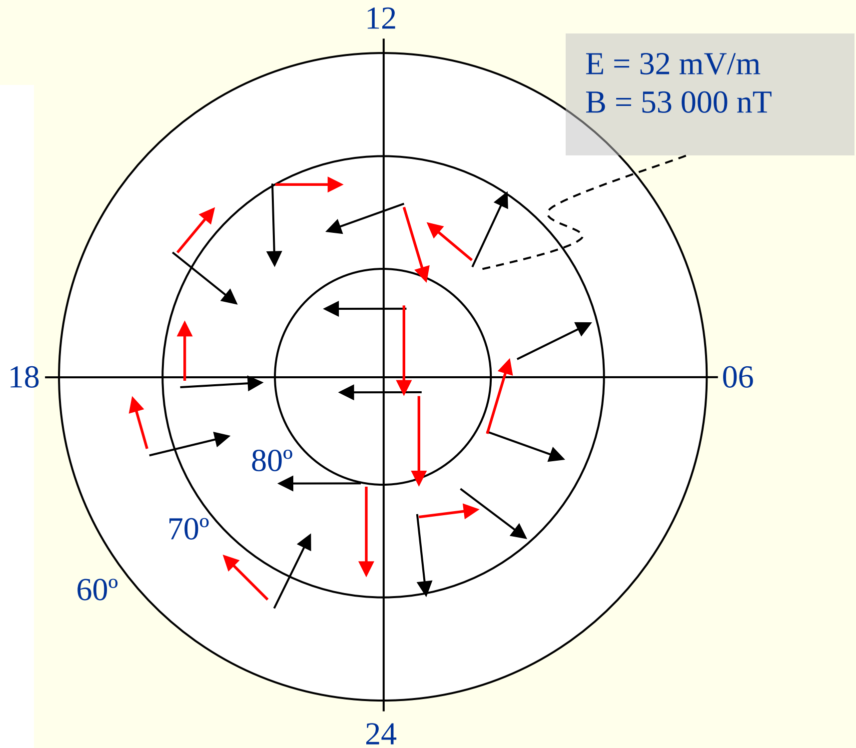
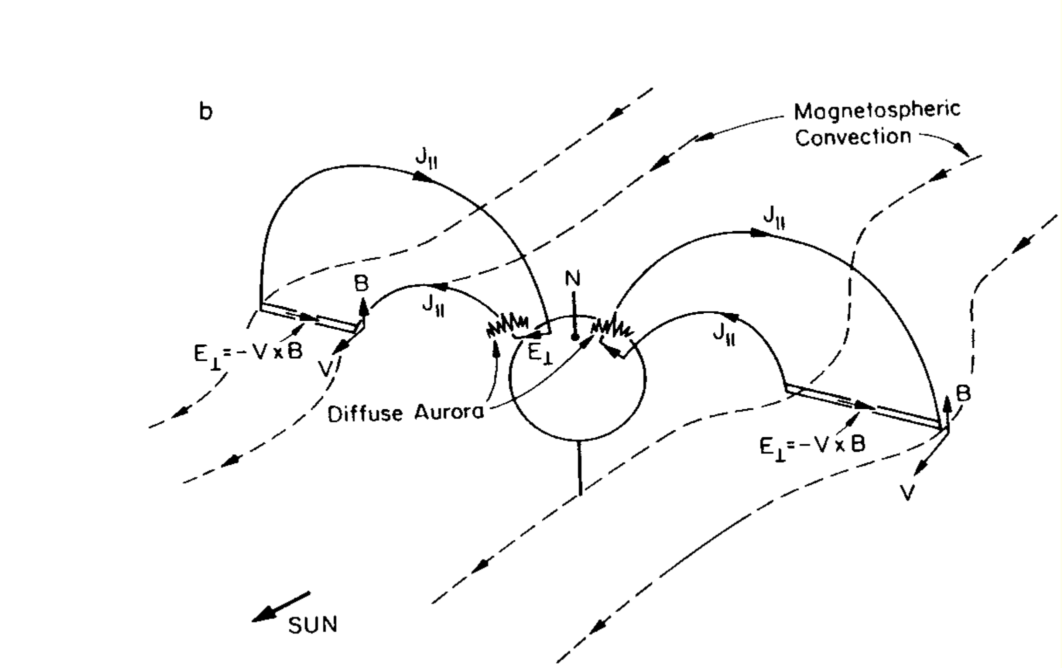
Plasma convection in the ionosphere





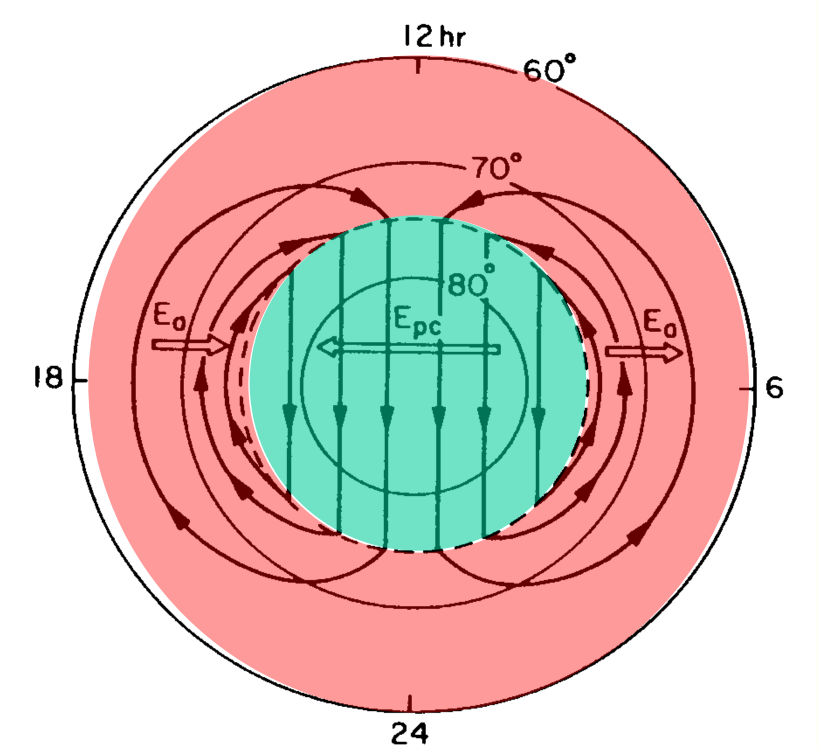
Static, large-scale MI-coupling

Magnetospheric and ionospheric convection



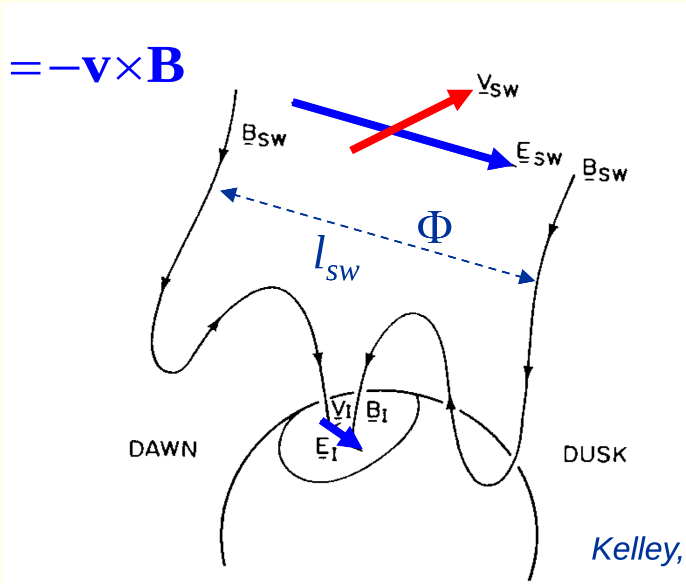
Kelley, 1989

Ionospheric convection

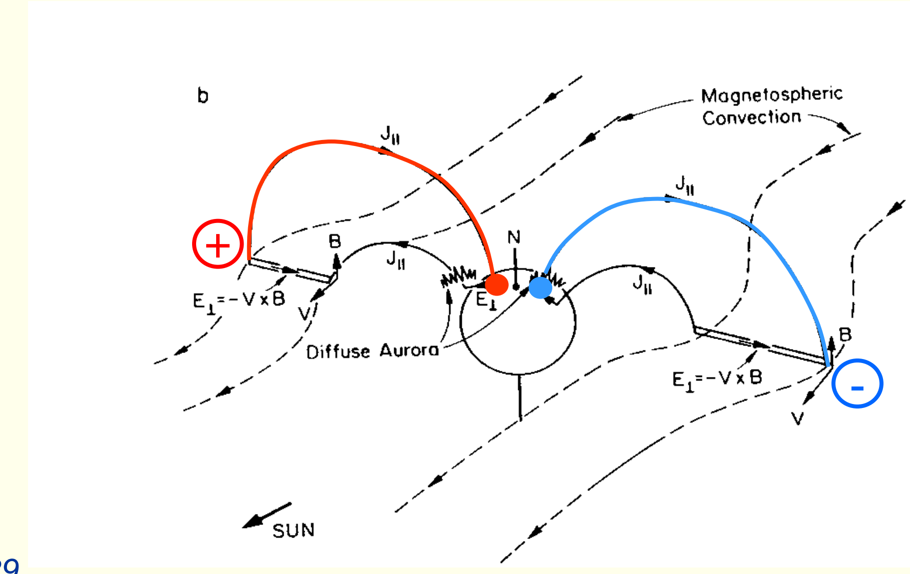


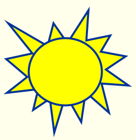
Magnetospheric plasma convection

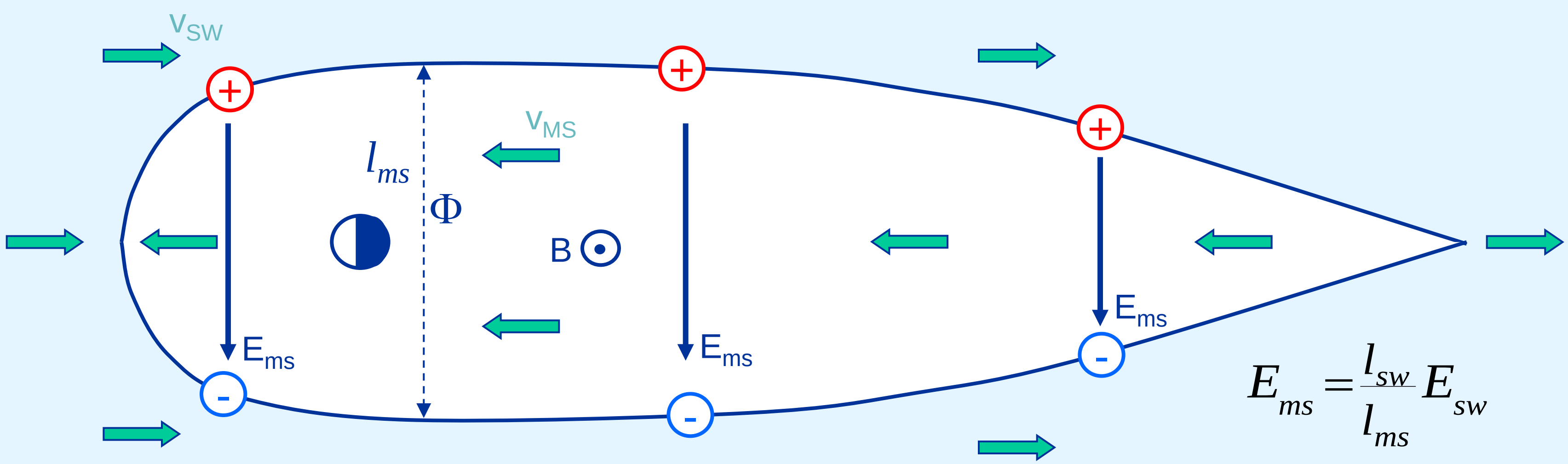
$$\mathbf{E}_{sw} = -\mathbf{v} \times \mathbf{B}$$



Kelley, 1989

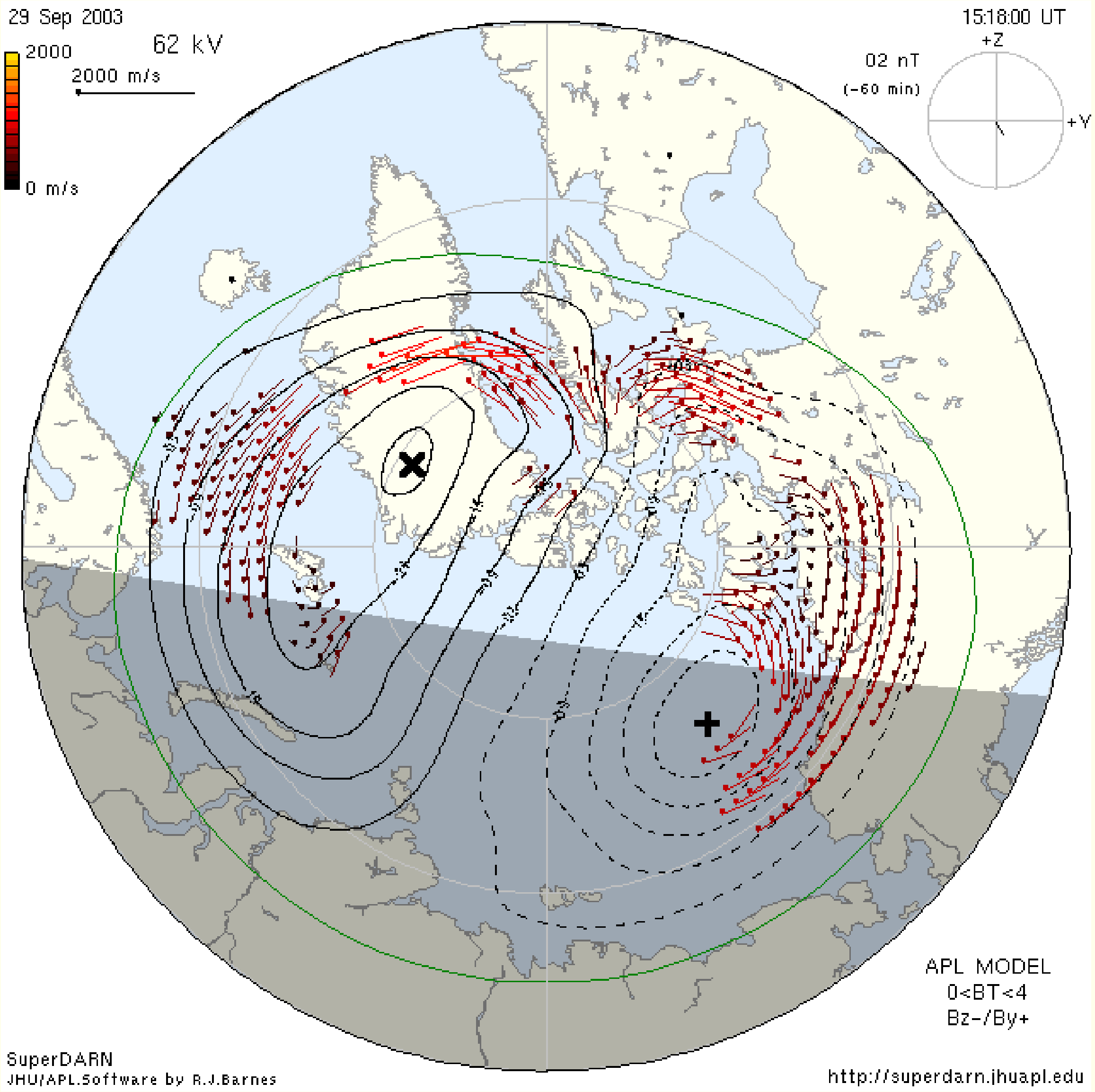






$$E_{ms} = \frac{l_{sw}}{l_{ms}} E_{sw}$$

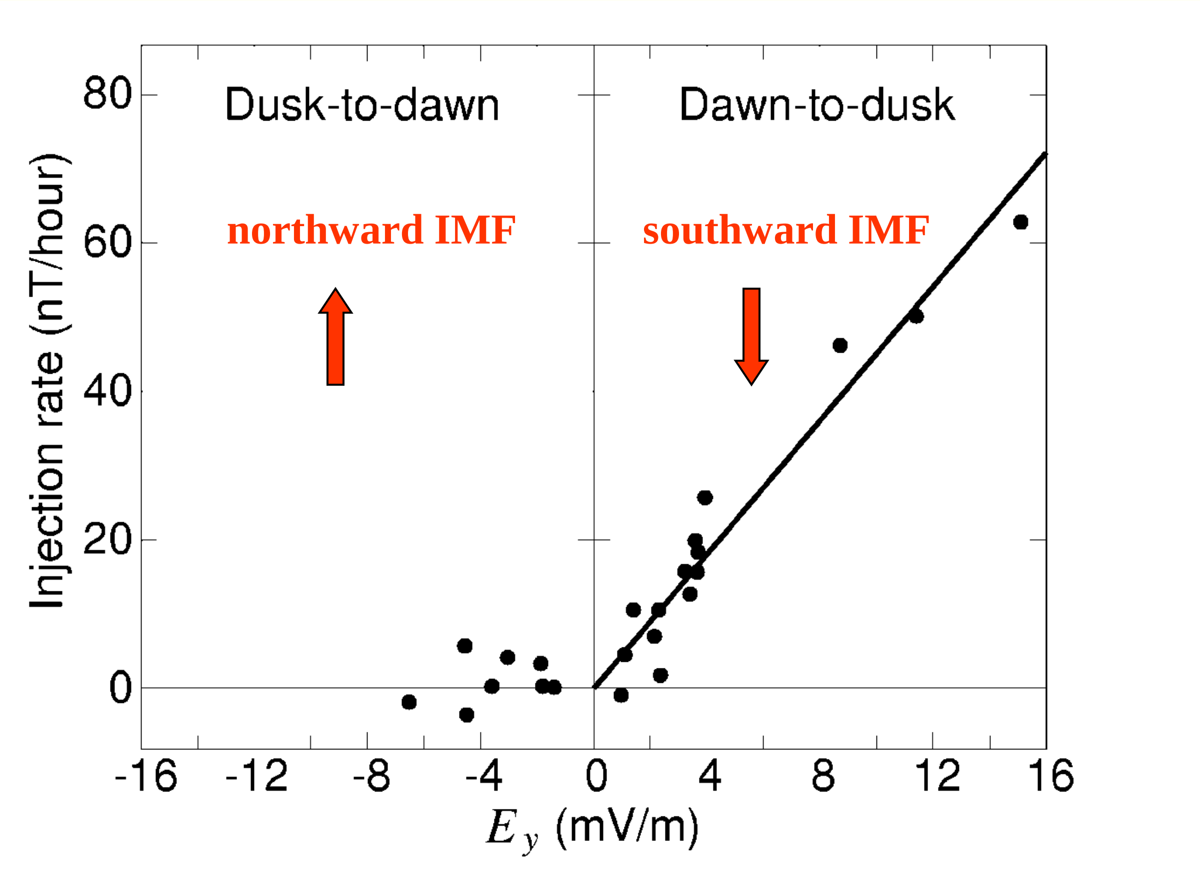
Measurements of plasma convection in the magnetosphere



Magnetospheric dynamics

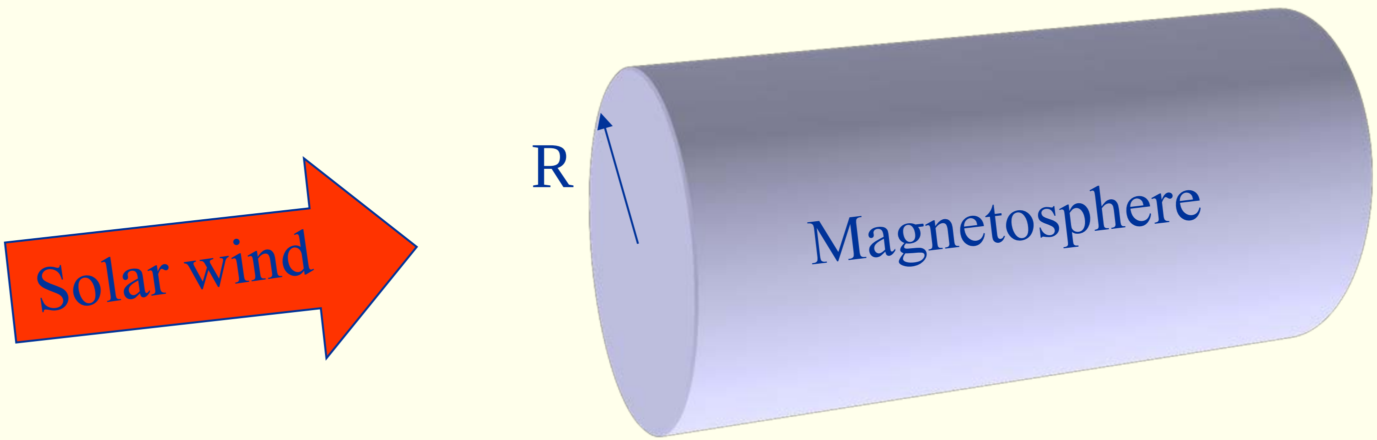
Energy input

Plasma convection in the magnetosphere



- Solar wind generates electric field **E** = **- v** × **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)



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

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

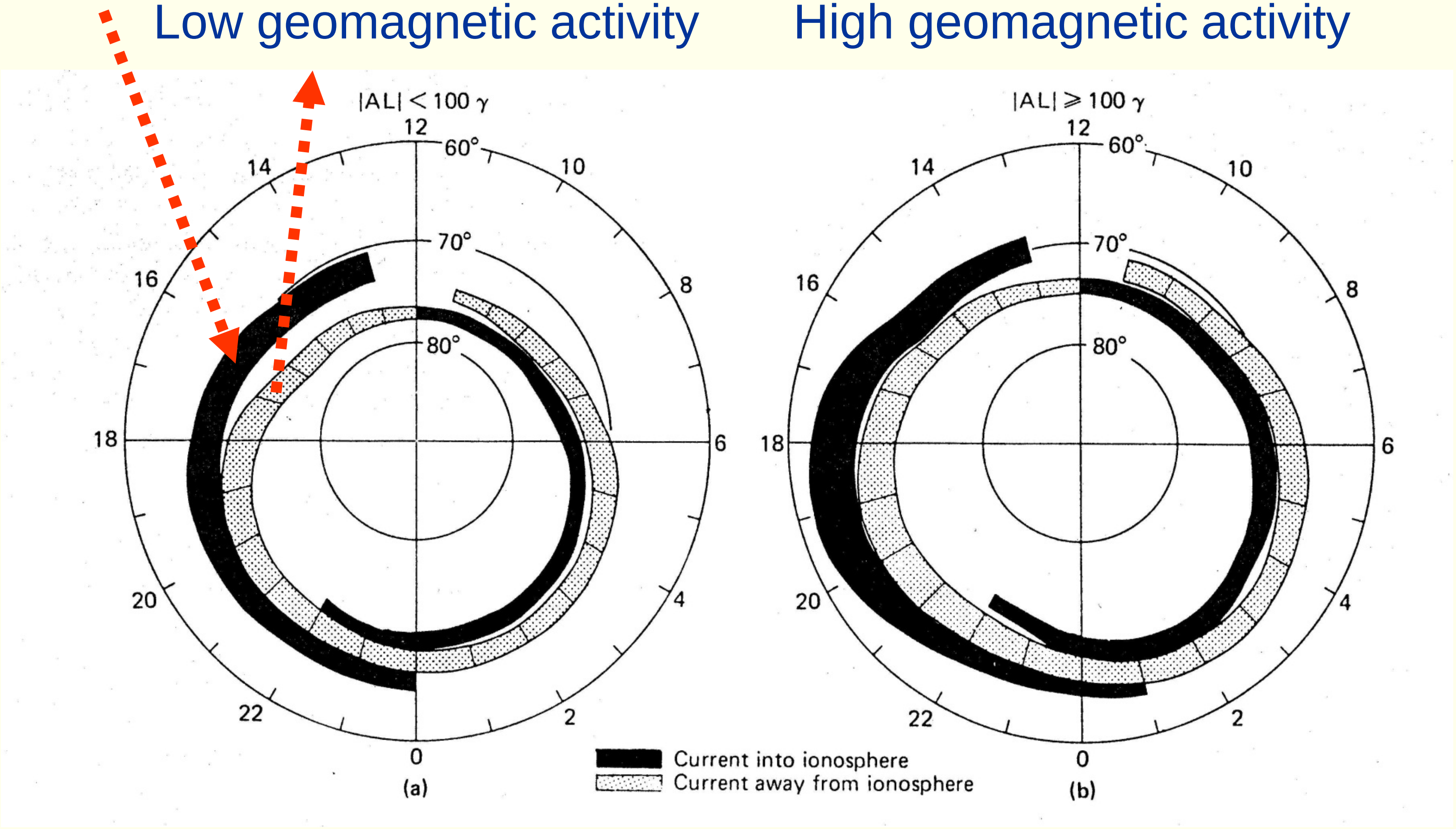
$A = \pi R^2 = \pi(10R_E)^2$

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

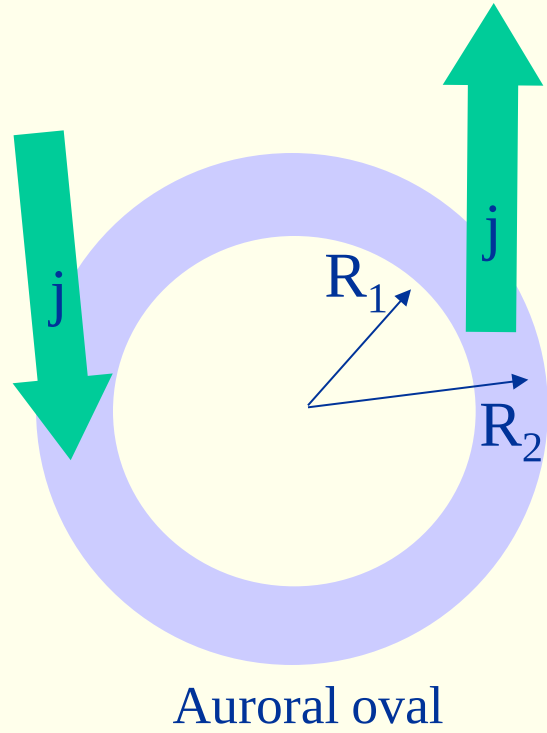
$$\mathbf{P_{sw} = \Phi_{kin} A = 3 \cdot 10^{12}\ W}$$

Birkeland currents in the auroral oval

Low geomagnetic activity High geomagnetic activity



Energy budget (2)



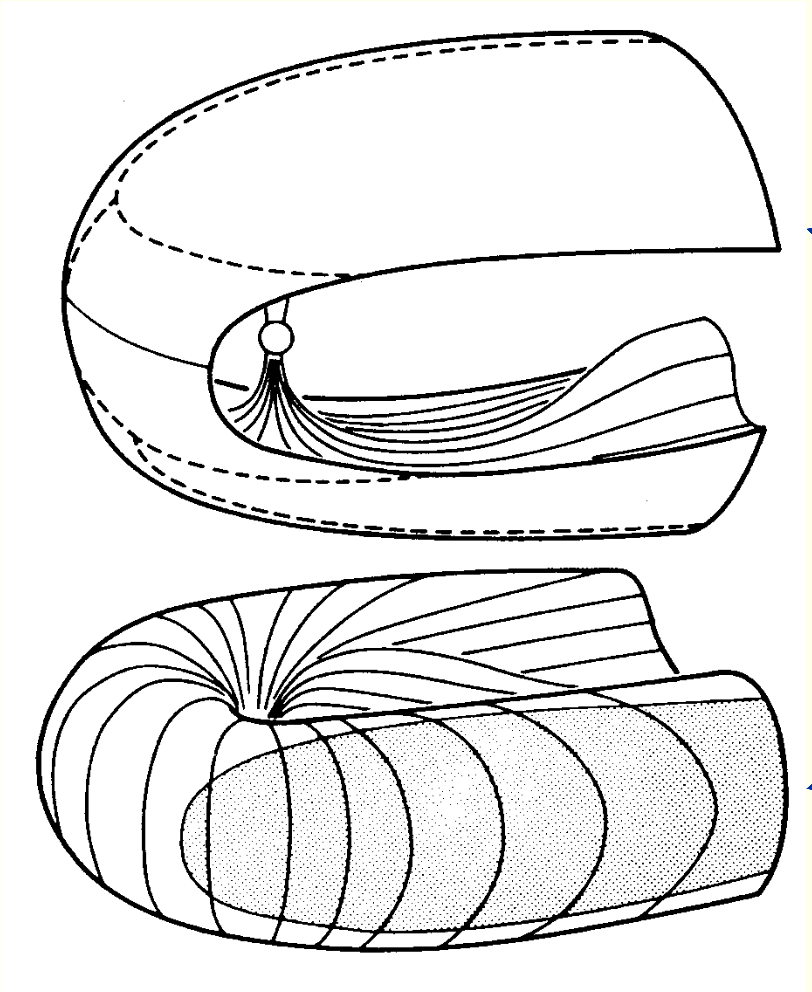
$A = \pi(R_2^2 - R_1^2) = 2 \cdot 10^{13}\ \mathrm{m}^2$

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

U = ?

P = UI = ?

Magnetospheric topology



Open field lines

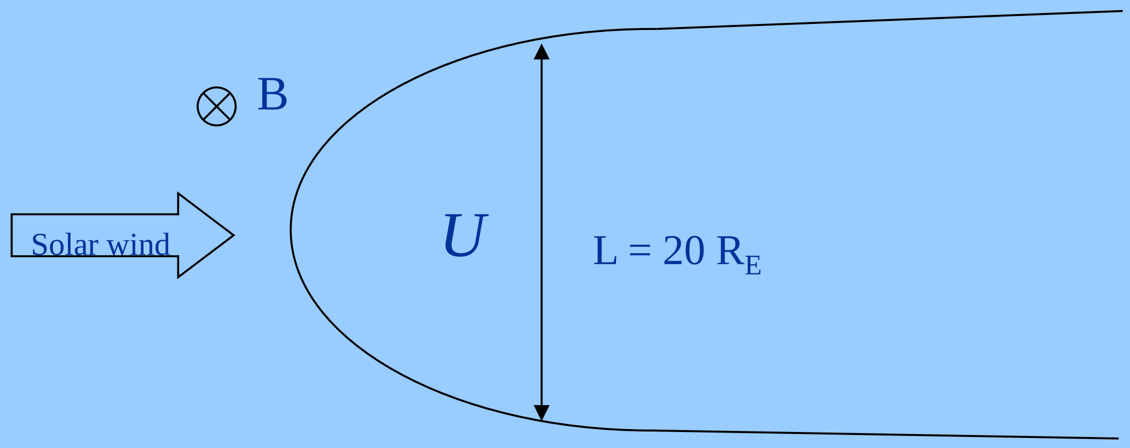
Closed field lines

What is the potential drop over the magnetosphere?

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

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

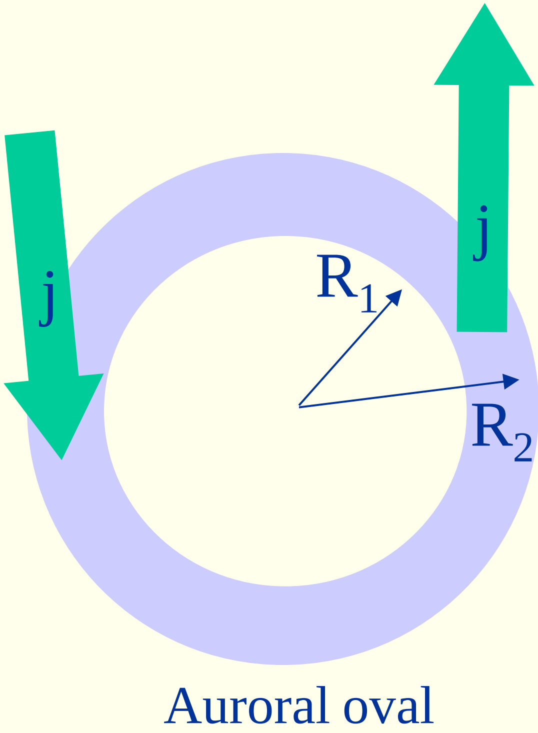
$$B_{SW} = 5 \text{ nT}$$



$$U = v_{SW} B_{SW} L = 300\cdot10^3\cdot5\cdot10^{-9}\cdot20\cdot 6378\cdot10^3 = 190 \text{ kV}$$

Red 200 kV

Energy budget (2)



$U = 200\ \text{kV}$

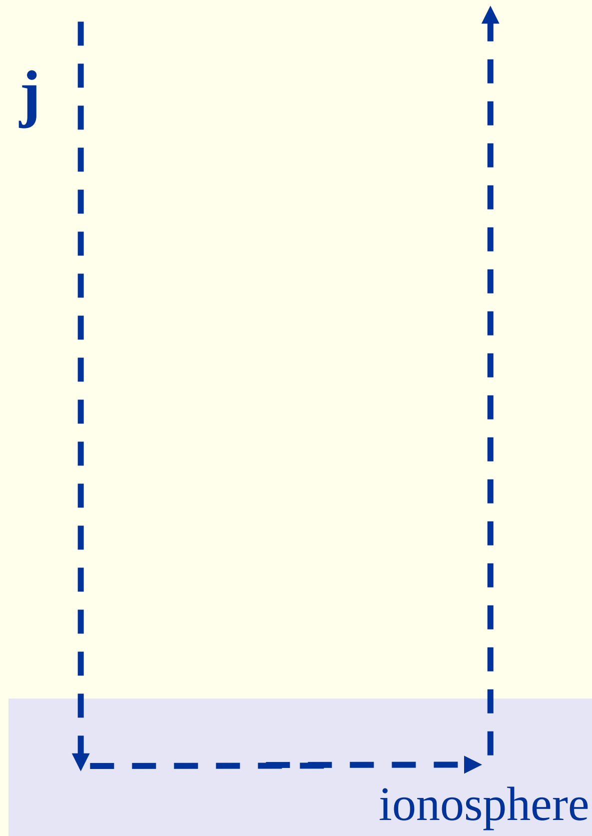
$A = \pi(R_2^2 - R_1^{2)} = 2{\cdot}10^{13}\ \text{m}^3$

$I = jA/2 = \tfrac{1}{2}\cdot 0.1\cdot 10^{-6}\ \text{Am}^{-2} \cdot 2{\cdot}10^{13}\ \text{m}^2 = 10\ \text{MA}$

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

Geomagnetic activity, definition

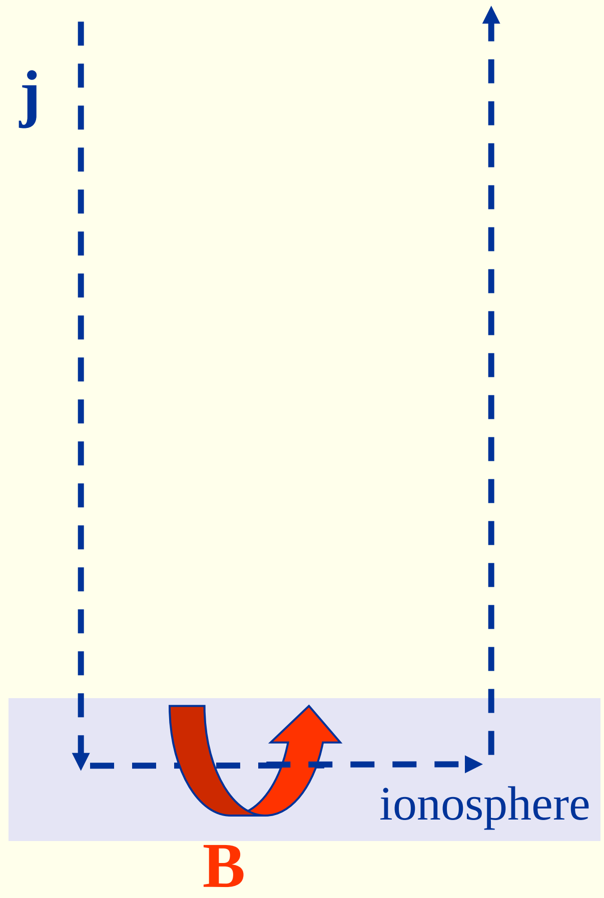
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.



How can you observe these changing currents on Earth?

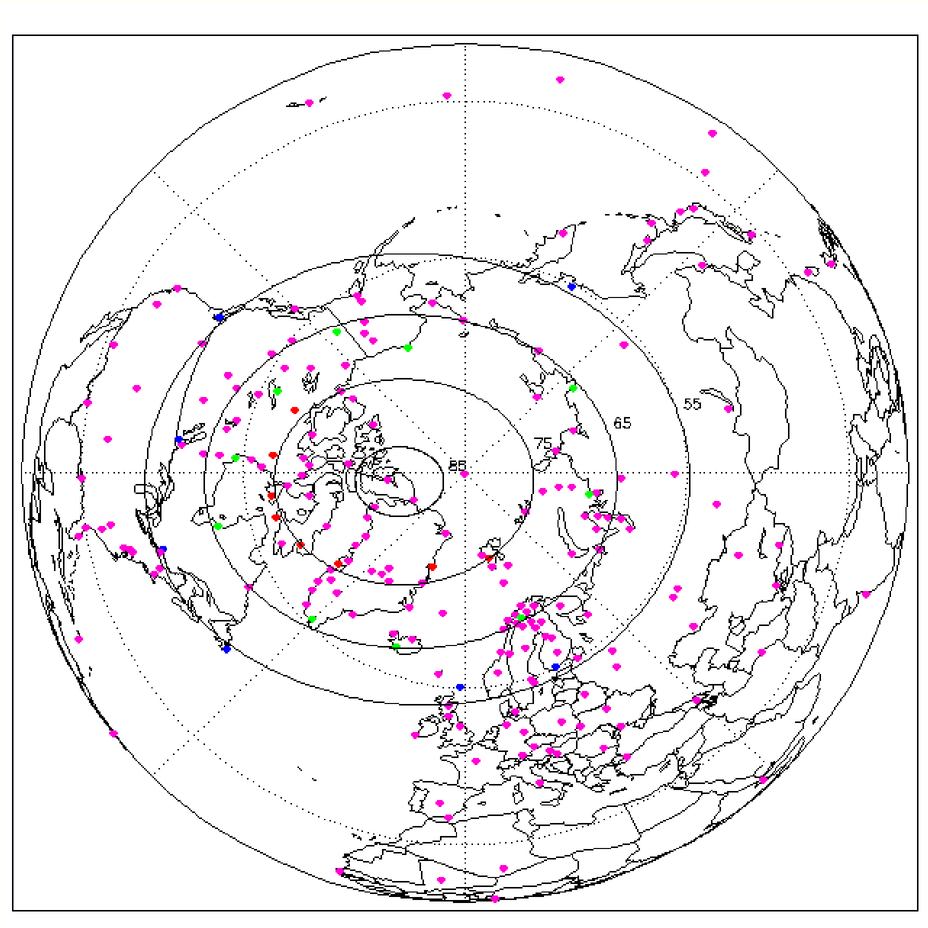
Geomagnetic activity, definition

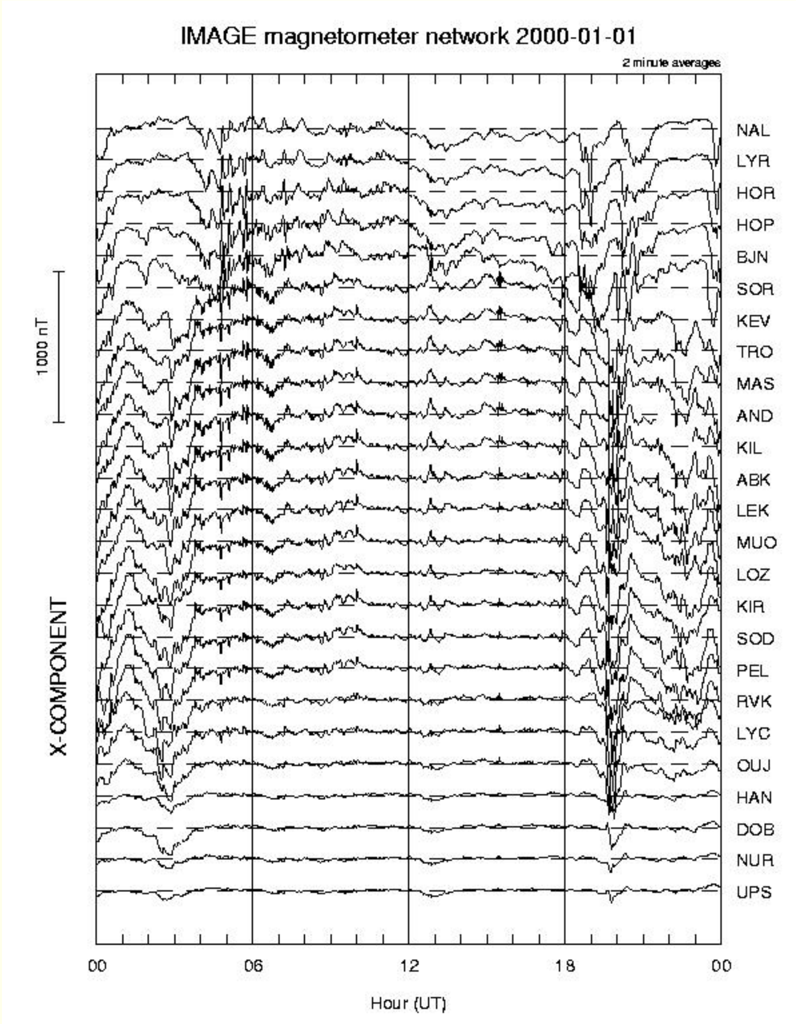
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.
- The variations are observed by geomagnetic observatories



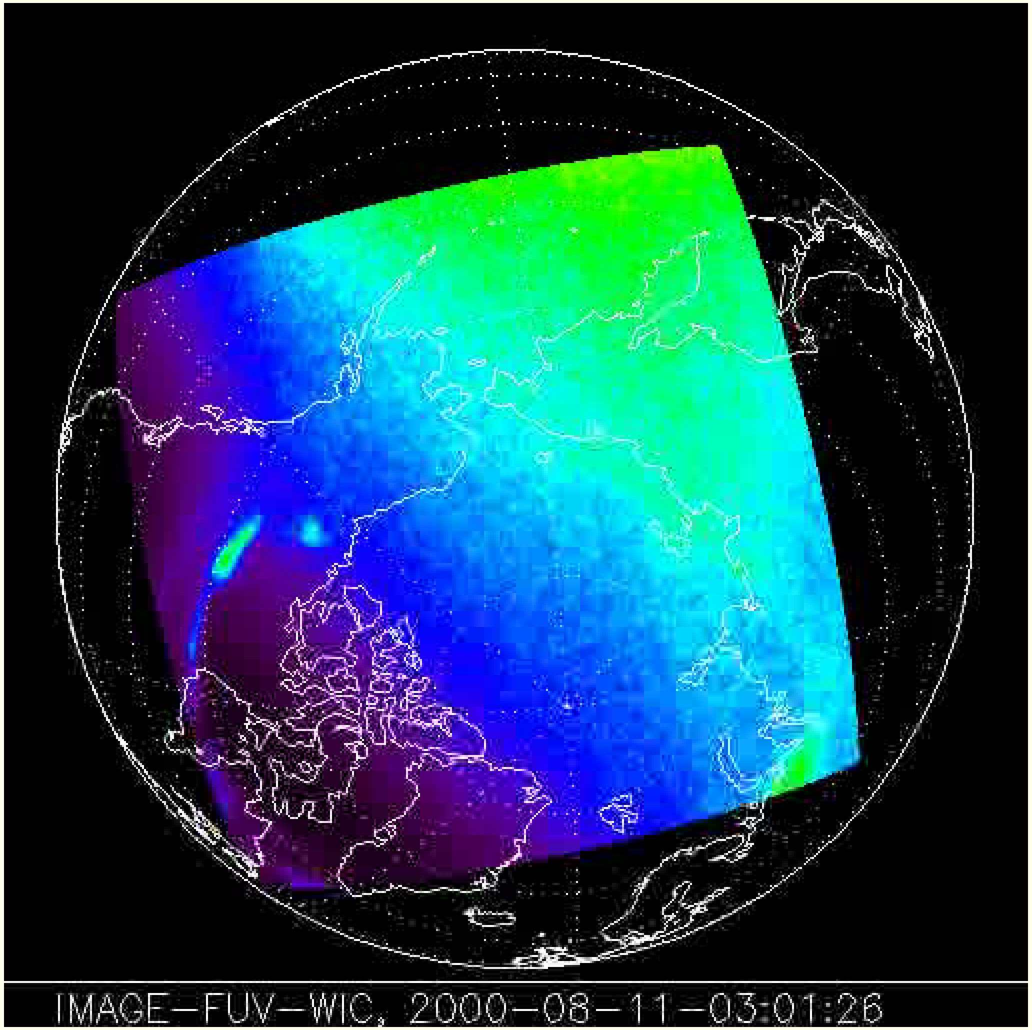
Magnetic observatories

Magnetogram

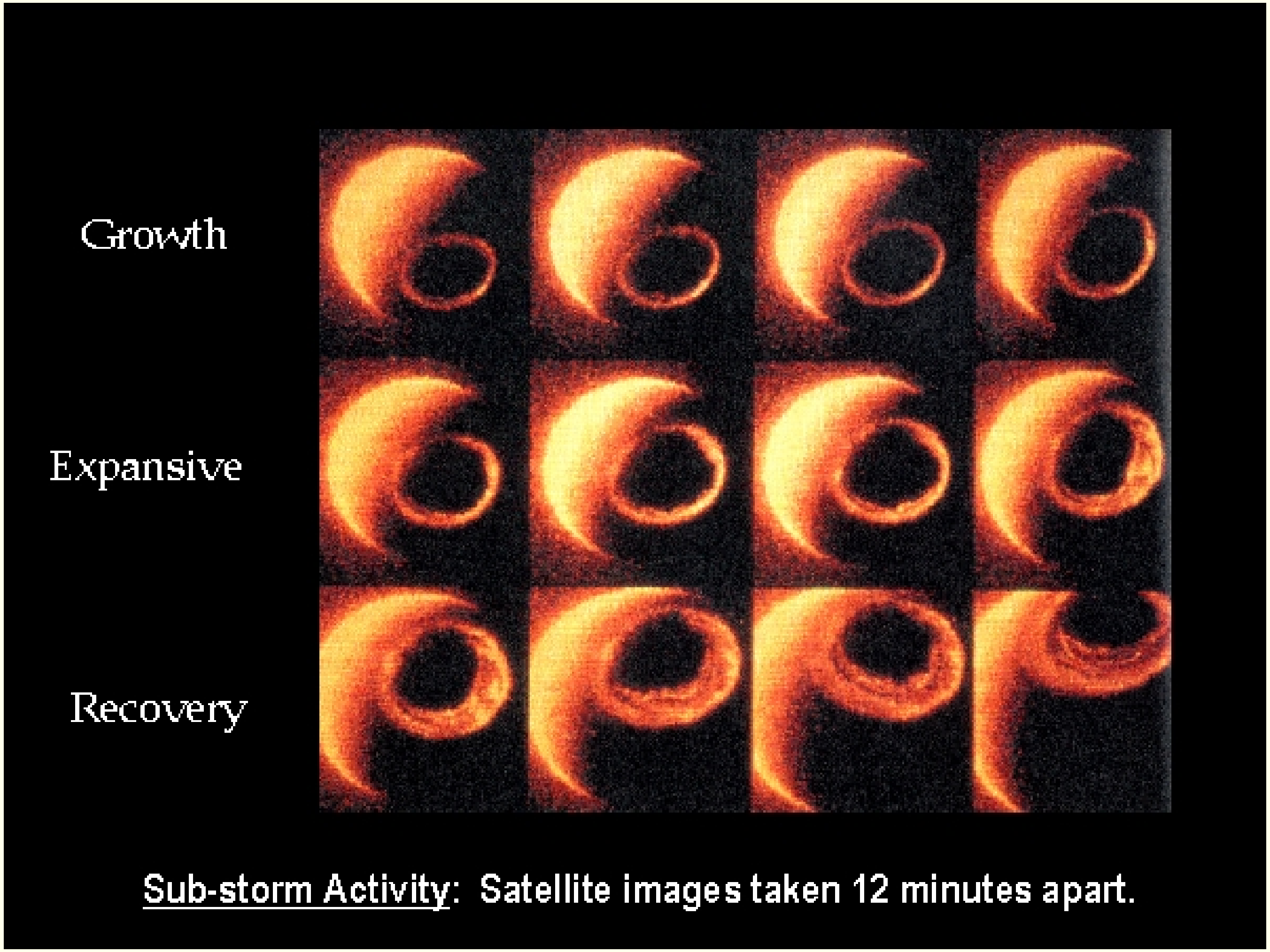




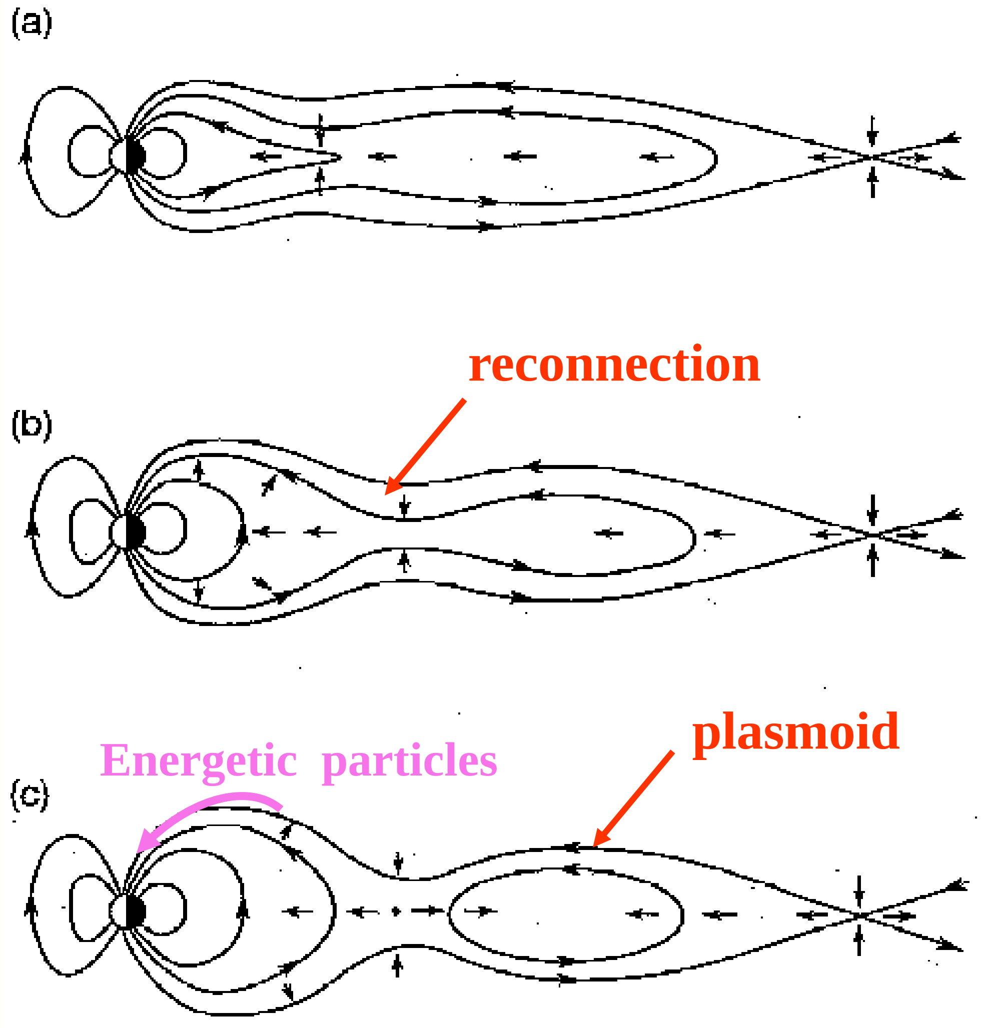
Aurora during substorm



Aurora during substorm

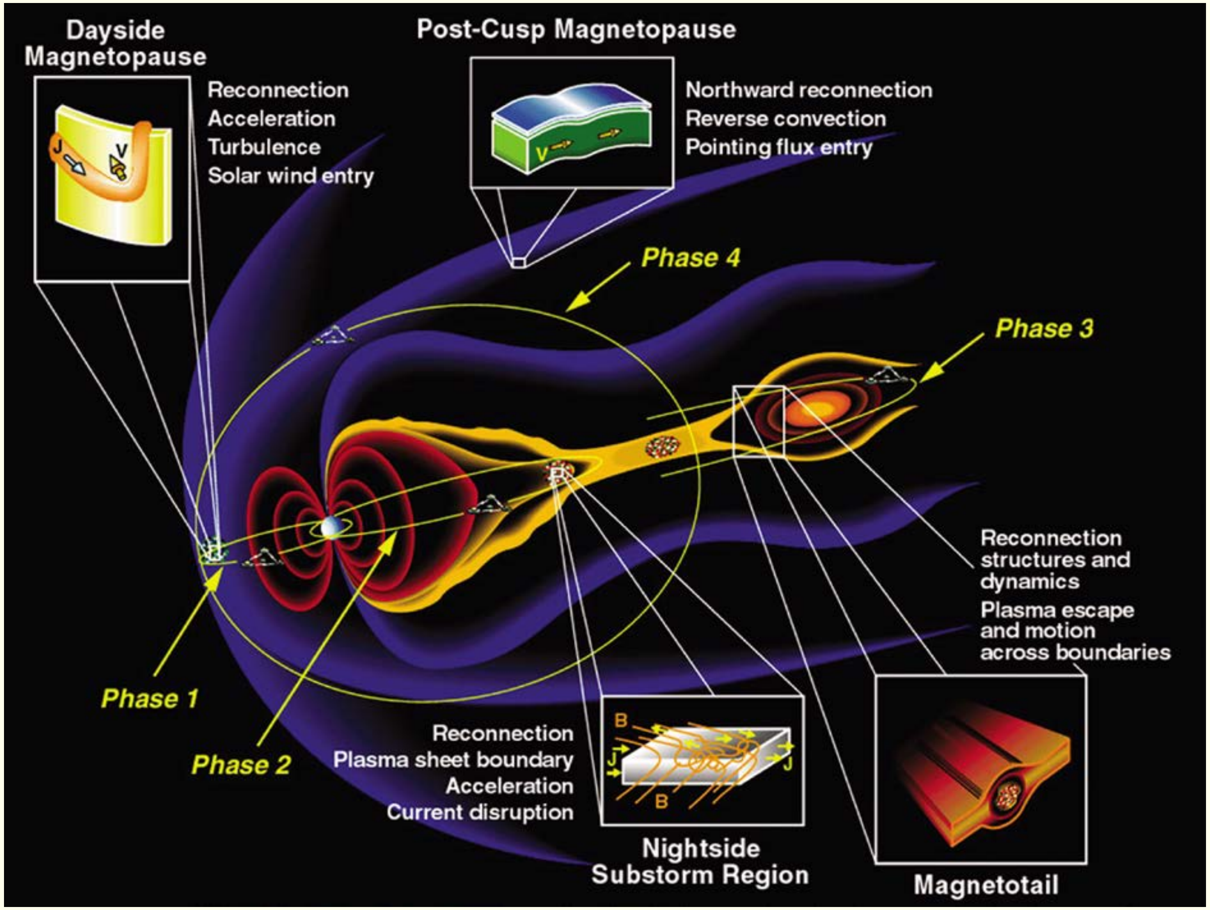


Substorms - magnetosphere



- **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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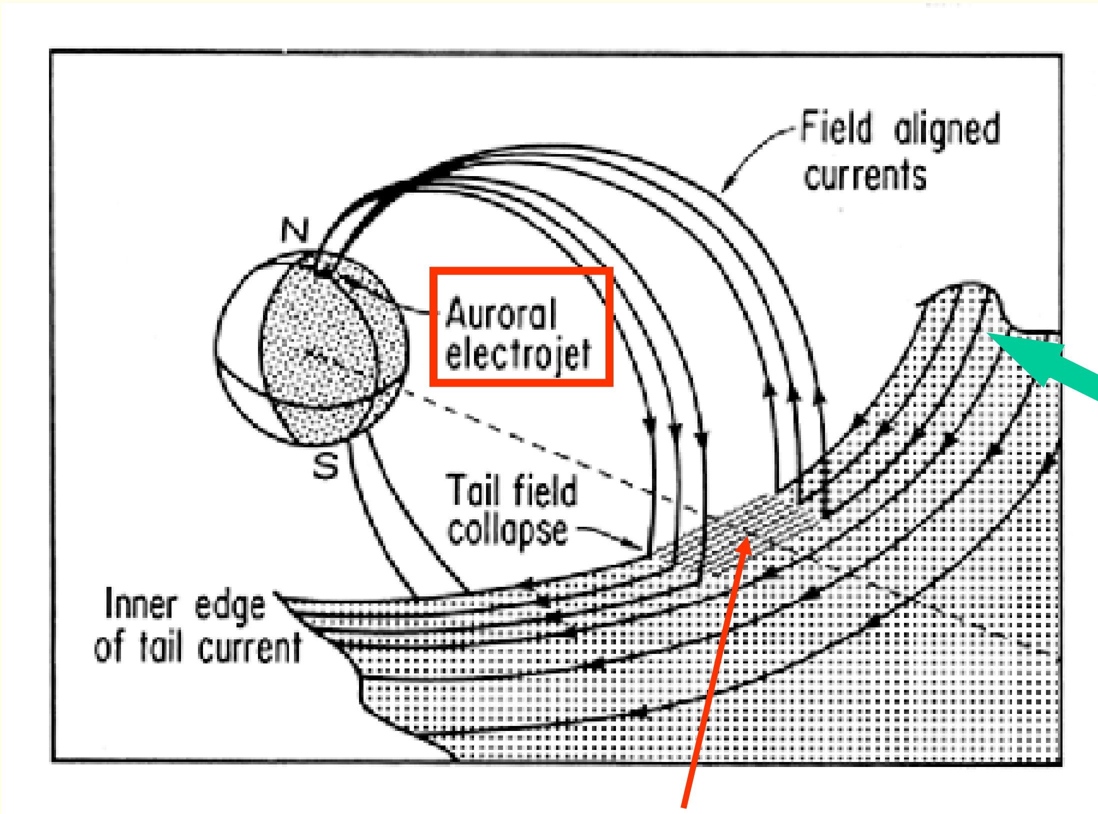
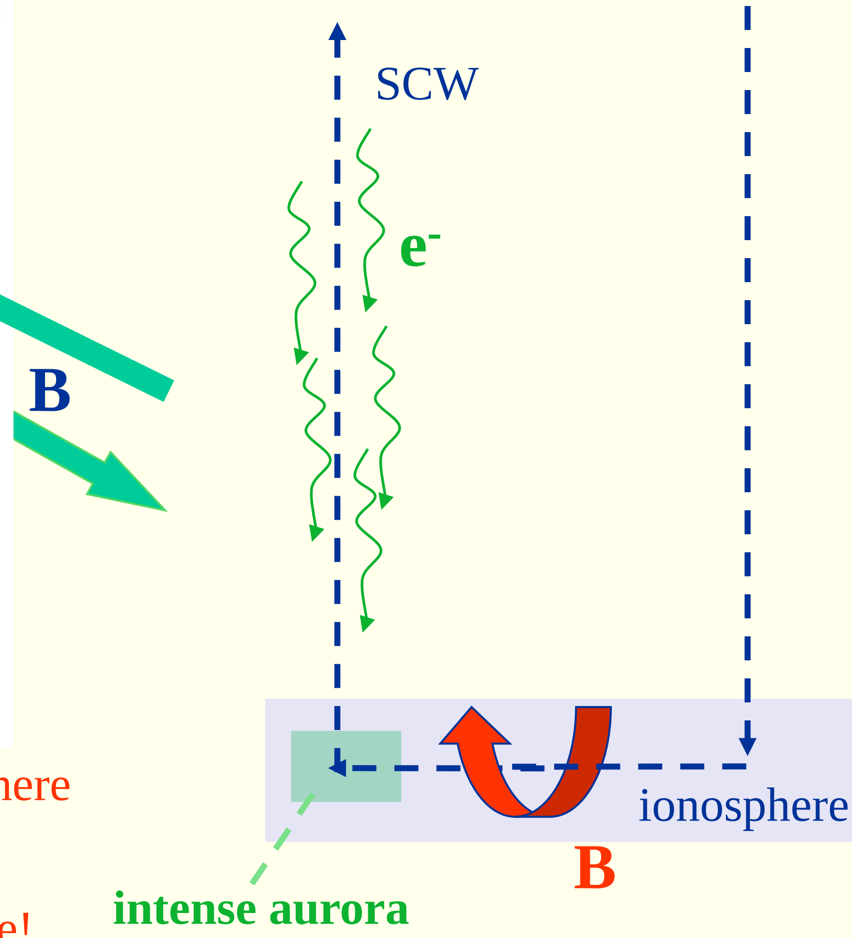
Substorm Current Wedge (SCW)



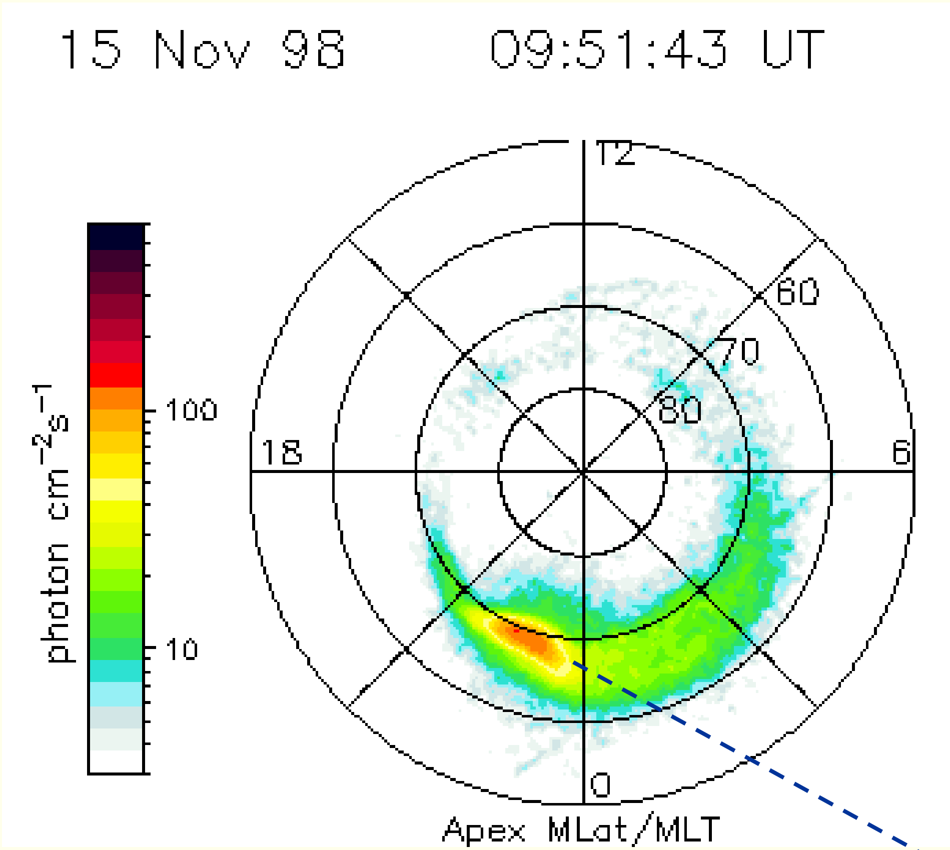


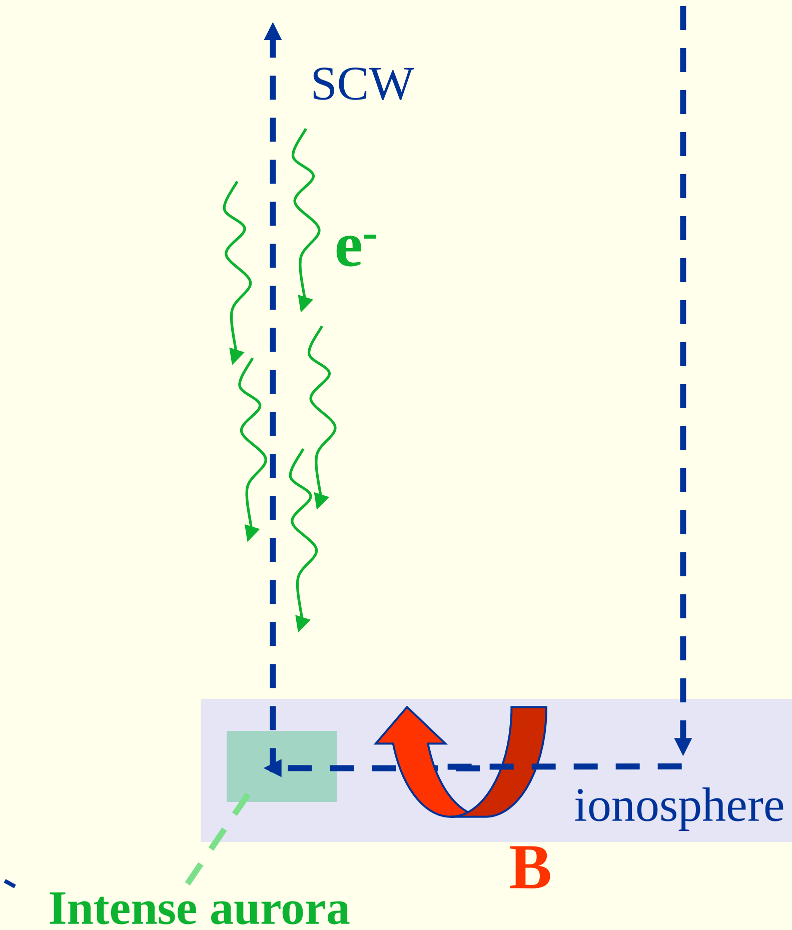
Due to reconnection processes the resistivity increases here

⇒

Current takes another direction – through the ionosphere!

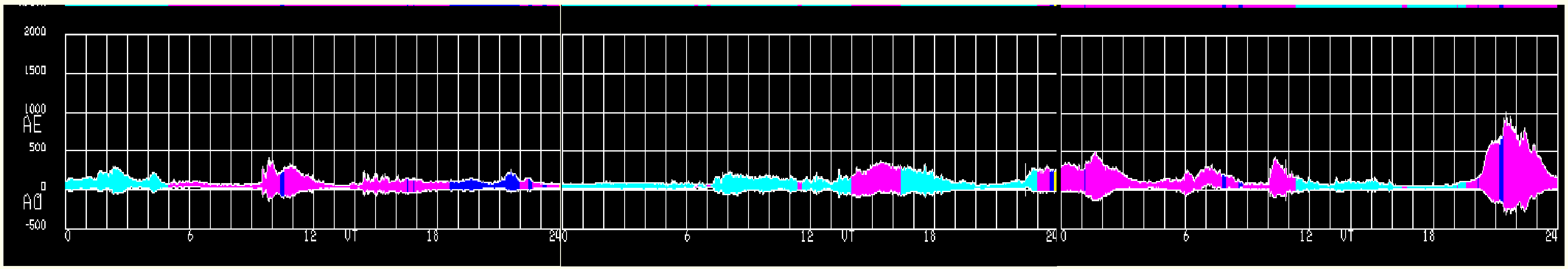
Substorm Current Wedge (SCW)

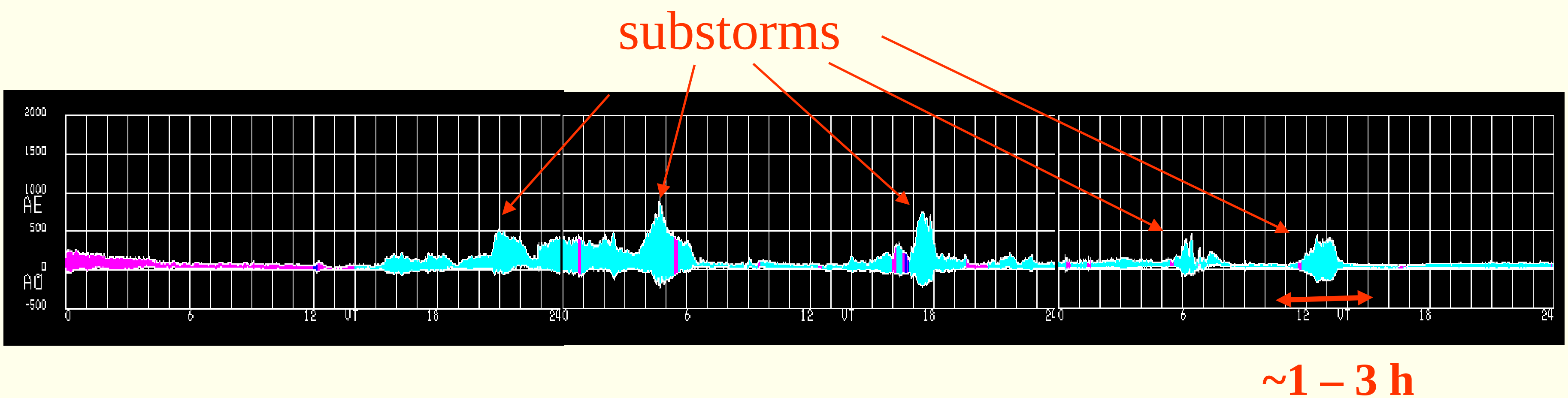




Auroral Electrojet (AE) index

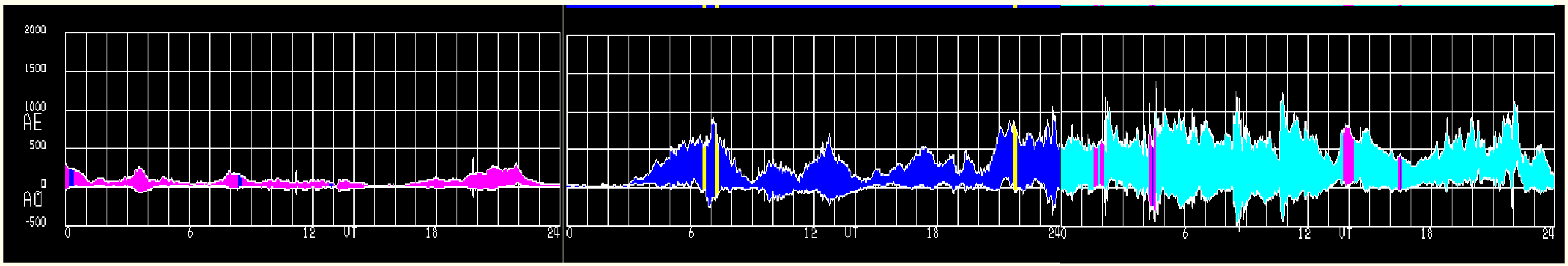
The AE index Measures the strength of the substorm current wedge (SCW), by using the information from several magnetic observatories.

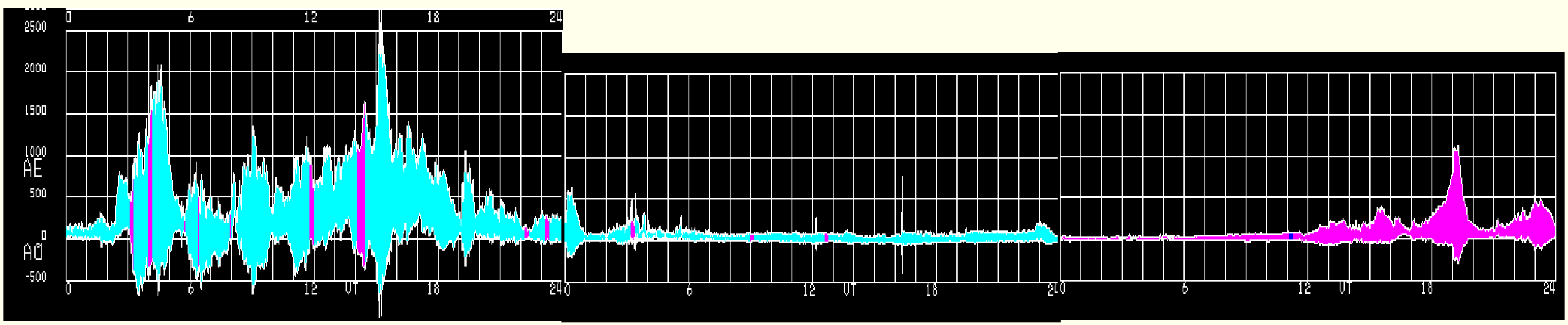




Geomagnetic storms

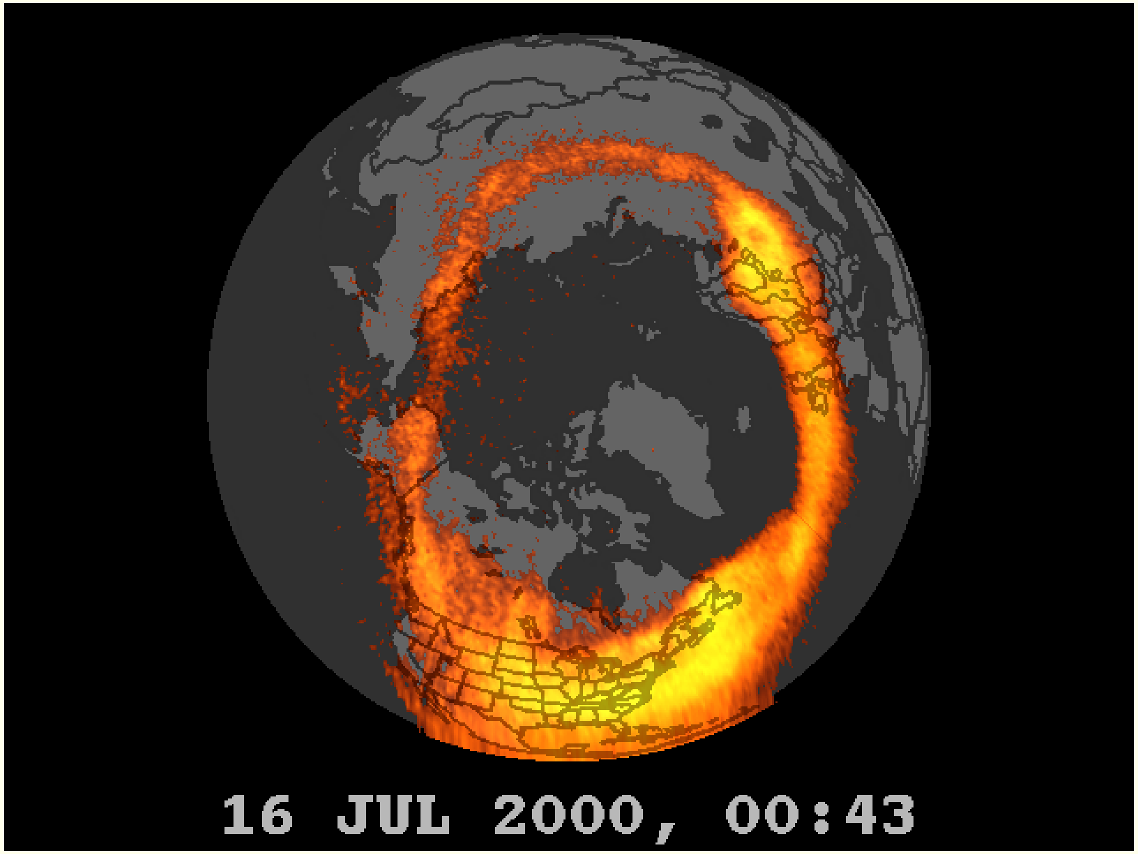
Geomagnetic storms are extended periods with southward interplanetary magnetic field (IMF) and a large energy input into the magnetosphere.



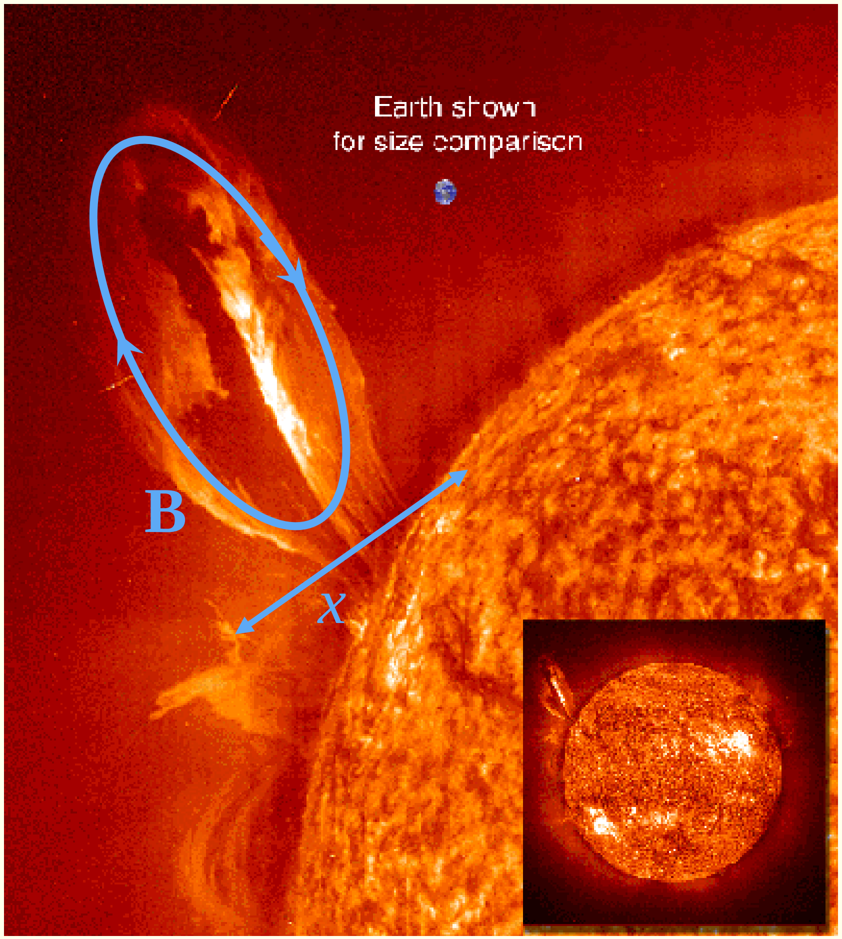


Geomagnetic storms

Auroral oval very extended

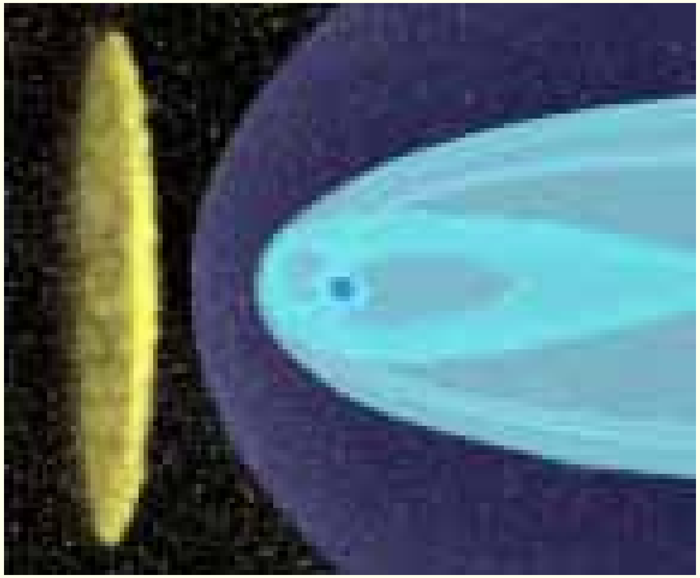


Geomagnetic storms and coronal mass ejections



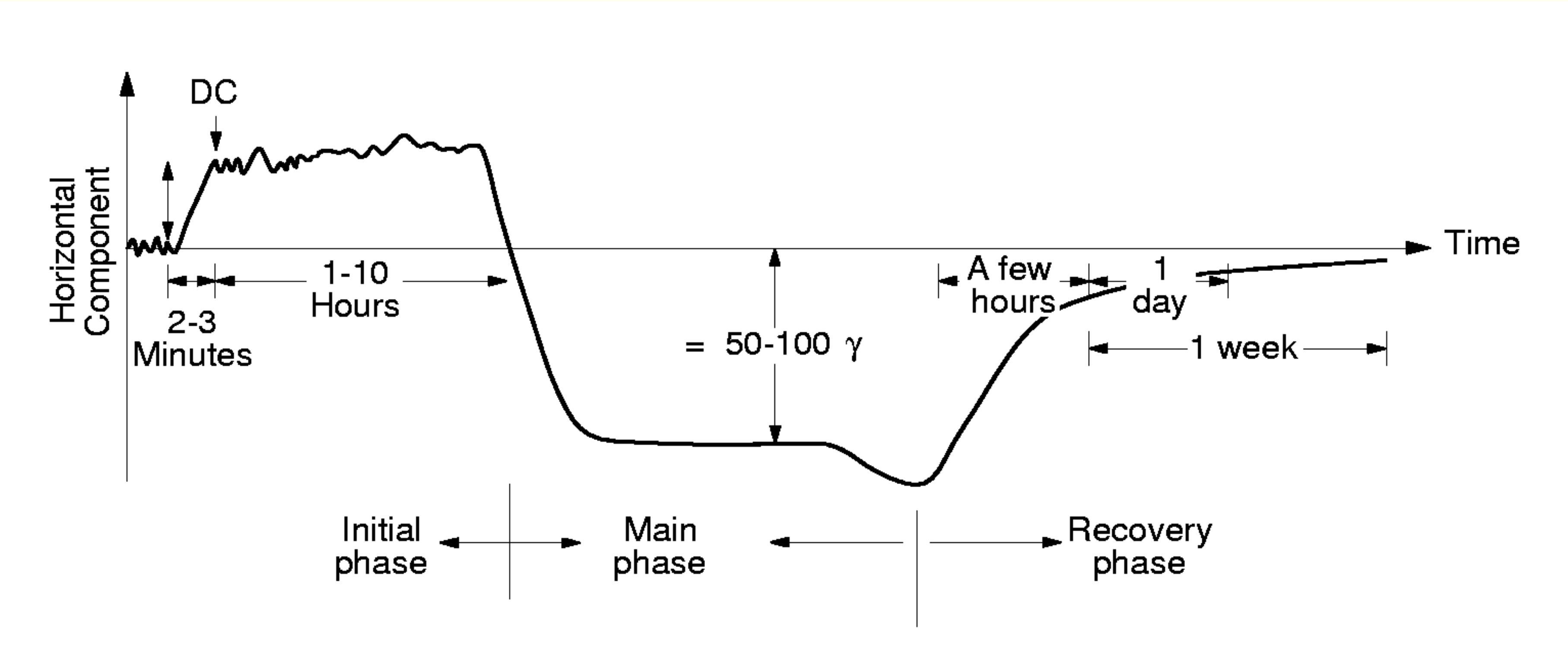
- Large geomagnetic storms are often associated with coronal mass ejections (CMEs)
- Because of their magnetic structure, they will give long periods with a constant IMF
- A typical time for a CME to pass Earth becomes $T = x/v \sim 10\ R_E/1000\ \mathrm{kms^{-1}} \sim 60$ h

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

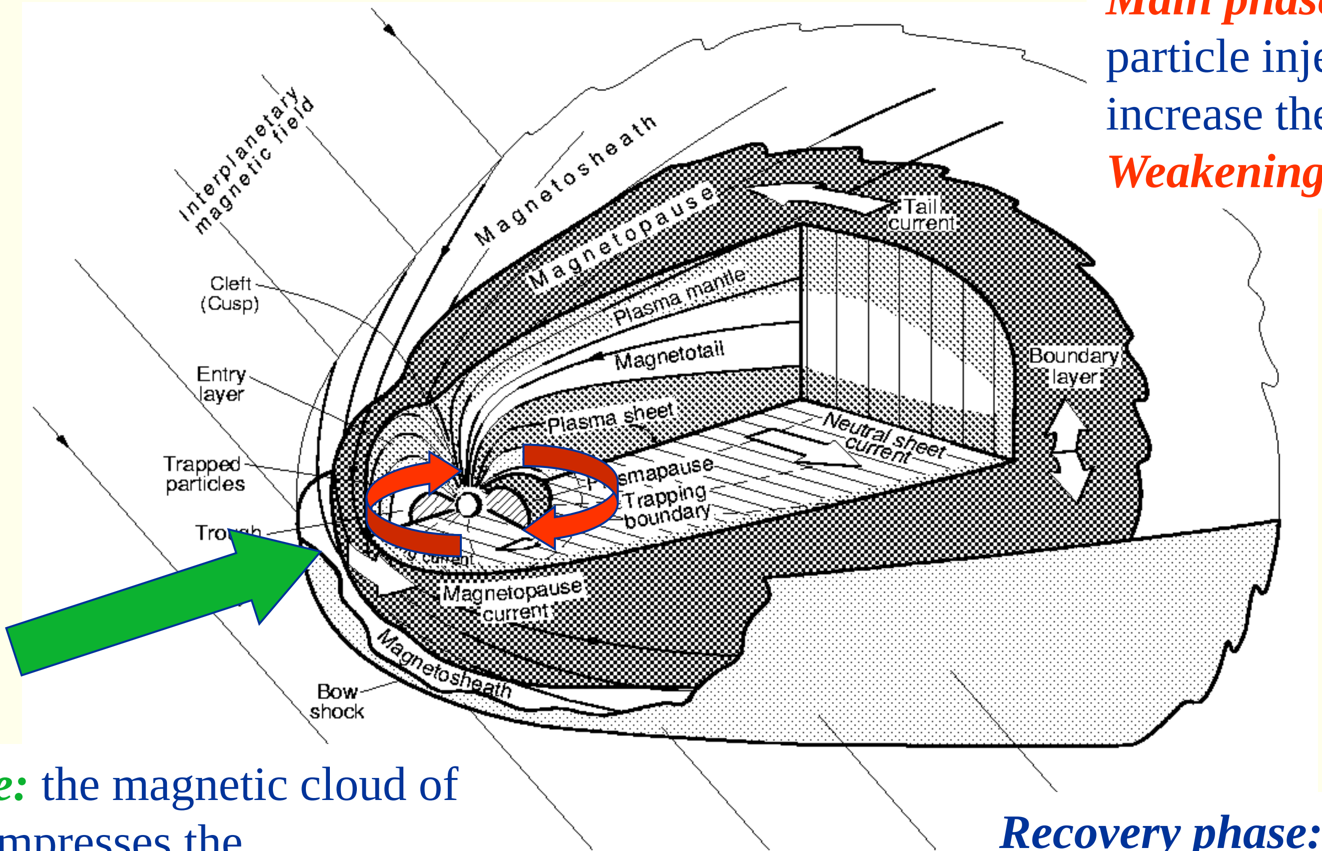


Geomagnetic storms - phases

Magnetogram



Geomagnetic storms - phases

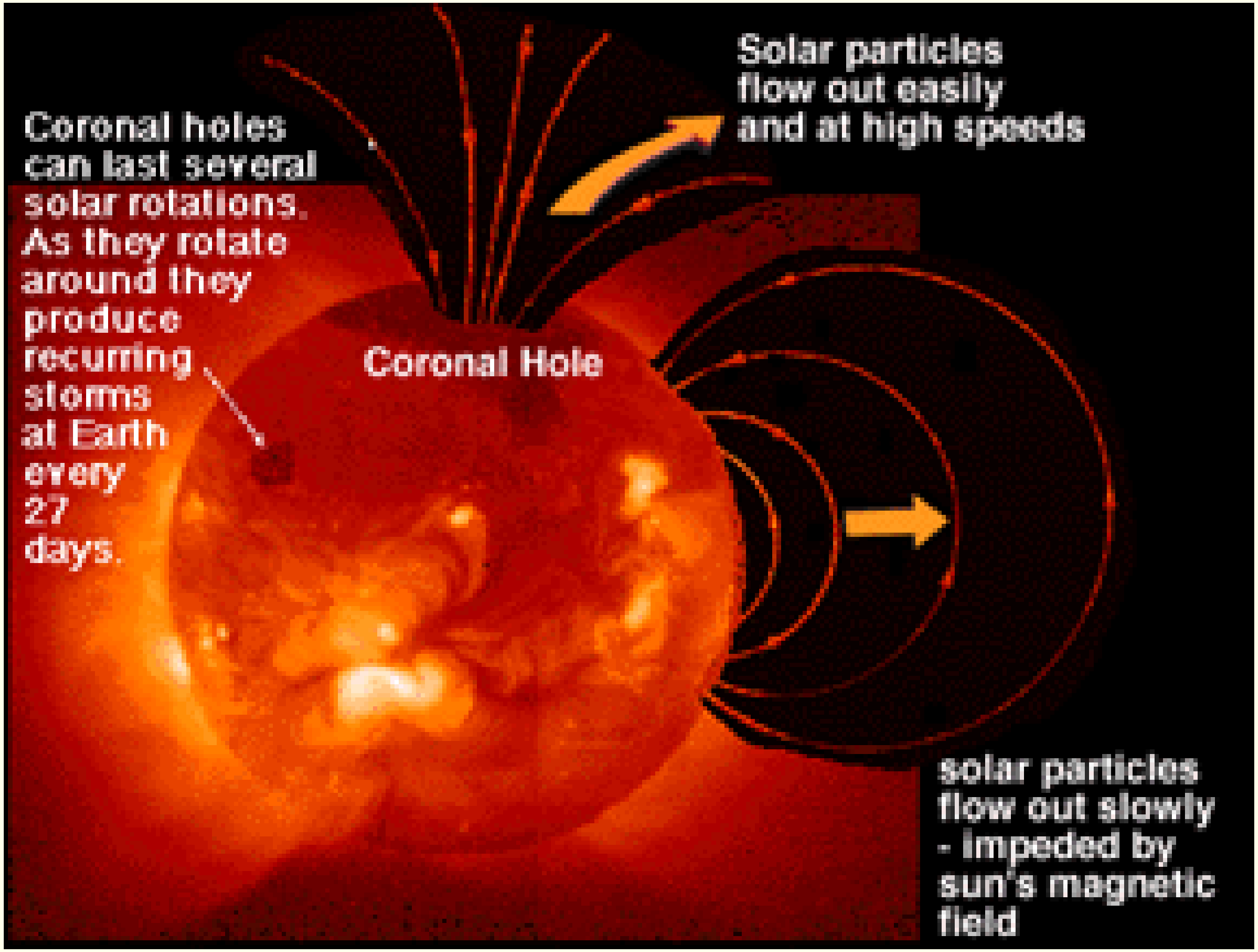


Main phase: Several particle injections increase the ring current.
Weakening of B

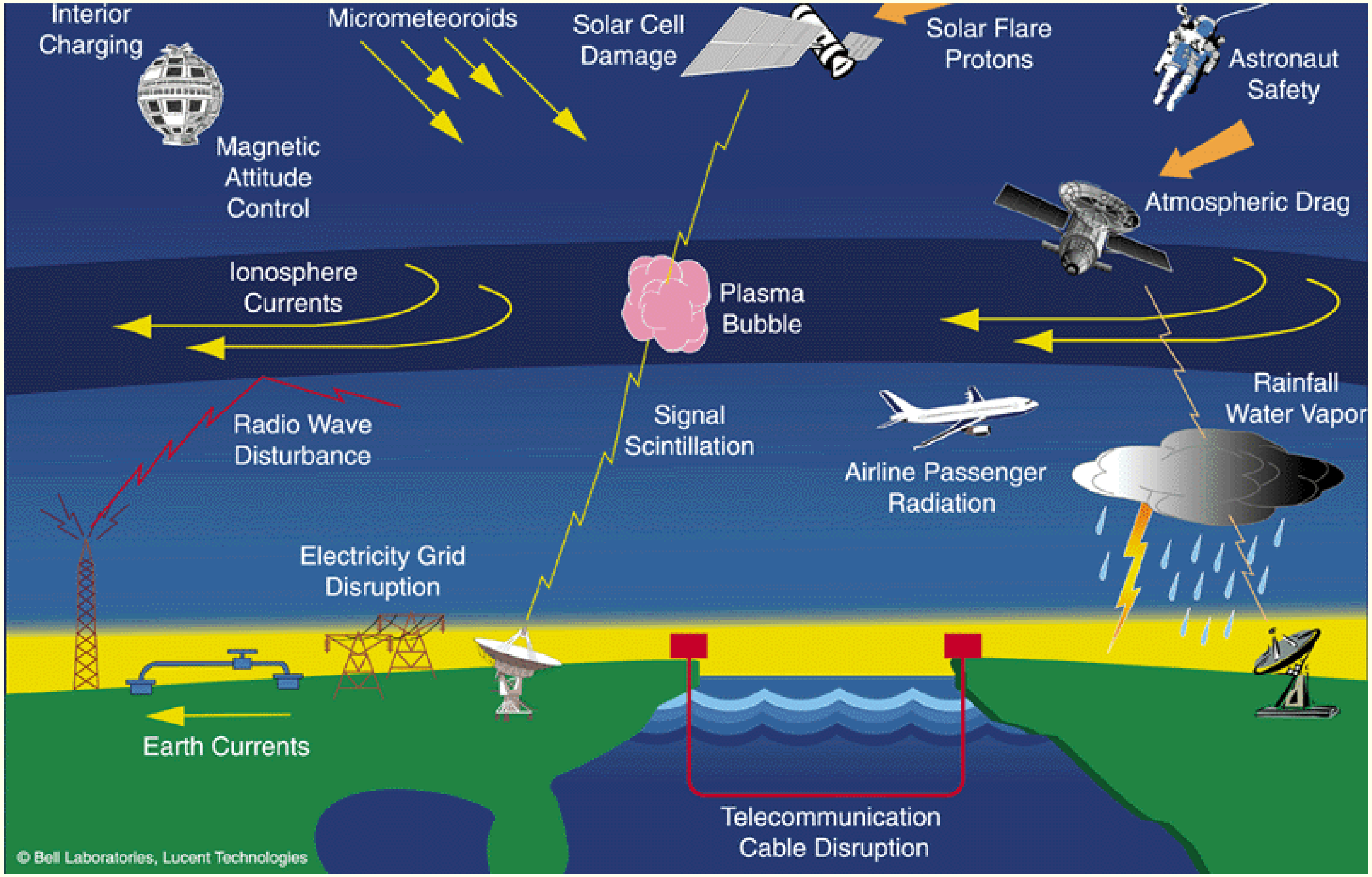
Initial phase: the magnetic cloud of the CME compresses the geomagnetic field.
Increase of B

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

Periodic geomagnetic activity

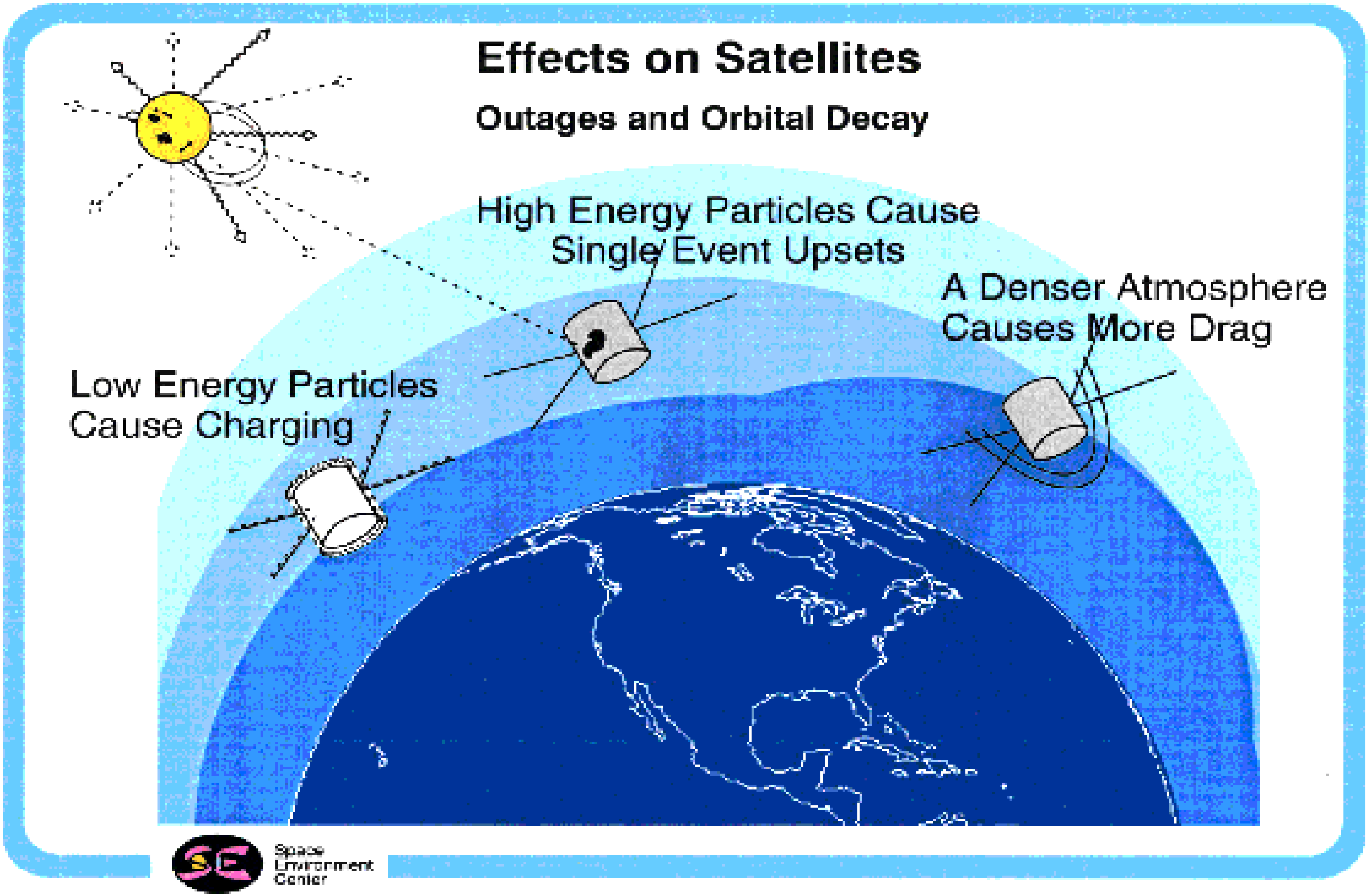


Space weather : consequences of solar and geomagnetic activity



"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

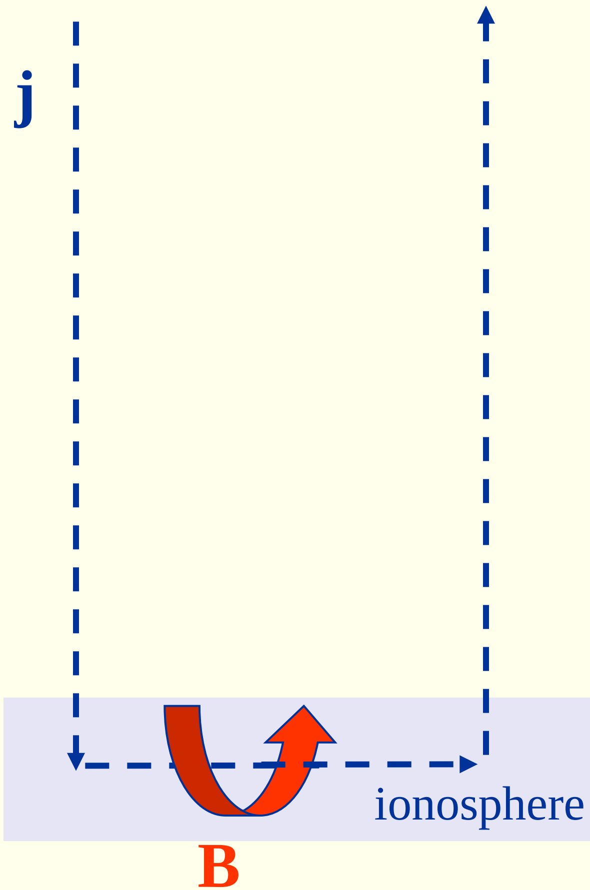

Effects on Satellites
Outages and Orbital Decay
High Energy Particles Cause
Single Event Upsets
A Denser Atmosphere
Causes More Drag
Low Energy Particles
Cause Charging
Space
Environment
Center

Damage To Solar Panels

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

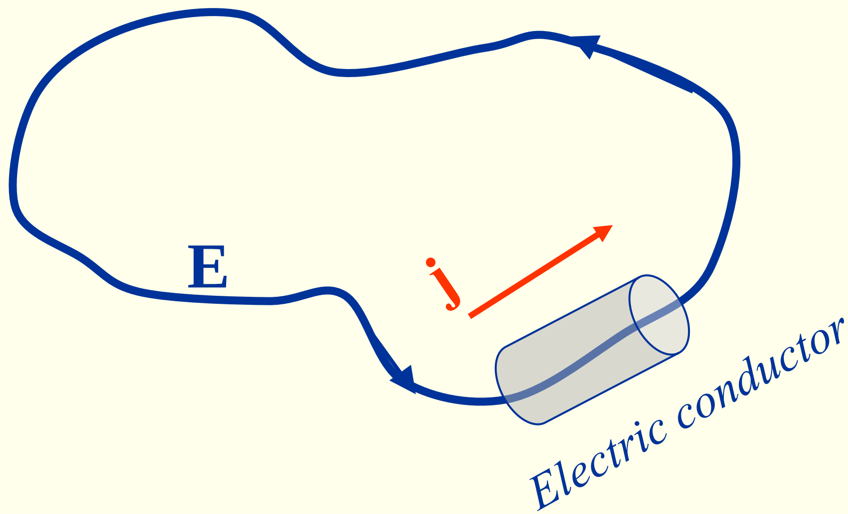
The damage is done by energetic particles which penetrate the surface of the panel and deposit a significant amount of energy inside the solar cells. This displaces the atoms within the cells and causes a loss in efficiency.

GIC – Geomagnetically Induced Currents



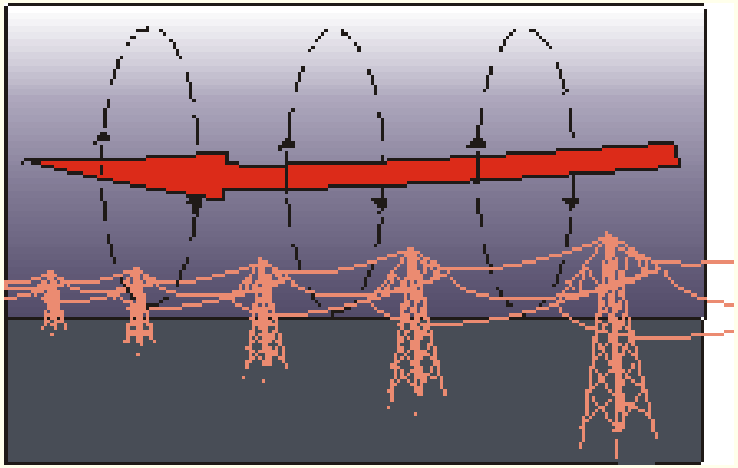
$$\frac{\partial B}{\partial t} = -\nabla \times \mathbf{E}$$

Faraday's law



GIC – Geomagnetically Induced Currents

Can damage electric power grids

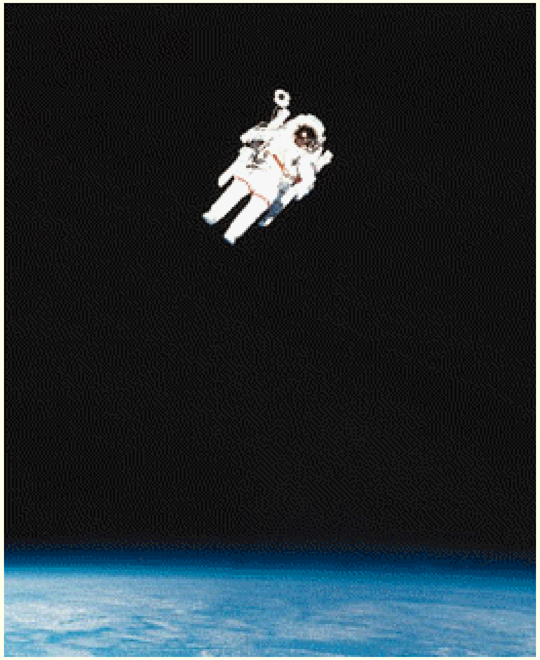


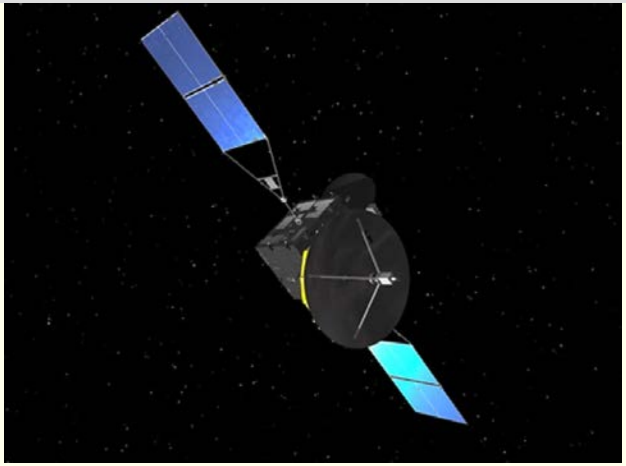
Induced currents is pipelines increase corrosion.

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)

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