Last lecture (7)

- Particle motion in magnetosphere
- Aurora

Today's lecture (8)

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

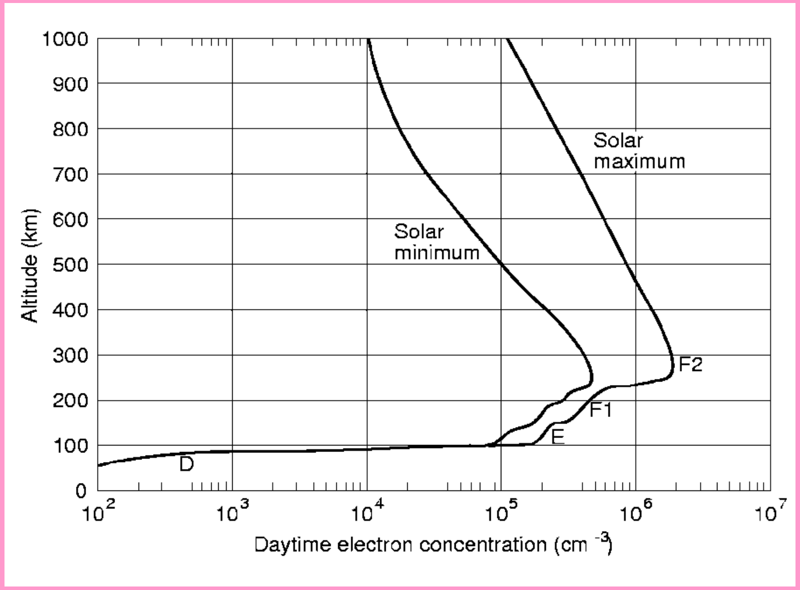
Today

Activity	Date	Time	Room	Subject	Litterature
L1	2/9	10-12	Q33	Course description, Introduction, The Sun 1, Plasma physics 1	**CGF** Ch 1, 5, (p 110-113)
L2	3/9	15-17	Q31	The Sun 2, Plasma physics 2	**CGF** Ch 5 (p 114-121), 6.3
L3	9/9	10-12	Q33	Solar wind, The ionosphere and atmosphere 1, Plasma physics 3	**CGF** Ch 6.1, 2.1-2.6, 3.1-3.2, 3.5, **LL** Ch III, Extra material
T1	11/9	10-12	Q34	Mini-group work 1	
L4	16/9	15-17	Q33	The ionosphere 2, Plasma physics 4	**CGF** Ch 3.4, 3.7, 3.8
L5	18/9	15-17	Q21	The Earth's magnetosphere 1, Plasma physics 5	**CGF** 4.1-4.3, **LL** Ch I, II, IV.A
T2	23/9	10-12	Q34	Mini-group work 2	
L6	25/9	10-12	M33	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
L7	30/9	14-16	L51	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
T3	3/10	10-12	V22	Mini-group work 3	
L8	7/10	10-12	V22	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
T4	9/10	15-17	Q31	Mini-group work 4	
L9	11/10	10-12	M33	Interstellar and intergalactic plasma, Cosmic radiation, Swedish and international space physics research.	**CGF** Ch 7-9
T5	15/10	10-12	L51	Mini-group work 5	
L10	16/10	13-15	Q36	Guest lecture: Swedish astronaut Christer Fuglesang	
T6	17/10	15-17	Q31	Round-up	
Written examination	30/10	14-19	B21-24		

Mini-groupwork 3

a)

$$\frac{\partial n_e}{\partial t} = q - \alpha n_e^2$$



$$\frac{dn_e(t)}{dt} = 0 \quad \Rightarrow$$

$$\alpha = \frac{q}{n_e^2}$$

$q = 1.7\cdot10^4\ cm^{-3}s^{-1} = 1.7\cdot10^{10}\ m^{-3}s^{-1}$

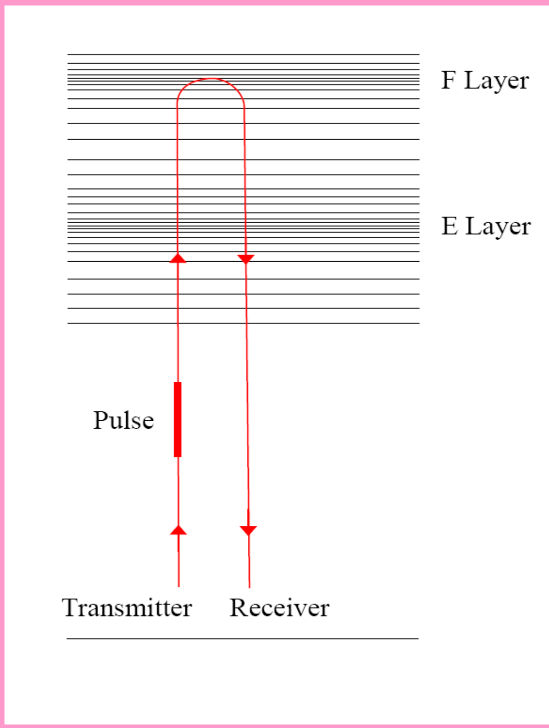
$n_e(150\ km) = 2\cdot10^5\ cm^{-3} = 2\cdot10^{11}\ m^{-3}$

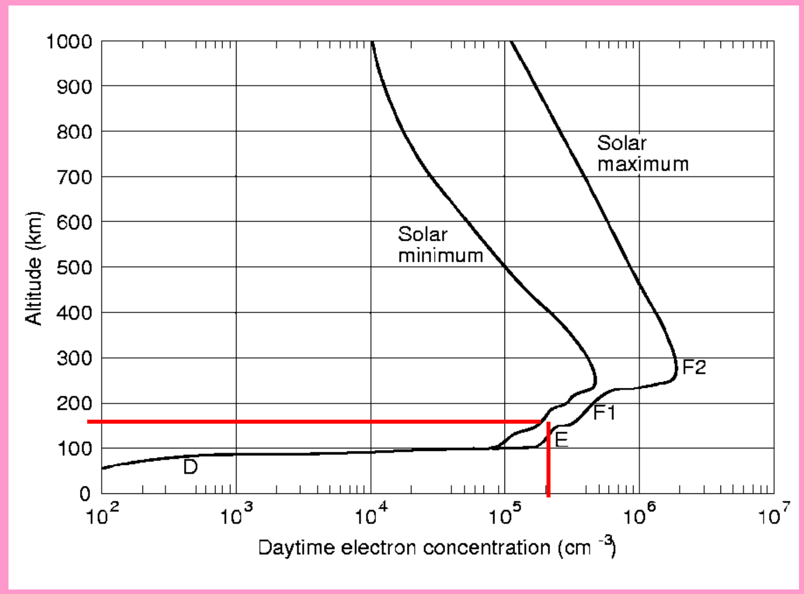
Thus

$\alpha = 4.2\cdot10^{-13}\ m^3s^{-1}$

Mini-groupwork 3

b)





$$f_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \quad \approx 9\sqrt{n_e}$$

$$f_p = 5\cdot 10^6 = 9\sqrt{n_e}$$

$$\Rightarrow$$

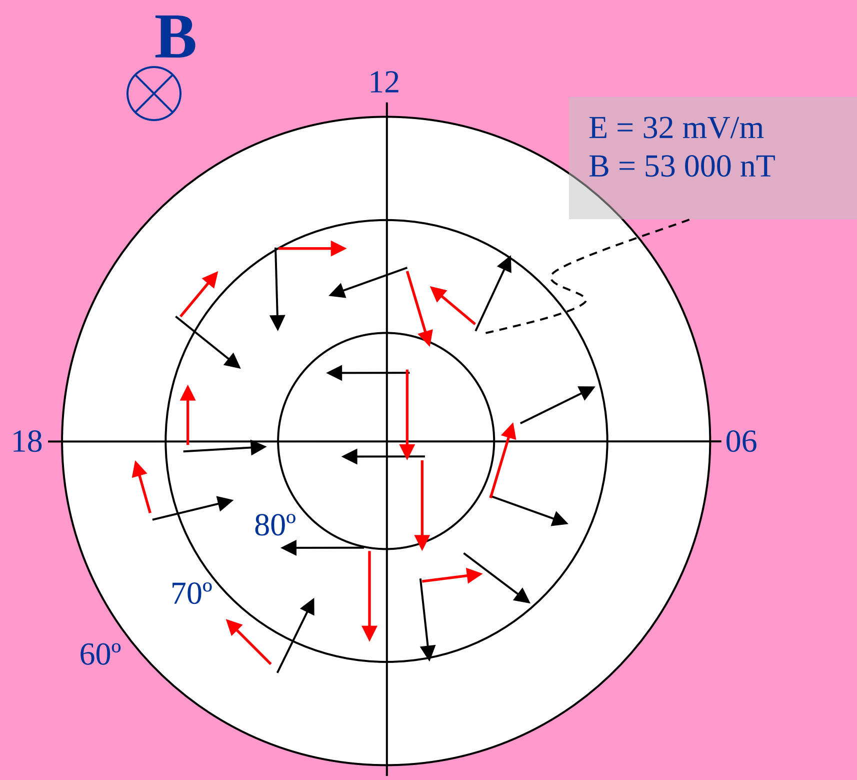
$$n_e = \left(\frac{5\cdot 10^6}{9}\right)^2 = 3\cdot 10^{11} m^{-3}$$

$$h = 150\ km$$

$$t = \frac{2h}{c} = \frac{300\cdot 10^3}{3\cdot 10^8} = 10^{-3} s$$

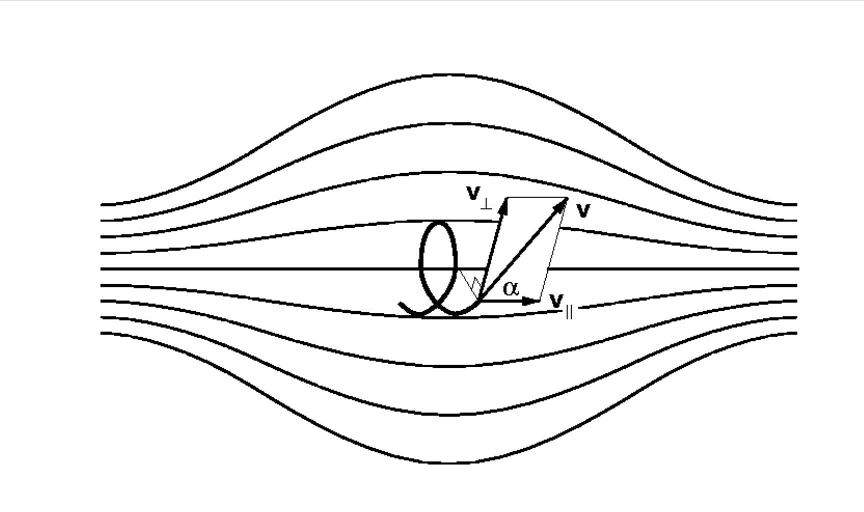
Mini-groupwork 3

c)



$$v_d = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{E}{B} = \frac{32\cdot 10^{-3}}{53000\cdot 10^{-9}} = 604\ ms^{-1}$$

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

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

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

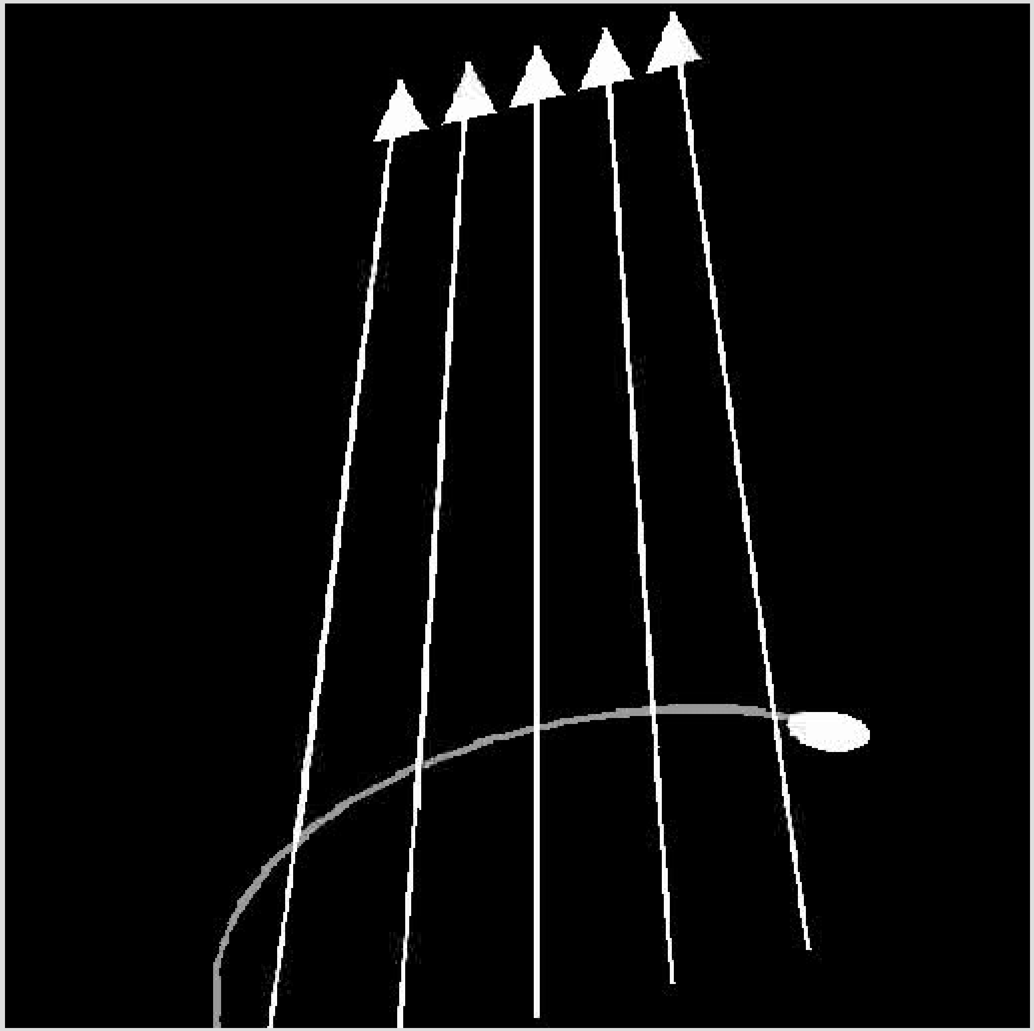
Particles in ***loss cone*** :

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

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

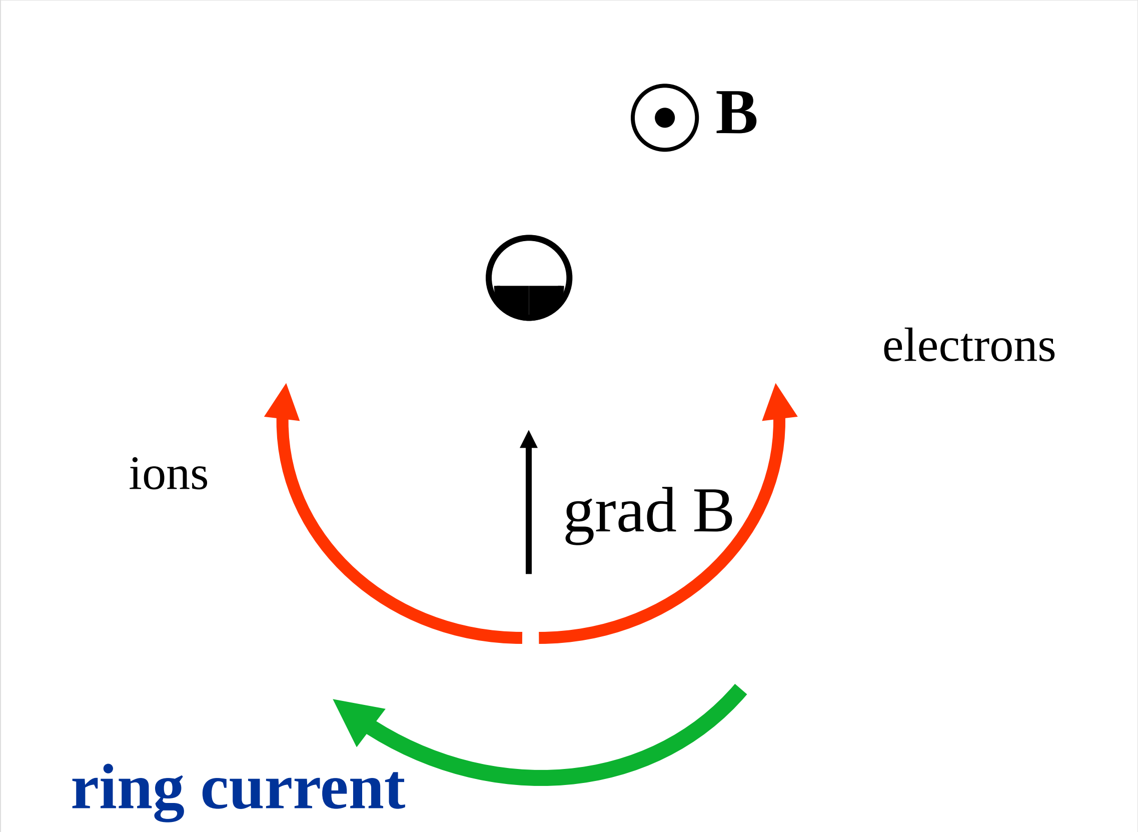
$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2\sin^2\alpha}{2B}$$

Magnetic mirror

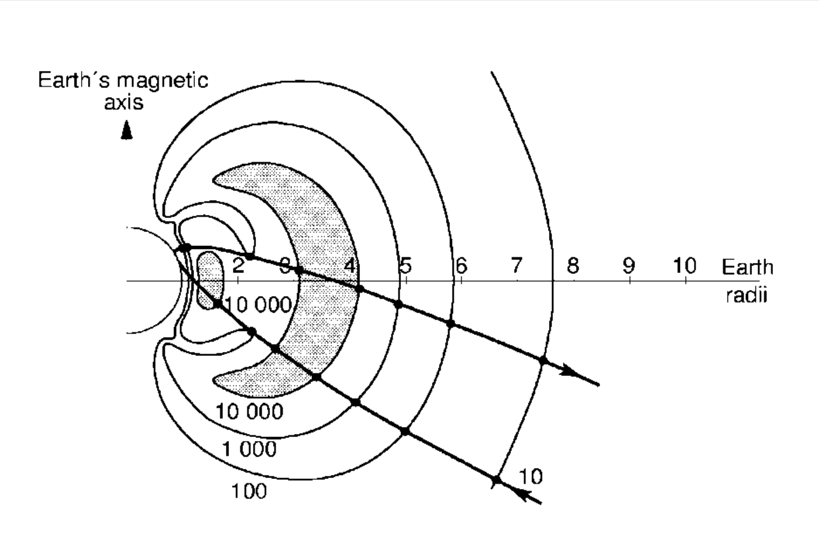


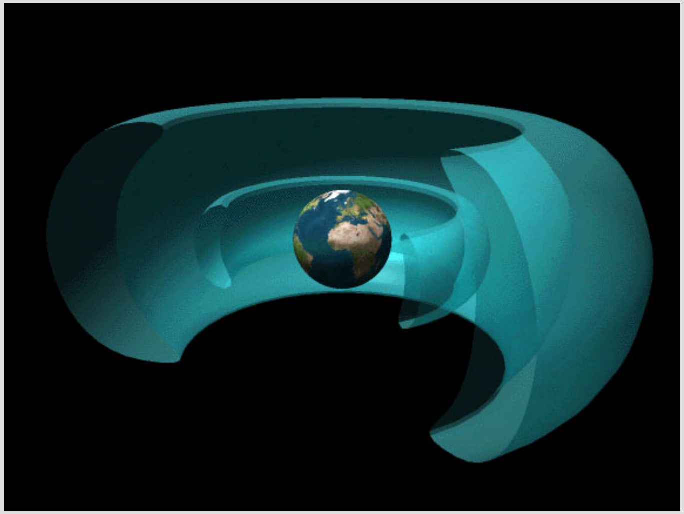
Ring current and particle motion

$$\mathbf{u} = -\frac{\mu \nabla B \times \mathbf{B}}{qB^2}$$



Radiation belts





I. Van Allen belts

- Discovered in the 50s , Explorer 1
- Inner belt contains protons with energies of ~30 MeV
- Outer belt (Explorer IV, Pioneer III): electrons, W >1.5 MeV

CRAND (Cosmic Ray Albedo Neutron Decay

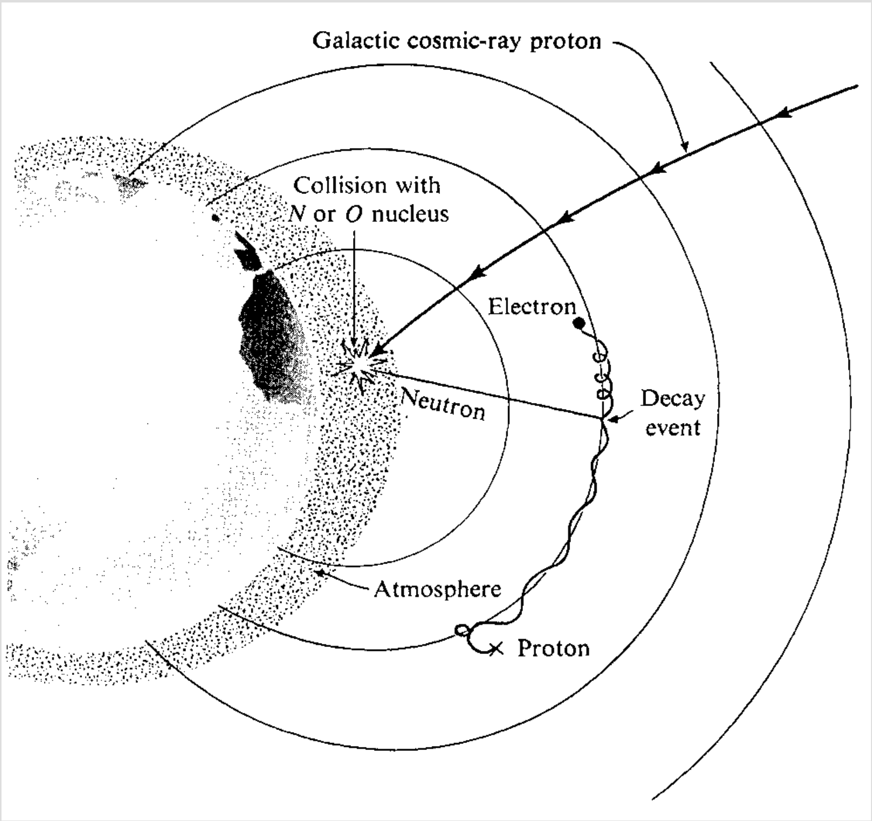


Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

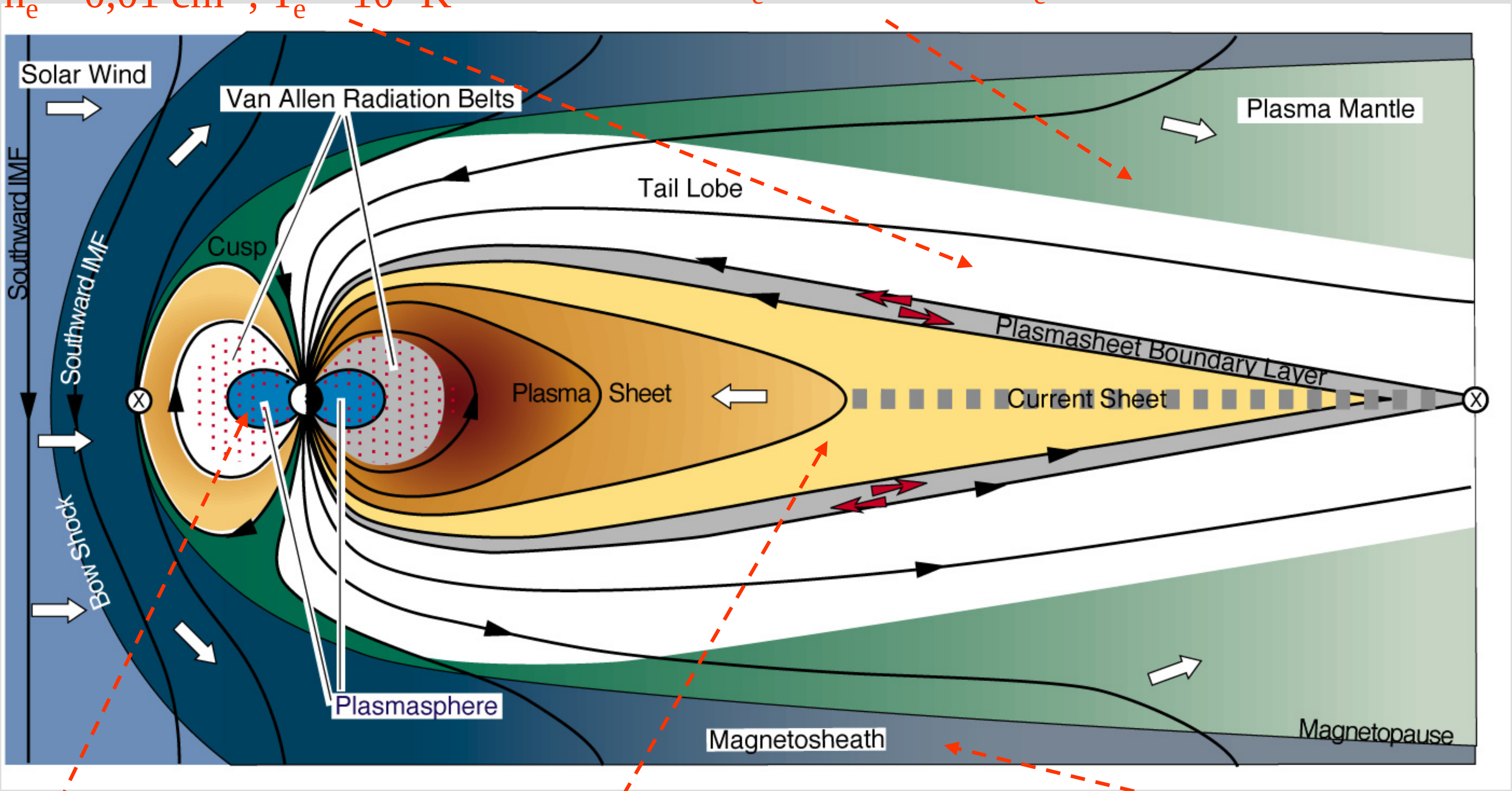
Collisions between cosmic ray particles and the Earth create new particles. Among these are neutrons, that are not affected by the magnetic field. They decay, soom eof them when they happen to be in the radiation belts. The resulting protons and electrons are trapped in the radiation belts.

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

Magnetospheric structure

polar plumes = tail lobe
$n_e \sim 0{,}01\ \mathrm{cm}^{-3}$, $T_e \sim 10^6$ K

plasma mantle
$n_e \sim 0{,}1\text{-}1\ \mathrm{cm}^{-3}$, $T_e \sim 10^6$ K



plasmasphere:
$n_e \sim 10\text{-}100\ \mathrm{cm}^{-3}$, $T_e \sim 1000$ K

plasma sheet:
$n_e \sim 1\ \mathrm{cm}^{-3}$, $T_e \sim 10^7$ K

magnetosheath:
$n_e \sim 5\ \mathrm{cm}^{-3}$, $T_e \sim 10^6$ K

Planetary magnetospheres

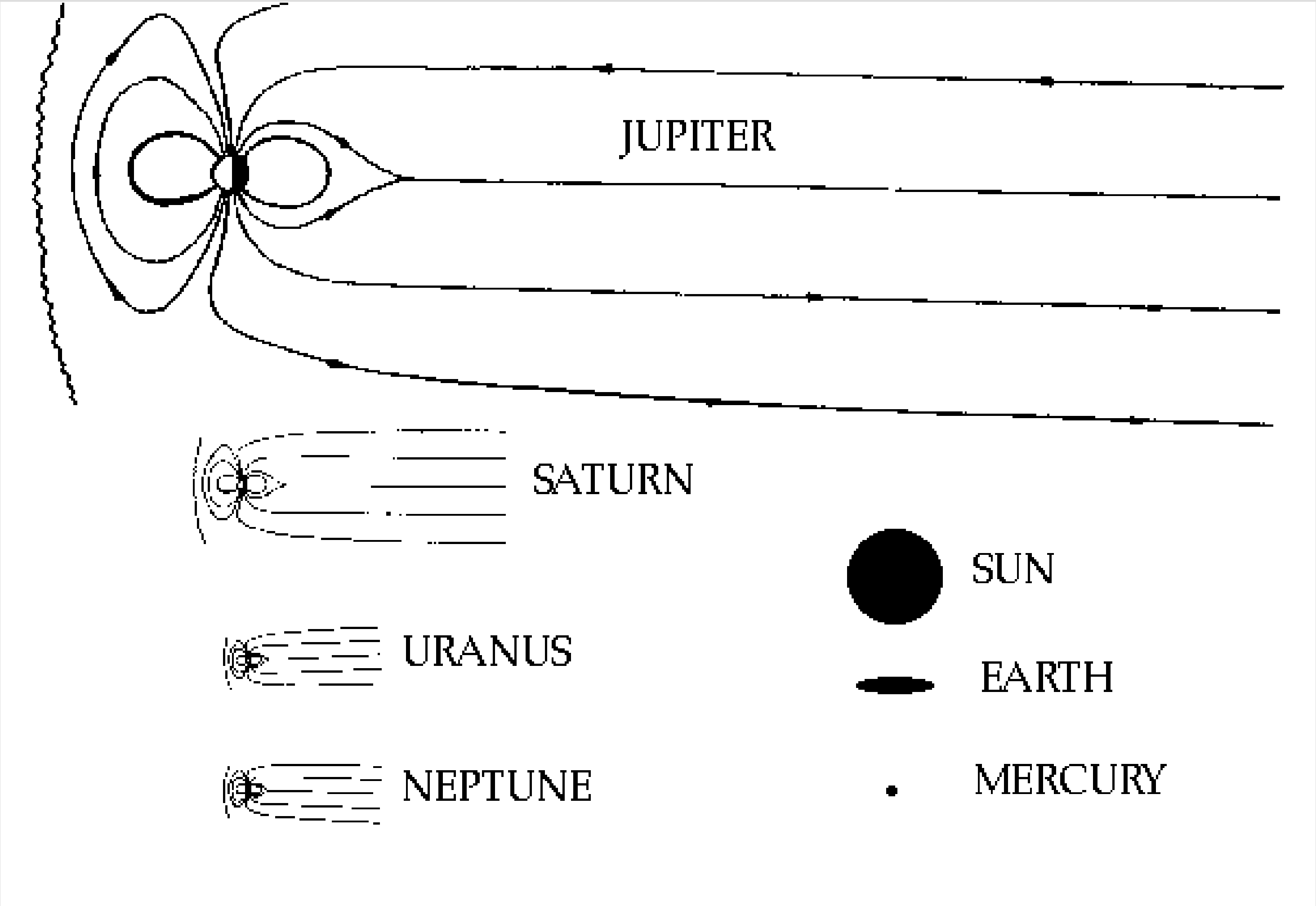
	Radius Earth radii	Spin period (days)	Equatorial field strength (μT)	Magnetic axis direction relative to spin axis	Polarity relative to Earth´s	Typical magneto-pause distance (planetary radii)
Mercury	0.38	58.6	0.35	10^o	Same	1.1
Venus	0.95	243	**< 0.03**	-	-	1.1
Earth	1.0	1	31	11.5^o	Same	10
Mars	0.53	1.02	**0.065**	-	Opposite	?
Jupiter	11.18	0.41	410	10^o	Opposite	60-100
Saturn	9.42	0.44	40	$<1^o$	Opposite	20-25
Uranus	3.84	0.72	23	60^o	Opposite	18-25
Neptune	3.93	0.74	20-150 *)	47^o	Opposite	26 **)

*) The magnetic field differs greatly from a dipole field. The numbers represent maximum and minimum strength at the planetary surface

**) Based on single passage

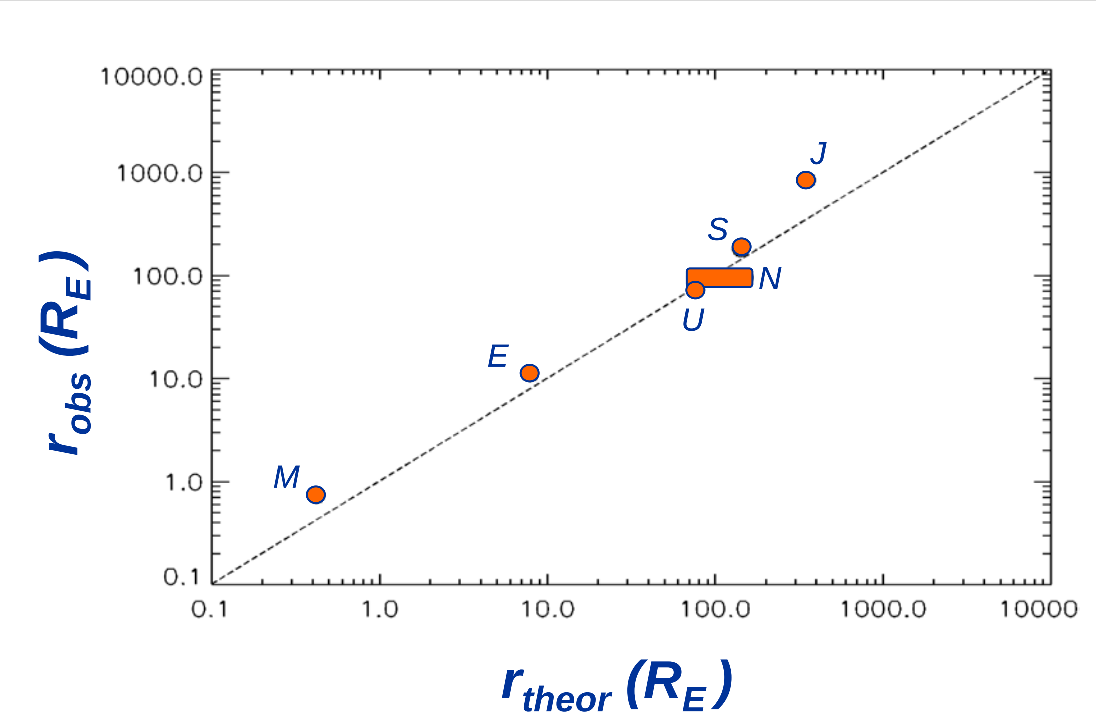
Very weak magnetic fields

Relative size of the magnetospheres

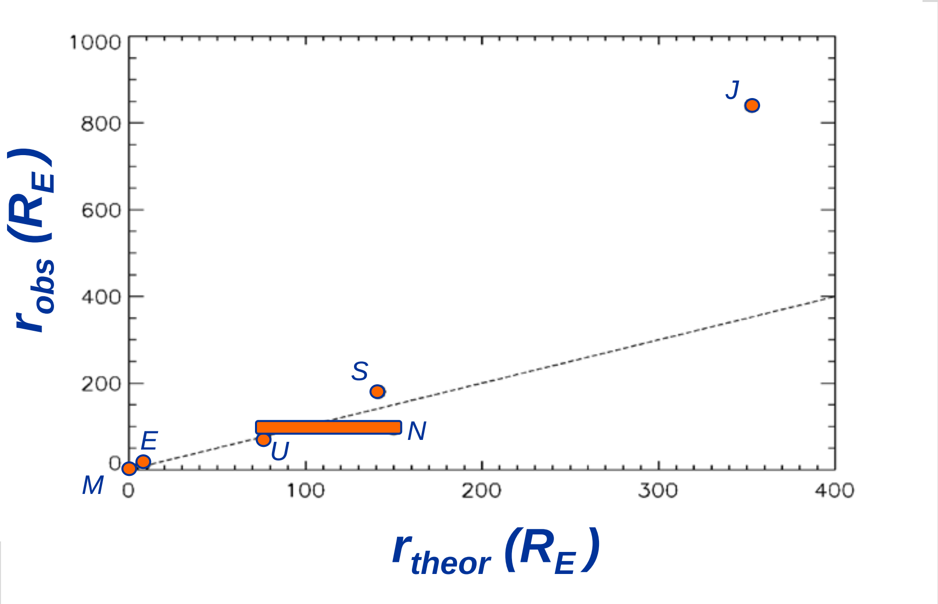


Comparative magnetospheres

Observed vs. theoretical standoff-distance

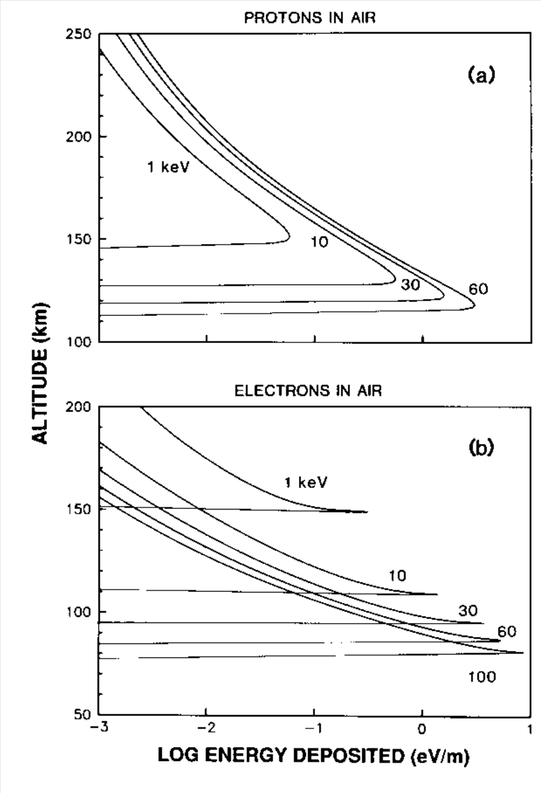


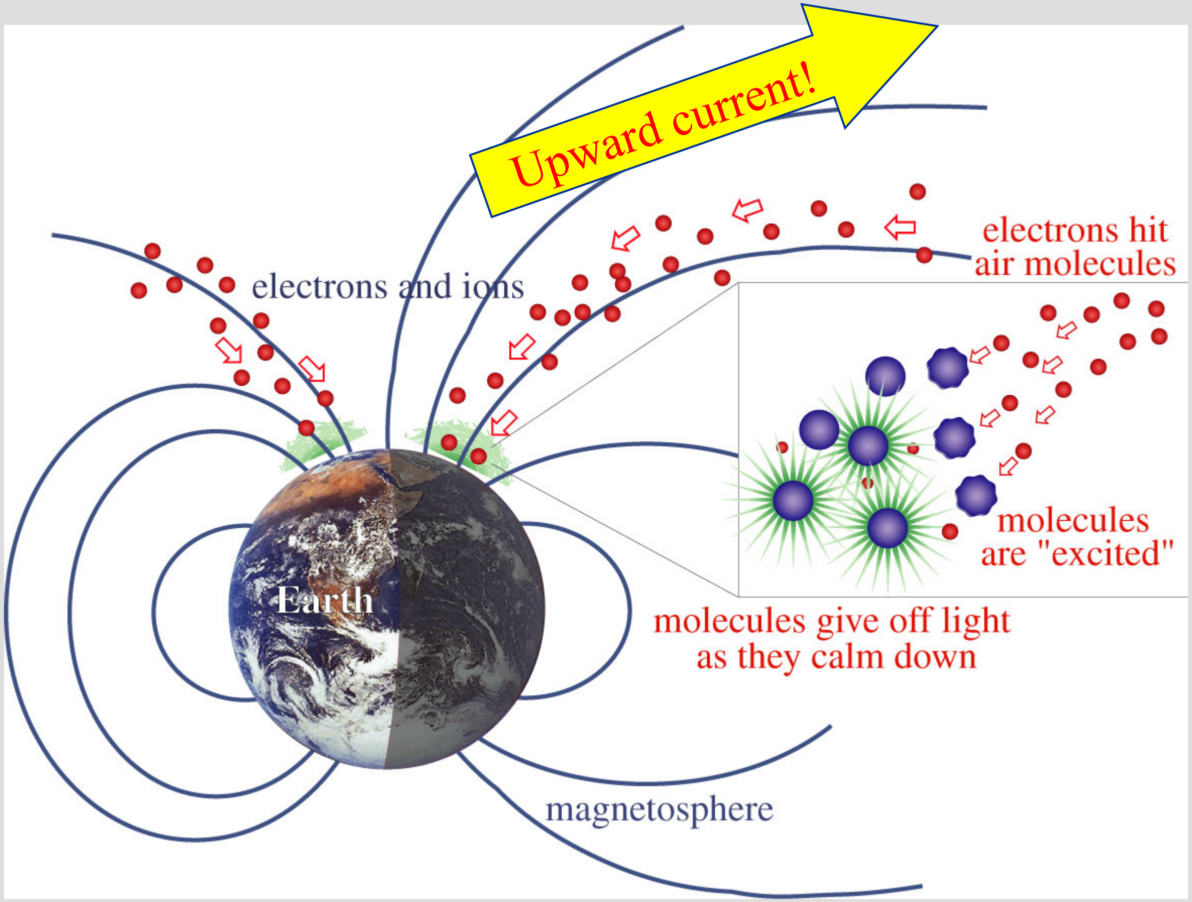
$$r_{theor} = \left(\frac{\mu_0 a}{4\pi}\right)^{1/3} \left(2\mu_0 \rho_{SW} v_{SW}^2\right)^{-1/6}$$



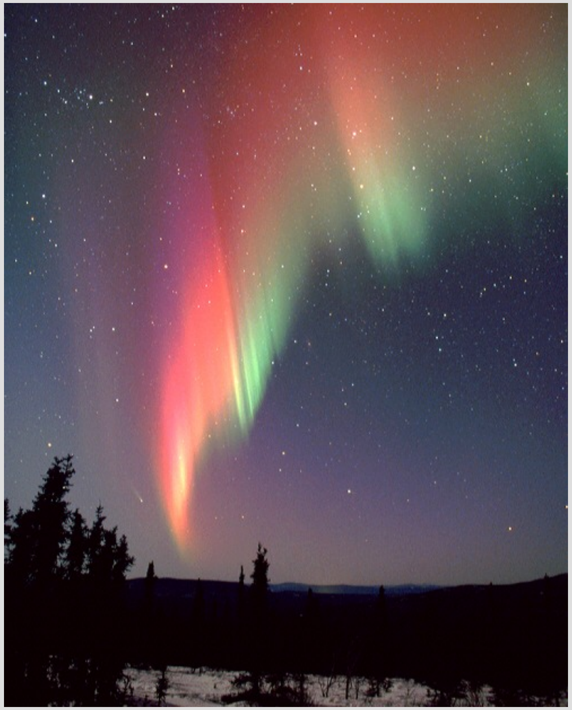
- *Model reasonably valid over three orders of magnitude*
- *Size of Jupiter's (and maybe Saturn's) magnetosphere underestimated*

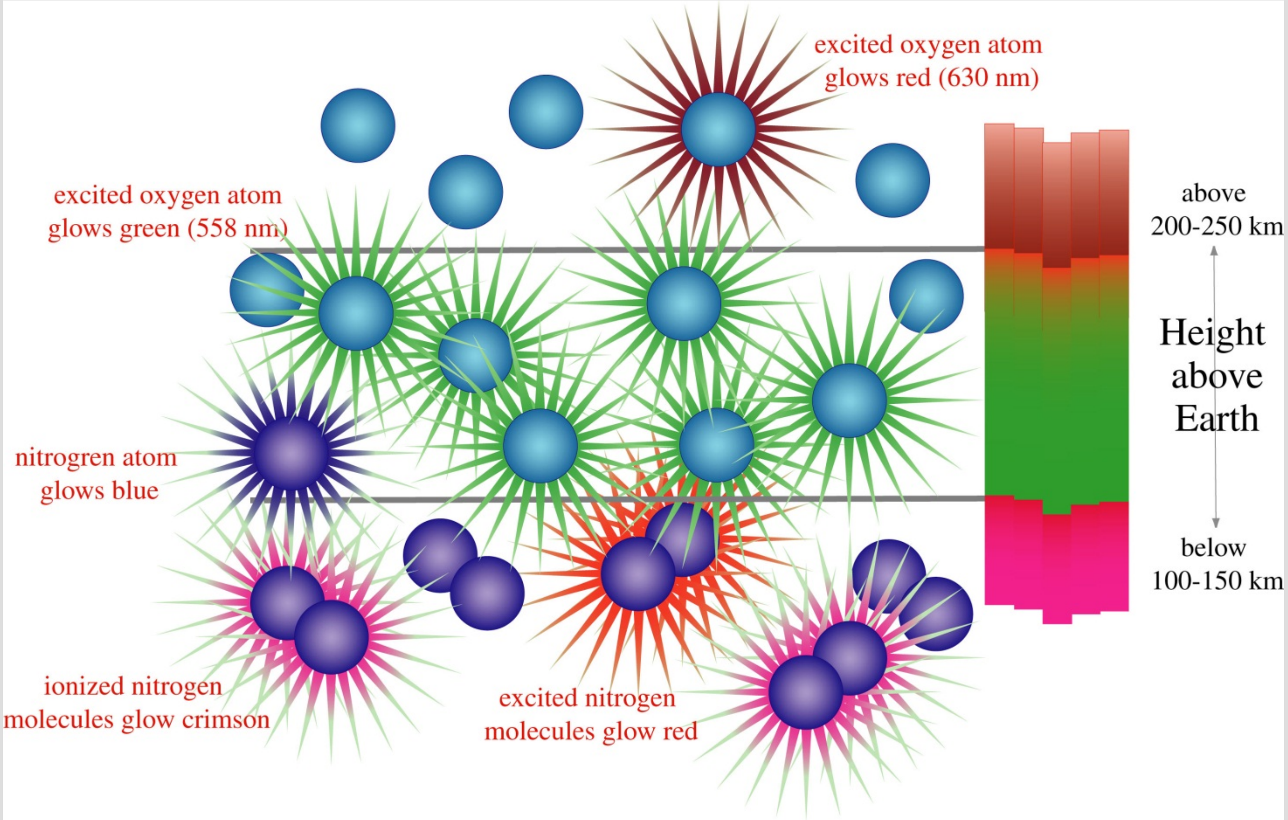
Collisions - emissions





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

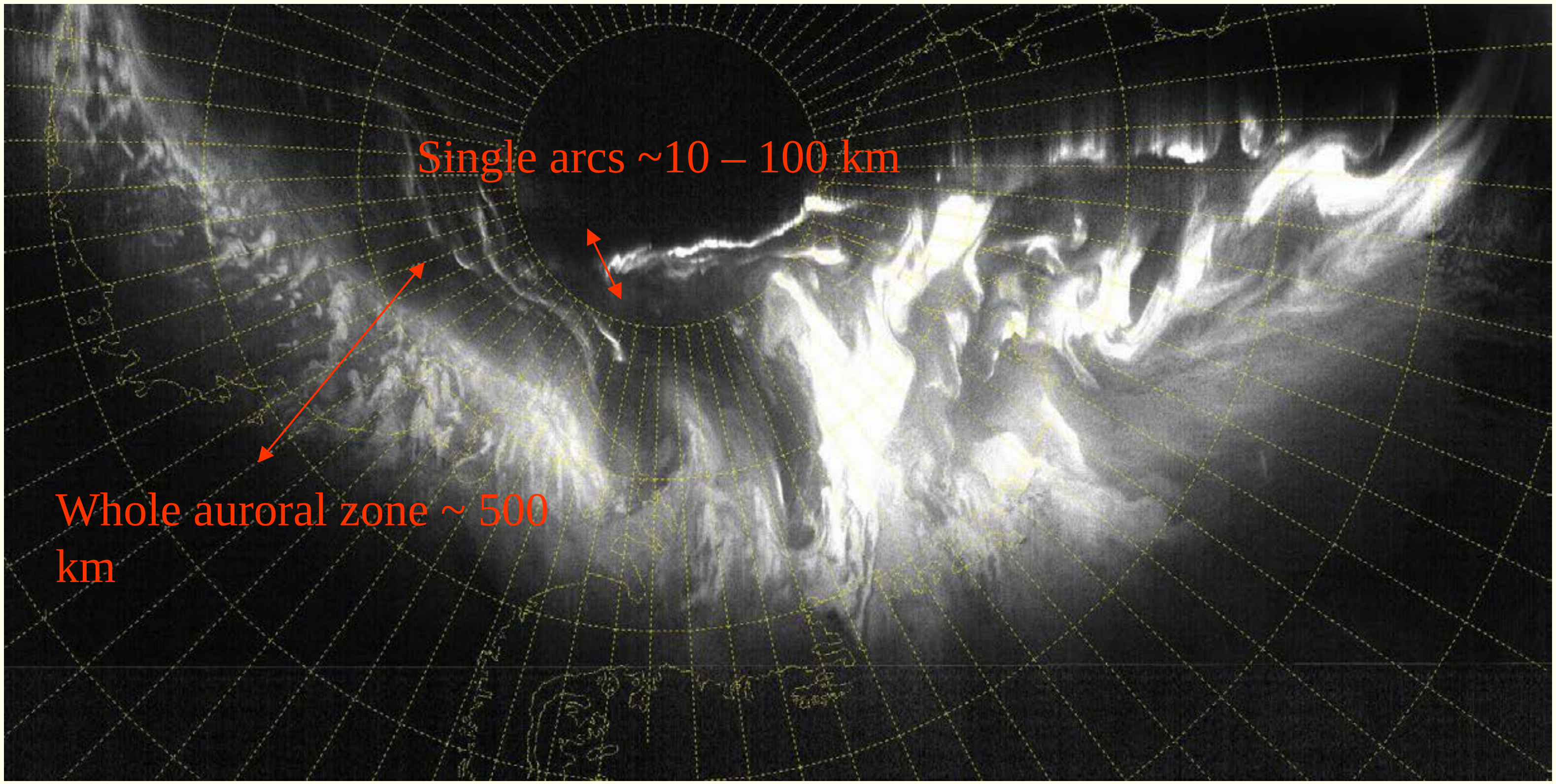
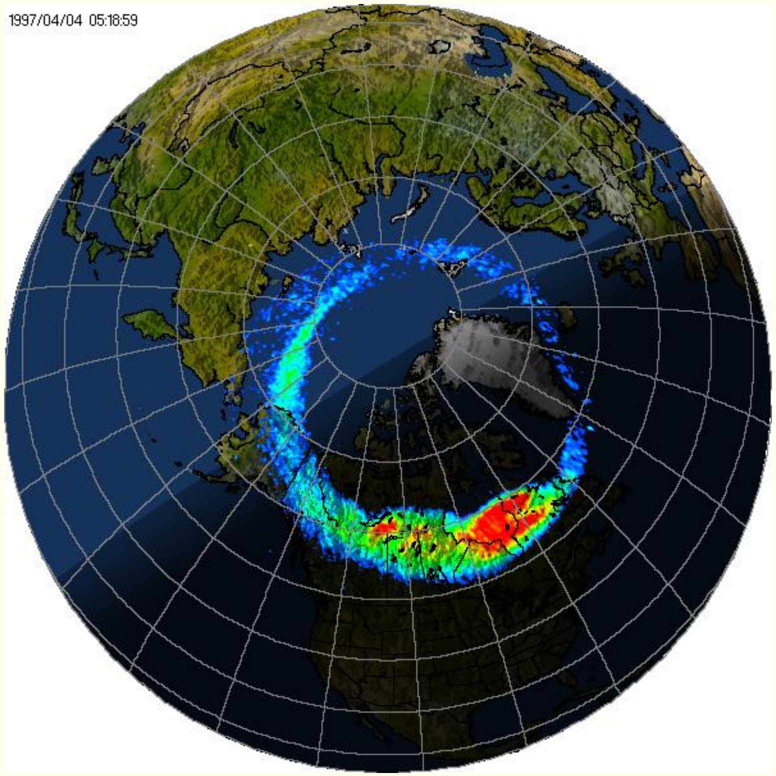
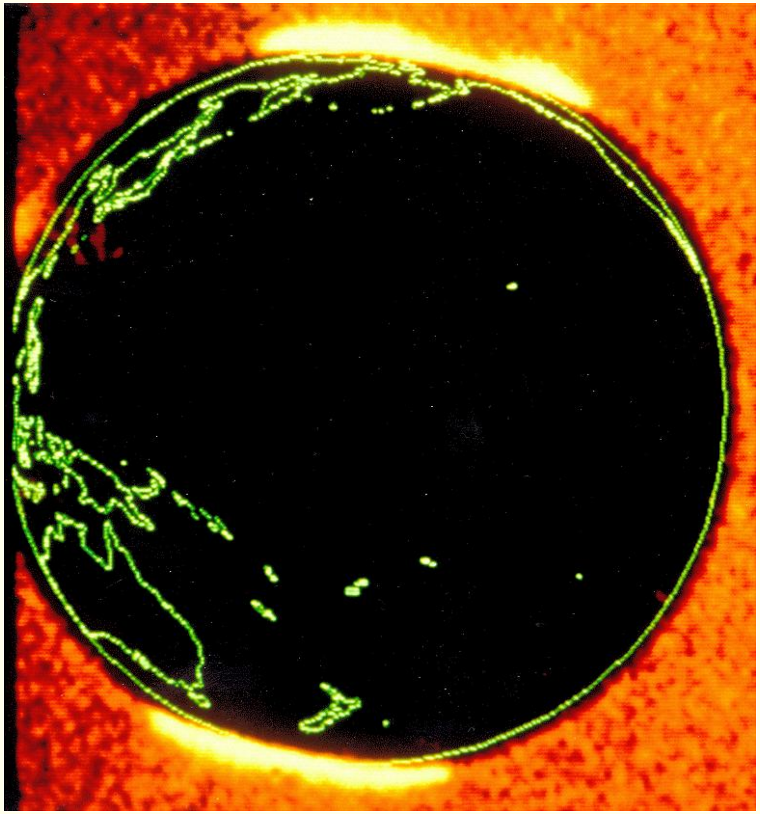


Foto från DMSP-satelliten

Auroral ovals



Polar

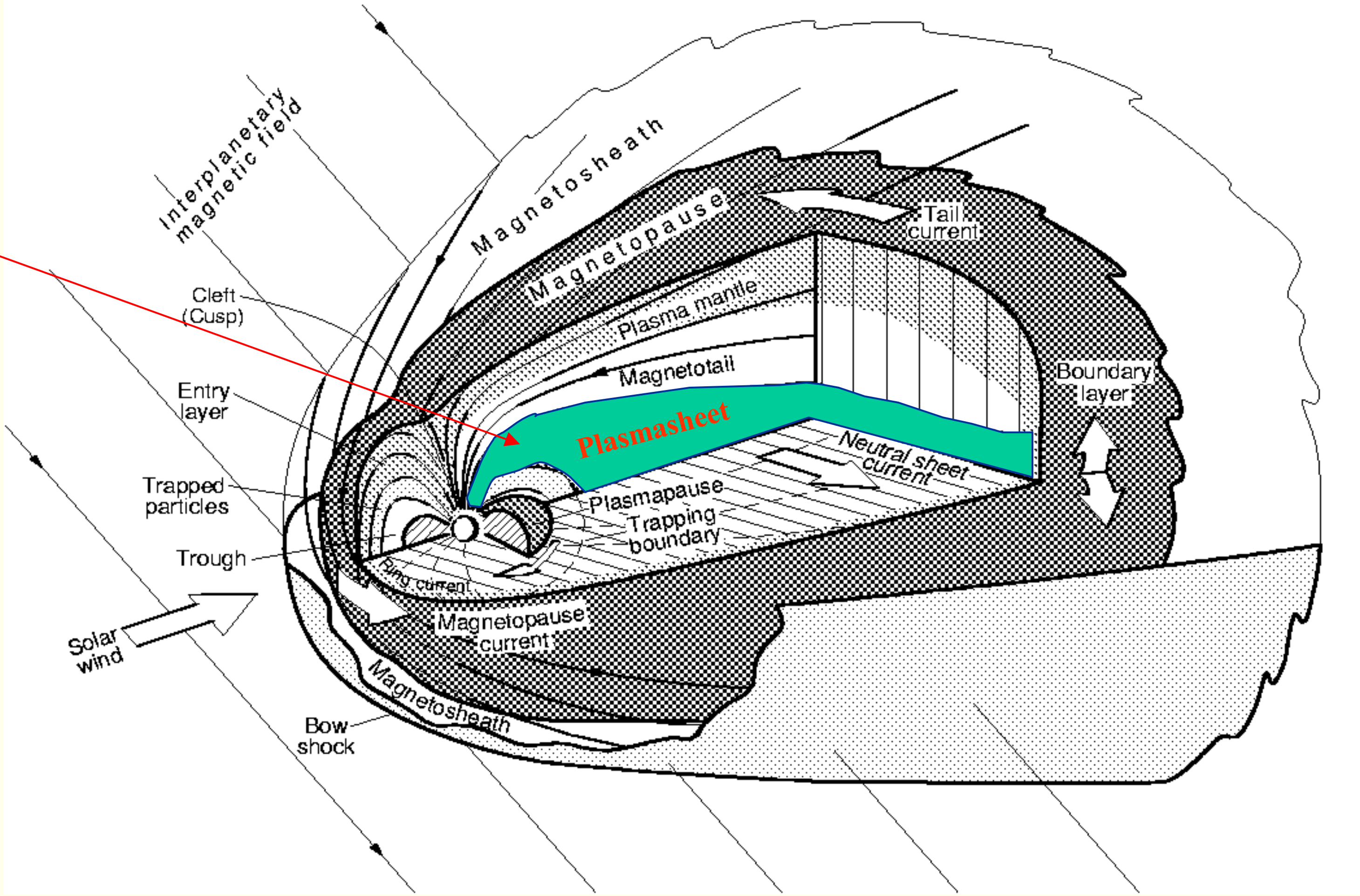


Dynamics Explorer

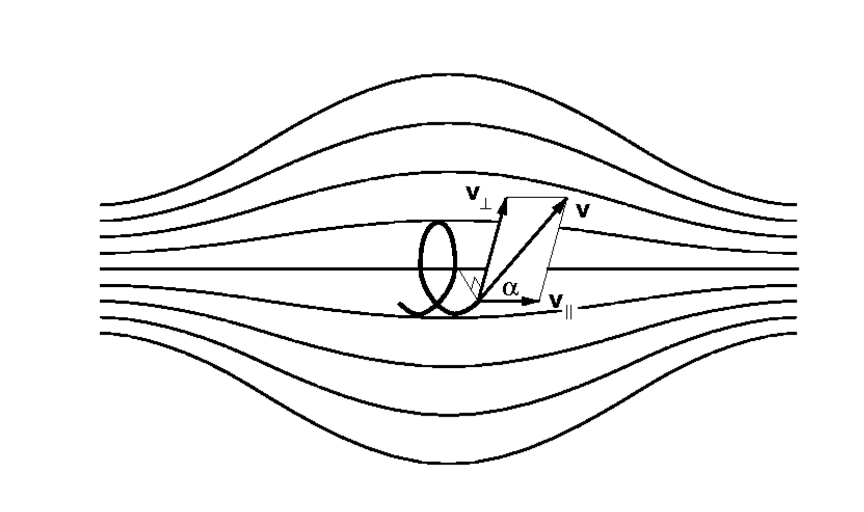
The auroral oval is the projection of the plasmasheet onto the atmosphere

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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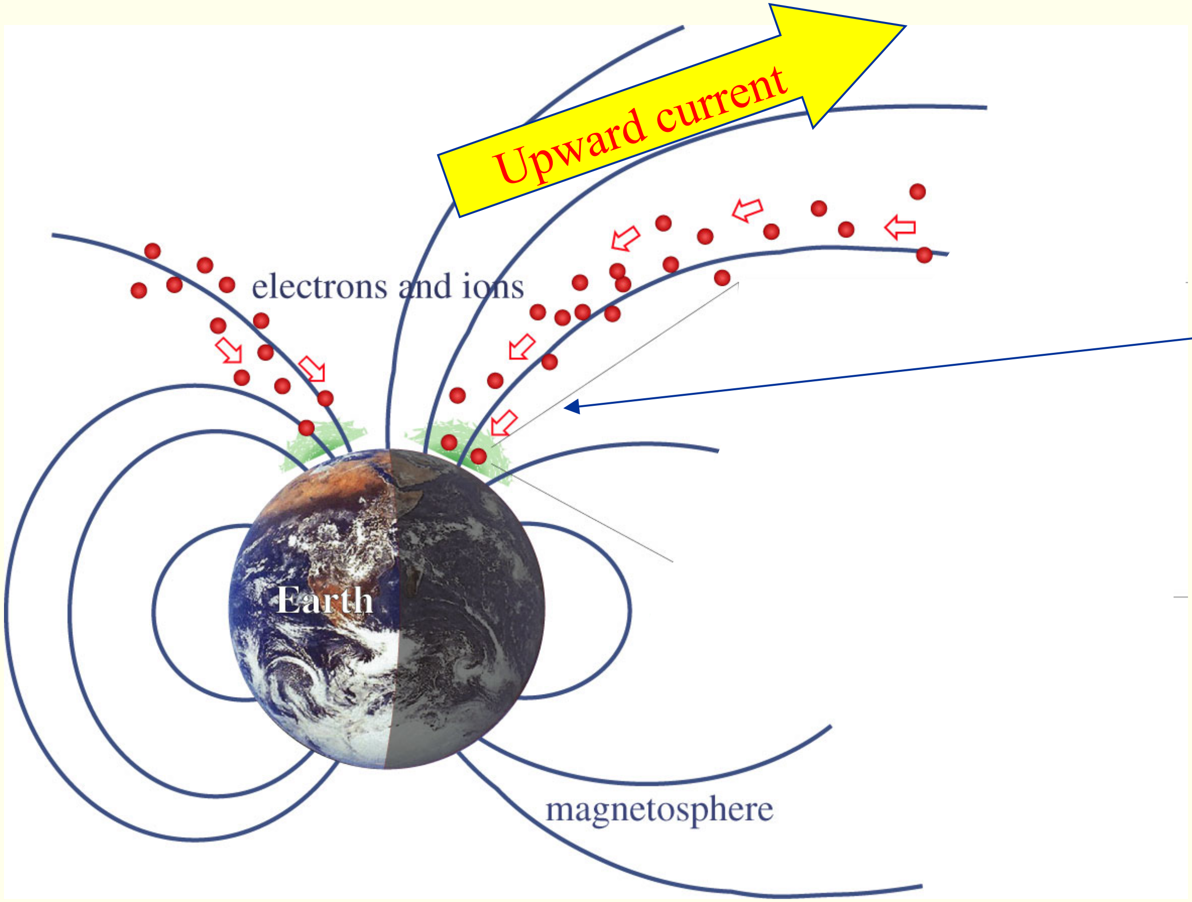
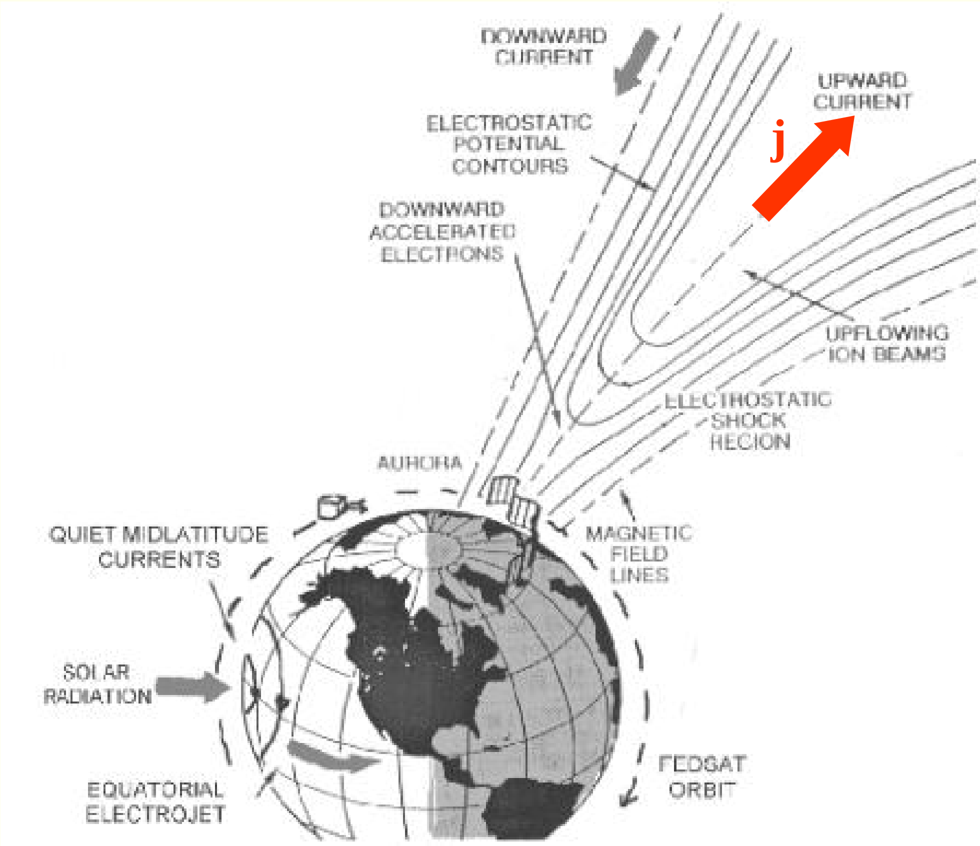
Why particle acceleration?



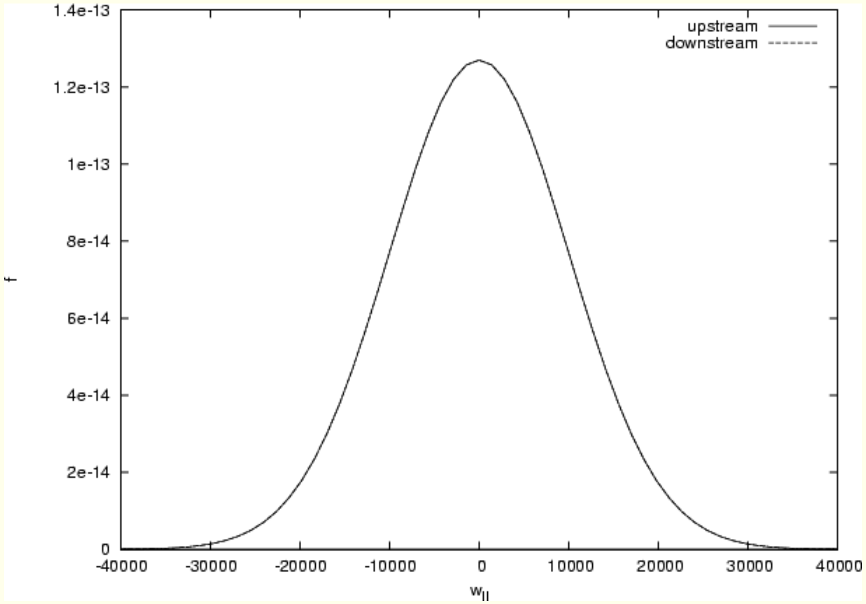
- The magnetosphere often seems to act as a current generator.
- The lower down you are on the field line, the more particles have been reflected by the magnetic mirror.
- At low altitudes there are not enough electrons to carry the current.

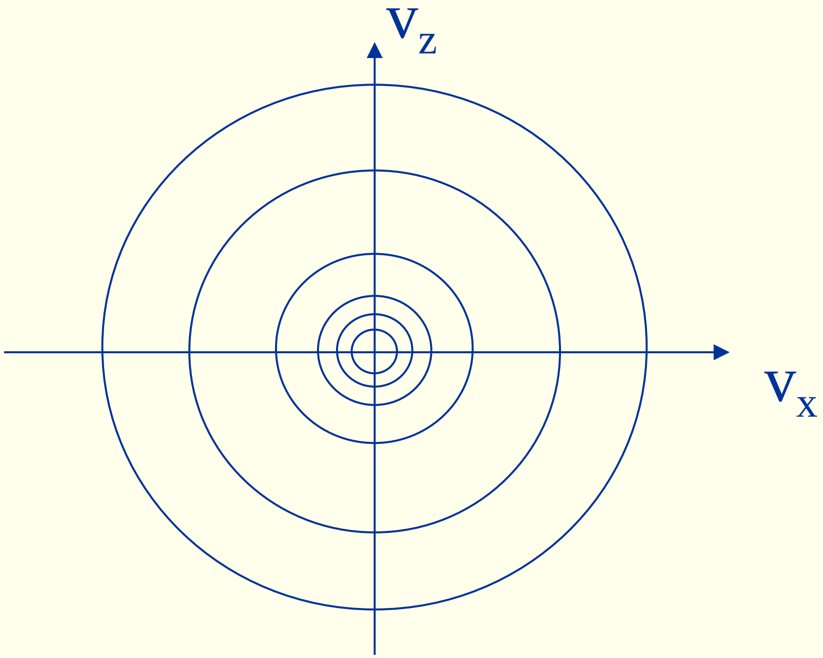
Why particle acceleration?



- 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

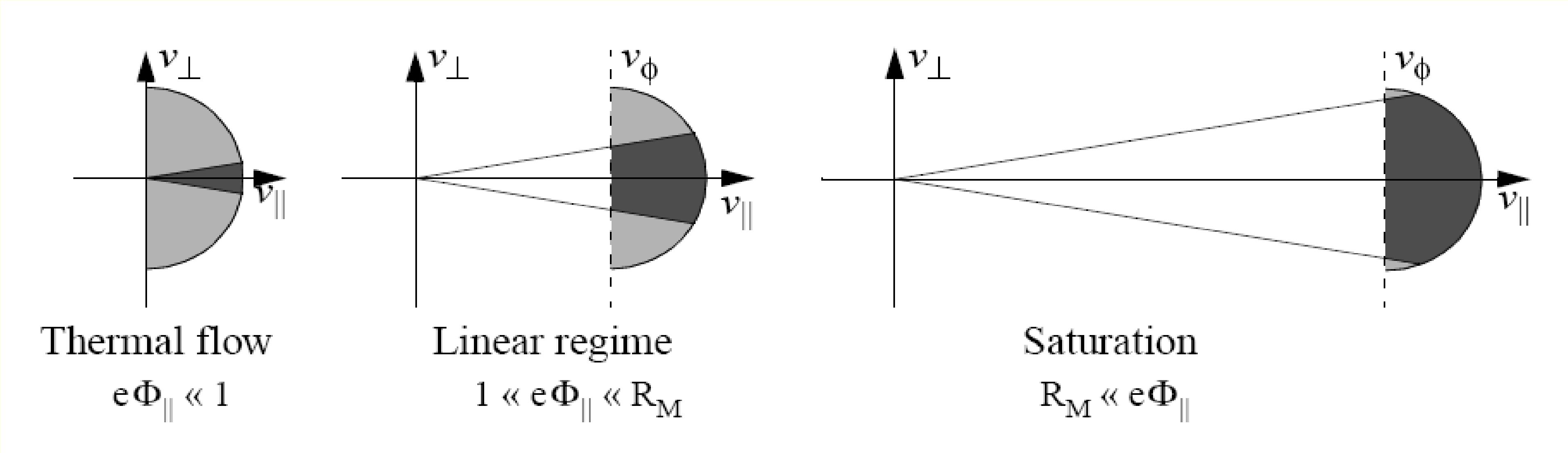




Example:
Maxwellian distribution

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

Why particle acceleration?



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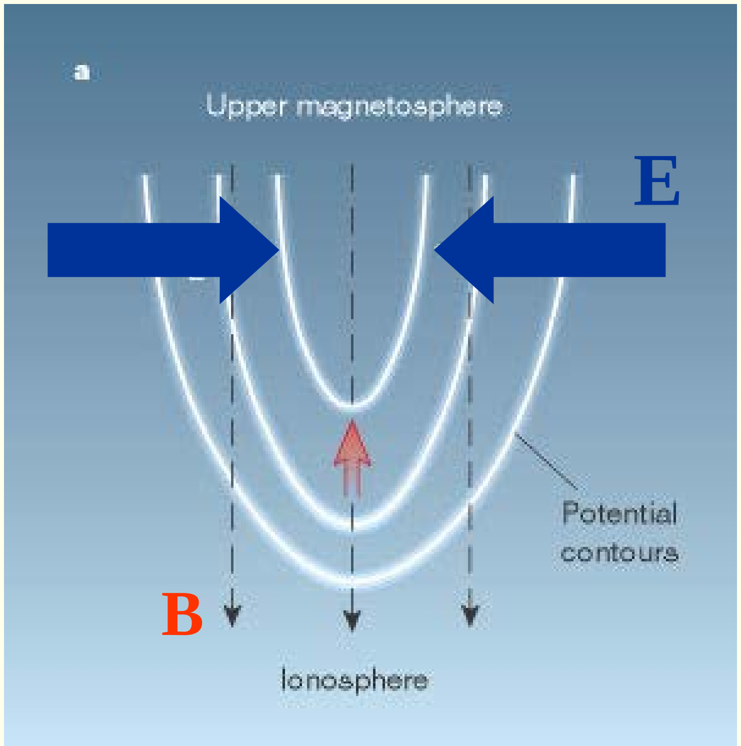
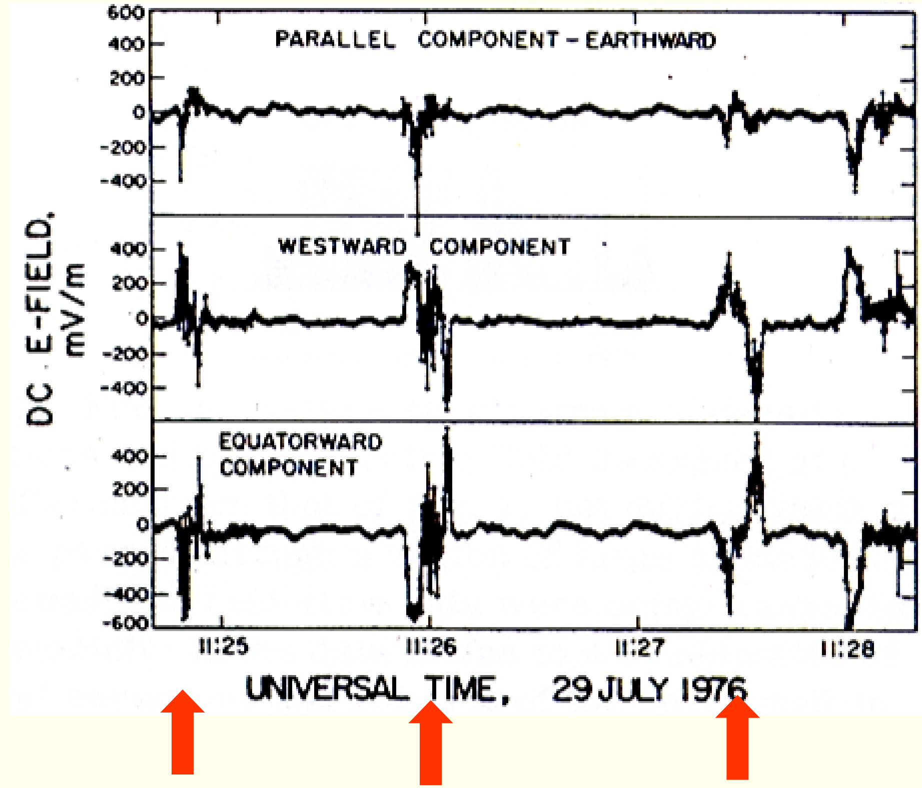
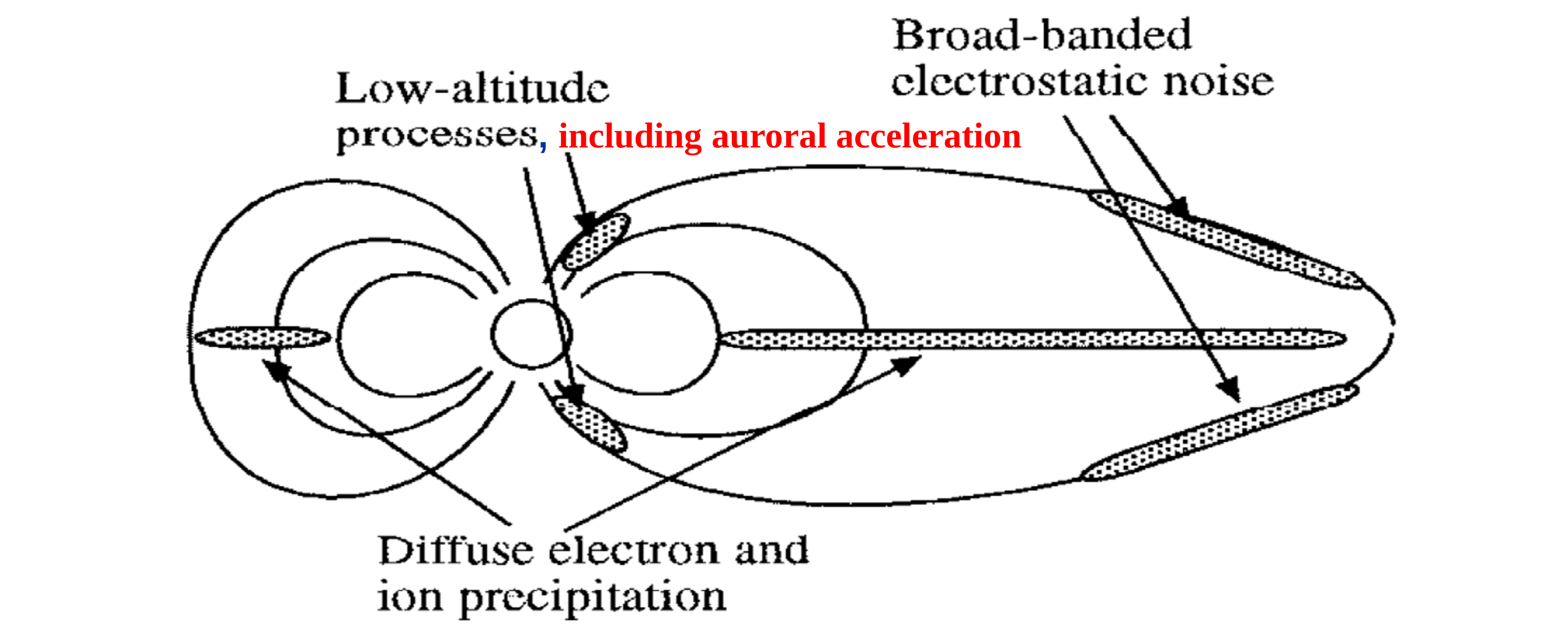
Satellite signatures of U potential





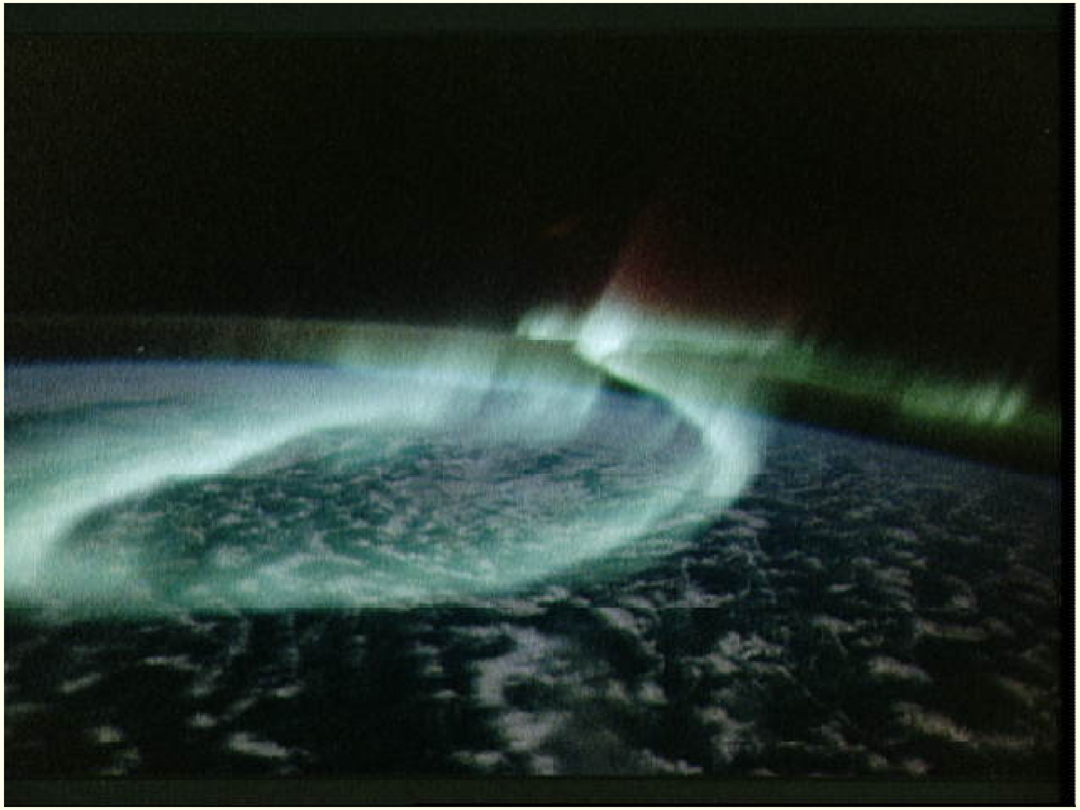
Measurements made by the ISEE satellite (Mozer et al., 1977)

Acceleration regions



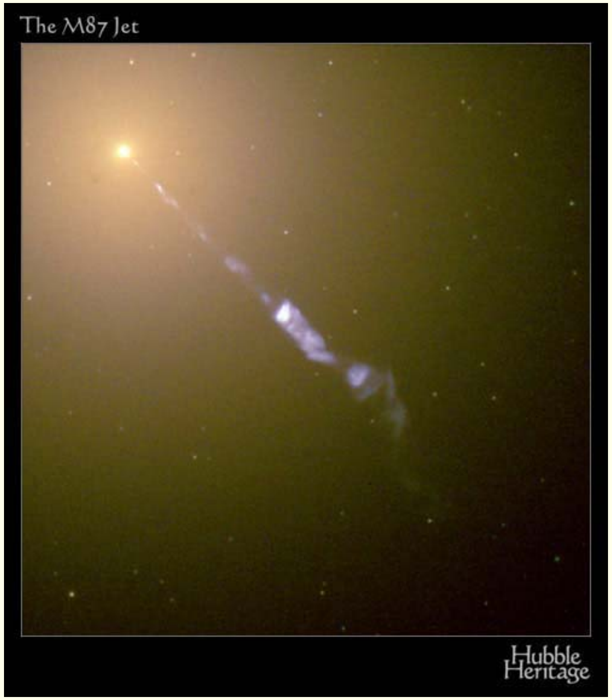
Auroral acceleration region typically situated at altitude of 1-3 R_E

Auroral spirals

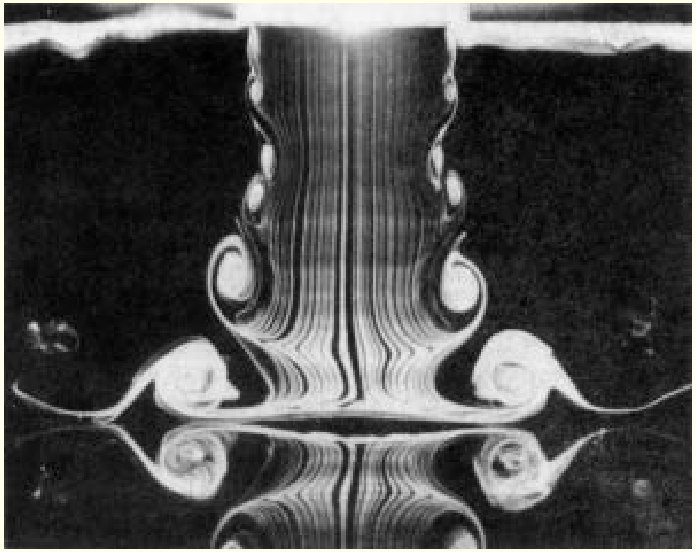


Develop when arcs become unstable

Kelvin-Helmholz-instability – a general phenomenon

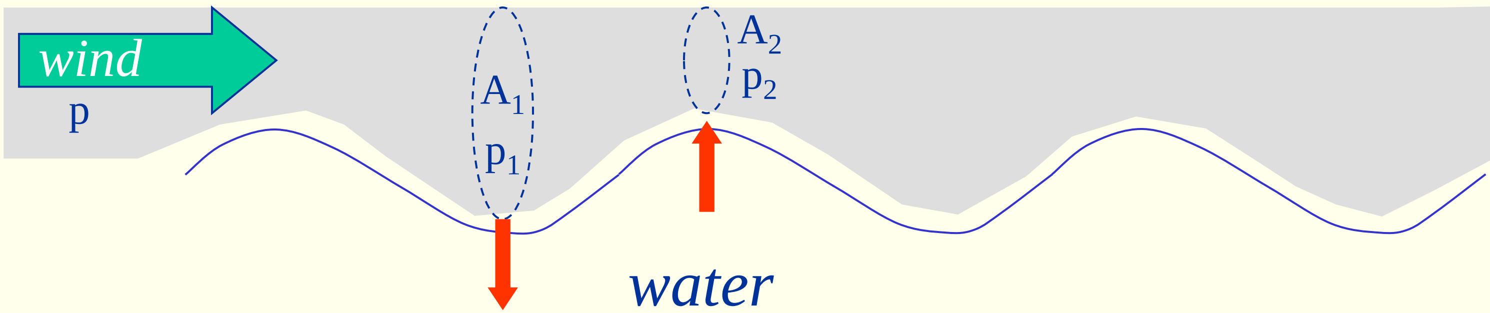


Extragalactic jet (M87)


Aero- and fluid dynamics


Cluds

Kelvin-Helmholz instability
Example: water waves



Continuity equation:

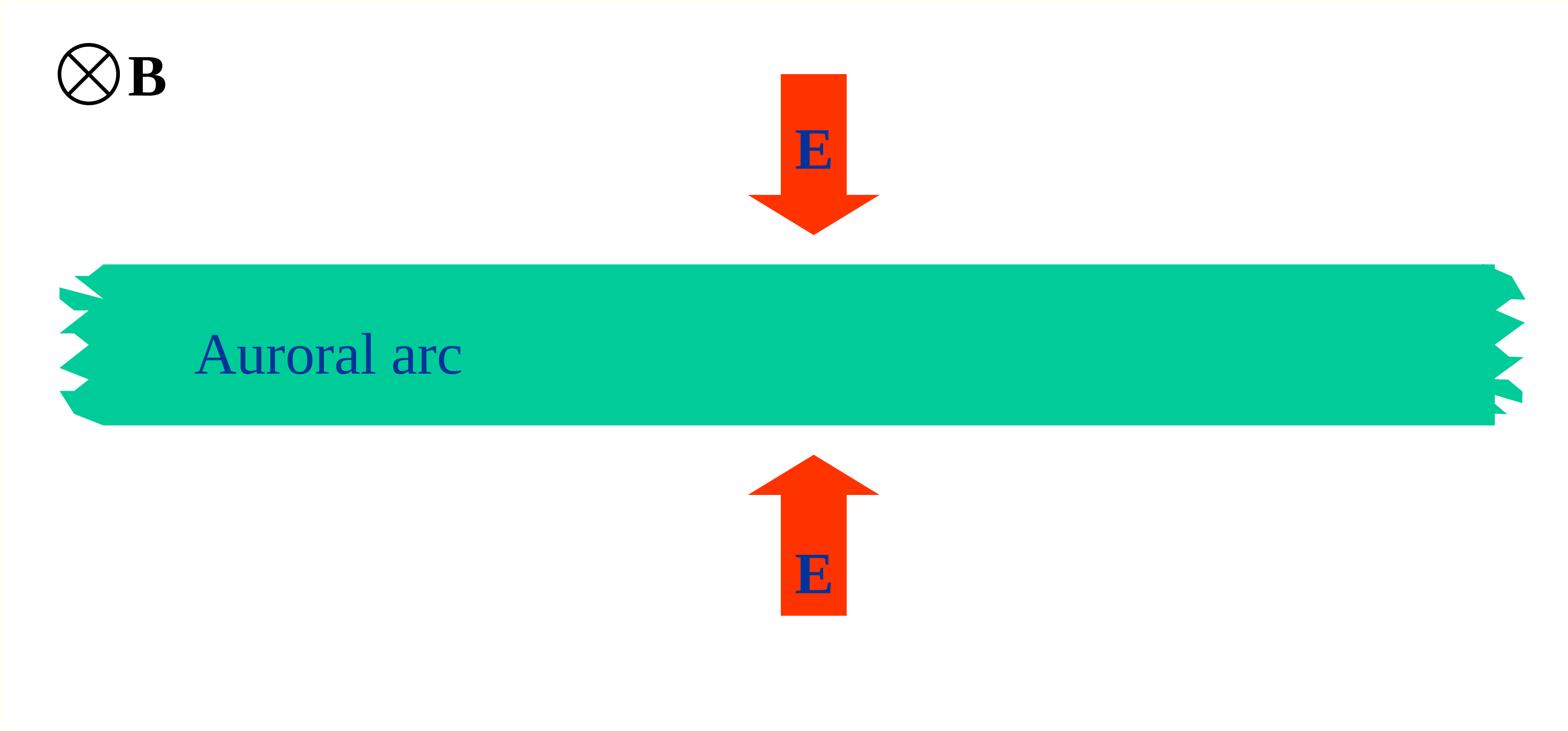
$$A_1 v_1 = A_2 v_2$$

Bernoulli's equation:

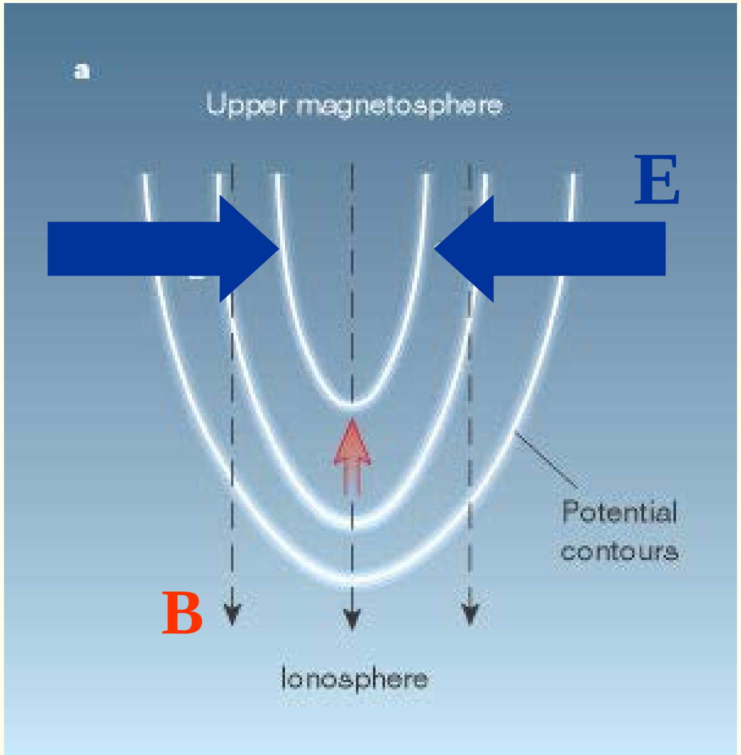
$$p_1 + \rho v_1^{\,2} = p_2 + \rho v_2^{\,2} = const.$$

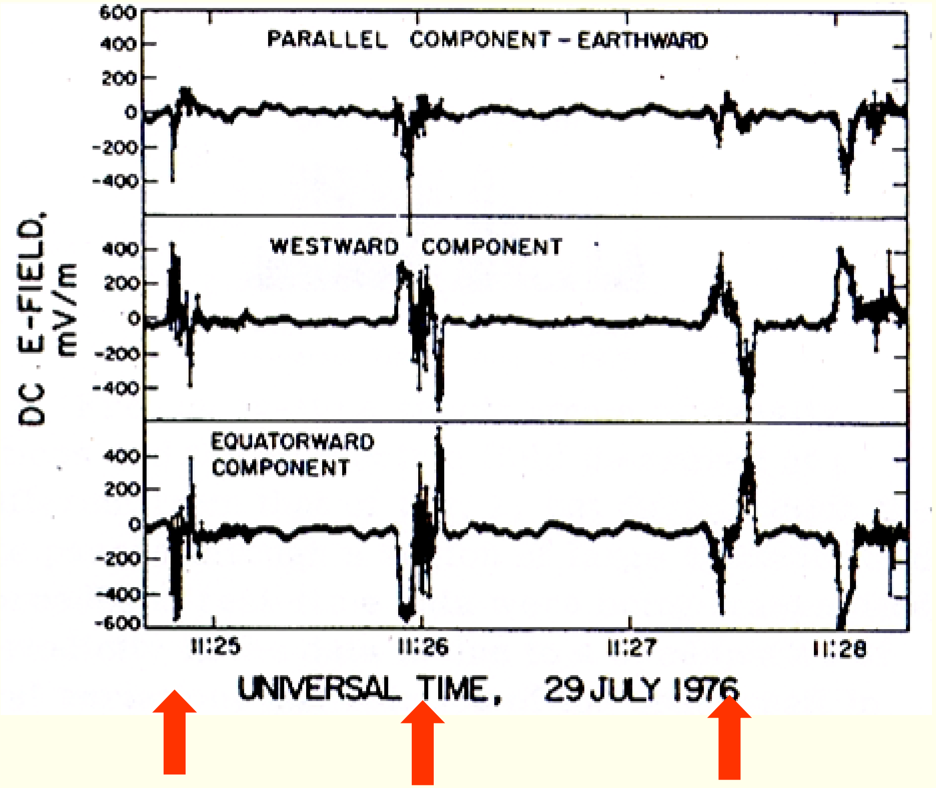
$$\because\ p_1 > p > p_2$$

Spirals – Kelvin-Helmholz instability



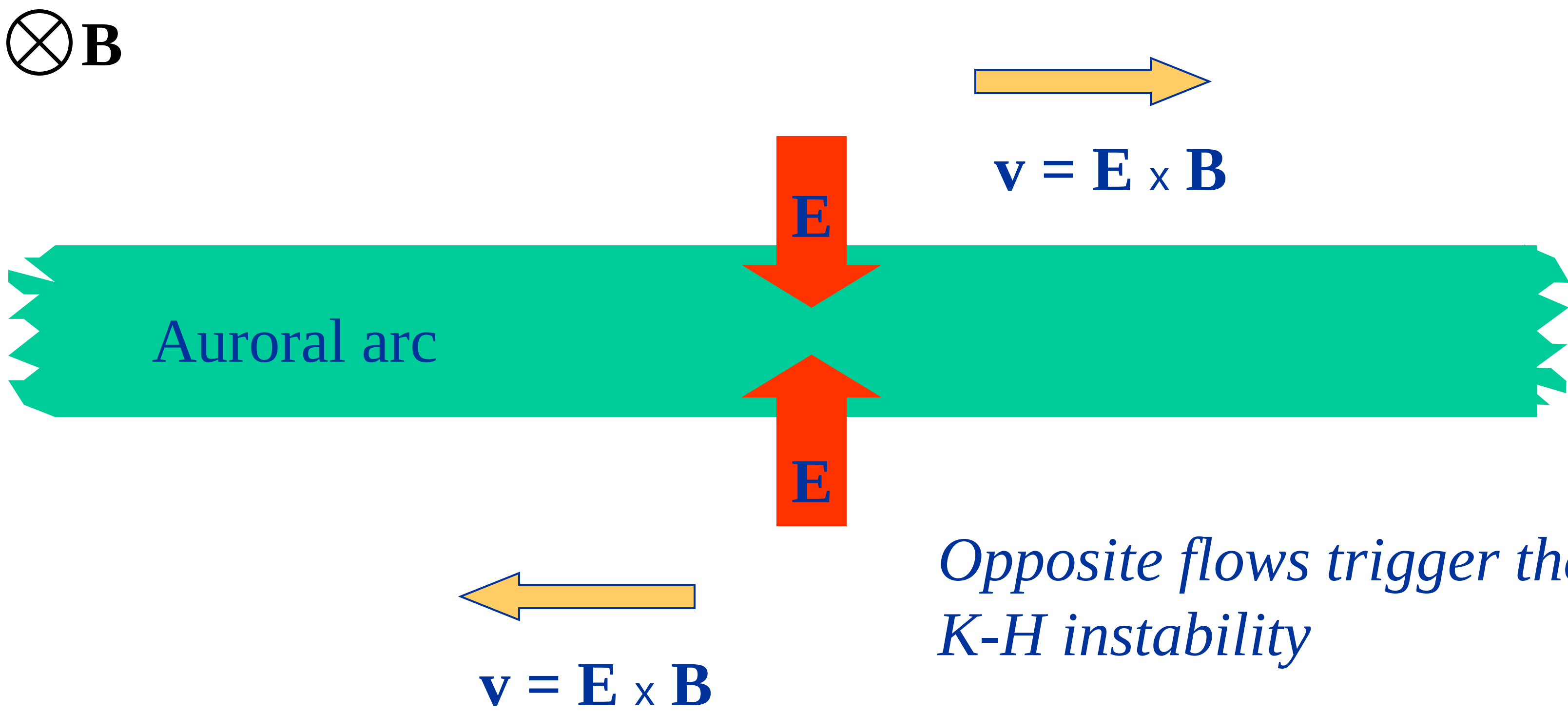
Satellite signatures of U potential





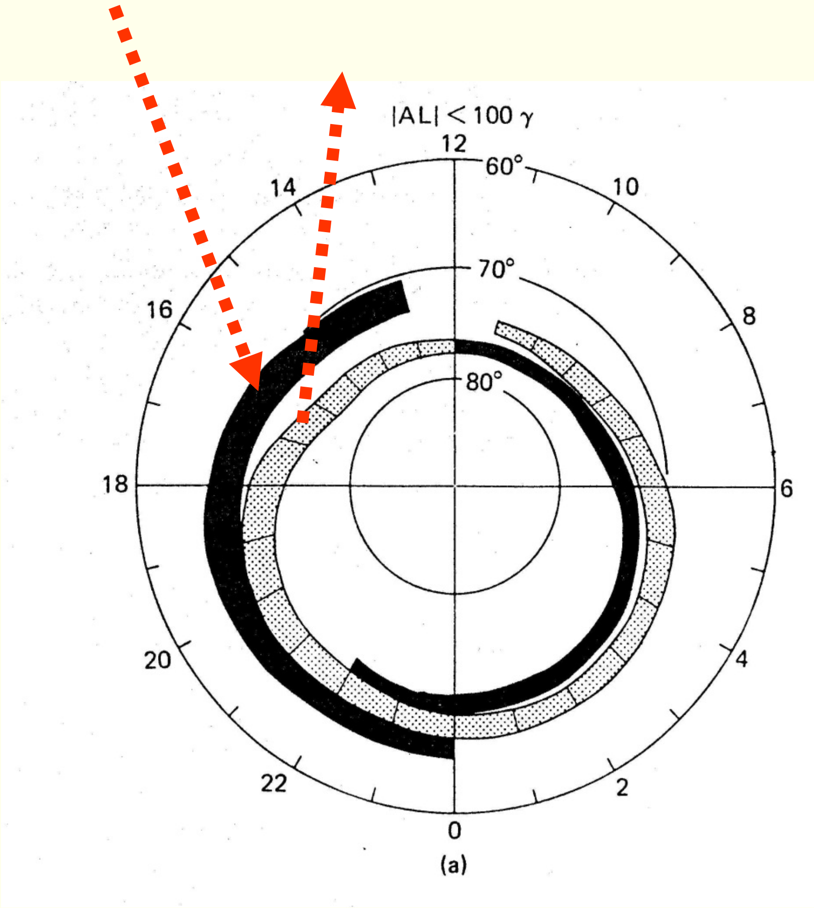
Measurements made by the ISEE satellite (Mozer et al., 1977)

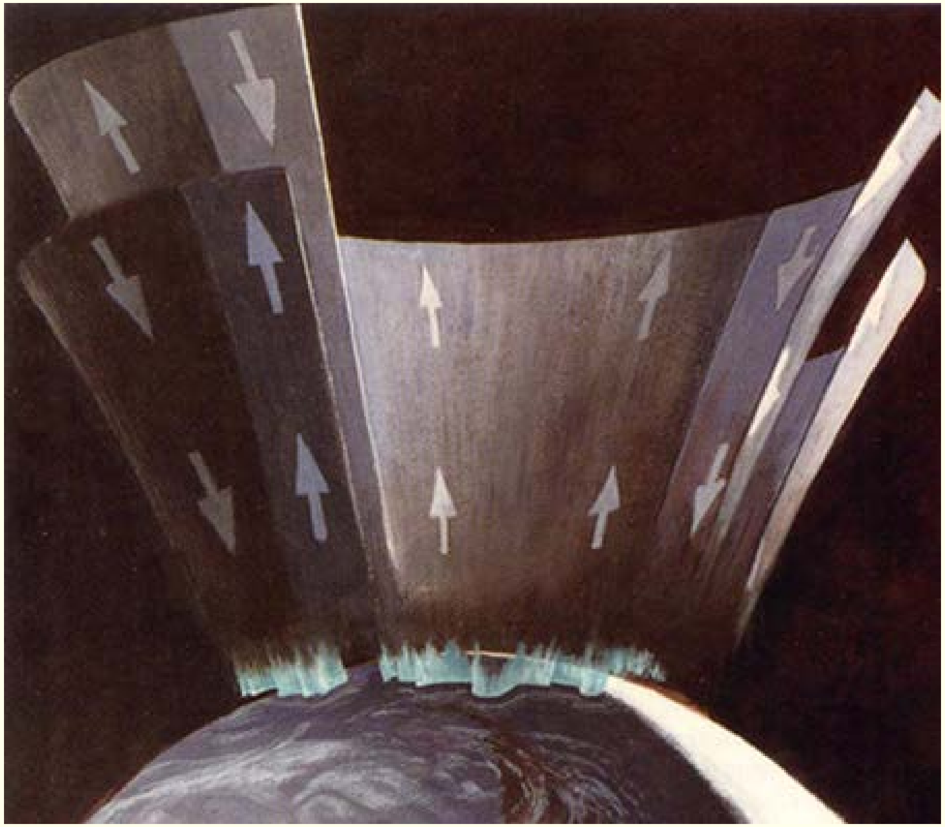
Spirals – Kelvin-Helmholz instability



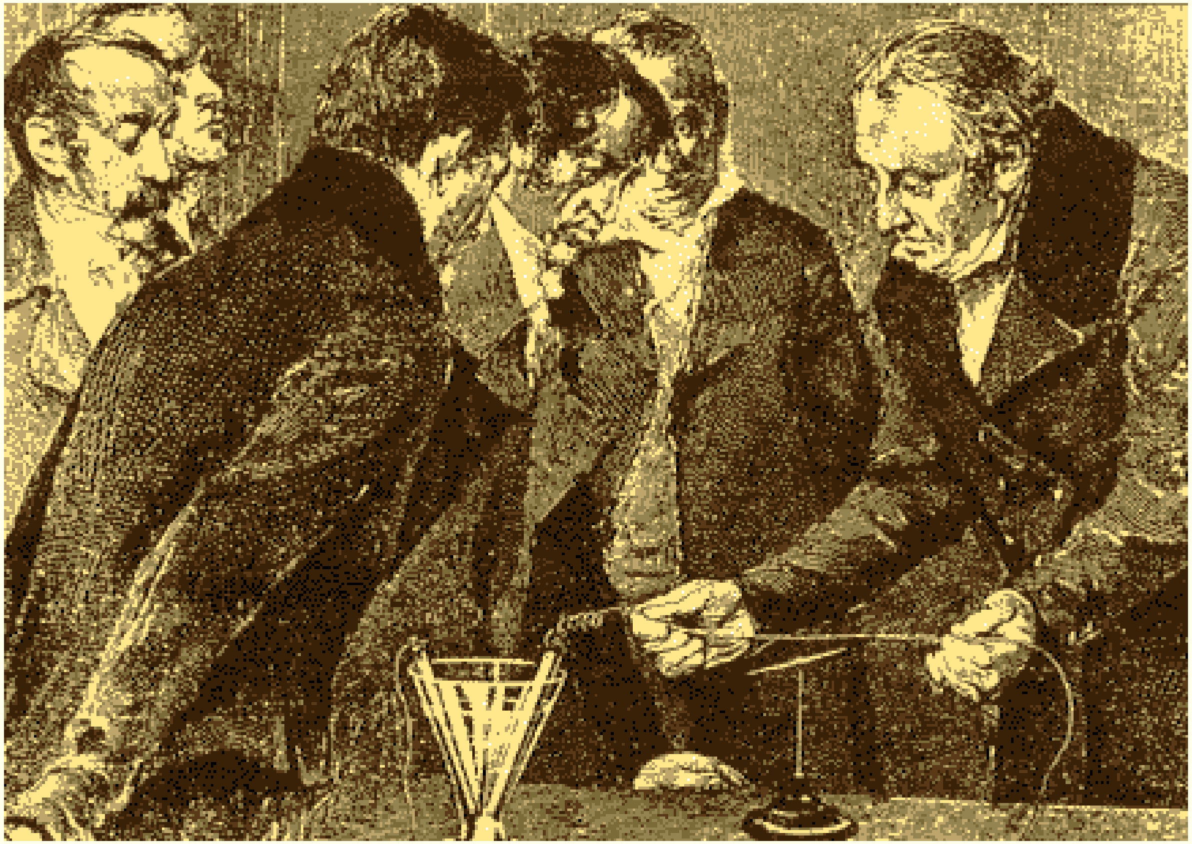
Opposite flows trigger the K-H instability

Birkeland currents in the auroral oval

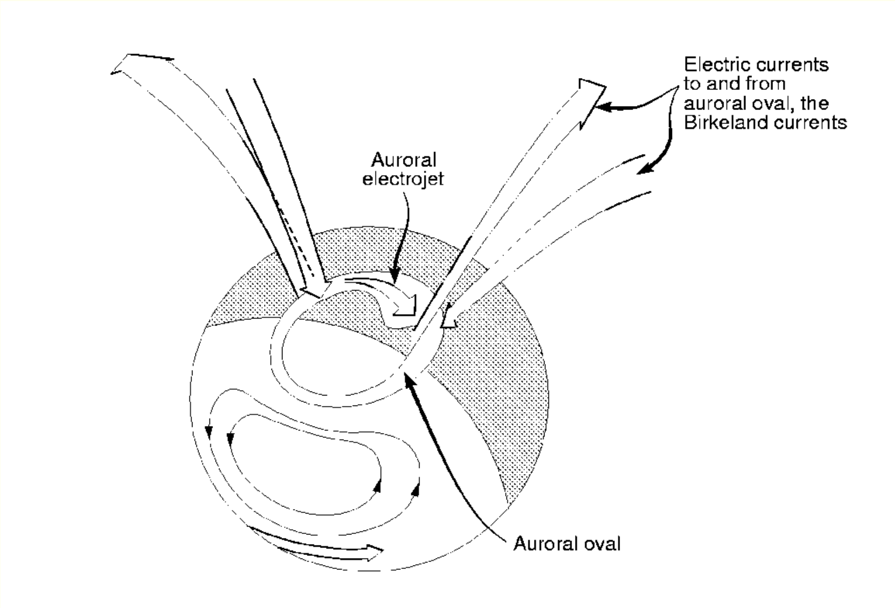




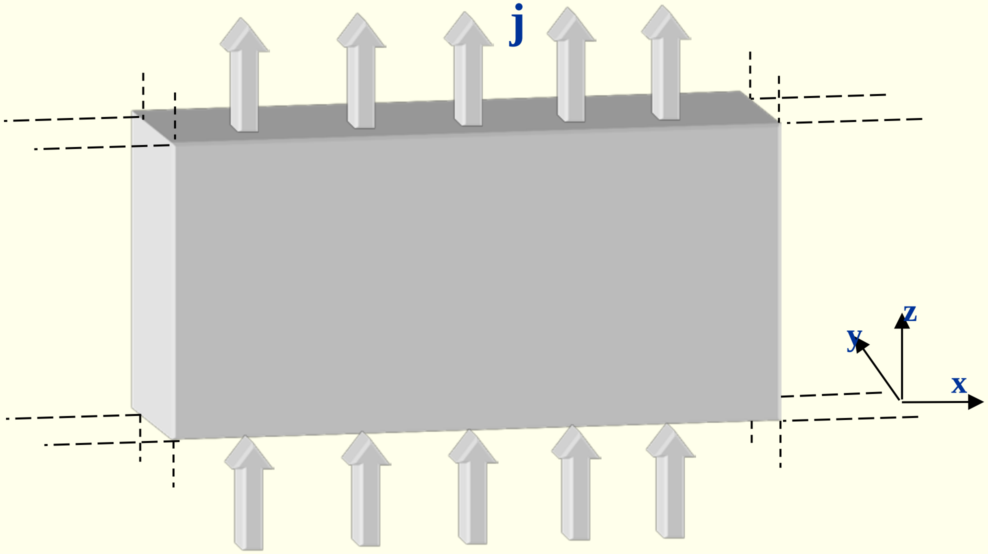
How can you measure currents in space?



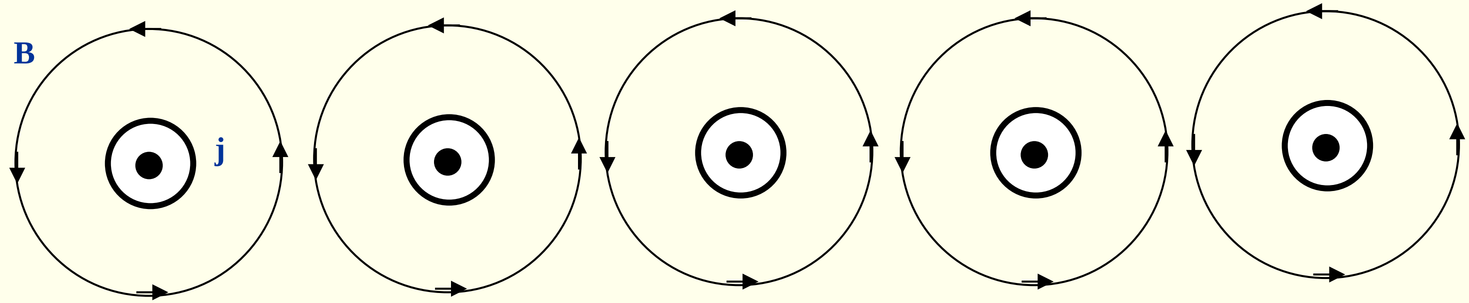
Current sheet approximation



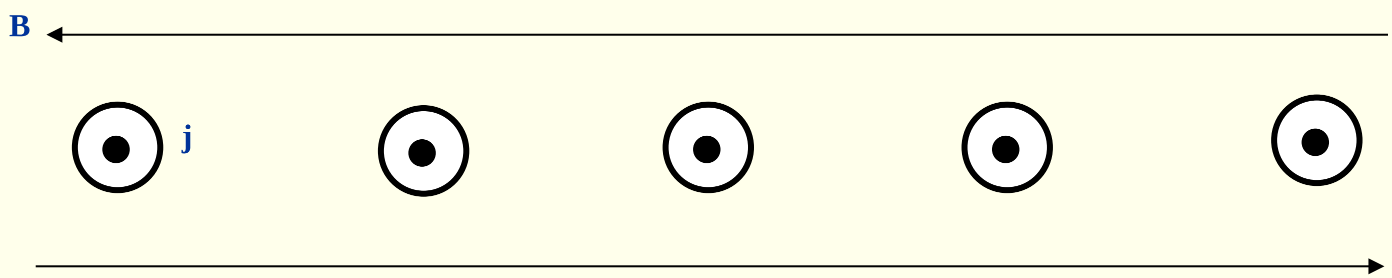
Approximate currents by thin current sheets with infinite size in the x- och z-directions.



Current sheet approximation

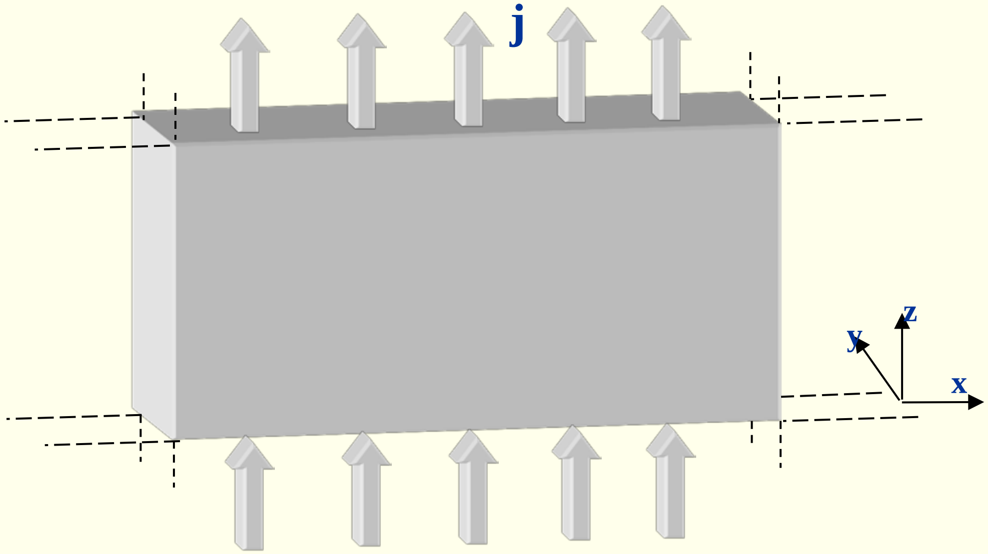


What will the magnetic field around such a current configuration be? Start by approximating with line currents to get a qualitative picture.



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

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

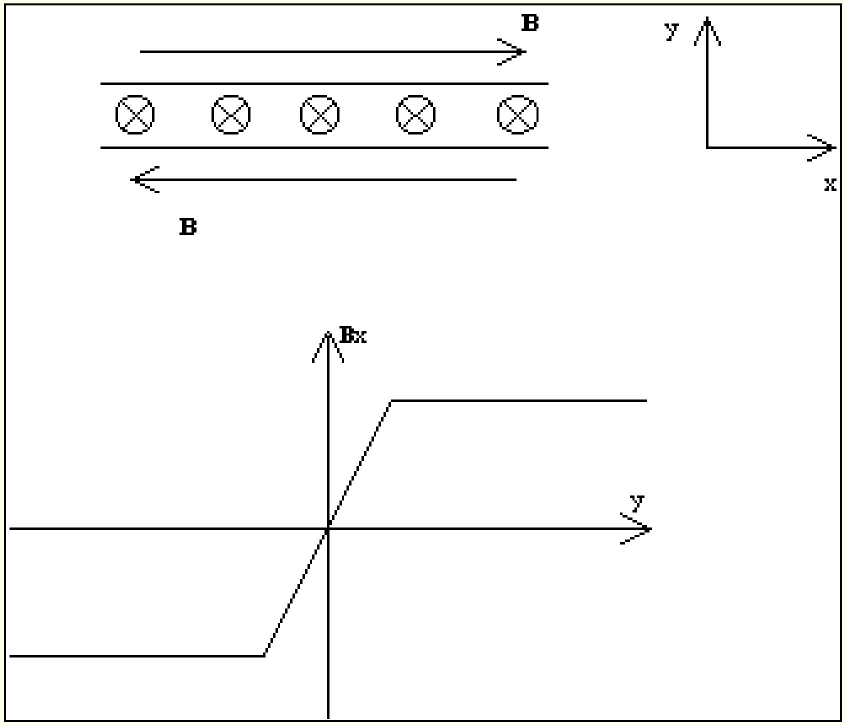
eller

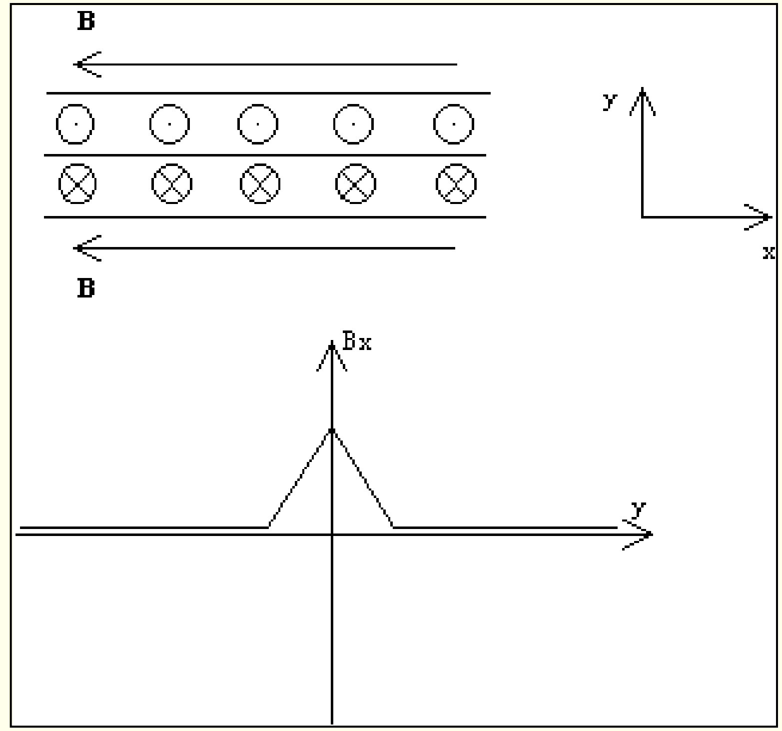
Ampére's law (no time dependence):

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

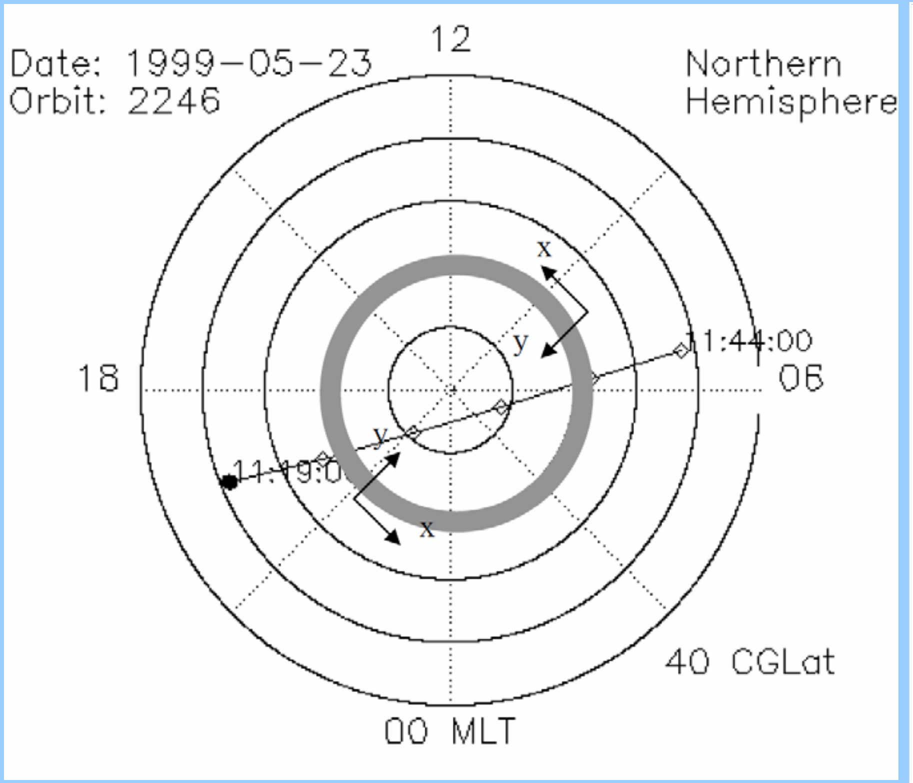
$$j_z=-\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

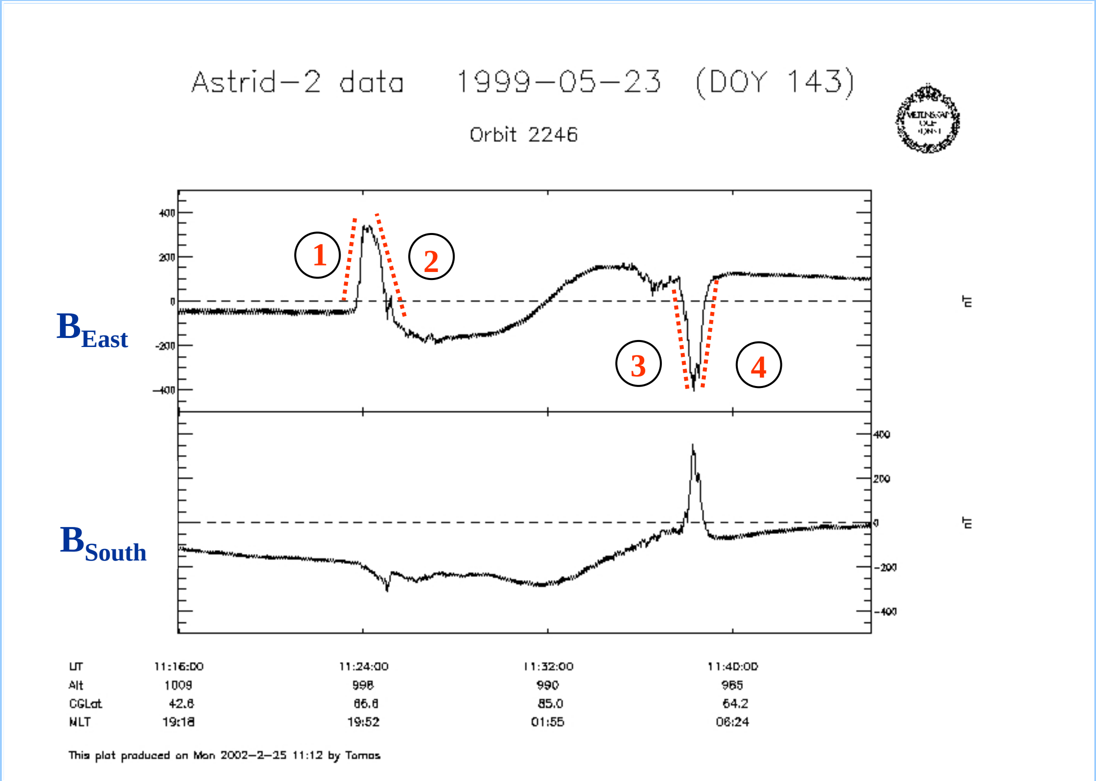
Current sheet - example





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

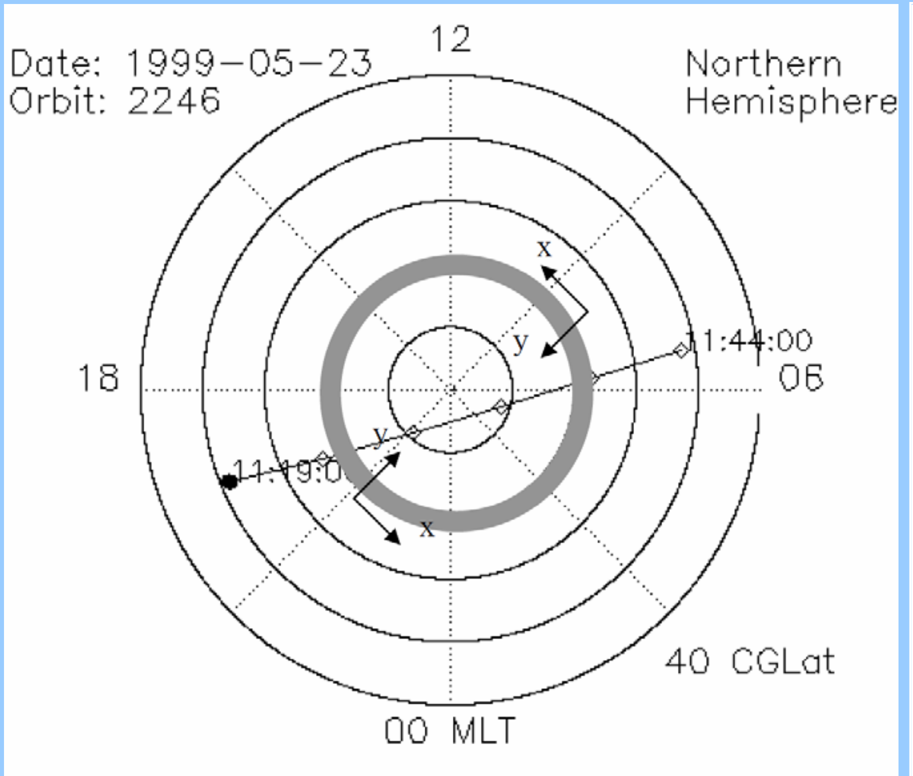


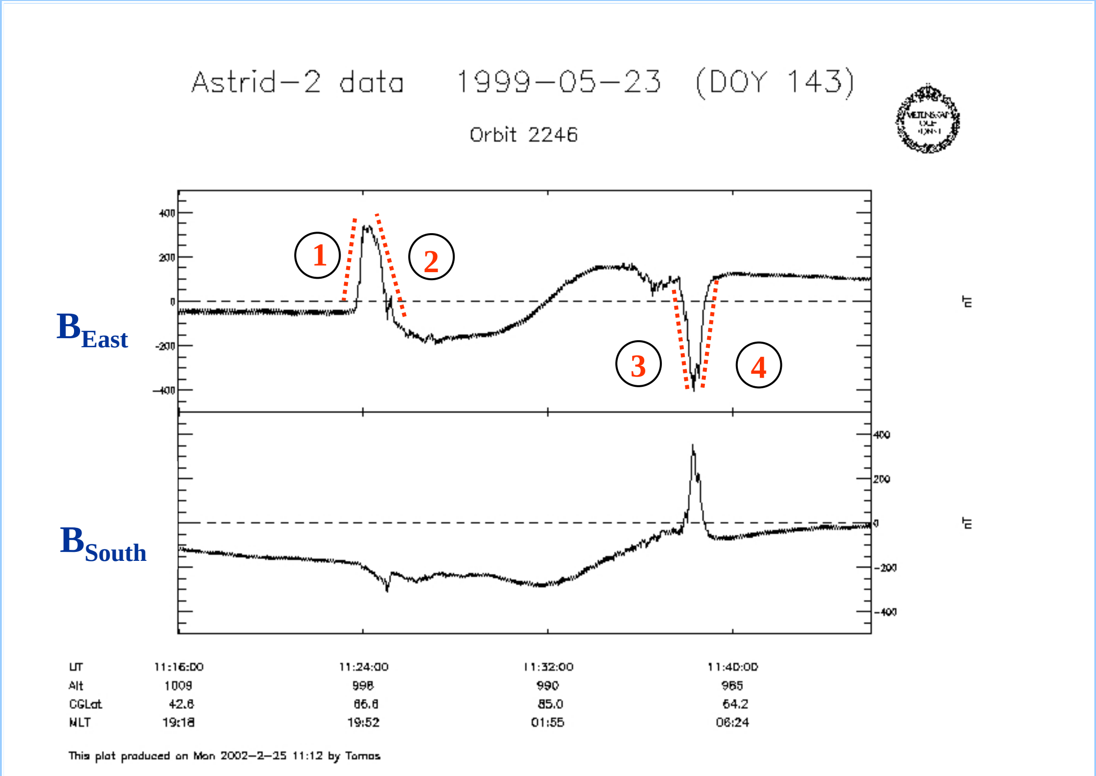


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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

Blue	Into the ionosphere
Red	Out of the ionosphere





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

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

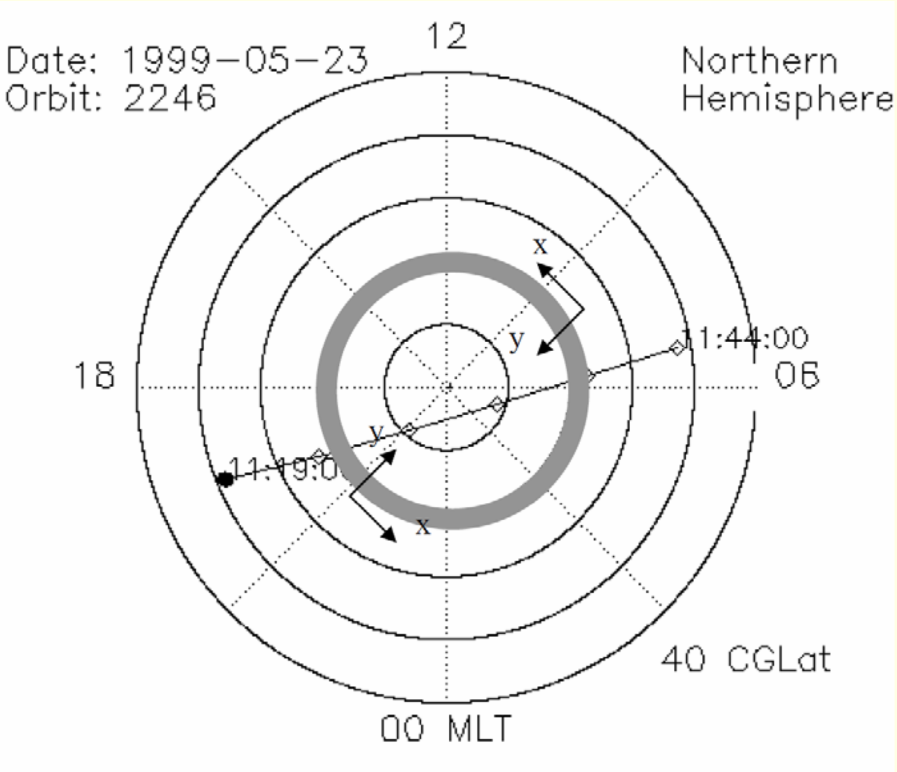
$$\frac{\partial B_x}{\partial y} = \frac{\partial B_{East}}{\partial y} > 0$$

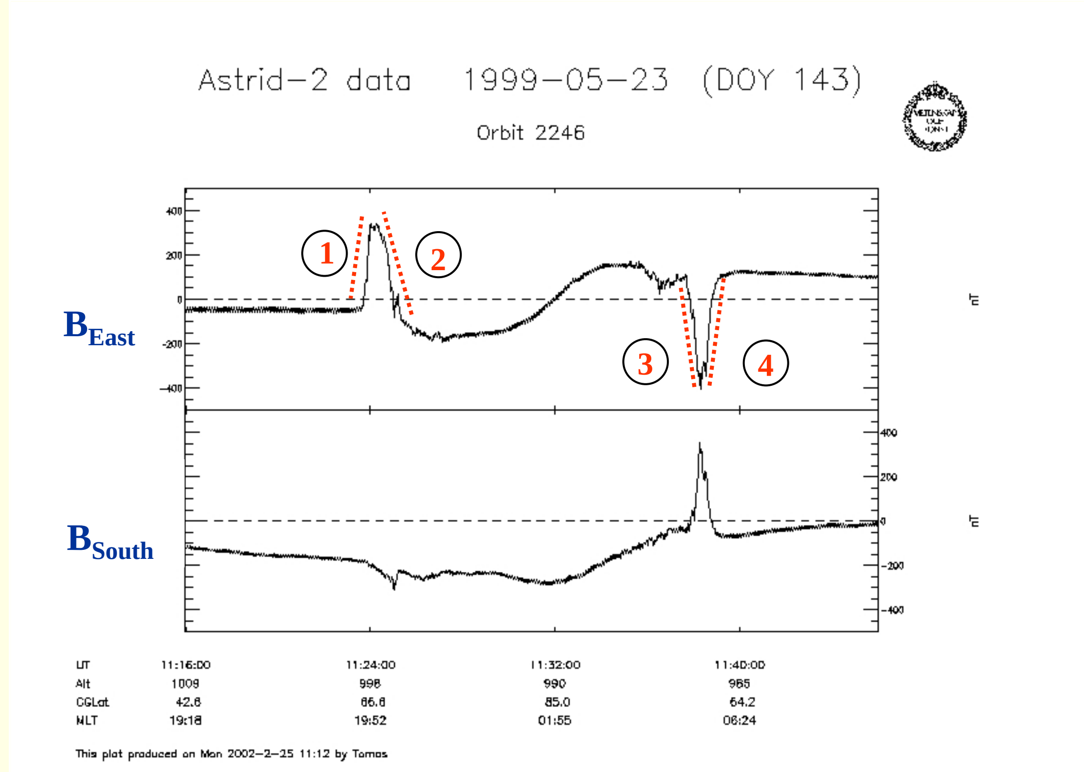
$$\Rightarrow$$

$$j_z < 0$$

Blue

Into the ionosphere

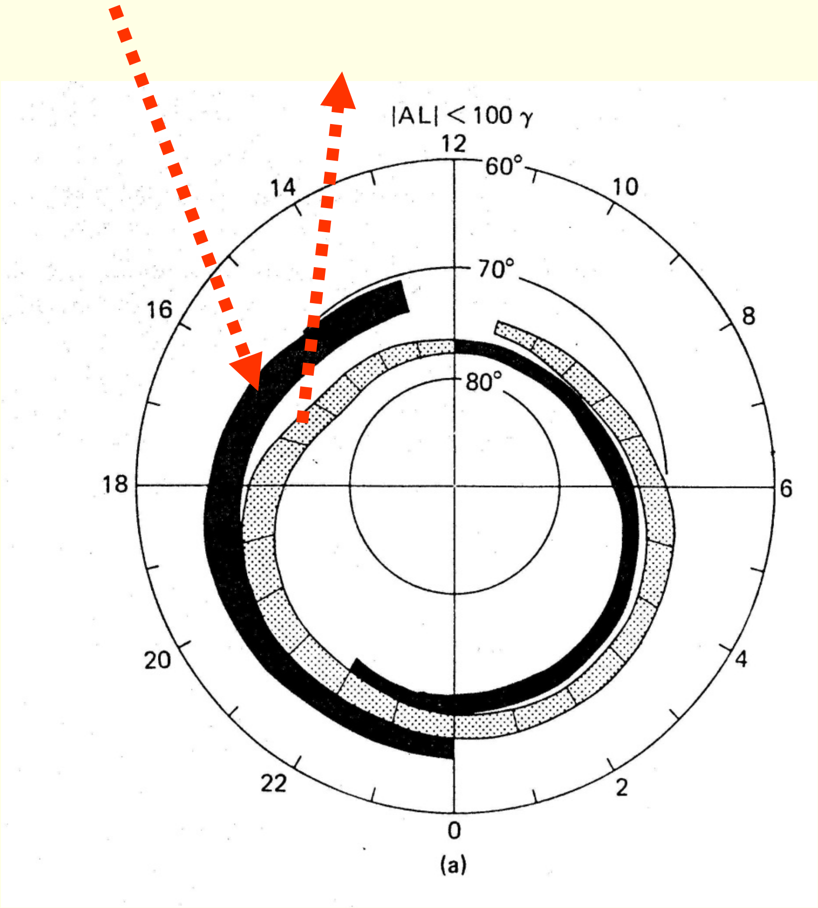


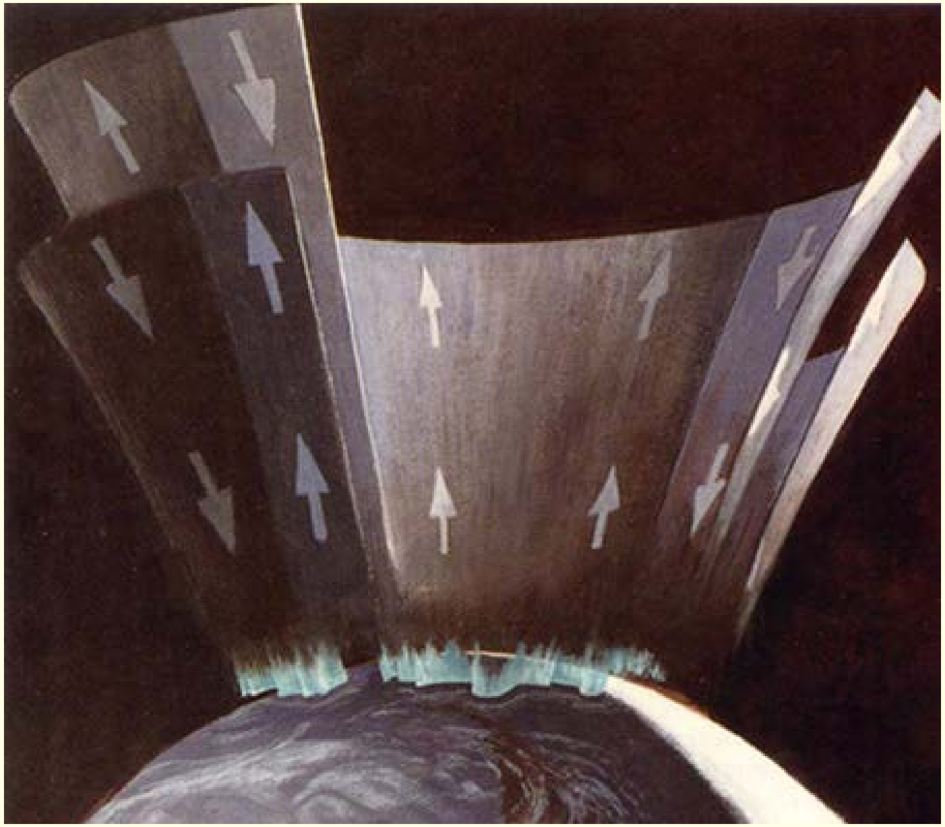


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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

Birkeland currents in the auroral oval





At what planets do you expect aurora to exist?

Blue	Earth, Mercury, Jupiter, Saturn
Yellow	Earth, Venus, Jupiter, Saturn, Uranus, Neptune
Green	Earth, Mars, Jupiter, Saturn, Uranus, Neptune
Red	Earth, Jupiter, Saturn, Uranus, Neptune

What do we need to have an aurora?

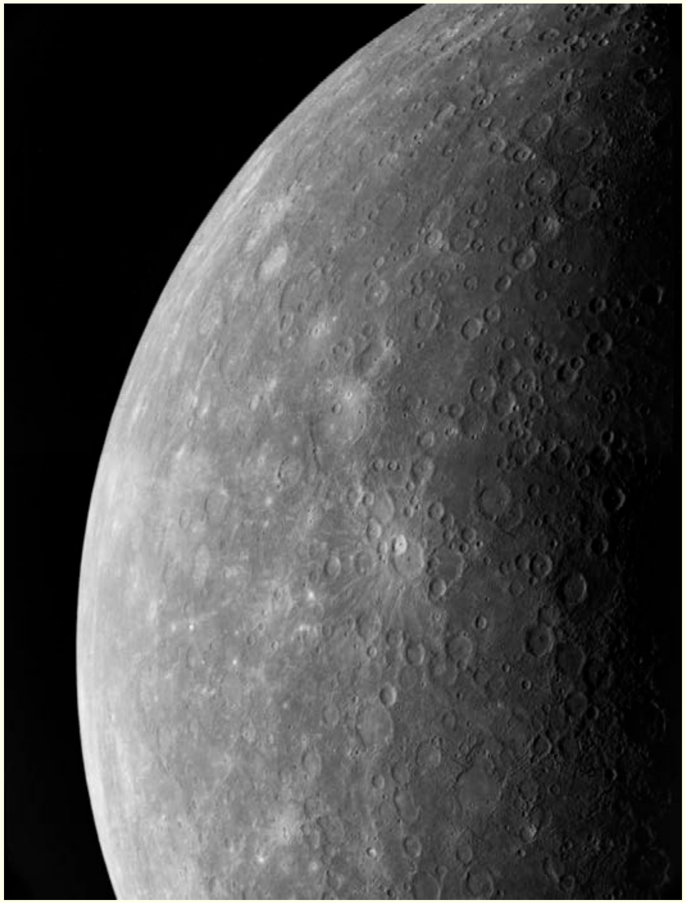
- Magnetic field (to guide the plasma particles towards the planet)
- Atmosphere (to create emissions)

At what planets do you expect aurora to exist?

Red

Earth, Jupiter, Saturn,
Uranus, Neptune

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

- 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!

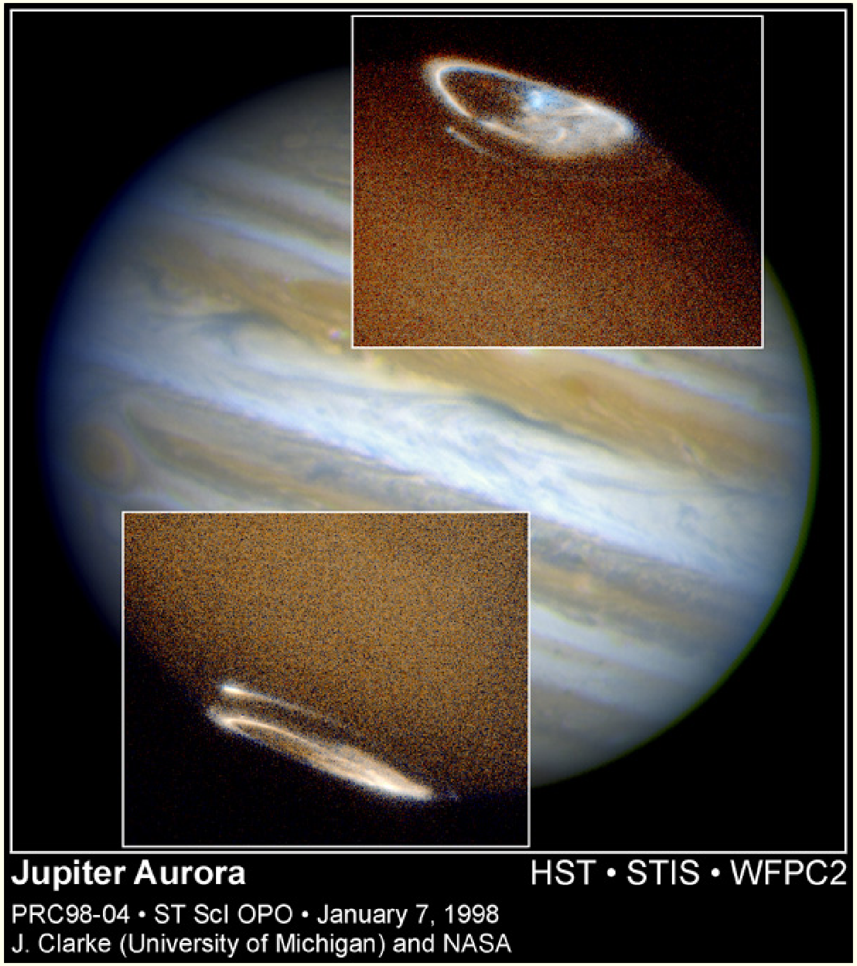
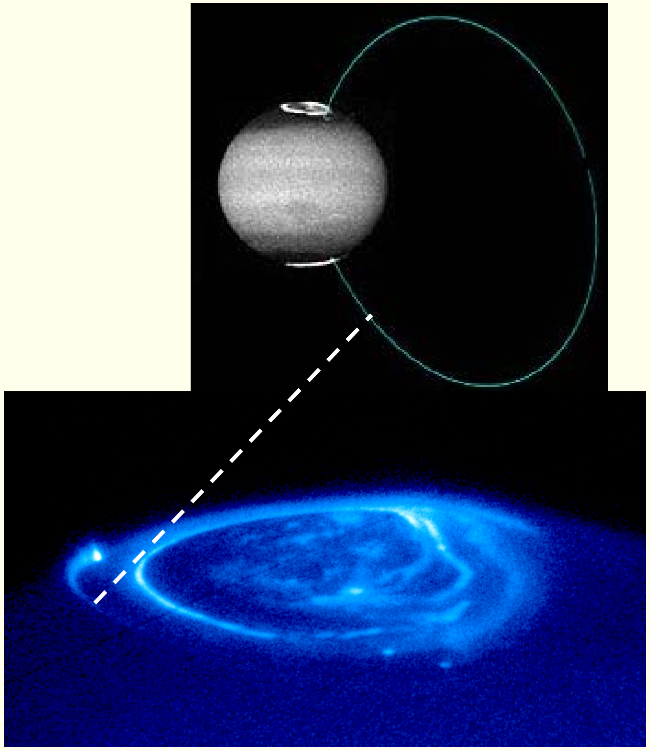
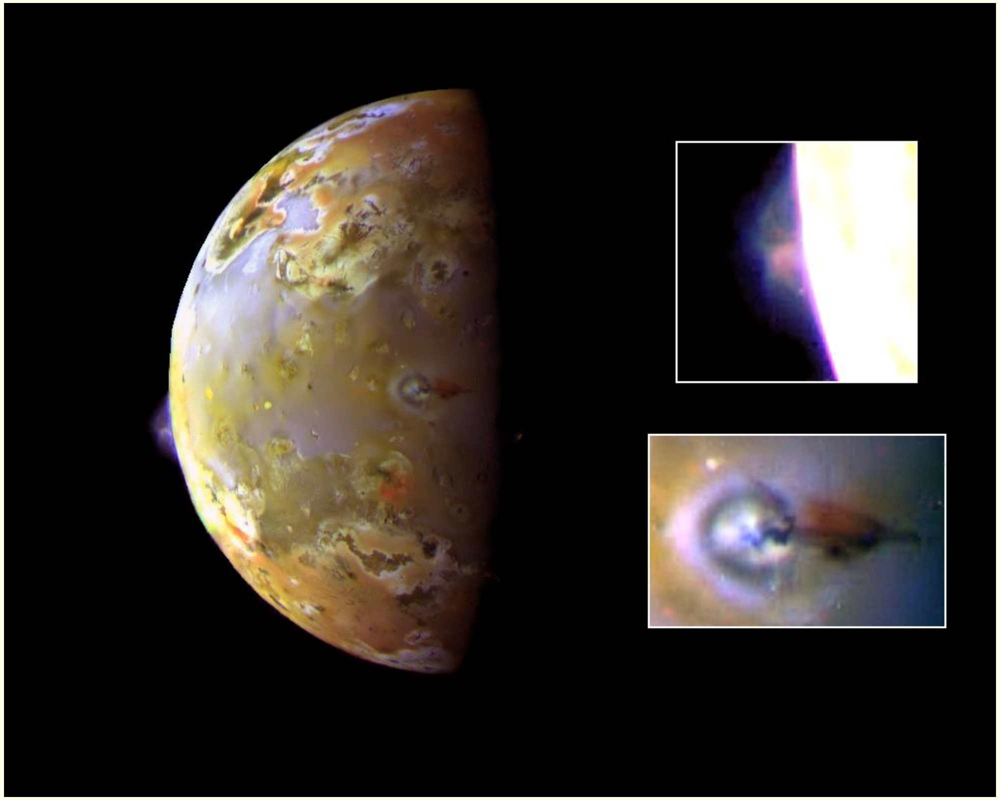


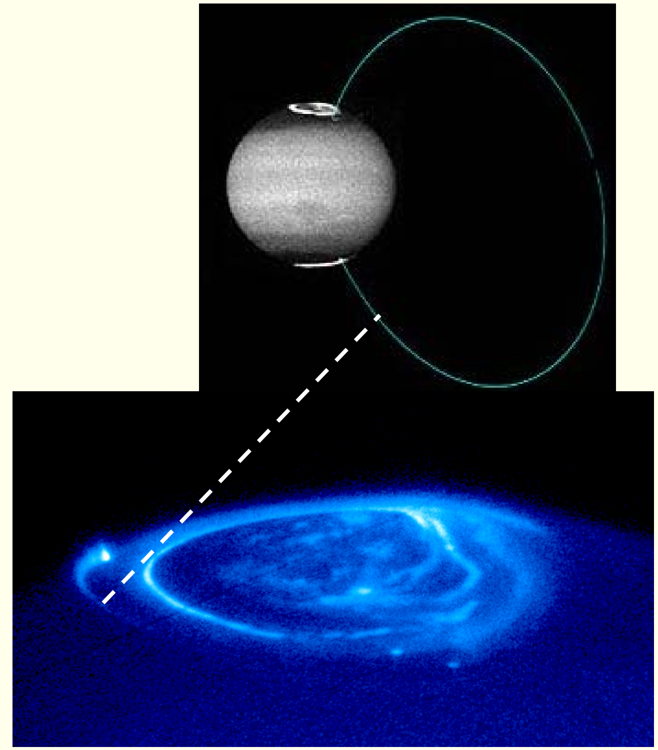
Foto från Hubble Space Telescope



Jupiter and Io

Photo from rymdsonden Galileo

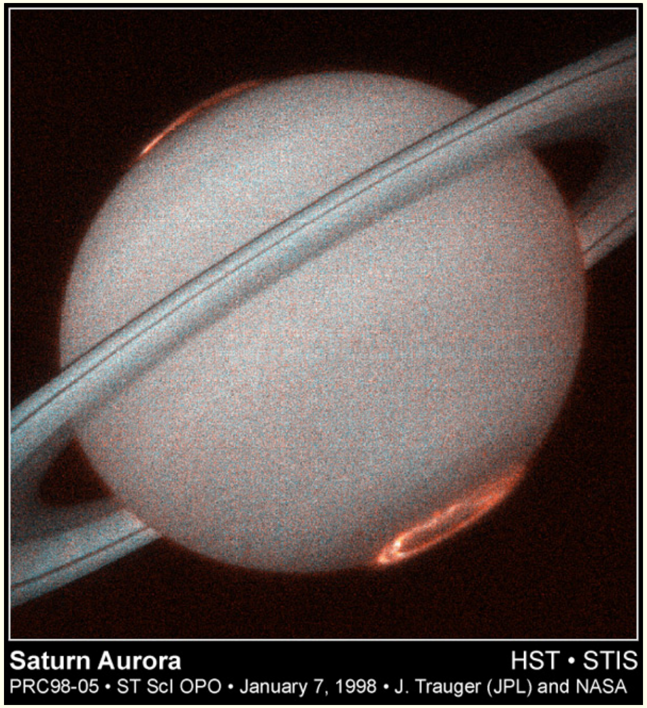




The Jupiter moon Io is very volcanically active, and deposes large amounts of dust and gas in Jupiter’s magnetosphere. This is ionized by the sunlight, and the charged plasma partícles follow Jupiter’s magnetic field lines towards the atmosphere and cause auroral emissions.

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

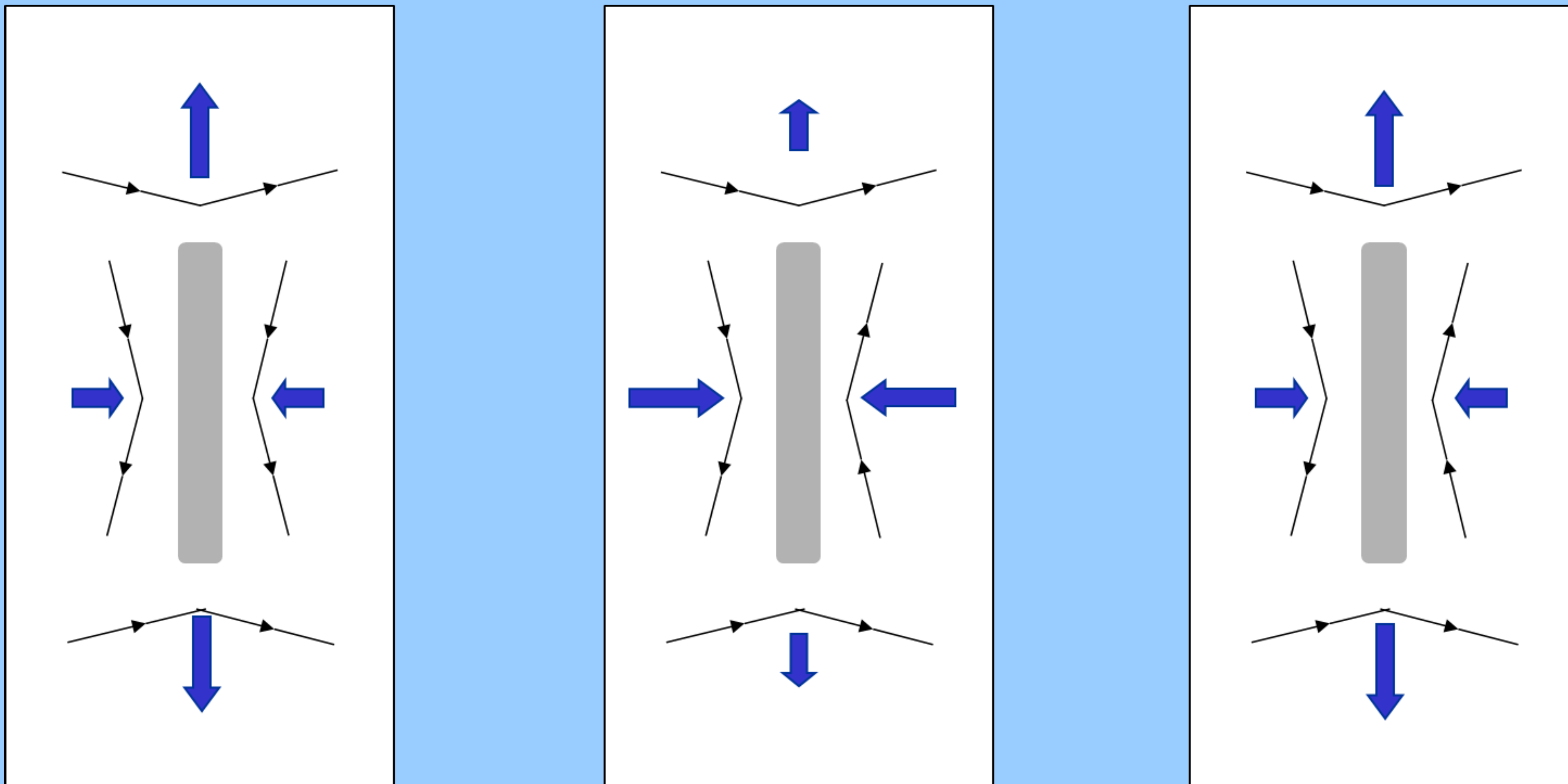
Kiruna all-sky camera:
http://www.irf.se/allsky/rtasc.php

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

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

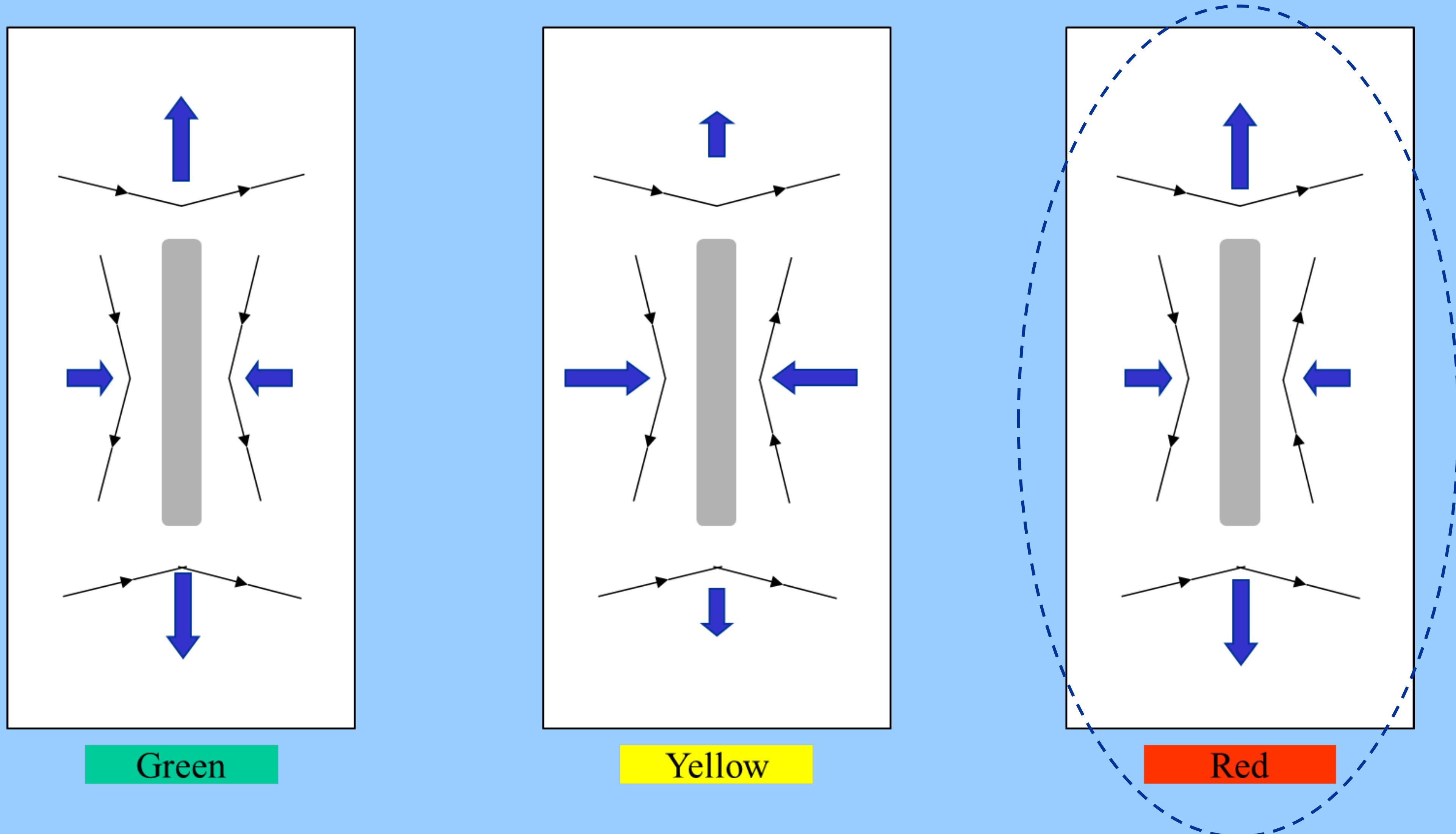
http://www.irf.se/Observatory/?link[All-skycamera]=Aurora_sp_statistics

Magnetic reconnection

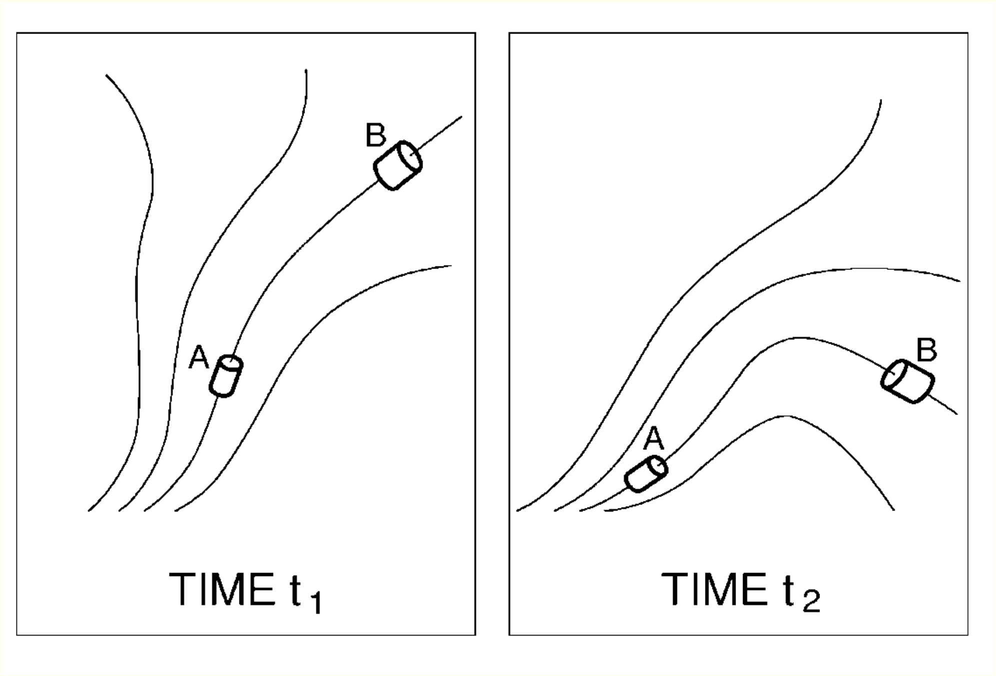


Green | Yellow | Red

Magnetic reconnection



Frozen in magnetic field lines



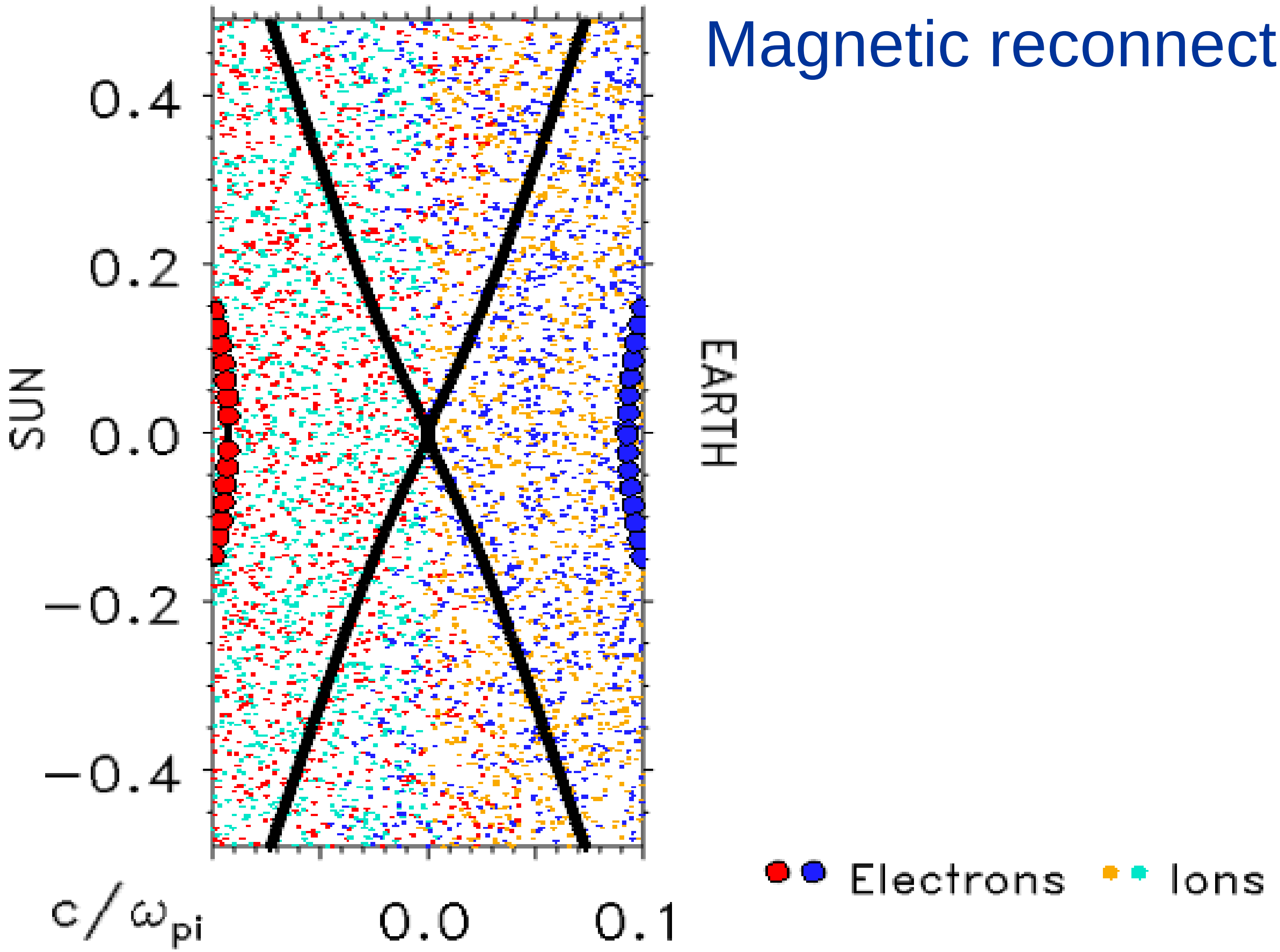
In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

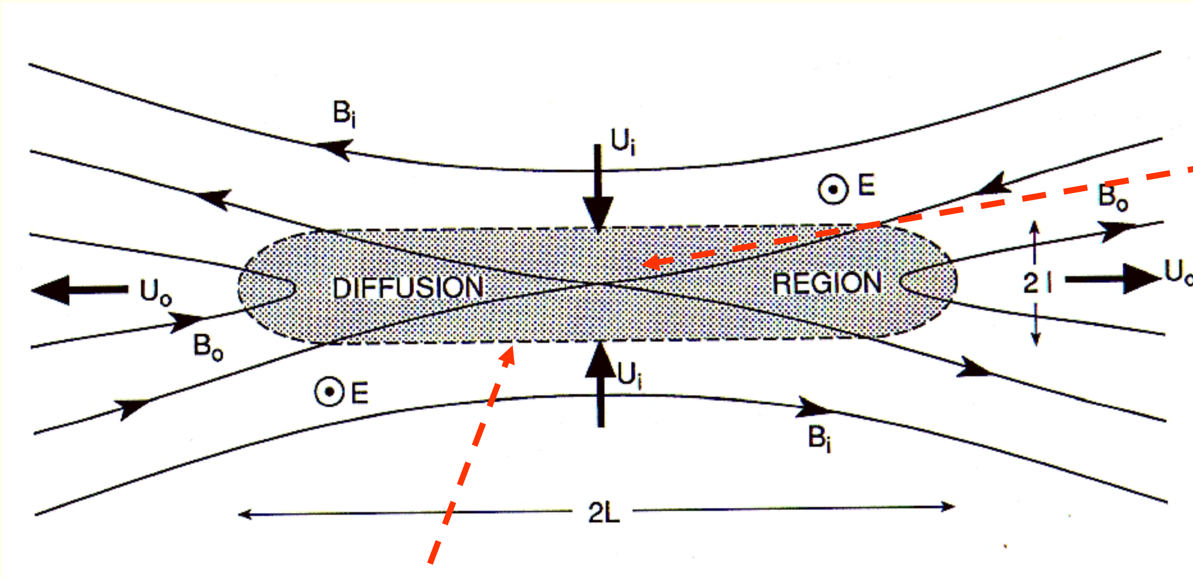
$$R_m = \mu_0 \sigma l_c v_c >> 1$$

An example of the collective behaviour of plasmas.

Magnetic reconnection



Reconnection



In 'diffusion region':

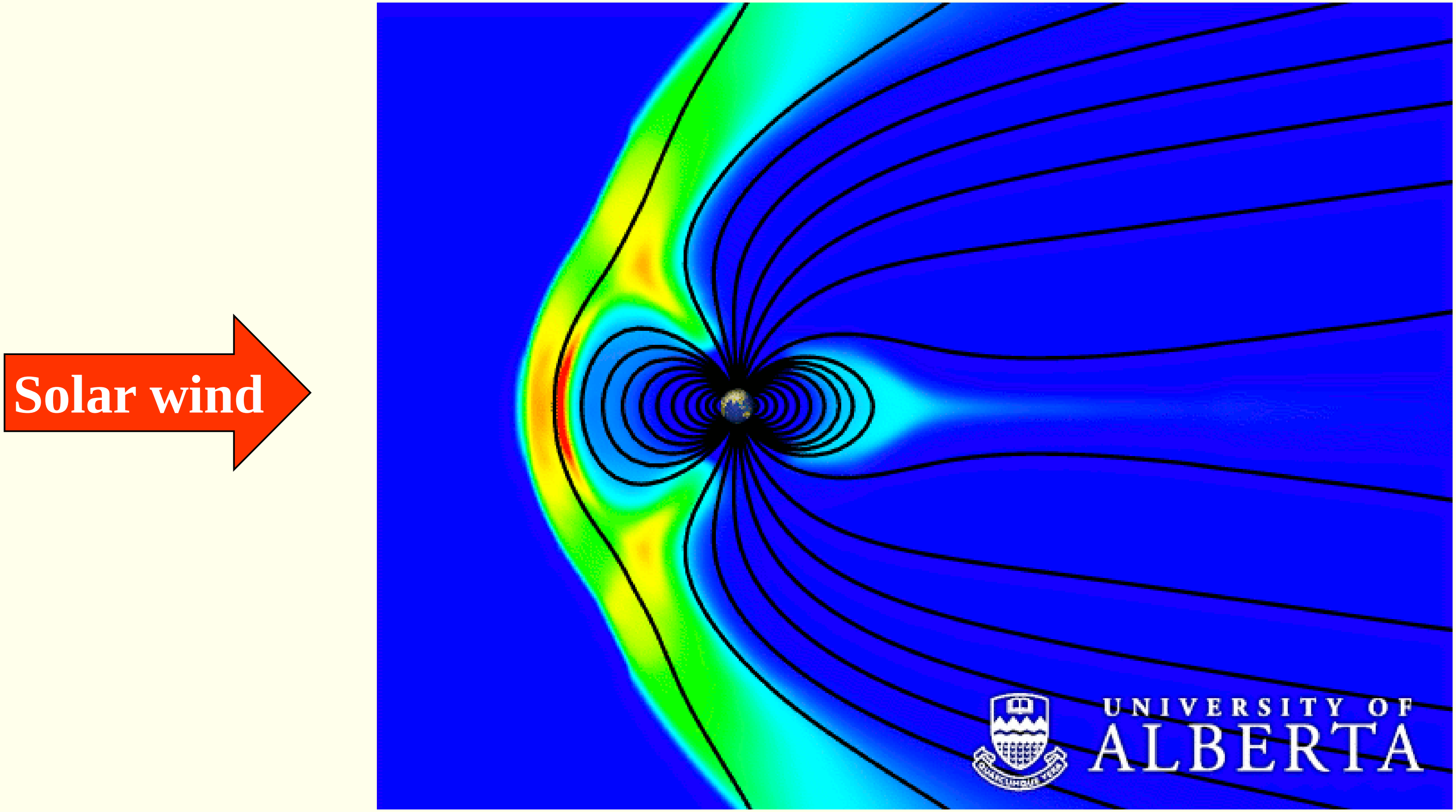
$R_m = \mu_0 \sigma l v \sim 1$

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:

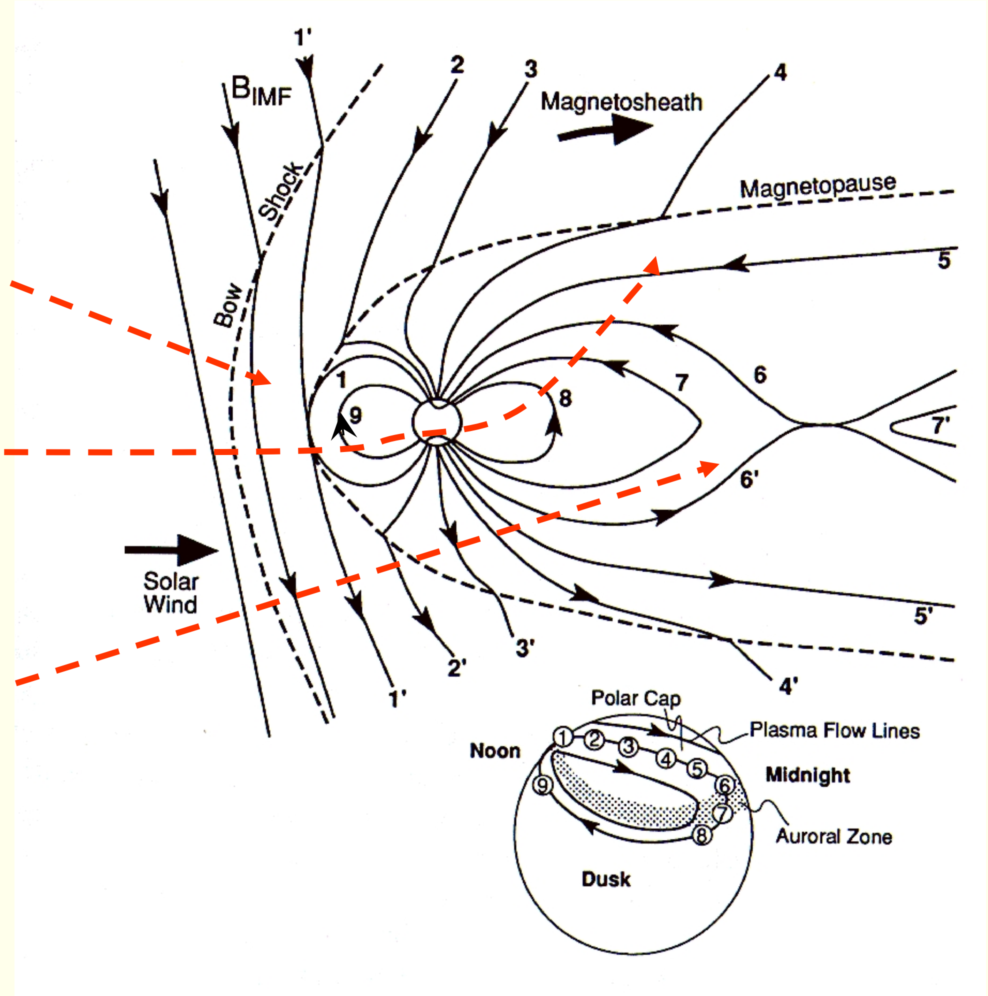
- Field lines are "cut" and can be re-connected to other field lines
- **Magnetic energy is transformed into kinetic energy ($U_o >> U_i$)**
- **Plasma from different field lines can mix**

Reconnection and plasma convection

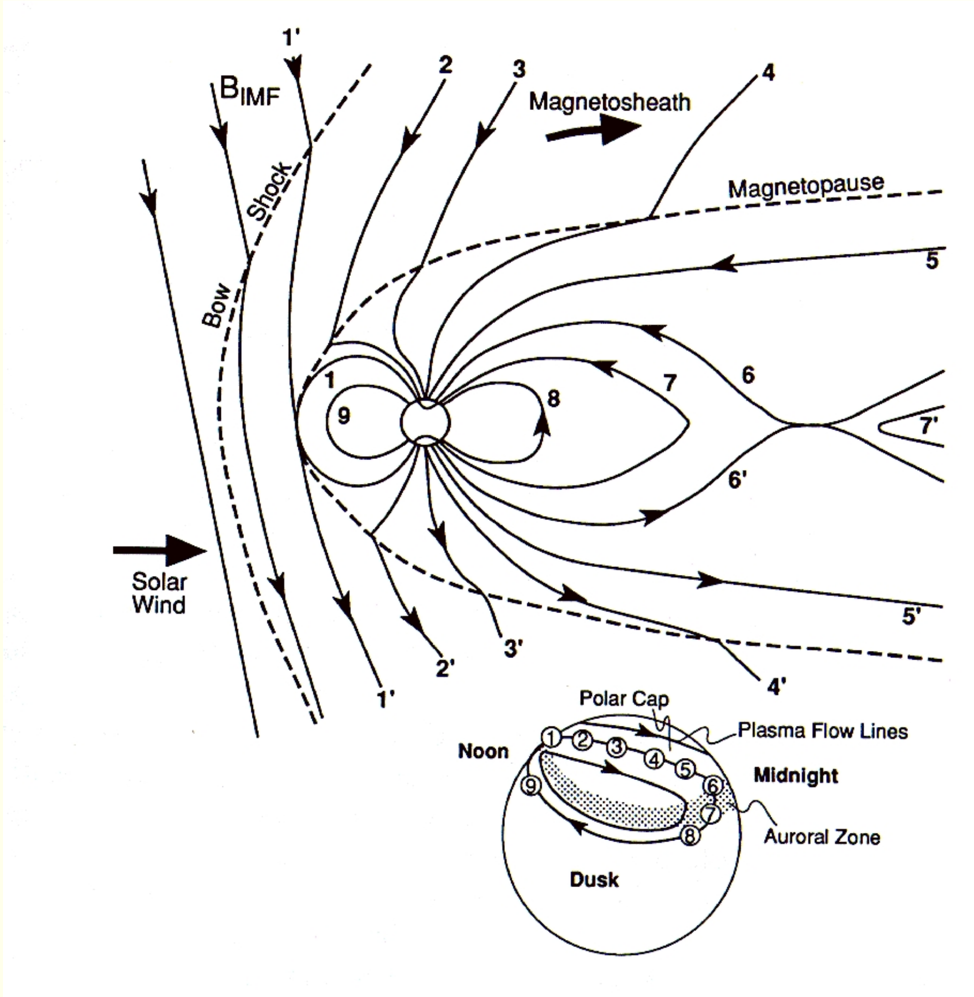


Reconnection och plasma convection

- 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.

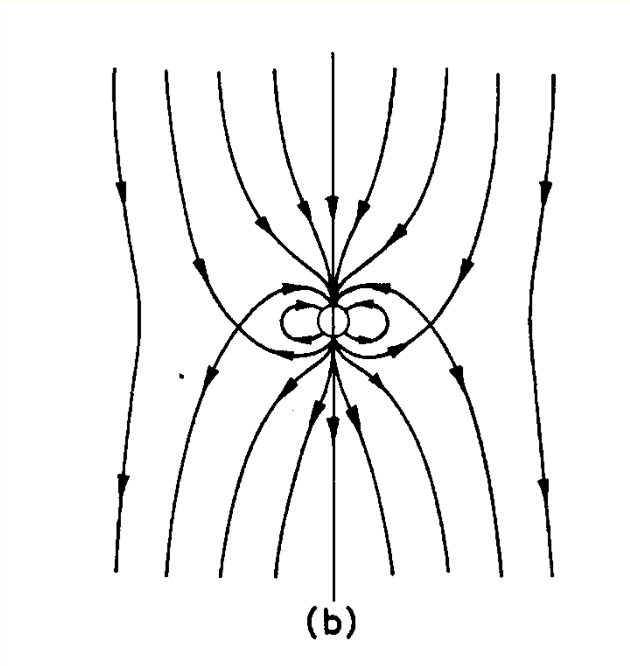


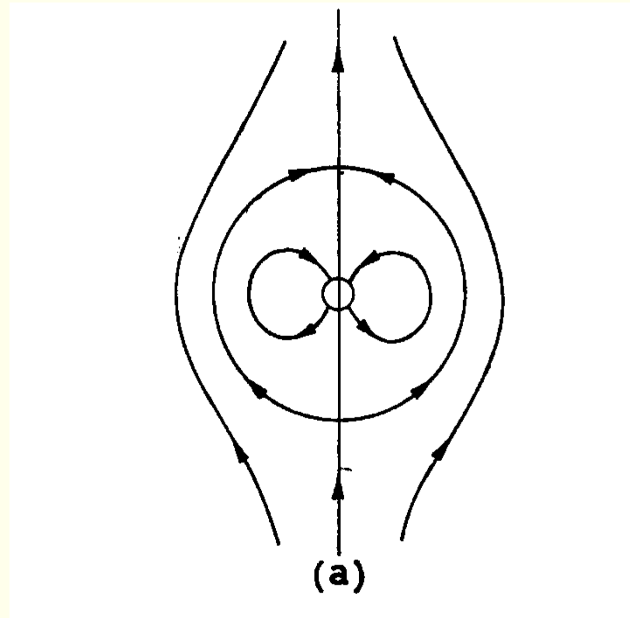
What happens if IMF is northward instead?



Magnetospheric dynamics

open magnetosphere ***closed magnetosphere***





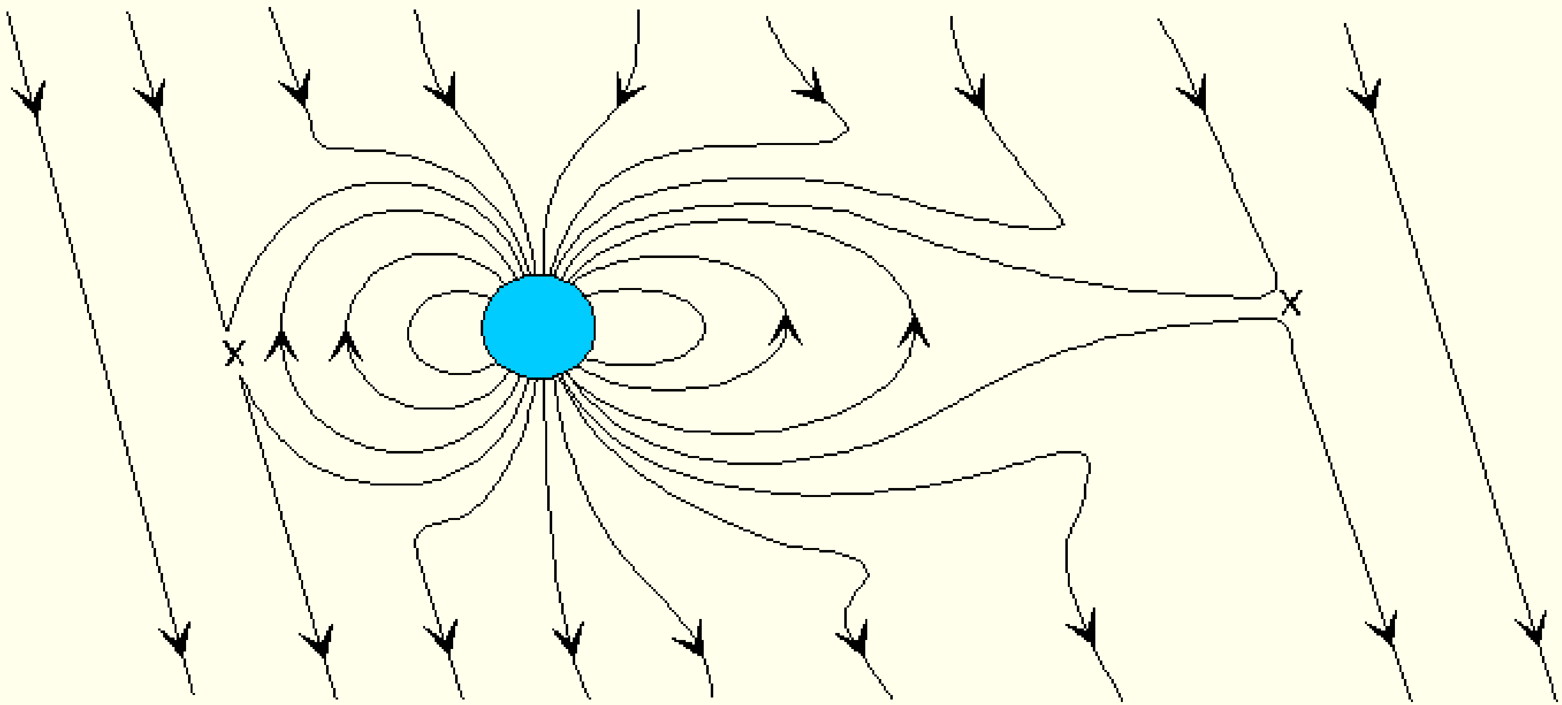
southward

Interplanetary
magnetic field (IMF)

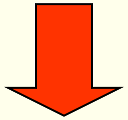
northward

Magnetospheric dynamics

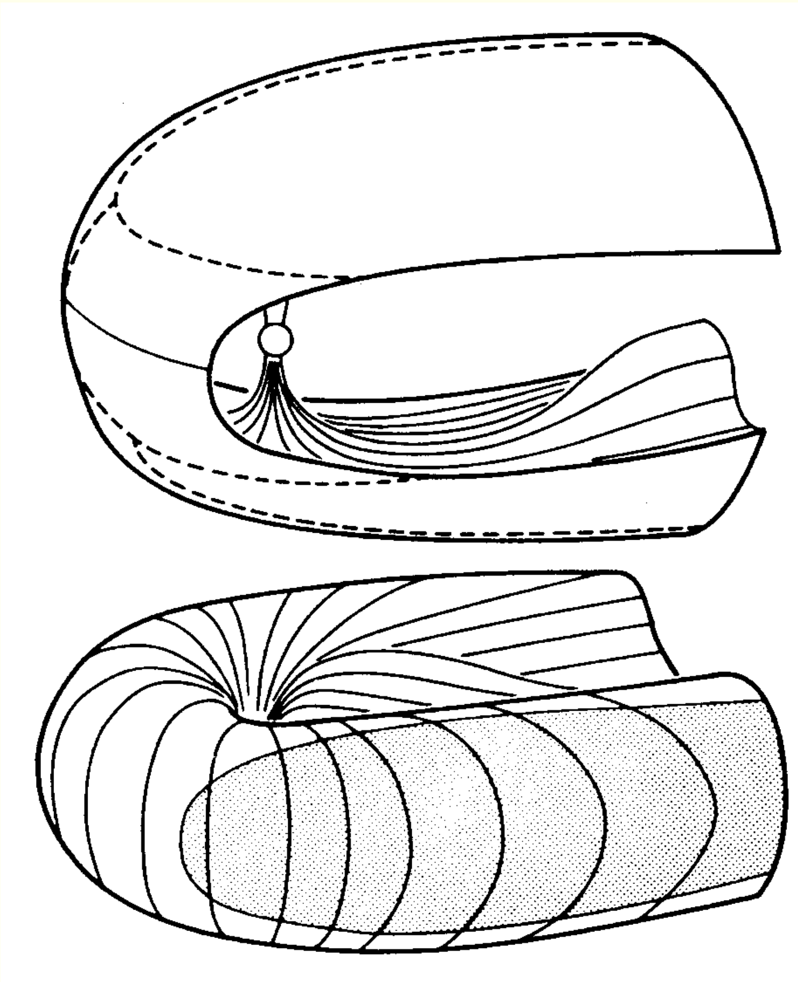
open magnetosphere



Southward IMF



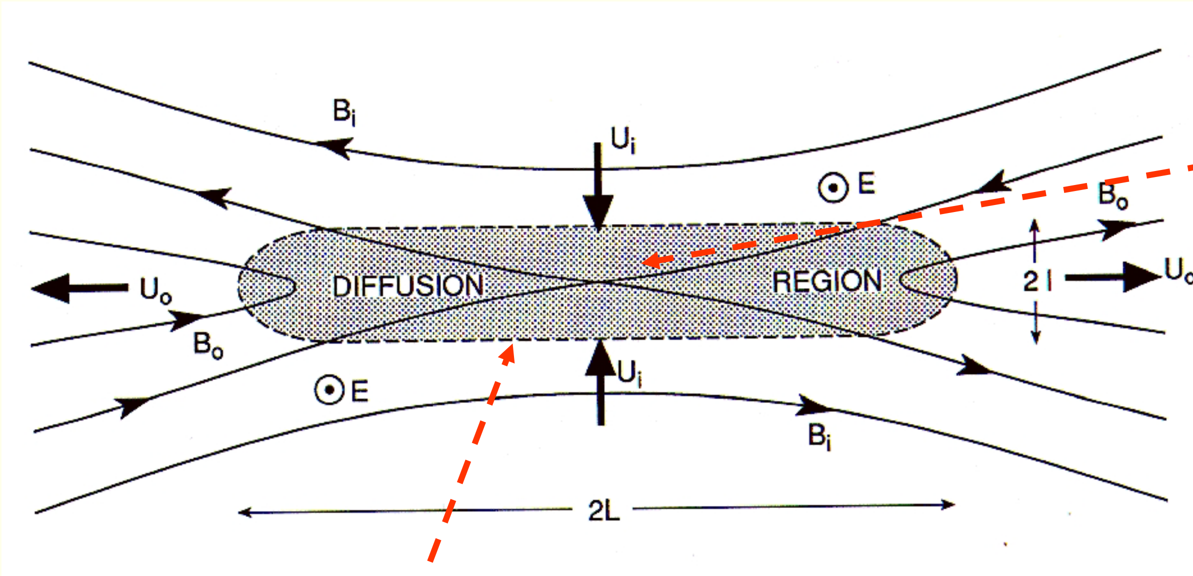
Magnetospheric topology



Open field lines

Closed field lines

Reconnection



In 'diffusion region':

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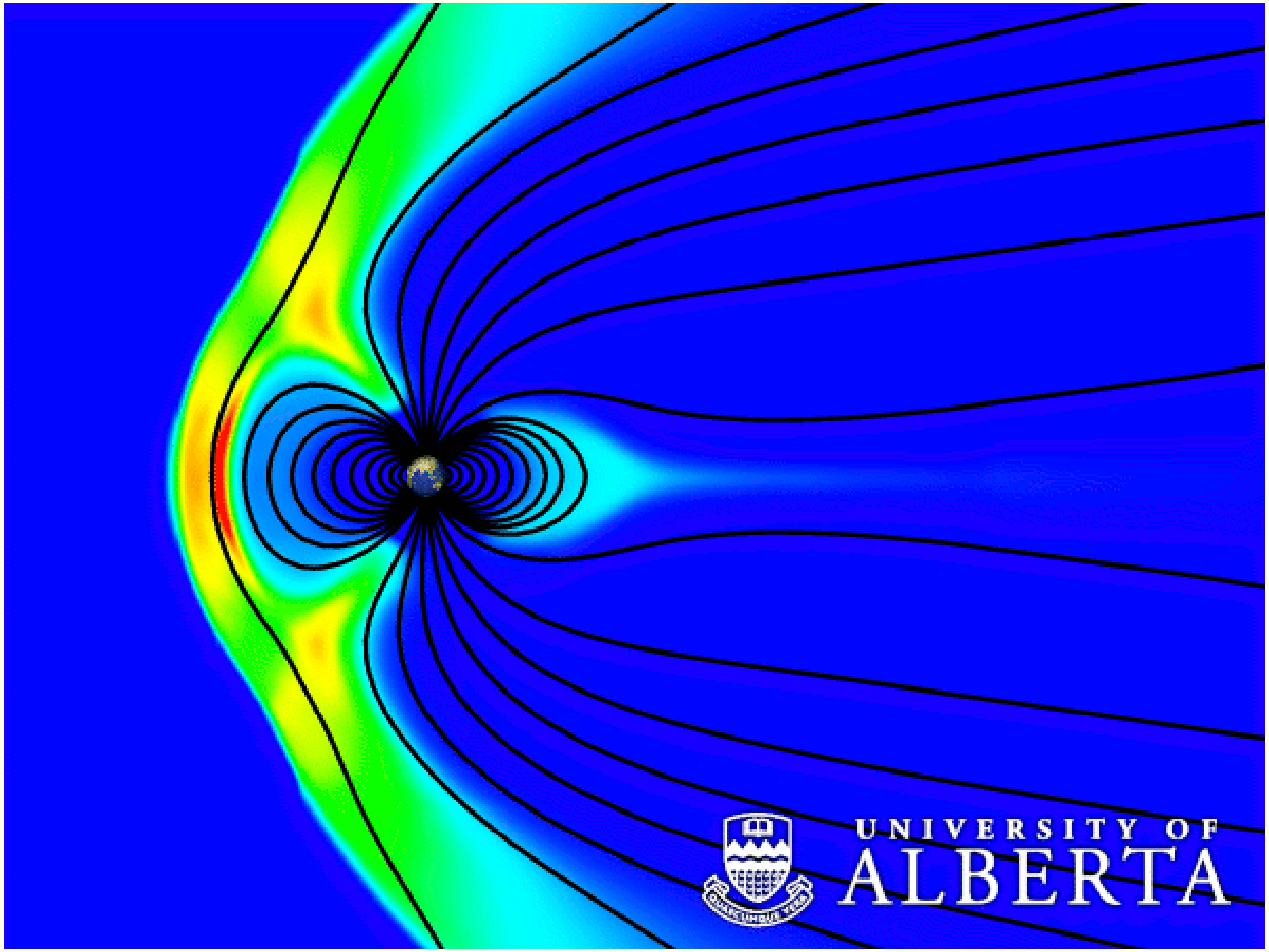
Reconnection and plasma convection

Solar wind



Reconnection och plasma convection

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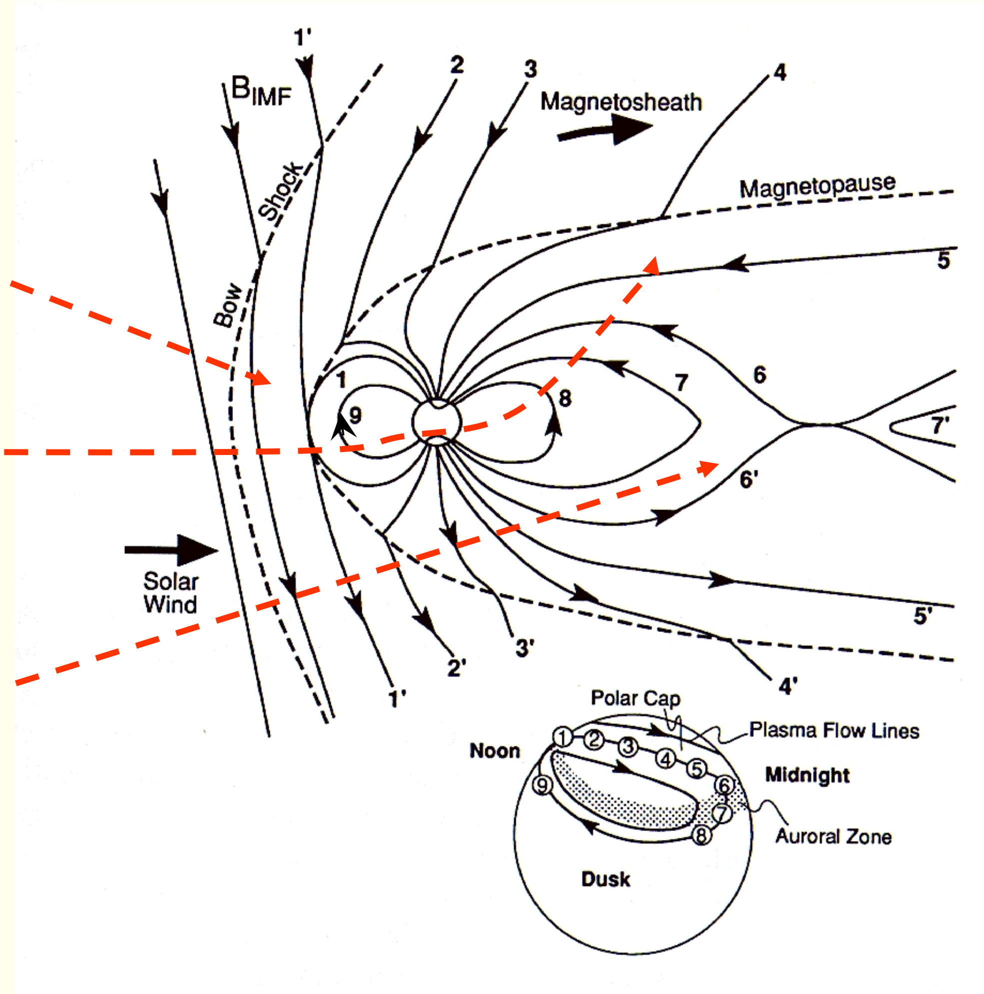
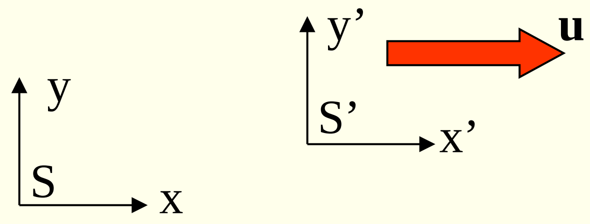


Field transformations (relativistic)



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 $u \ll c$*:*

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

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

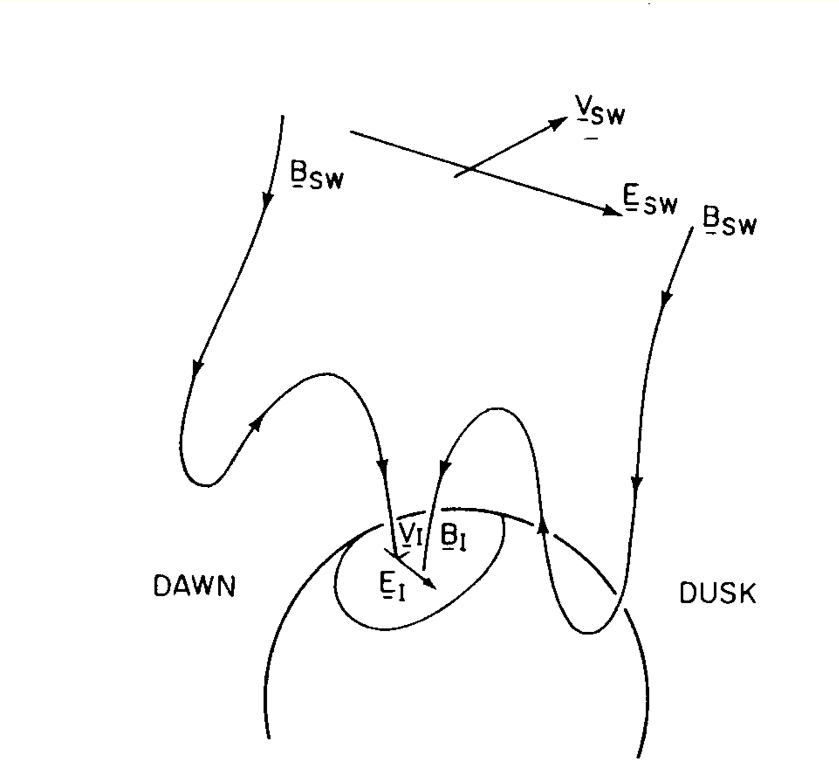
induced electric field

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 1



The solar wind generates an electric field

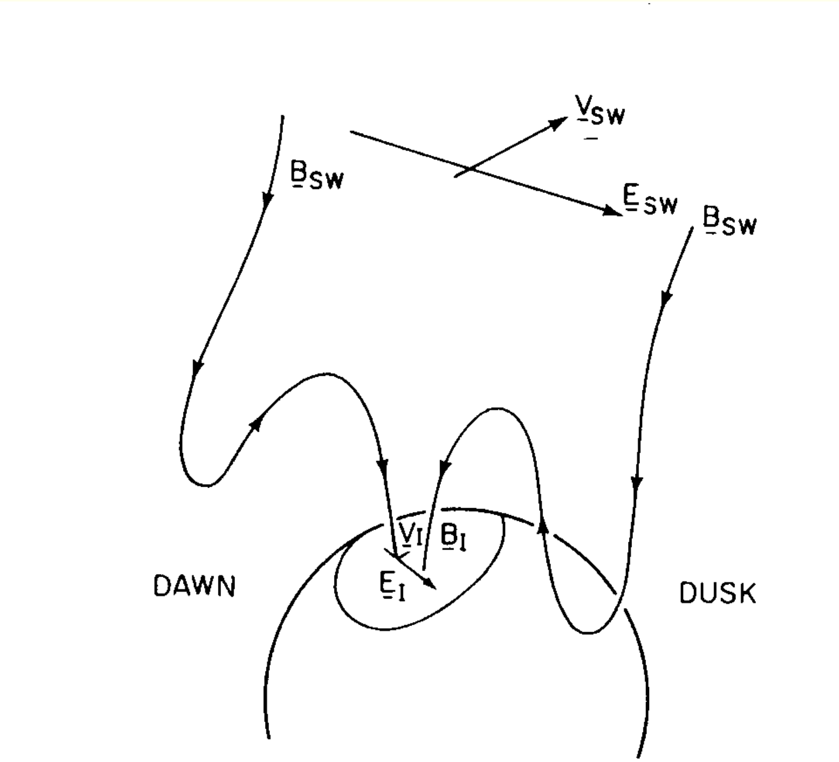
$$\mathbf{E}_{SW} = - \mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 2



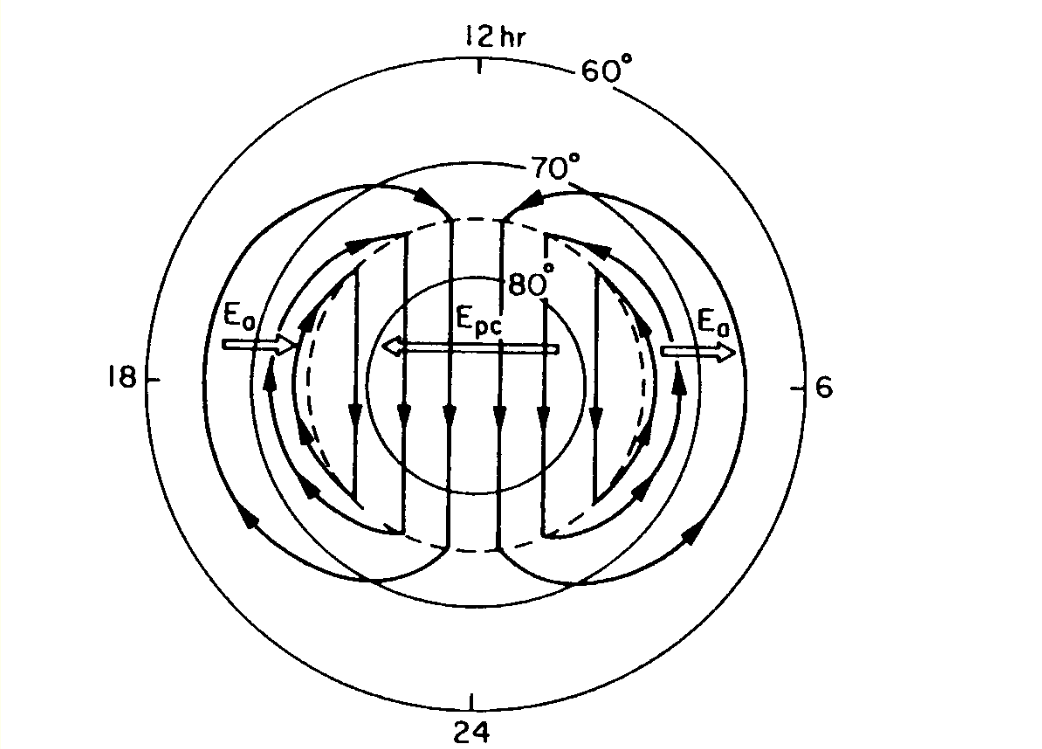
The solar wind magnetic field draws the ionospheric plasma with it, since the field is frozen into the plasma. This motion induces an ionospheric electric field

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

Magnetospheric dynamics

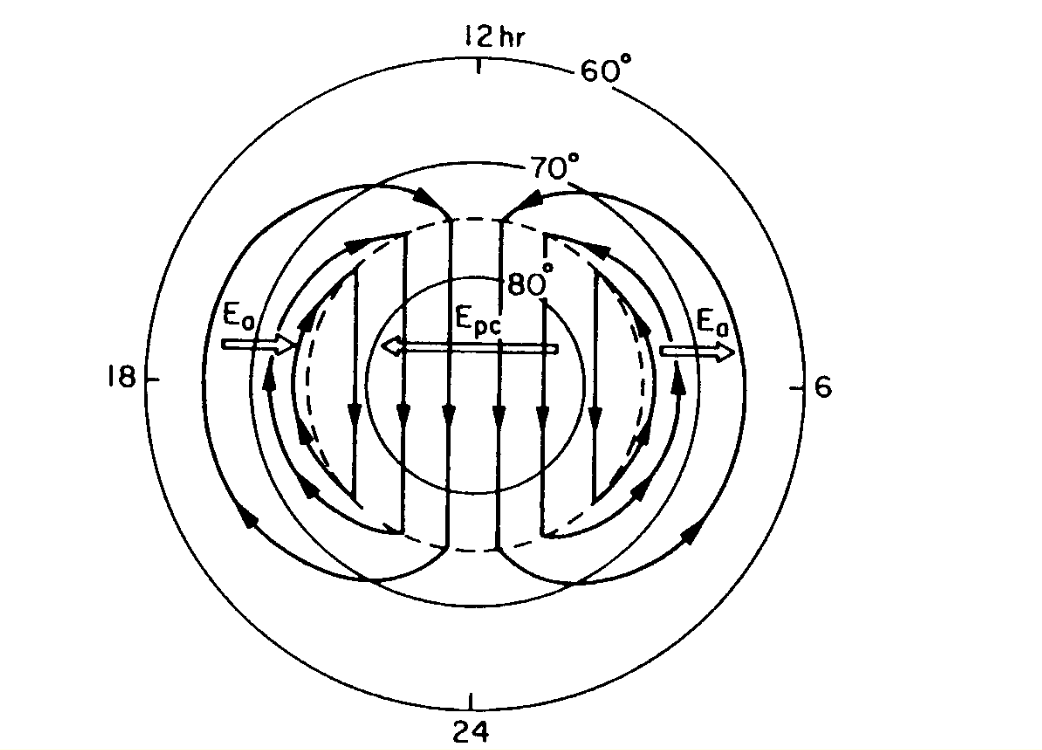
Plasma convection in the ionosphere

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



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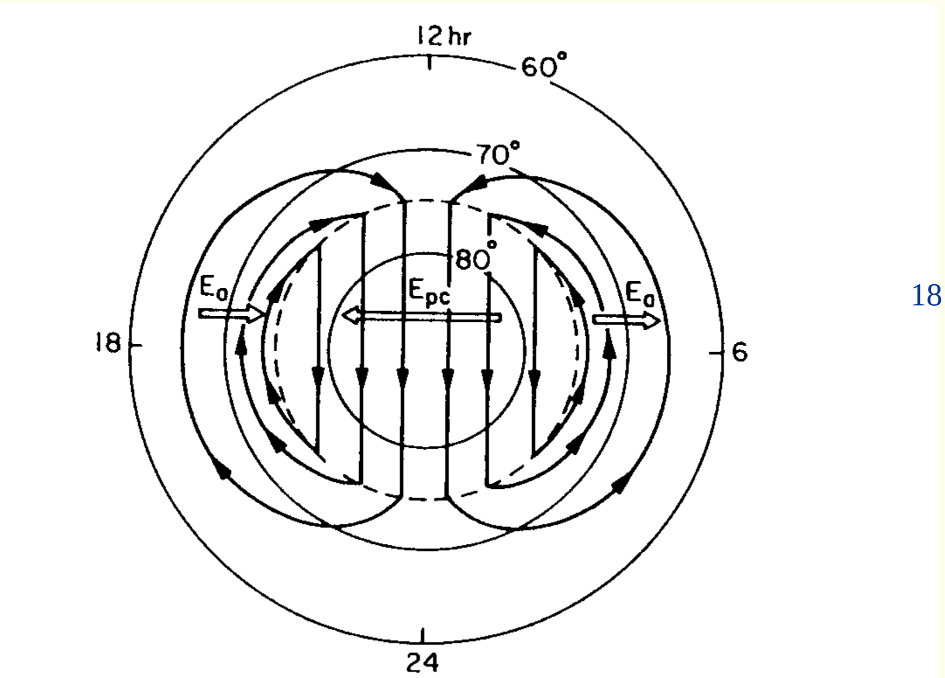
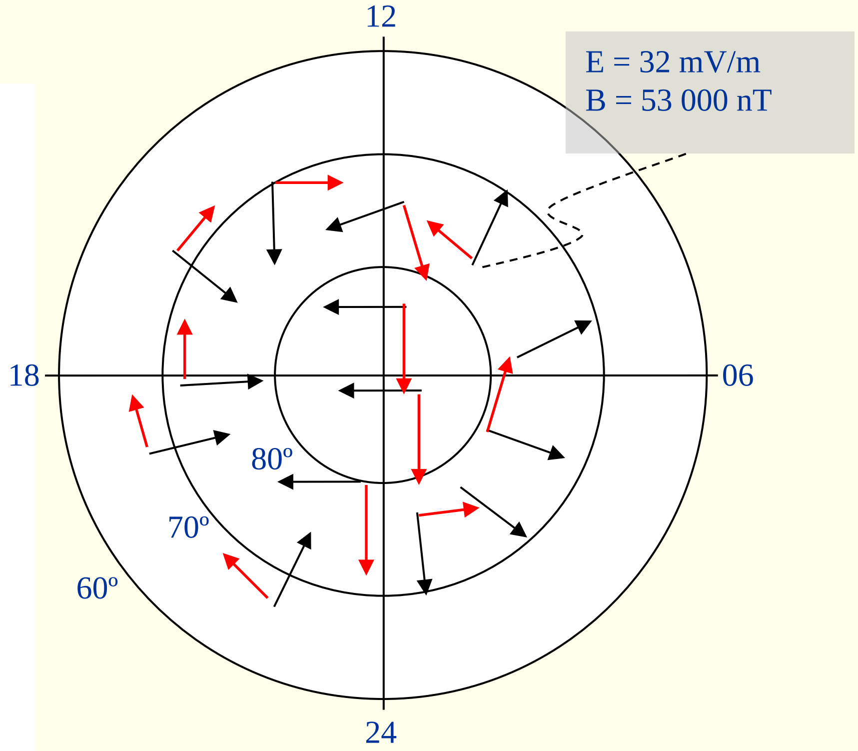
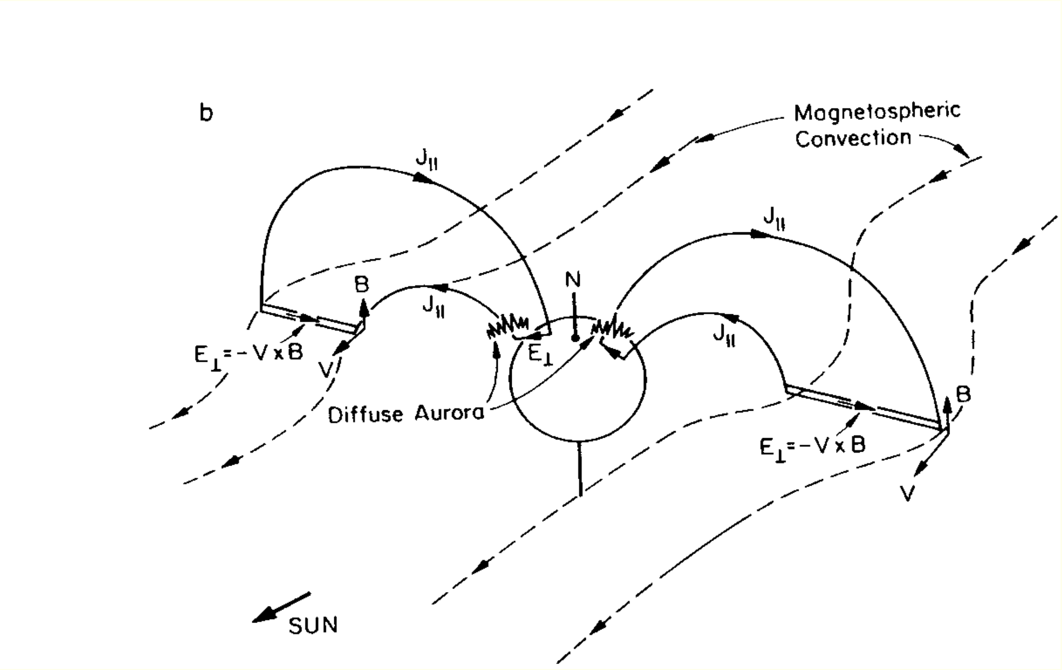
Plasma convection in the ionosphere





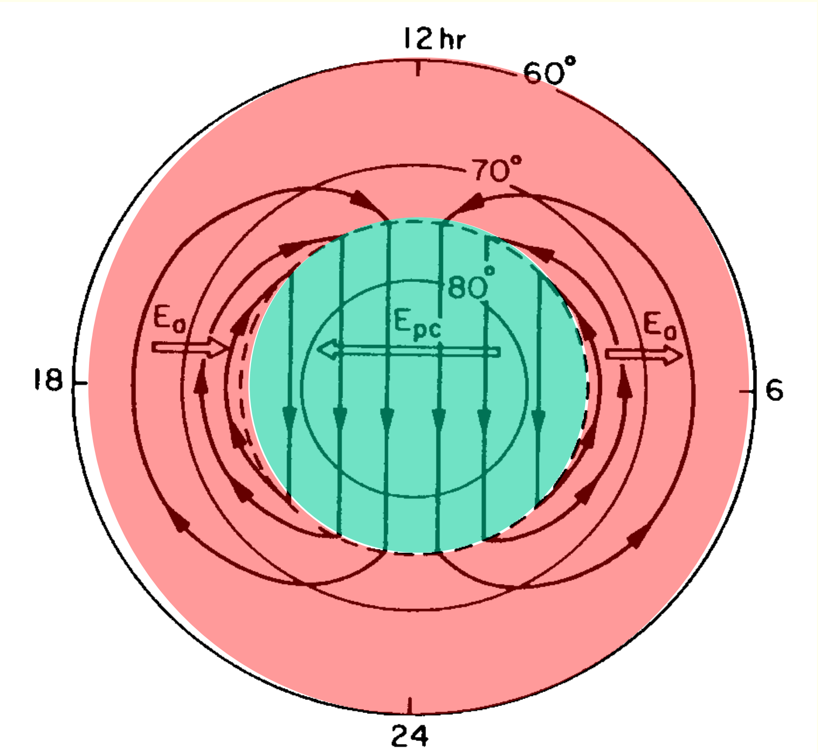
Static, large-scale MI-coupling

Magnetospheric and ionospheric convection



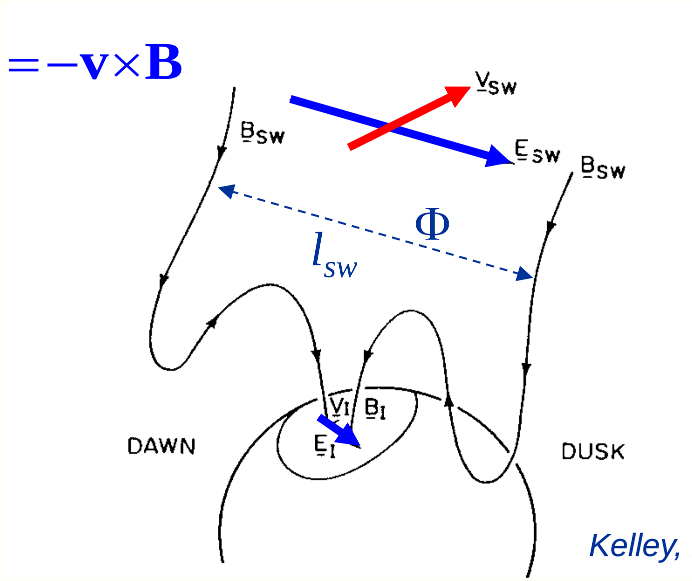
Kelley, 1989

Ionospheric convection

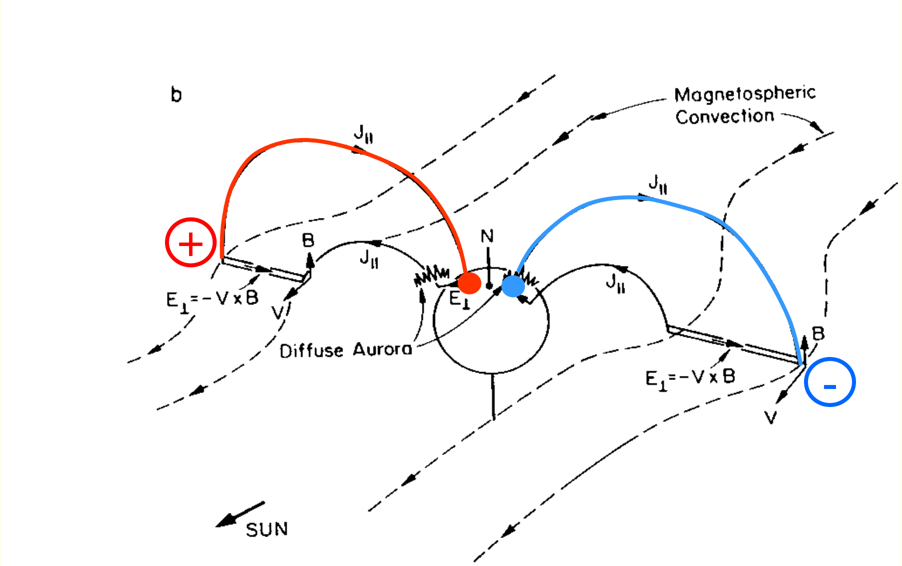


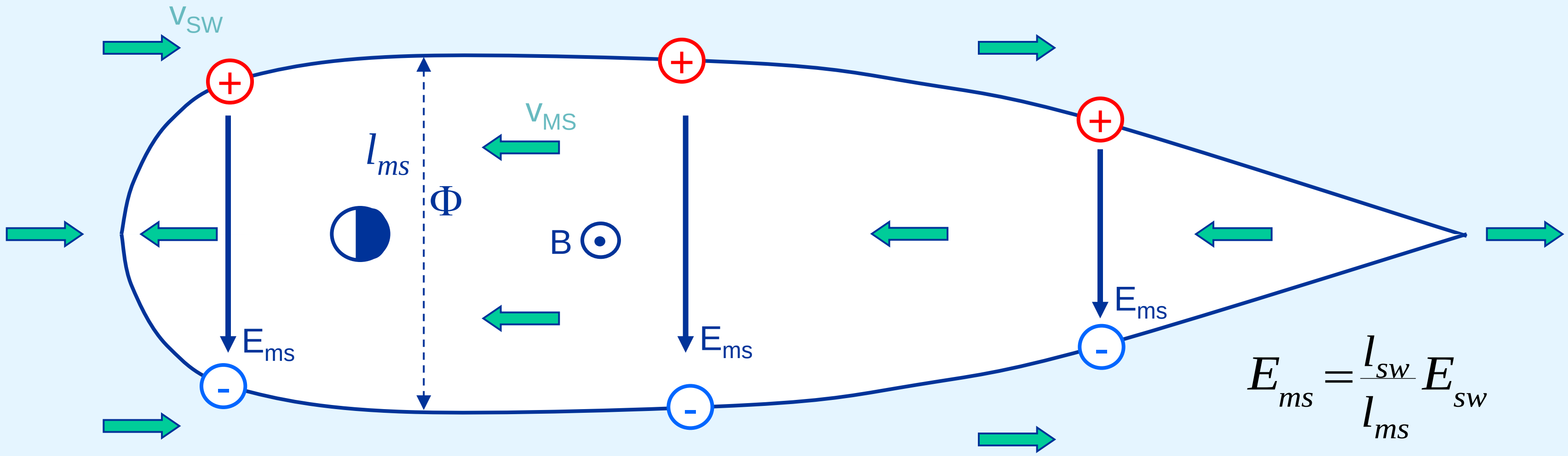
Magnetospheric plasma convection

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



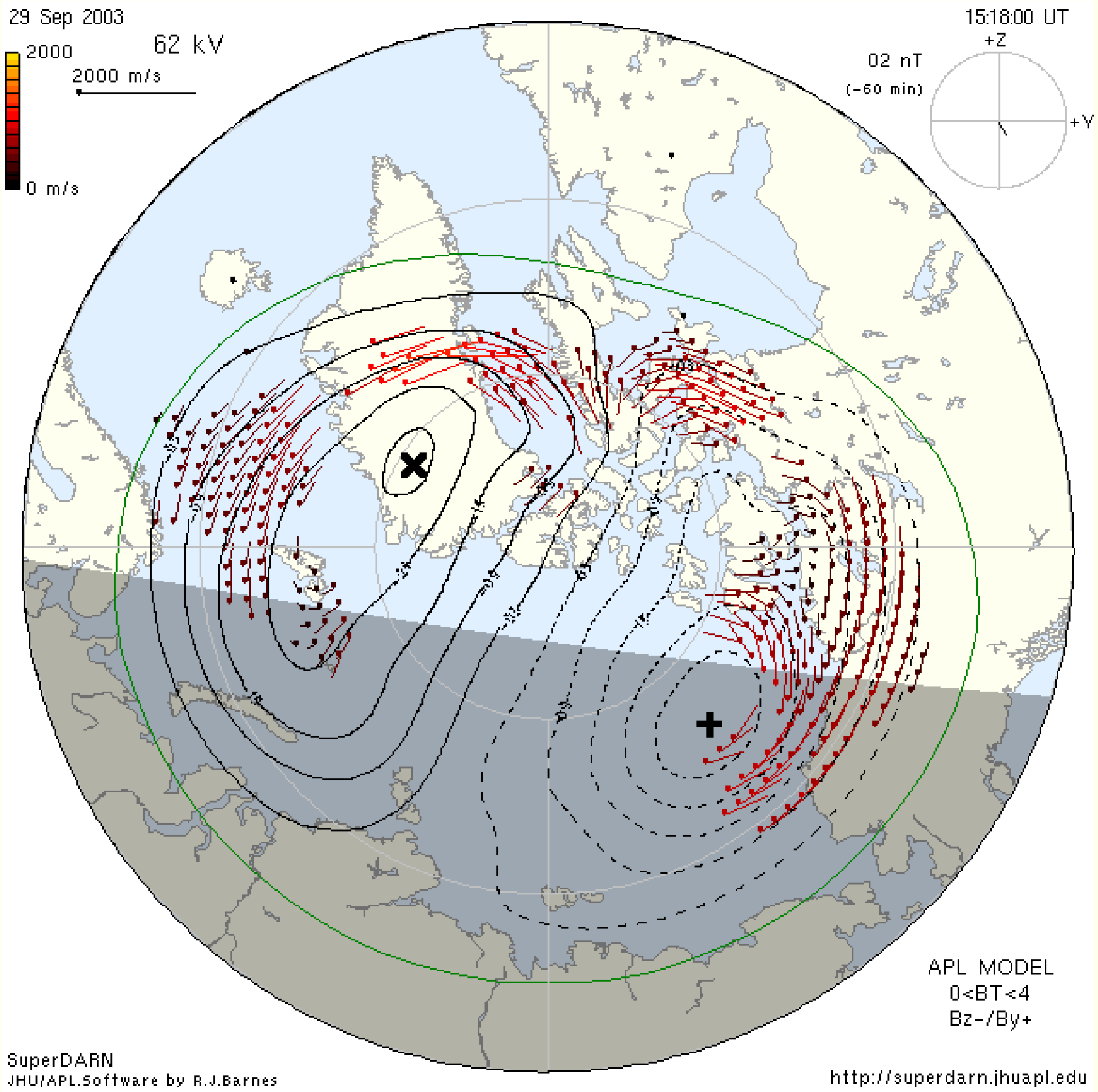
Kelley, 1989





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

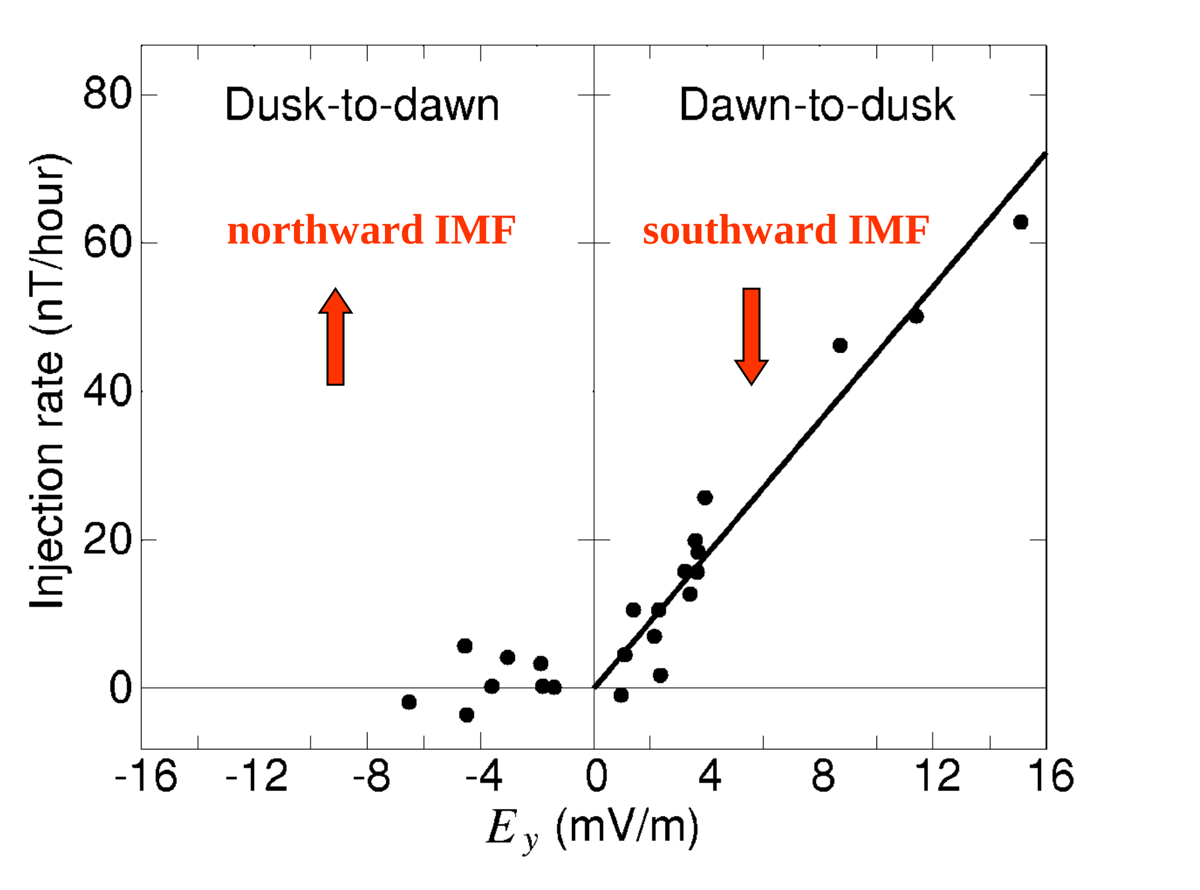
Measurements of plasma convection in the magnetosphere



Magnetospheric dynamics

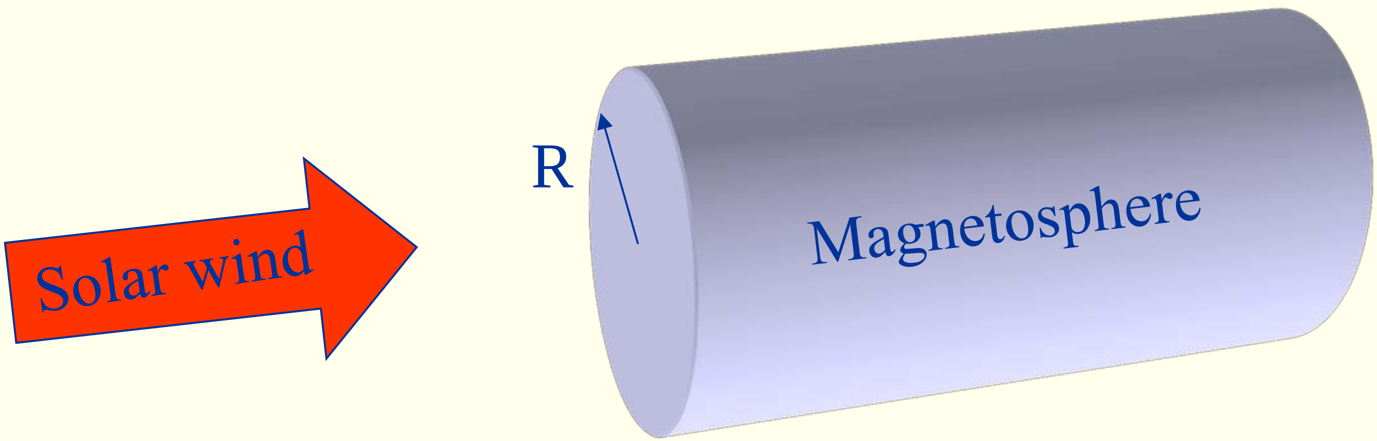
Energy input

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)



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

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

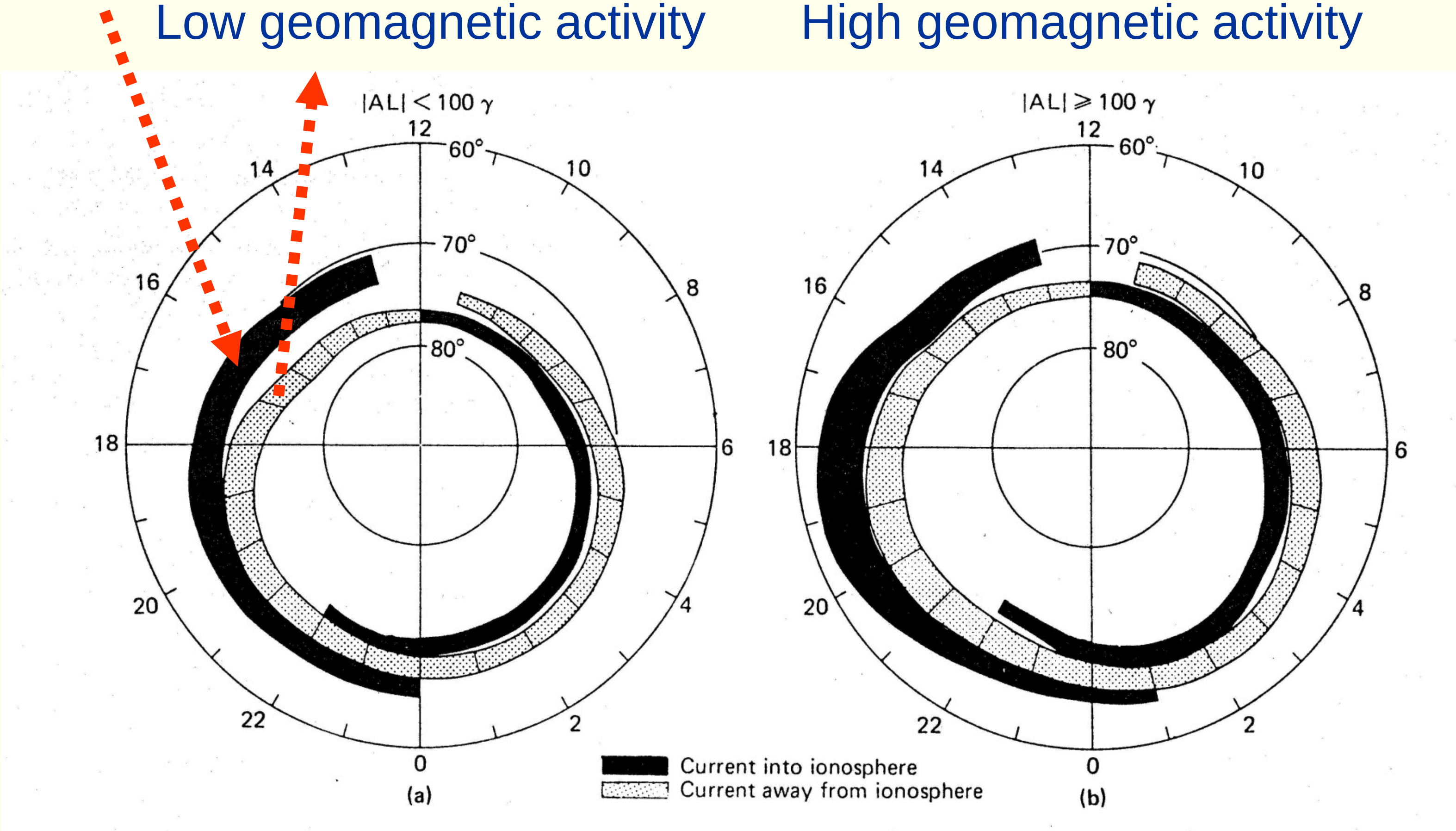
$$A = \pi R^2 = \pi(10R_E)^2$$

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

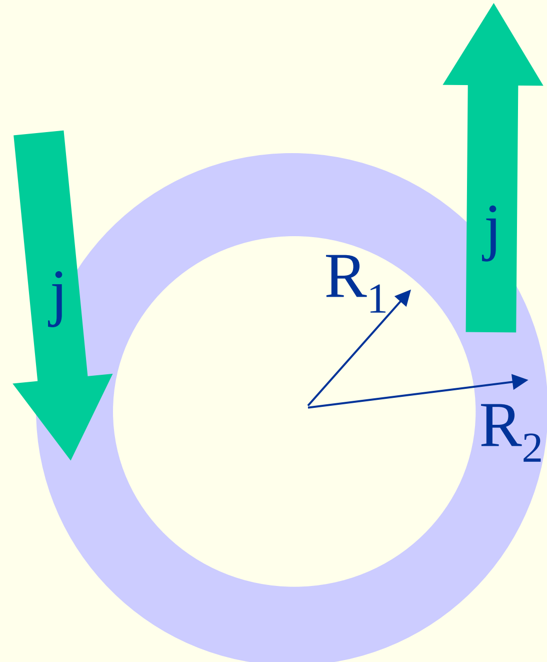
$$\mathbf{P_{sw} = \Phi_{kin} A = 3 \cdot 10^{12}\ W}$$

Birkeland currents in the auroral oval

Low geomagnetic activity   High geomagnetic activity



Energy budget (2)



Auroral oval

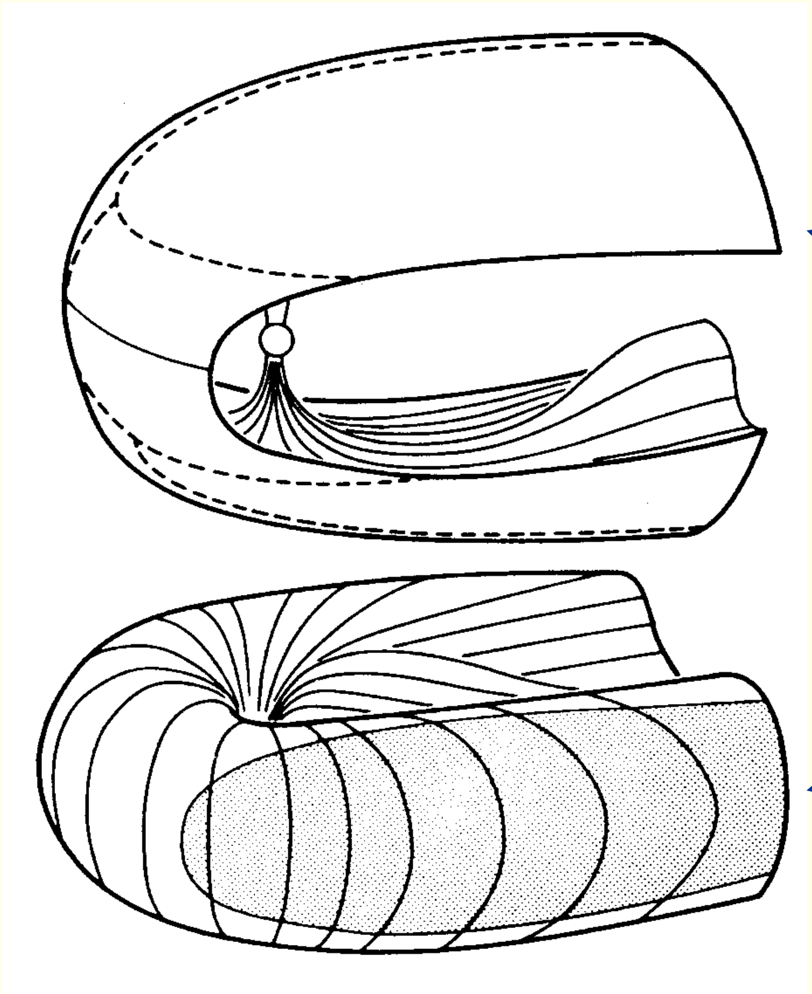
$A = \pi(R_2^2 - R_1^2) = 2 \cdot 10^{13}\ \mathrm{m}^2$

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

U = ?

P = UI = ?

Magnetospheric topology



Open field lines

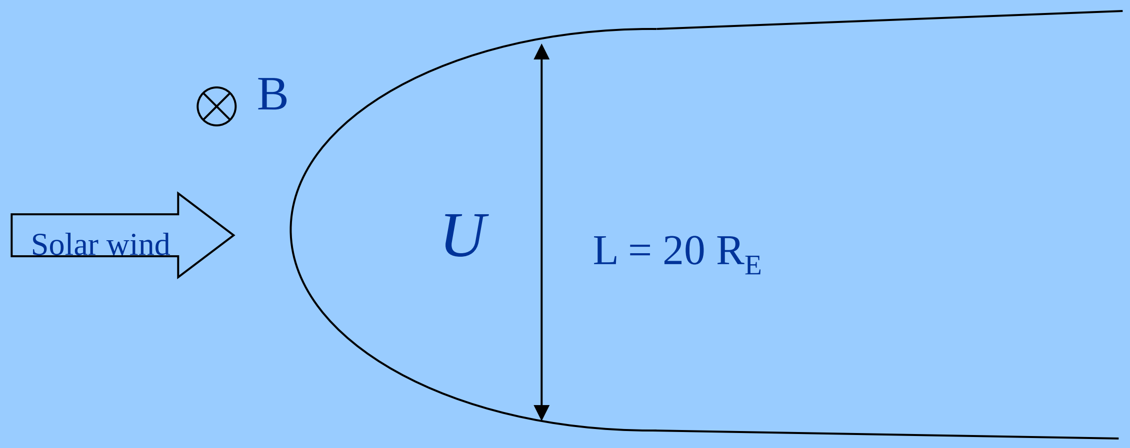
Closed field lines

What is the potential drop over the magnetosphere?

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

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

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



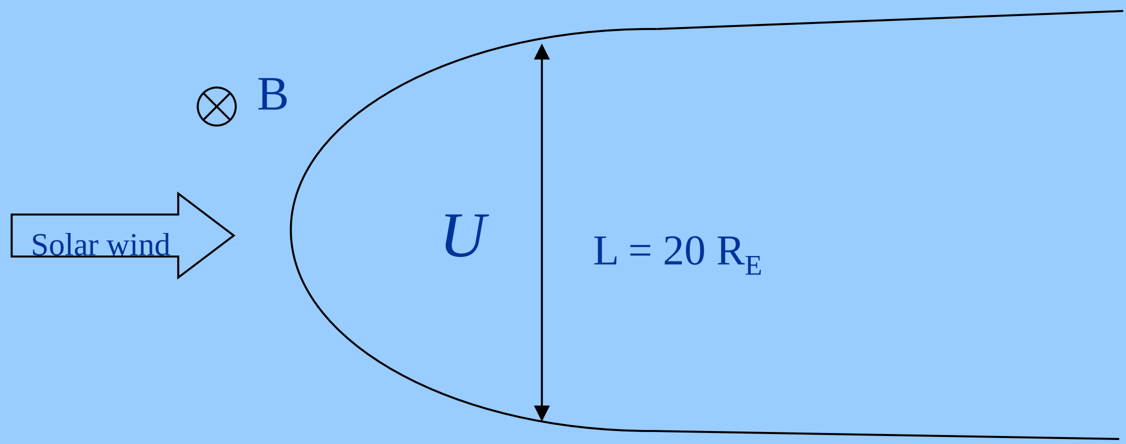
Blue	2 kV
Yellow	20 kV
Red	200 kV
Green	2 MV

What is the potential drop over the magnetosphere?

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

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

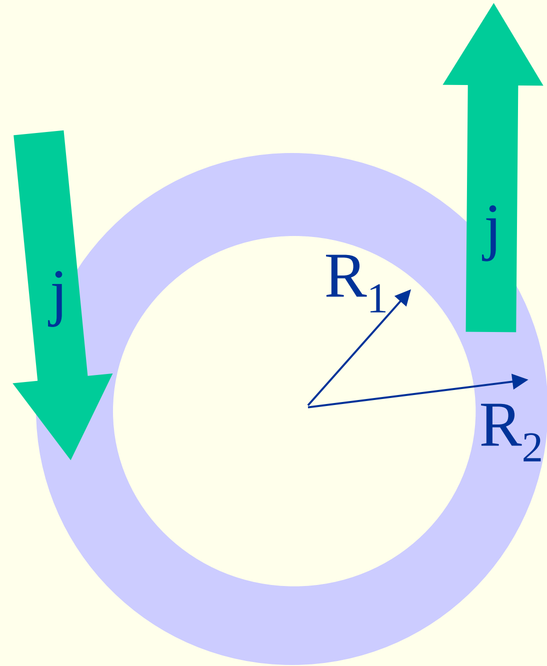
$$B_{SW} = 5 \text{ nT}$$



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

Red 200 kV

Energy budget (2)



$U = 200$ 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}*