Last lecture (8)

- Aurora

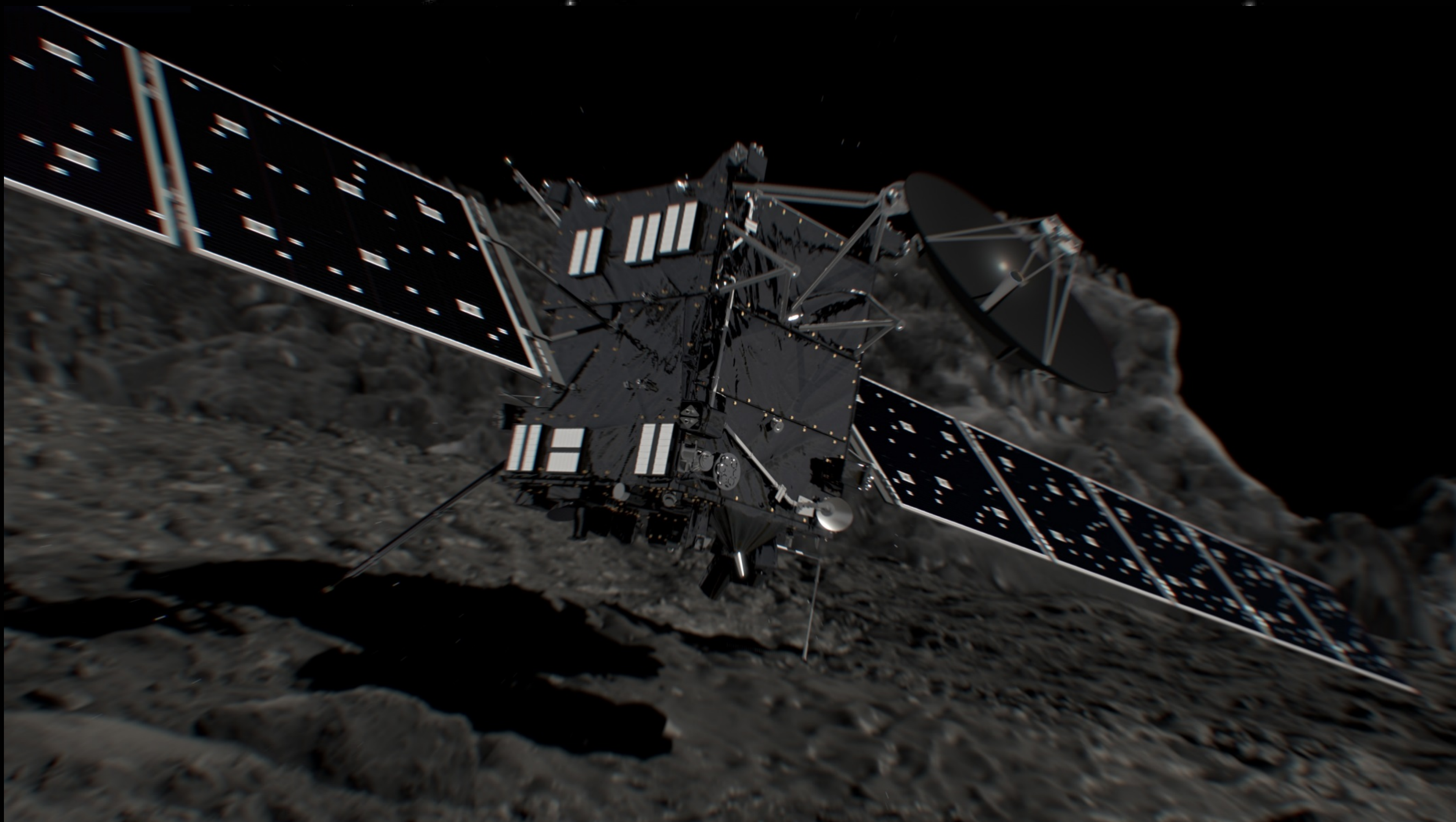
Today's lecture (9)

- Magnetospheric dynamics
- Cosmic radiation
- Interstellar plasma

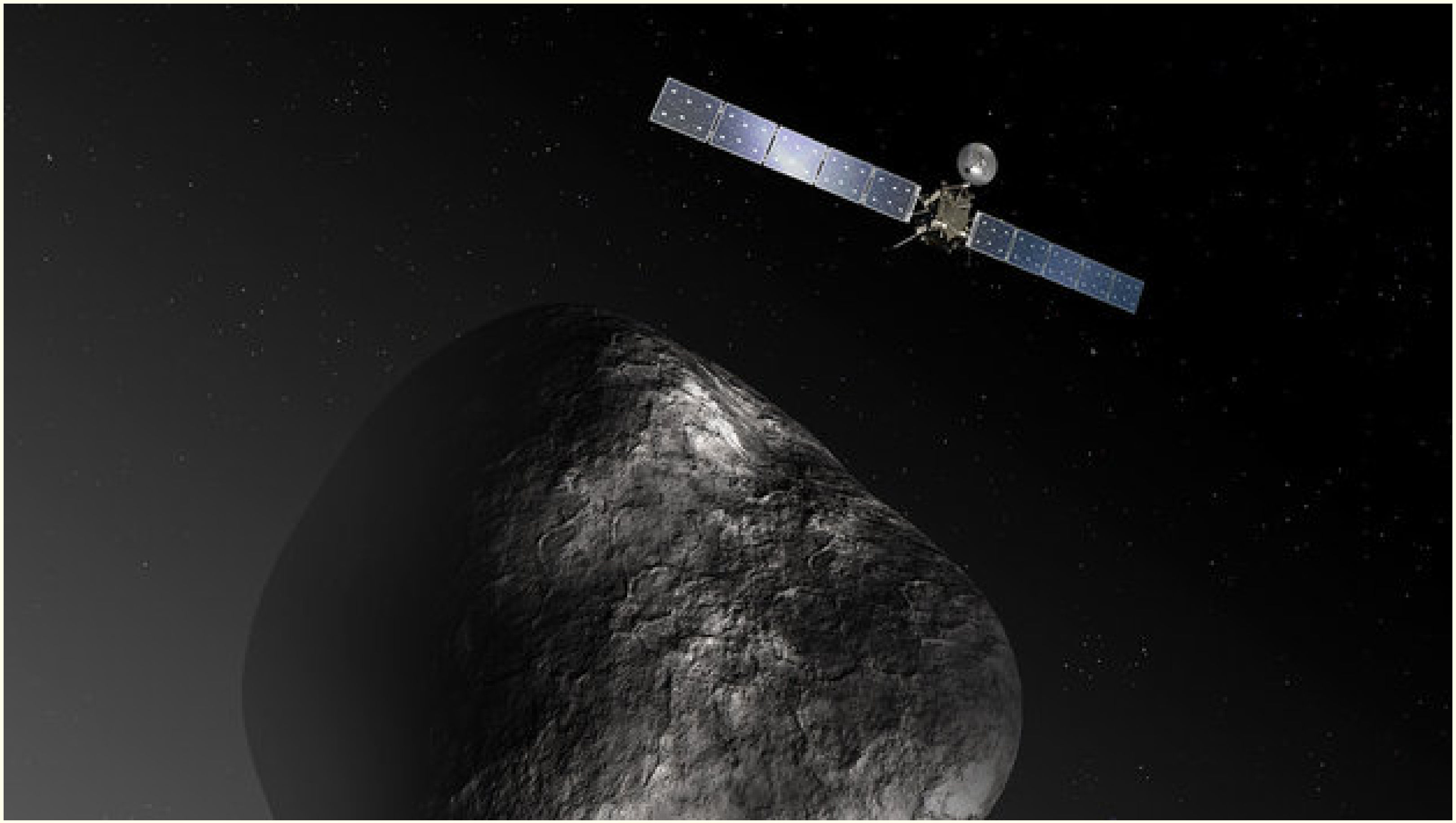
Today

Activity	Date	Time	Room	Subject	Litterature
L1	29/8	13-15	E52	Course description, Introduction, The Sun 1, Plasma physics 1	**CGF** Ch 1, 5, (p 110-113)
L2	1/9	15-17	L52	The Sun 2, Plasma physics 2	**CGF** Ch 5 (p 114-121), 6.3
L3	5/9	13-15	E51	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	8/9	15-17	D41	Mini-group work 1	
L4	12/9	13-15	E35	The ionosphere 2, Plasma physics 4	**CGF** Ch 3.4, 3.7, 3.8
L5	14/9	10-12	V32	The Earth's magnetosphere 1, Plasma physics 5	**CGF** 4.1-4.3, **LL** Ch I, II, IV.A
T2	15/9	15-17	E51	Mini-group work 2	
L6	19/9	13-15	M33	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
T3	22/9	15-17	E51	Mini-group work 3	
L7	26/9	13-15	E31	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
L8	28/9	10-12	L52	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
T4	29/9	15-17	M31	Mini-group work 4	
L9	3/10	13-15	E52	Interstellar and intergalactic plasma, Cosmic radiation,	**CGF** Ch 7-9
T5	6/10	15-17	E31	Mini-group work 5	
L10	10/10	13-15	E52	Swedish and international space physics research.	
T6	13/10	15-17	E31	Round-up, old exams.	
Written exami-nation	26/10	8-13	F2		

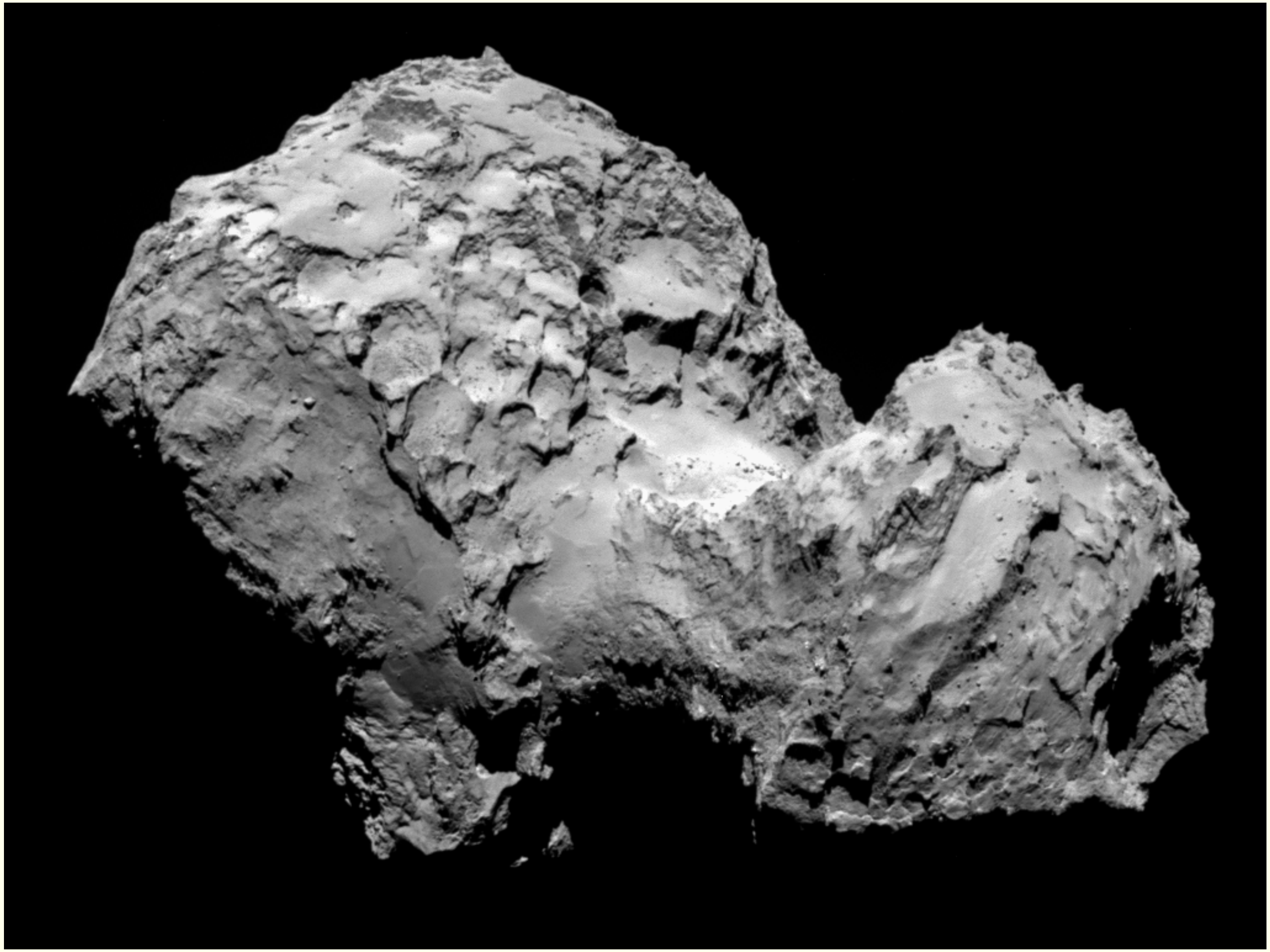
Rosetta’s final impact on comet 67/P Churyumov-Gerasimenko happened 13:19 on Friday.



The Rosetta mission to comet 67P/Churiumov-Gerasimenko

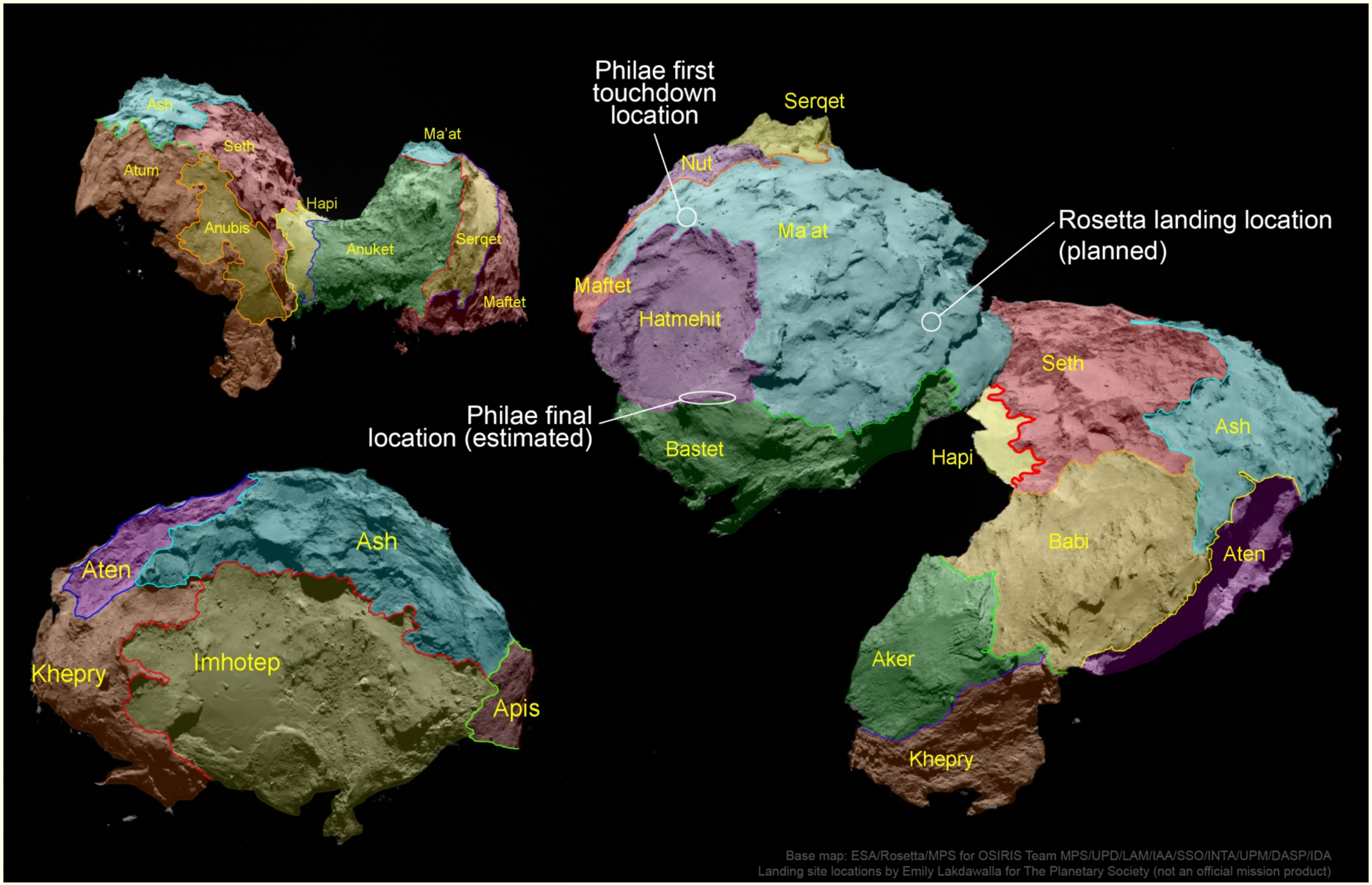


The Rosetta mission to comet 67P

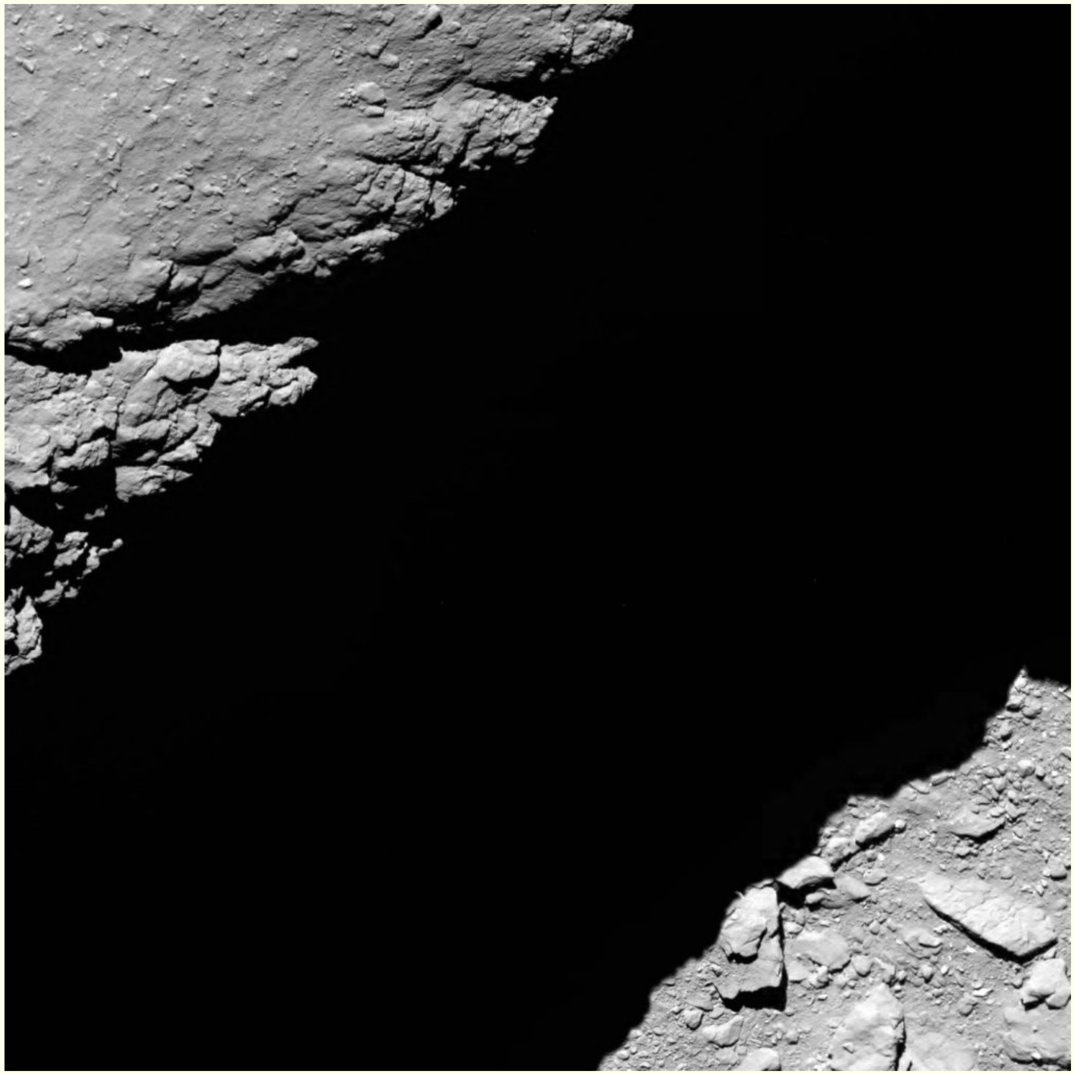


3 August 2014

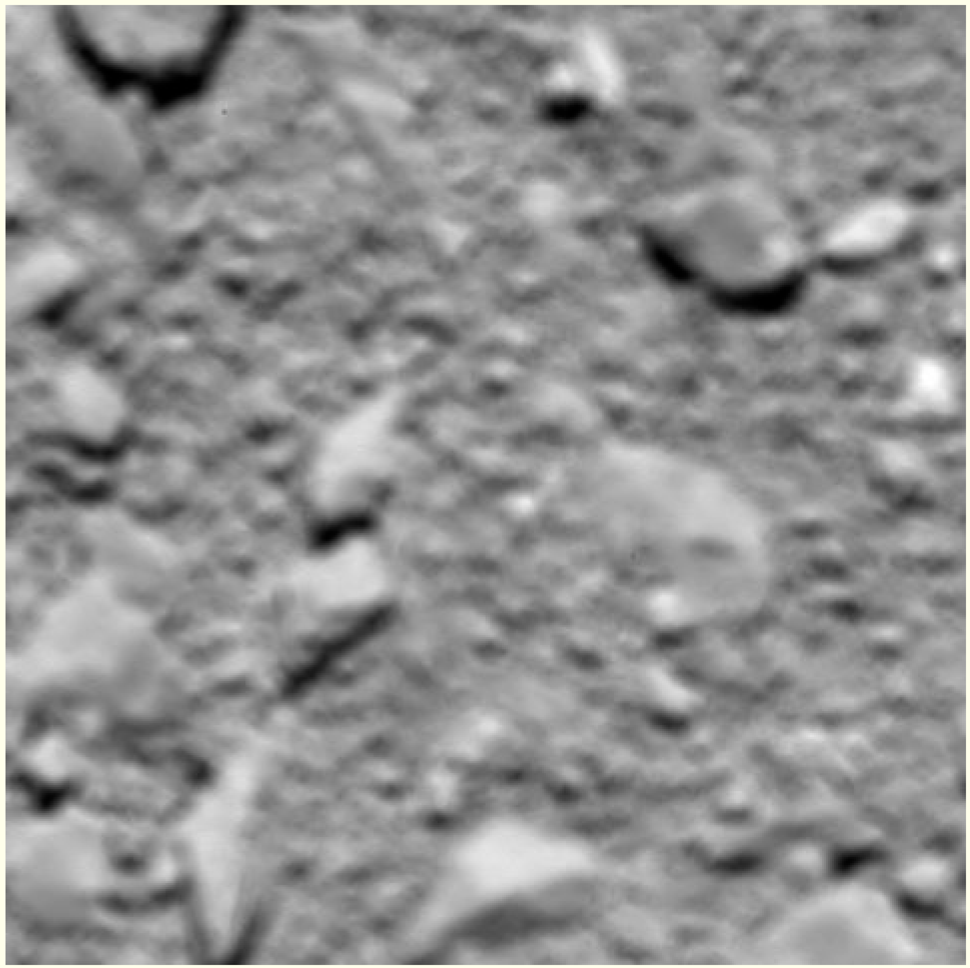
The end of the Rosetta mission 2016-09-30



The end of the Rosetta mission 2016-09-30, 1.2 km altitude



The end of the Rosetta mission
2016-09-30, 20 m altitude



96 cm

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)

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

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

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

$ax^2 + bx + c = 0$

with

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

$$b = 2 n_{e0} R_J^3 k_B T = 3.6 \times 10^{18}$$

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

$$x = \frac{-b}{2a} \pm \sqrt{\frac{b^2}{4a^2} - \frac{c}{a}} = -1.8 \cdot 10^{-28} + \sqrt{3.24 \cdot 10^{-56} + 2.635 \cdot 10^{-57}} =$$

$$= -1.8 \cdot 10^{-28} + 1.87 \cdot 10^{-28} = 7.18 \cdot 10^{-30}$$

From this you get $r \approx 73\ \mathrm{R_J}$

EF22445 Space Physics II
7.5 ECTS credits, P2

- shocks and boundaries in space
- solar wind interaction with magnetized and unmagnetized bodies
- sources of magnetospheric plasma
- magnetospheric and ionospheric convection
- auroral physics
- storms and substorms
- global oscillations of the magnetosphere

First lecture Tuesday November 4, 13.15 at Teknikringen 31, seminar room, second floor. (Signs will be posted)

Thesis work at Space and Plasma Physics

Talk to Tomas

Examination

1. Written examination (open book*), 26/10

100 p

2. Continous examination (mini-group works)

25 p

Grades:

A:	111-125 p
B:	96-110 p
C:	81-95 p
D:	66-80 p
E:	50-65 p

(Fx)

Written examination, 26/10, 2016, 8-13, F2
(No academic 15 minutes!)

You may bring:

- all the course material
- any notes you have made
- pocket calculator
- mathematics and physics formula books or your favourite physics book
- formula sheet

(No computers are allowed, due to the possibility to communicate with the outside world.)

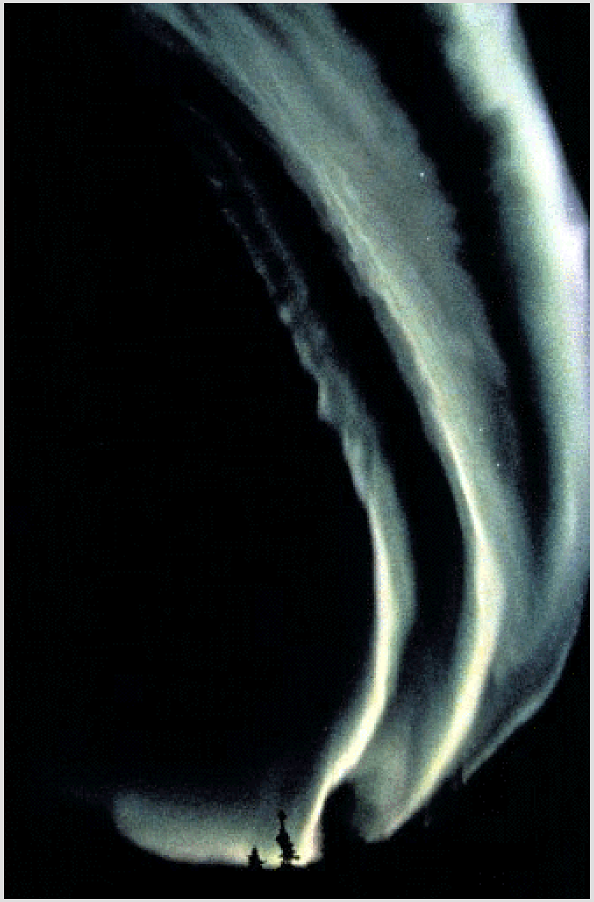
Approx. 5 different problems (which may contain sub-problems).

About the exam

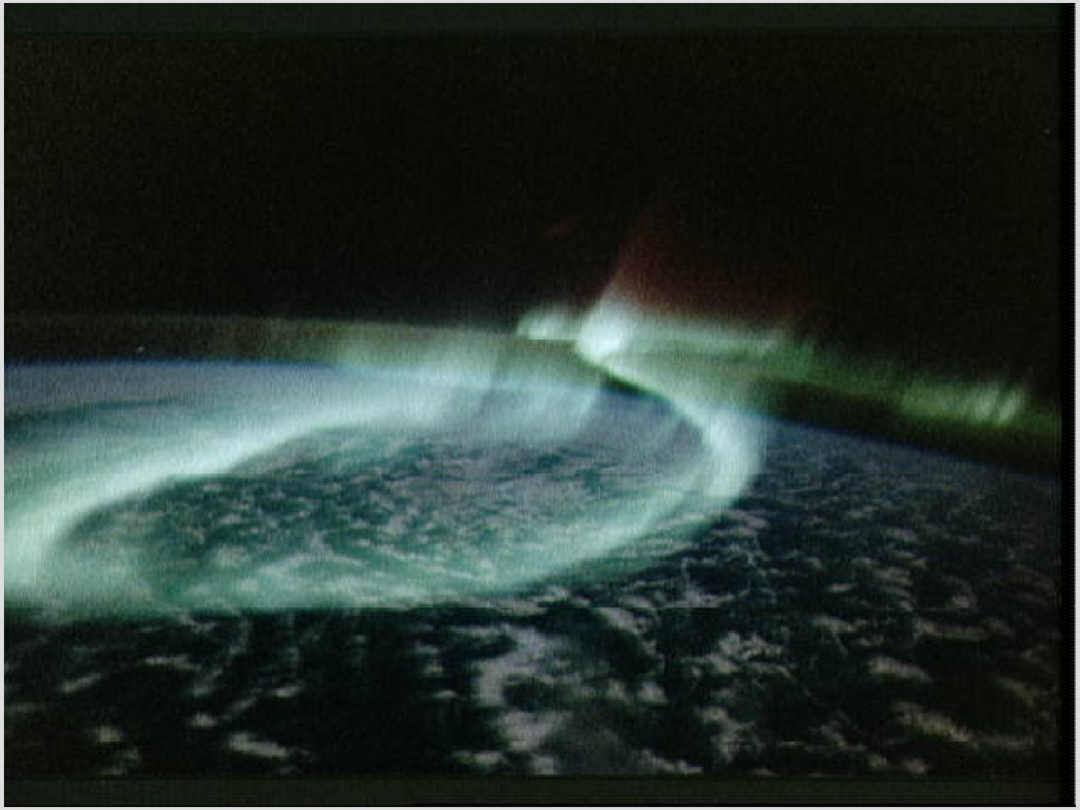
Motivate your answers!

Be careful with units and numerical calculations!

Homogenous auroral arcs



Auroral spirals



Develop when arcs become unstable

Aurora - altitude

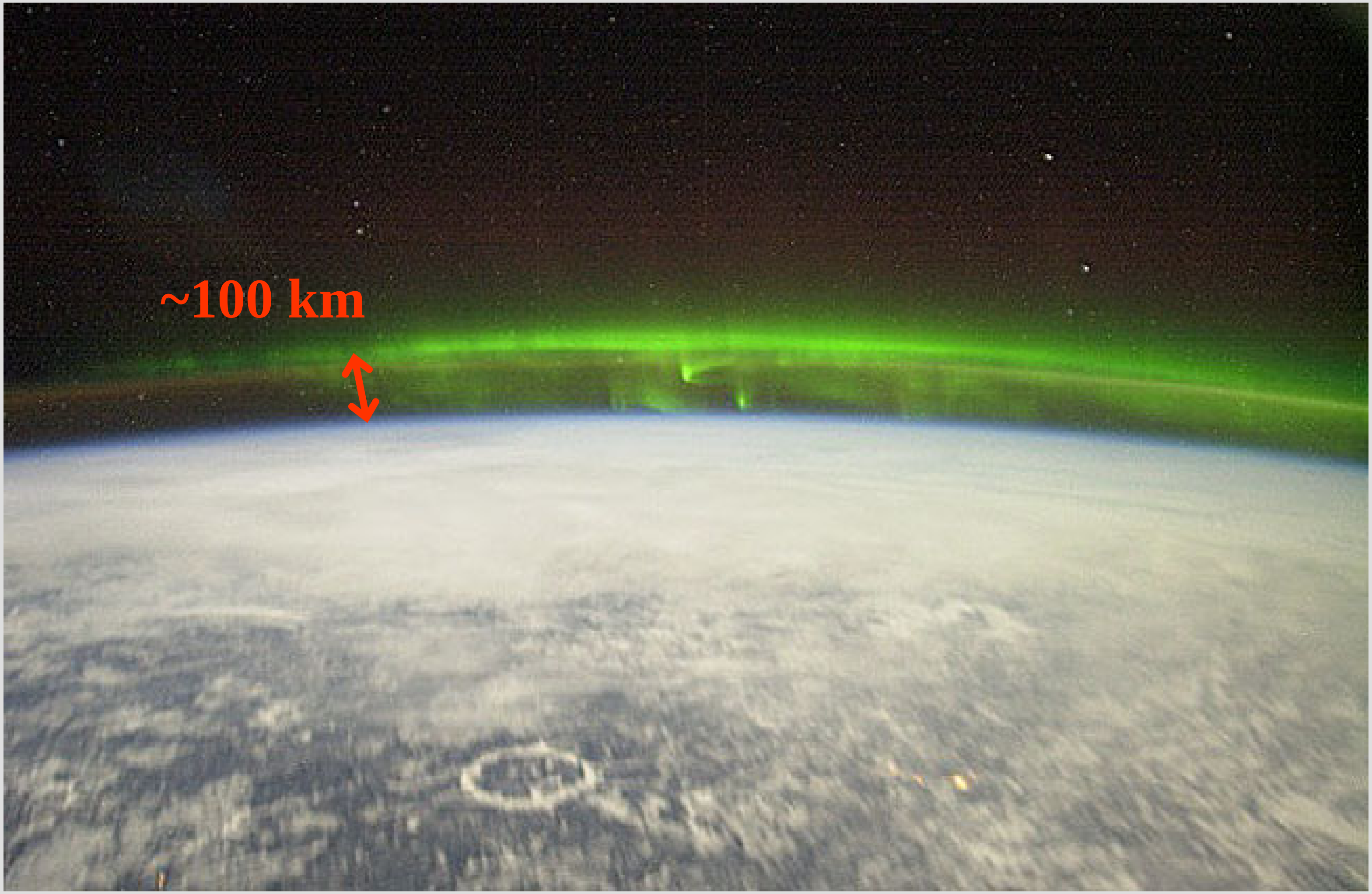
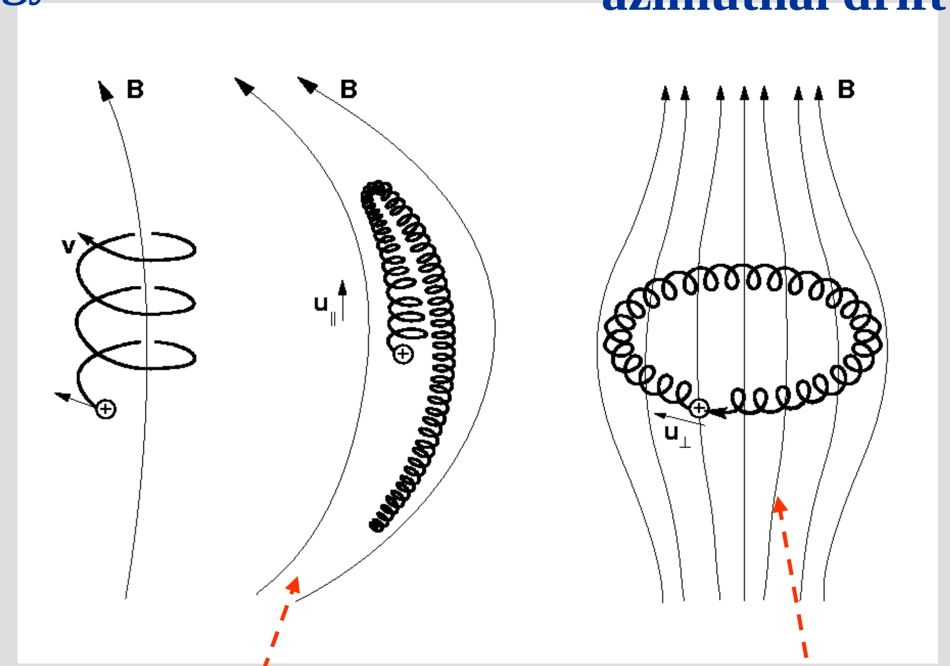


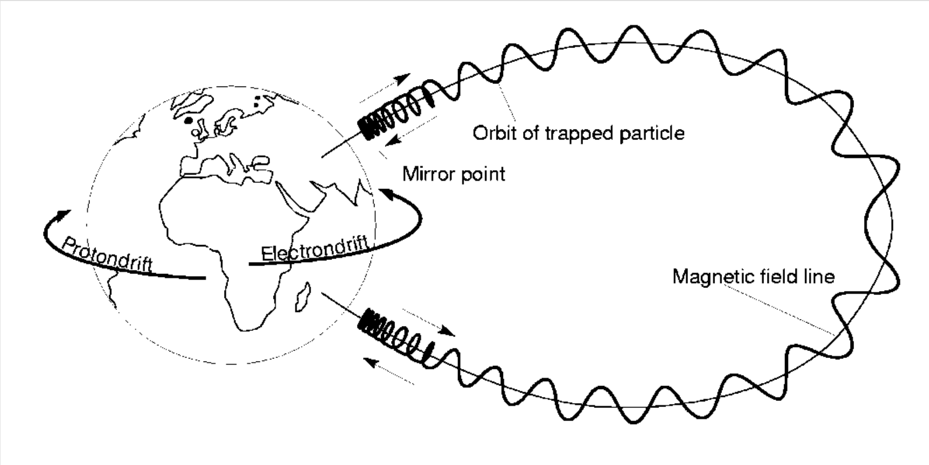
Foto from International Space Station

Particle motion in geomagnetic field

longitudinal oscillation

gyration **azimuthal drift**

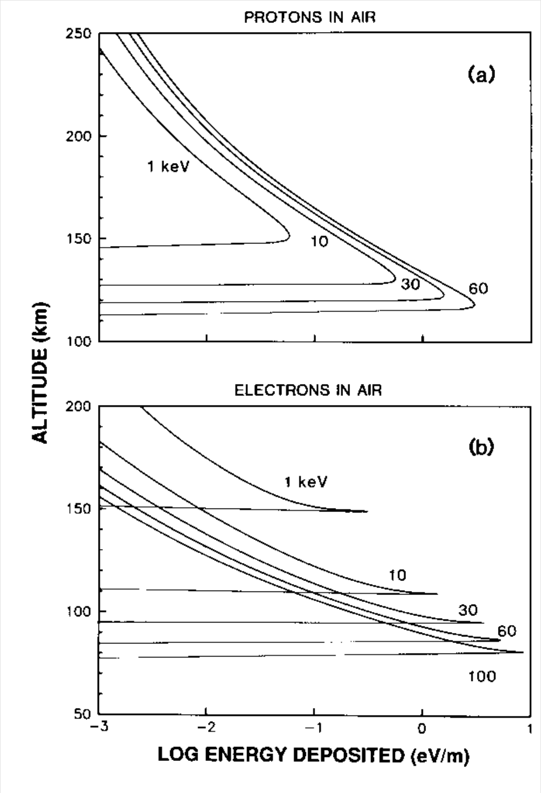


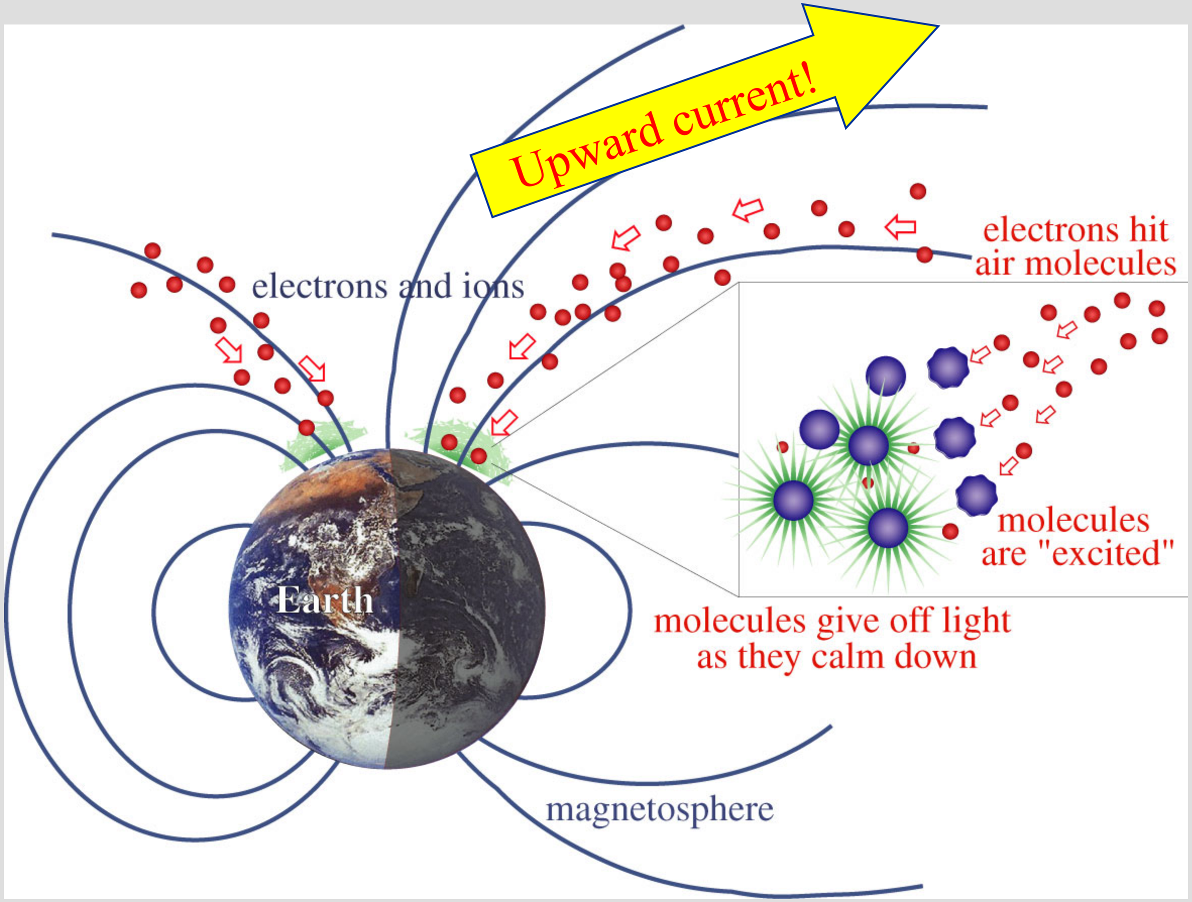


Magnetic mirror

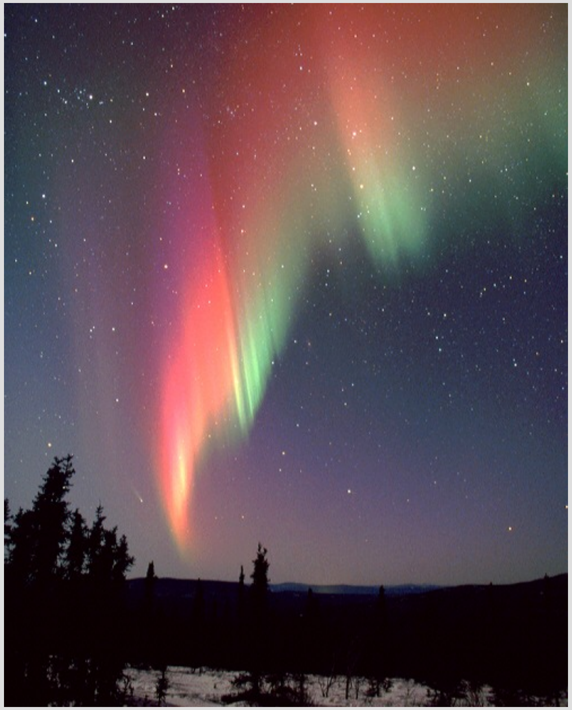
grad B drift

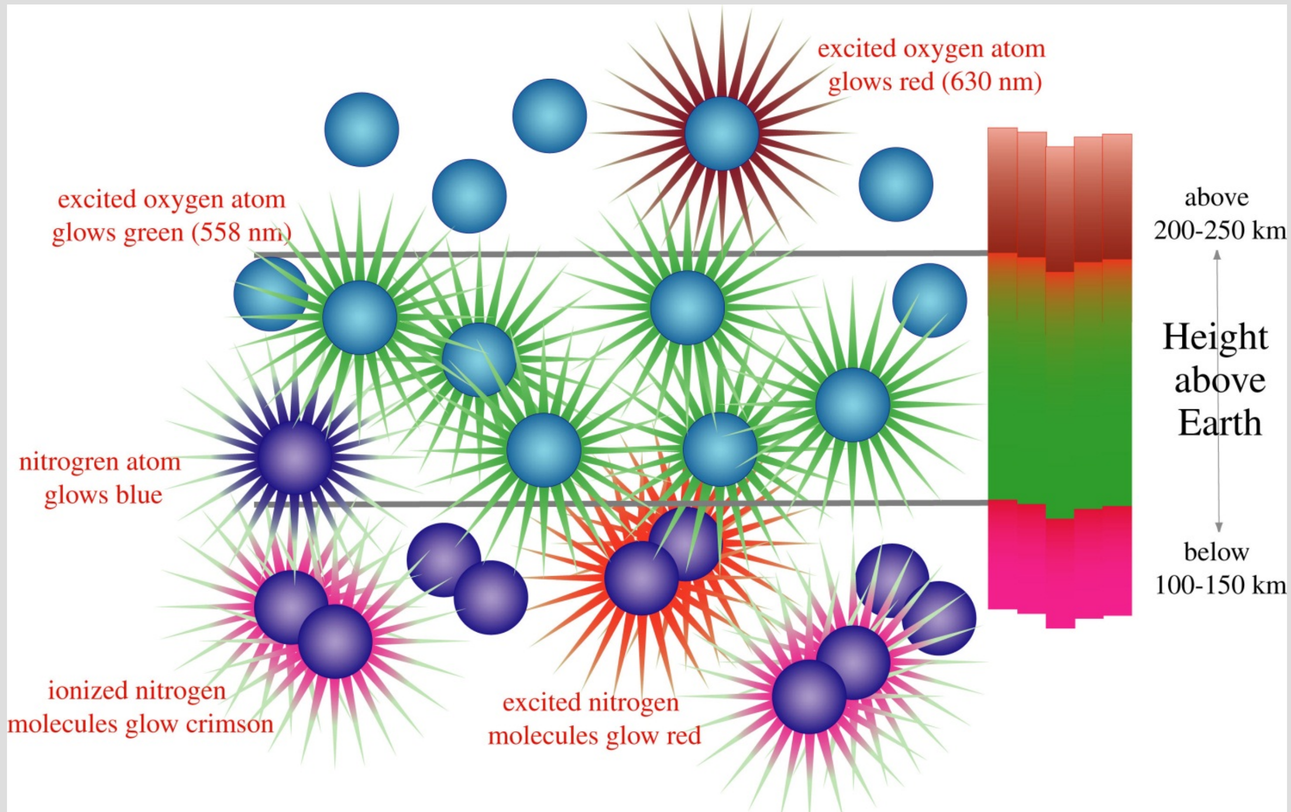
Collisions - emissions





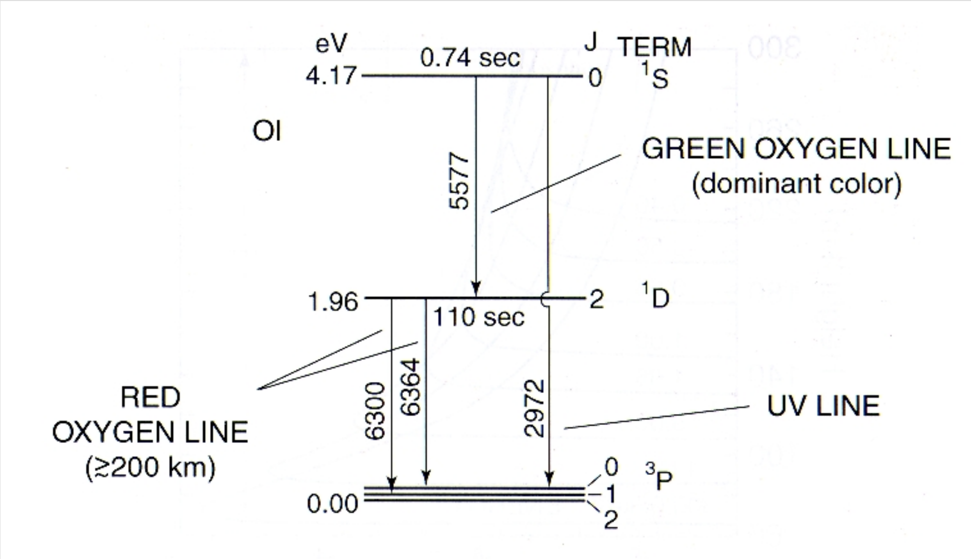
Emissions

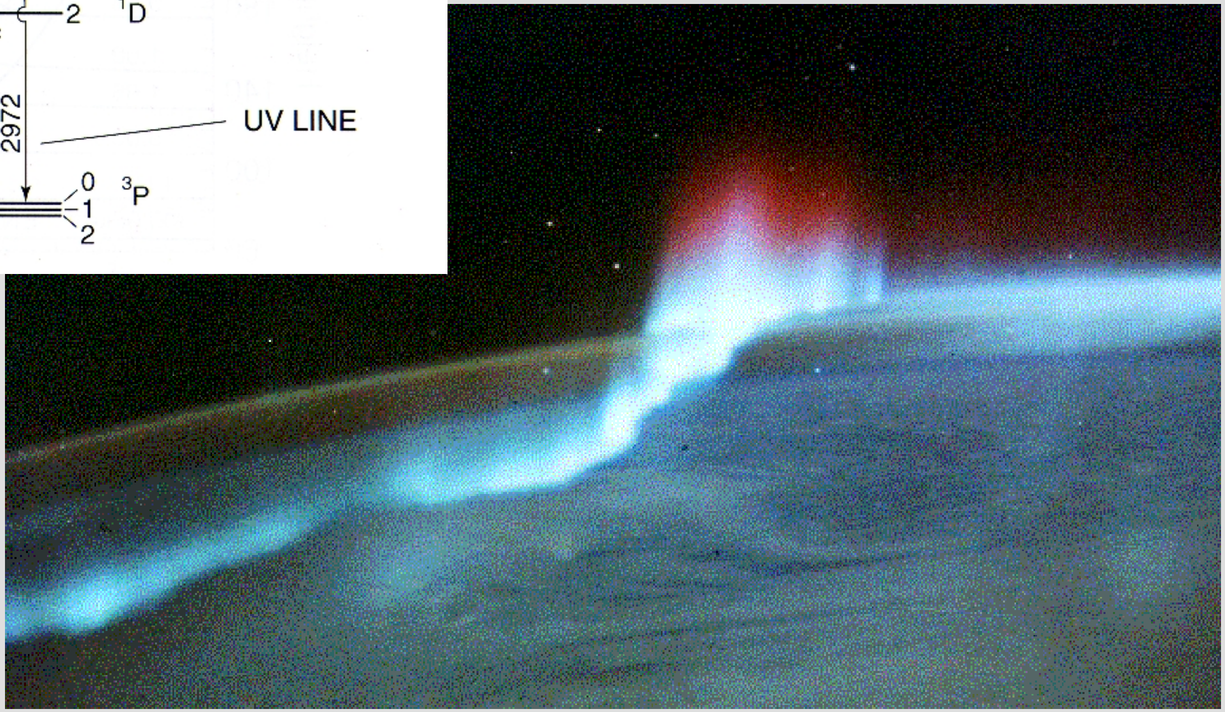




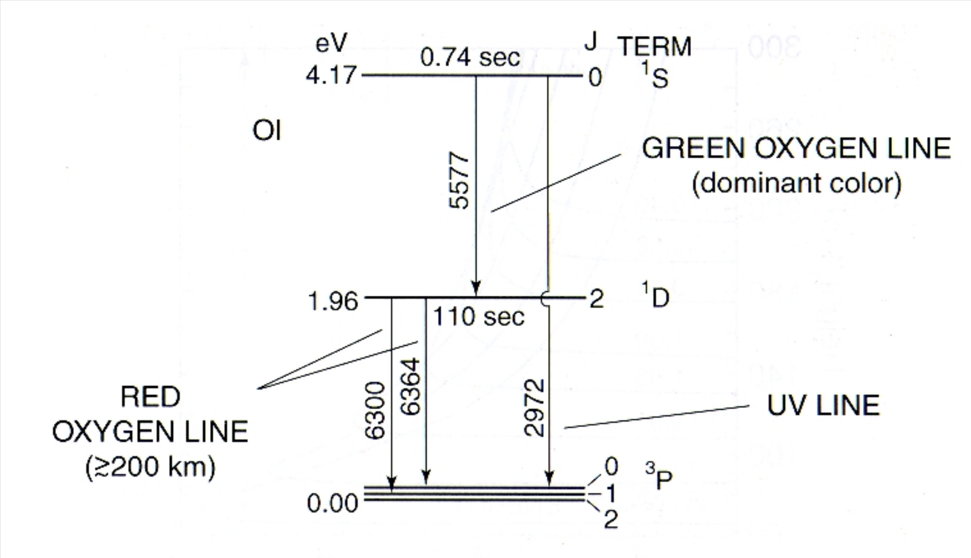
excited oxygen atom
glows red (630 nm)
excited oxygen atom
glows green (558 nm)
nitrogren atom
glows blue
ionized nitrogen
molecules glow crimson
excited nitrogen
molecules glow red
above
200-250 km
Height
above
Earth
below
100-150 km

Oxygen emissions

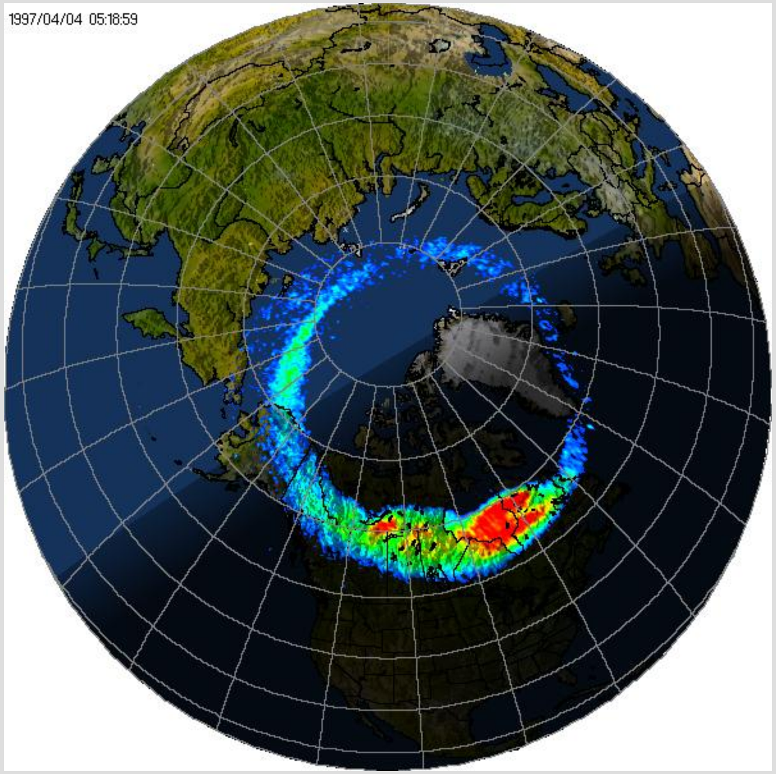




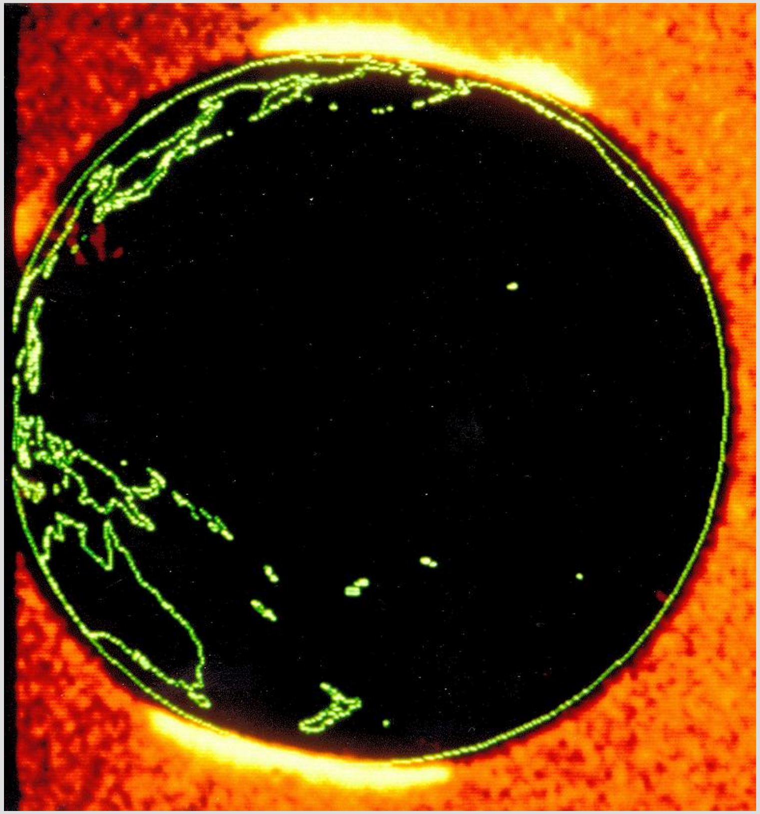
Why is there no red emissions at lower altitude?



Auroral ovals



Polar

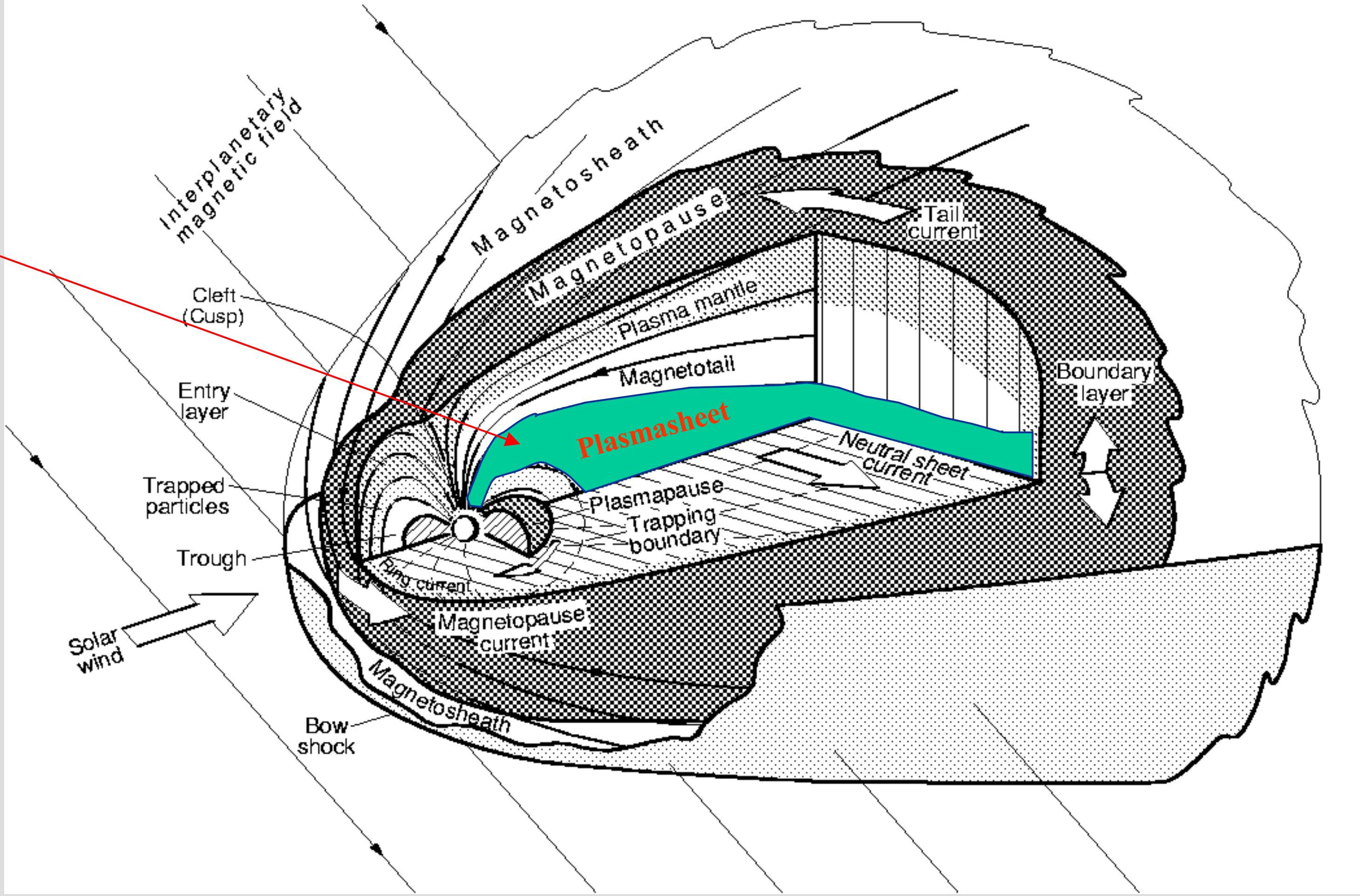


Dynamics Explorer

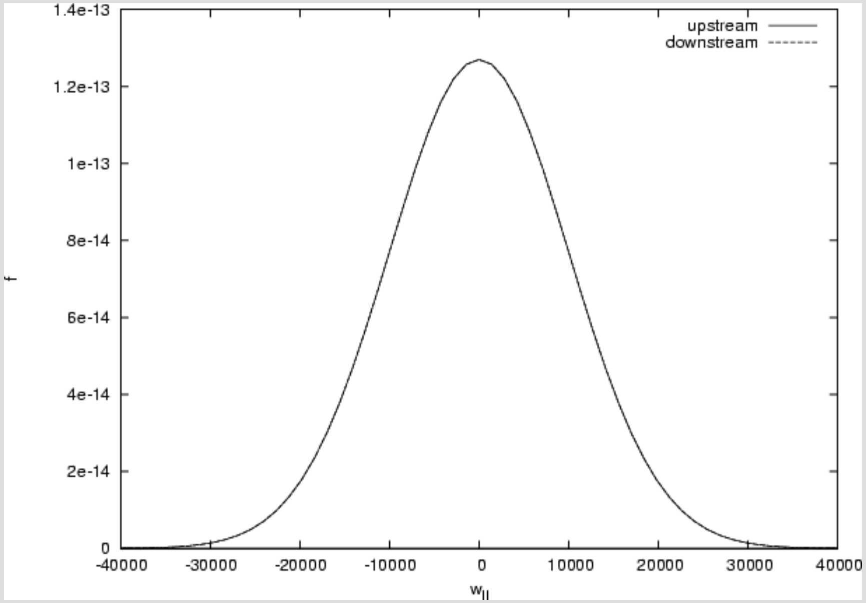
The auroral oval is the projection of the plasmasheet onto the atmosphere

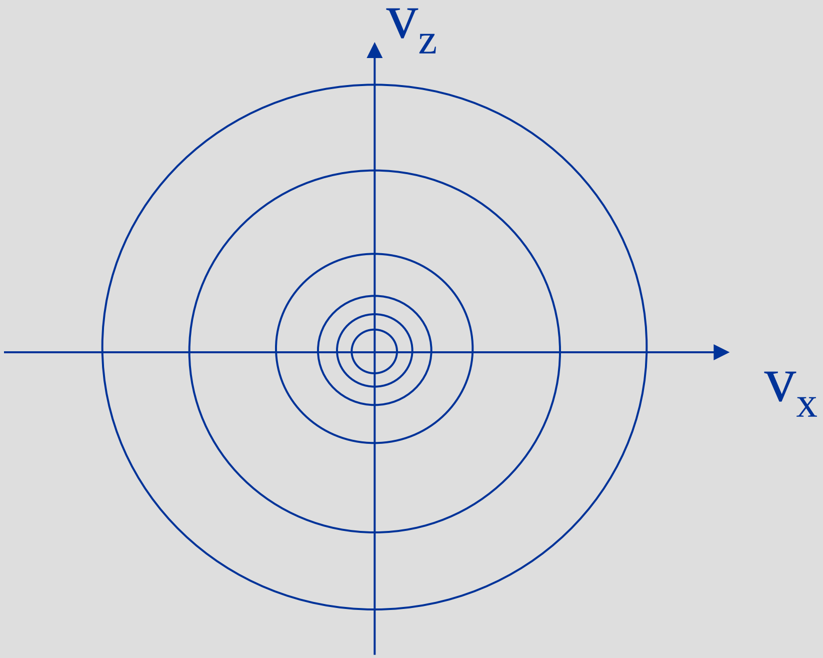
Mystery!

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



Distribution function

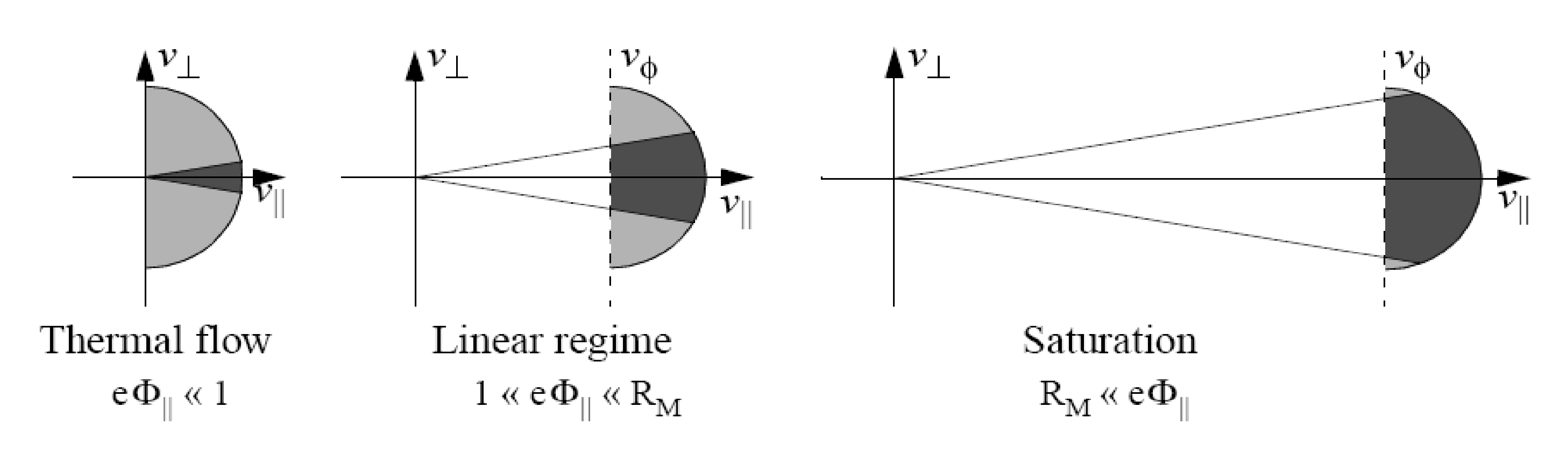




Example:
Maxwellian distribution

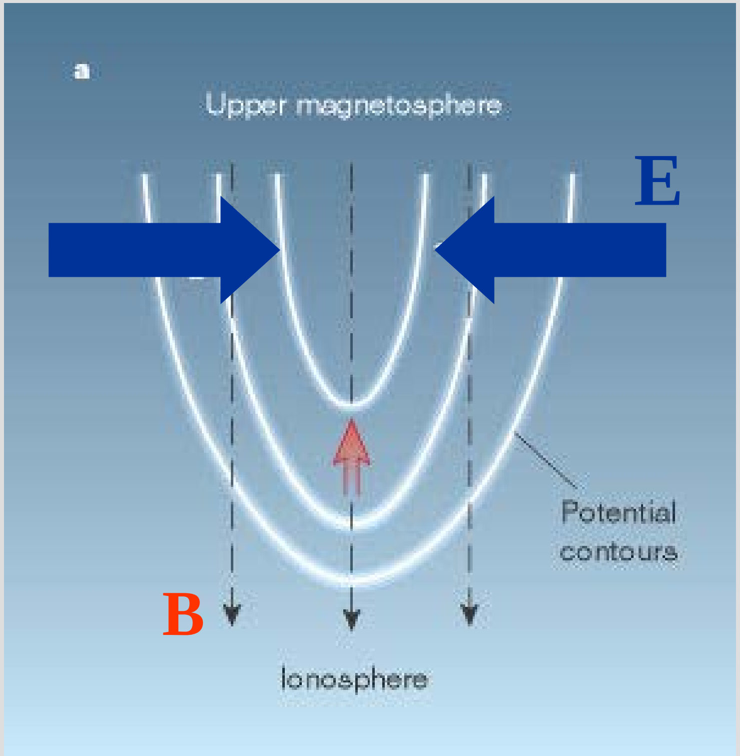
$$f = \frac{n}{\sqrt{(2\pi RT)^3}} \exp\left(-\frac{m(v_x^2 + v_y^2 + v_z^2)}{2kT}\right)$$

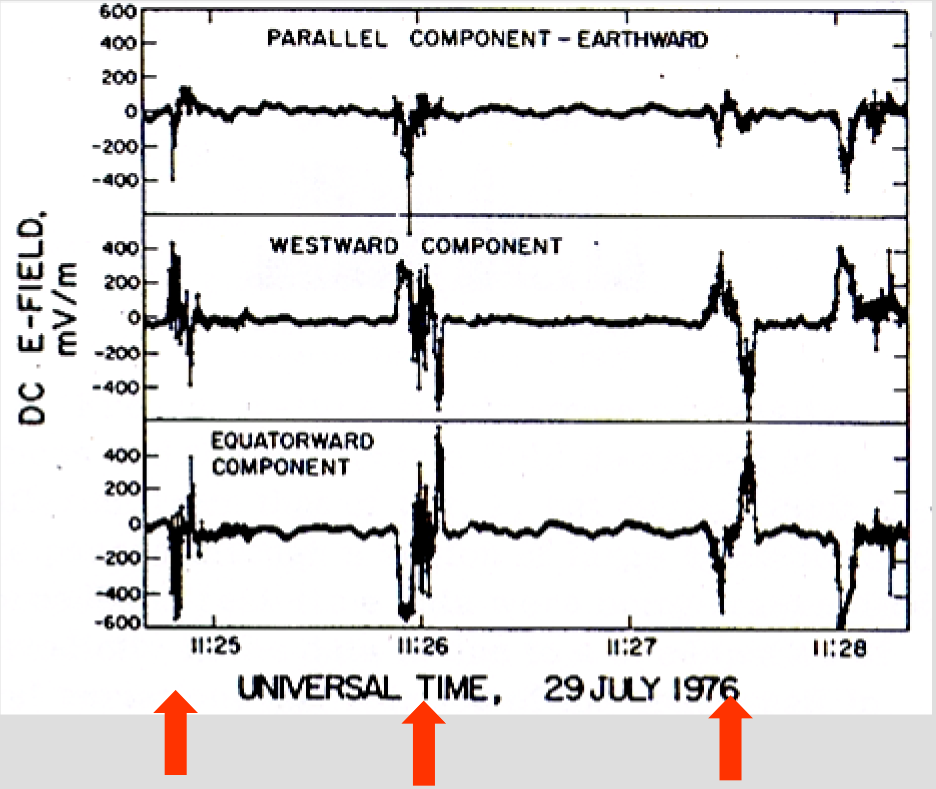
Why particle acceleration?



- 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.

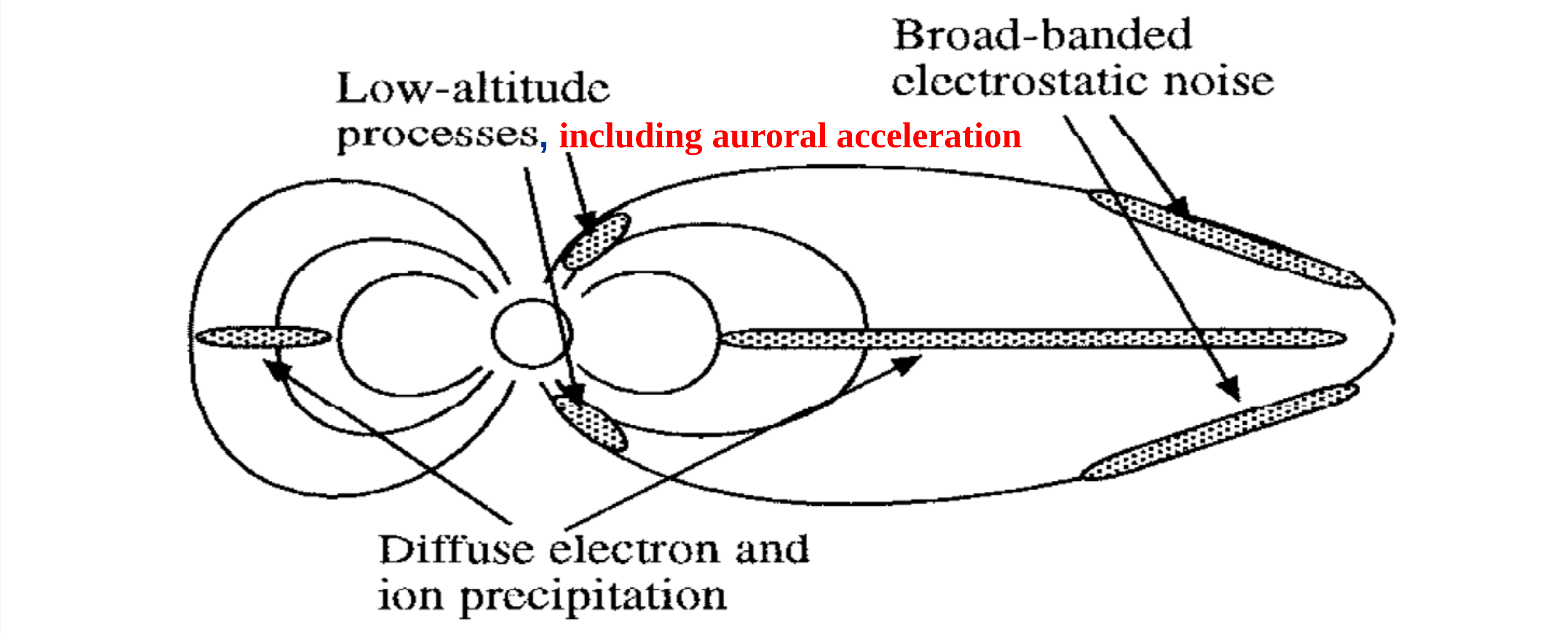
Satellite signatures of U potential





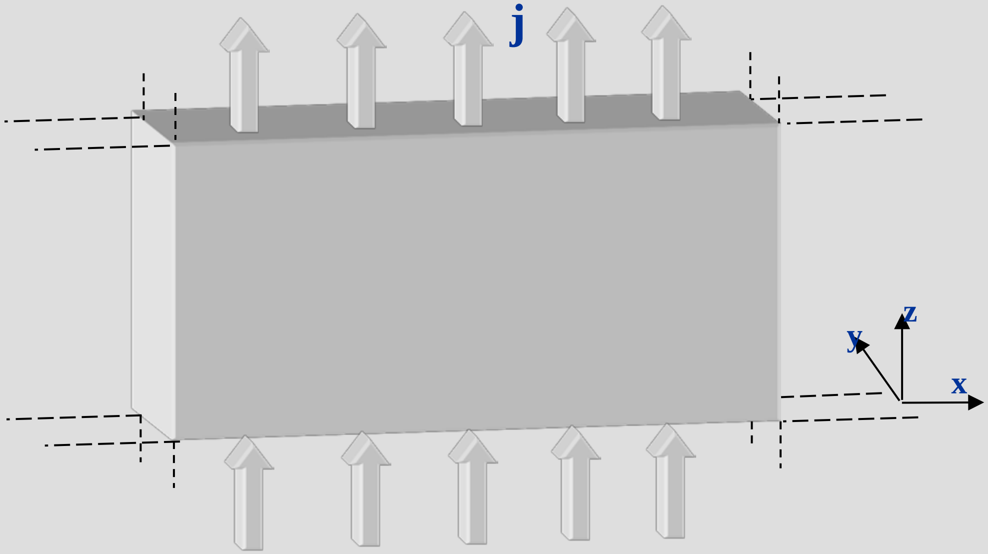
Measurements made by the ISEE satellite (Mozer et al., 1977)

Acceleration regions



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

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

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

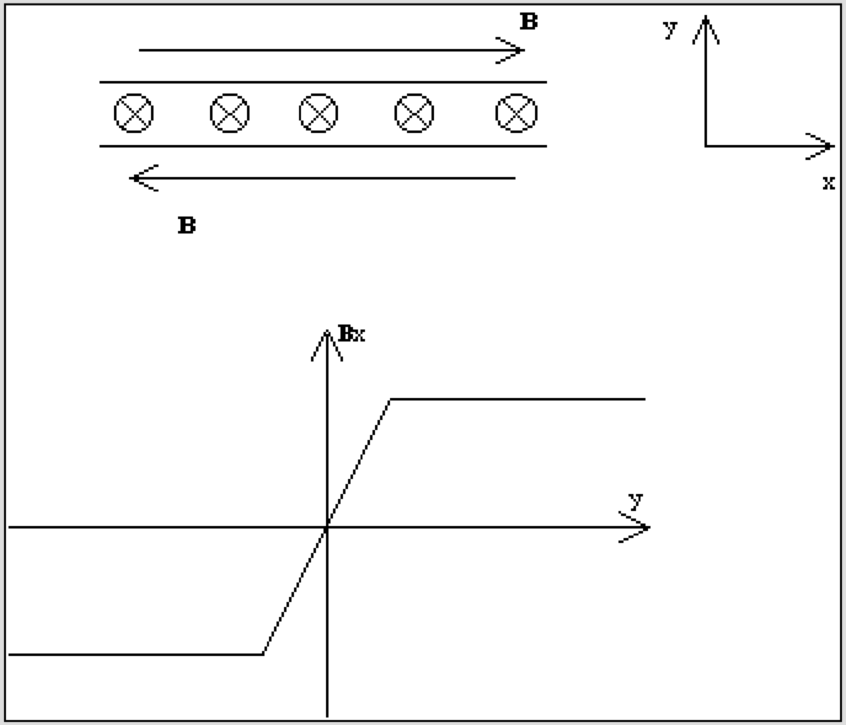
eller

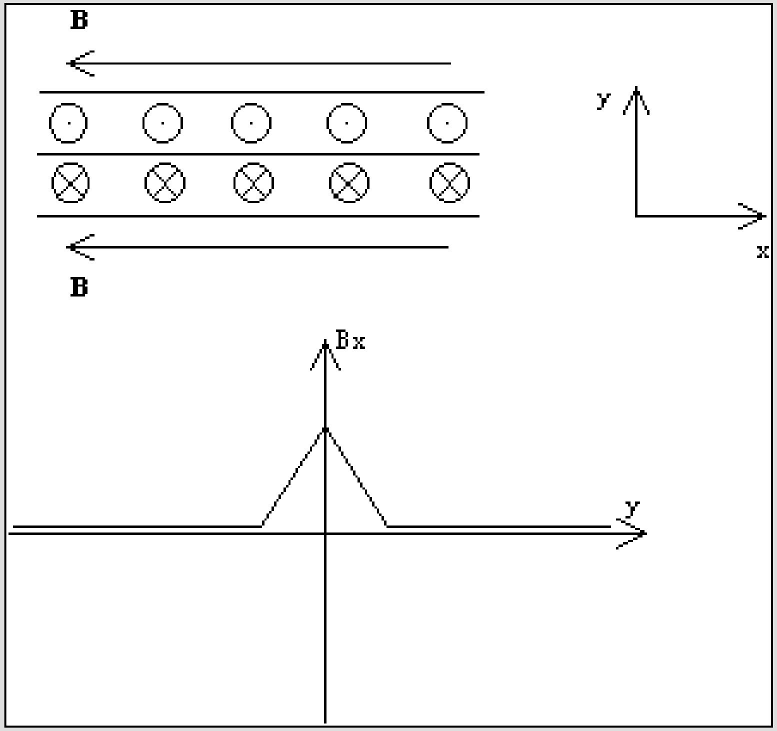
Ampére's law (no time dependence):

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

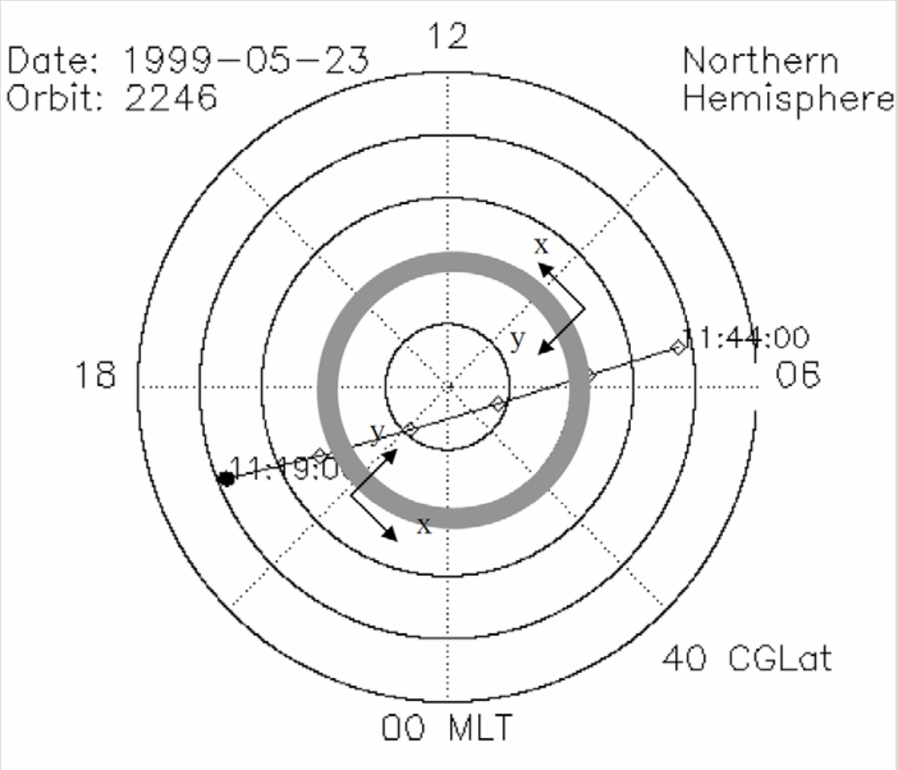
$$j_z=-\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

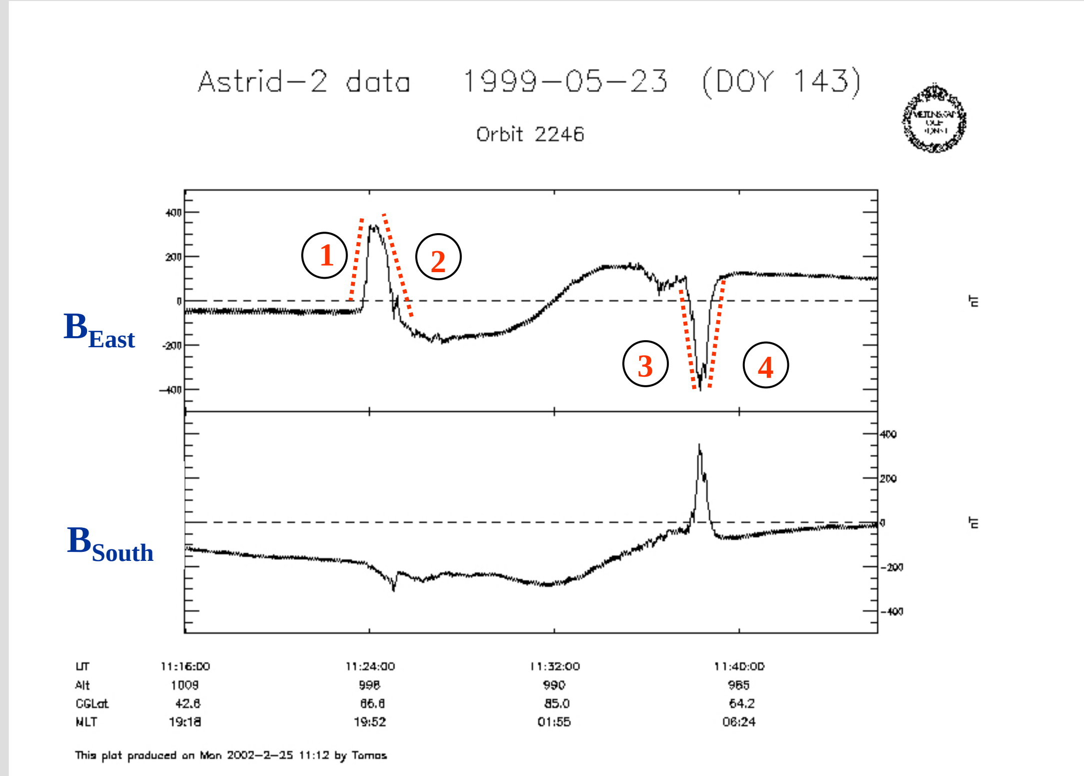
Current sheet - example





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

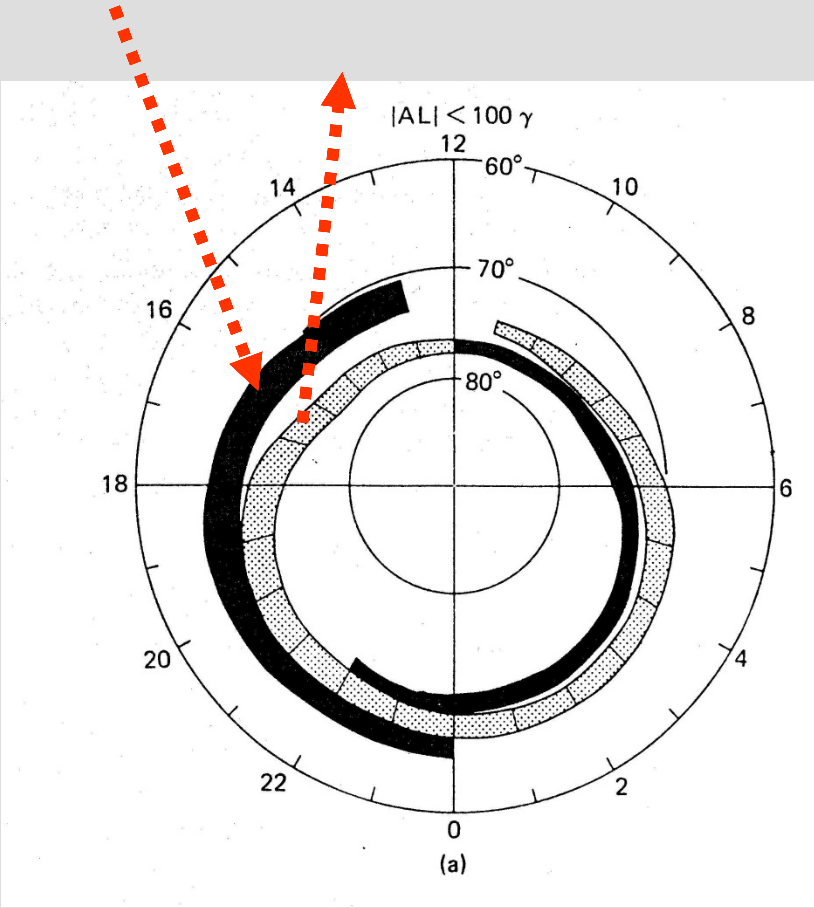


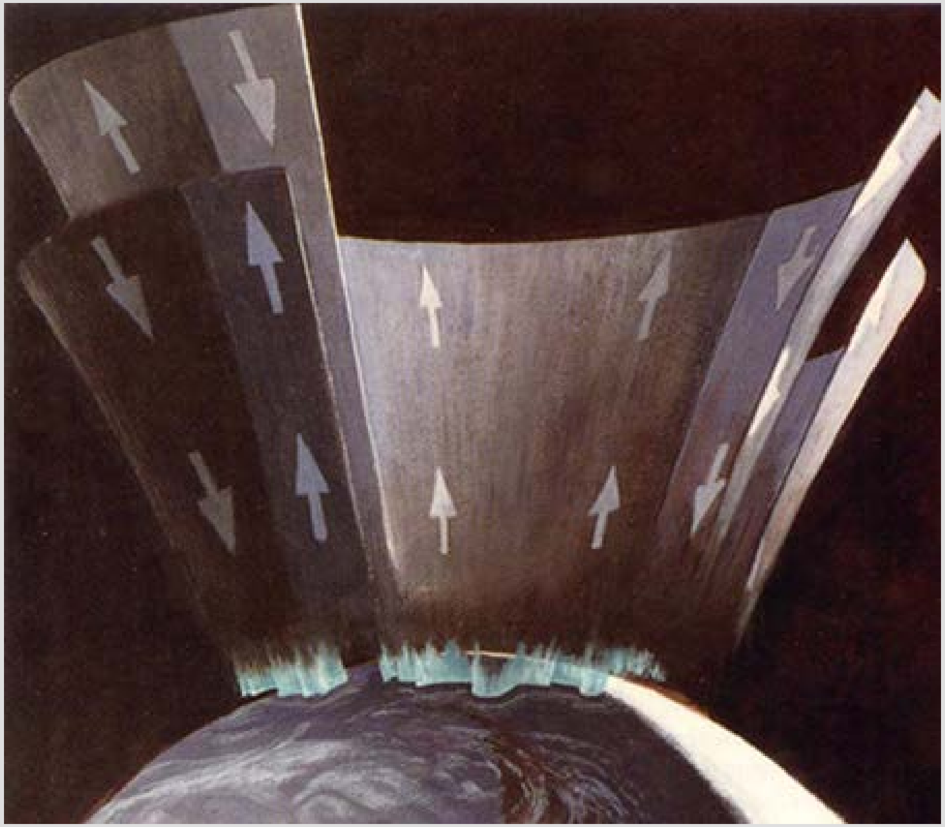


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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





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!

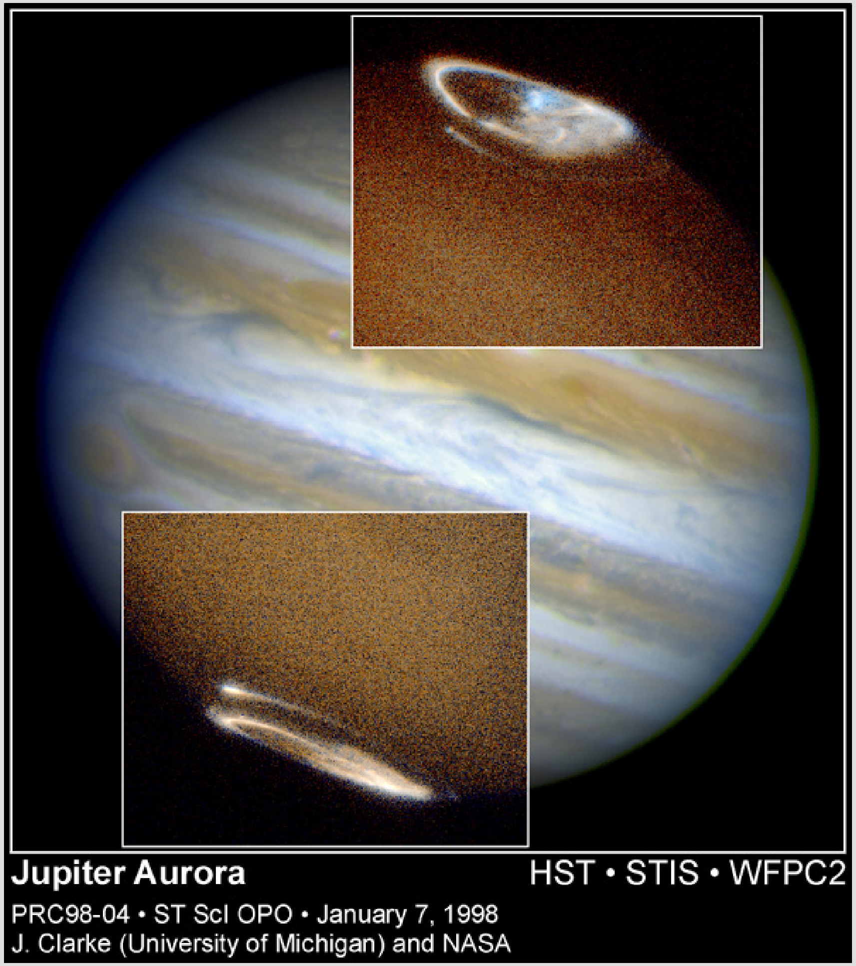
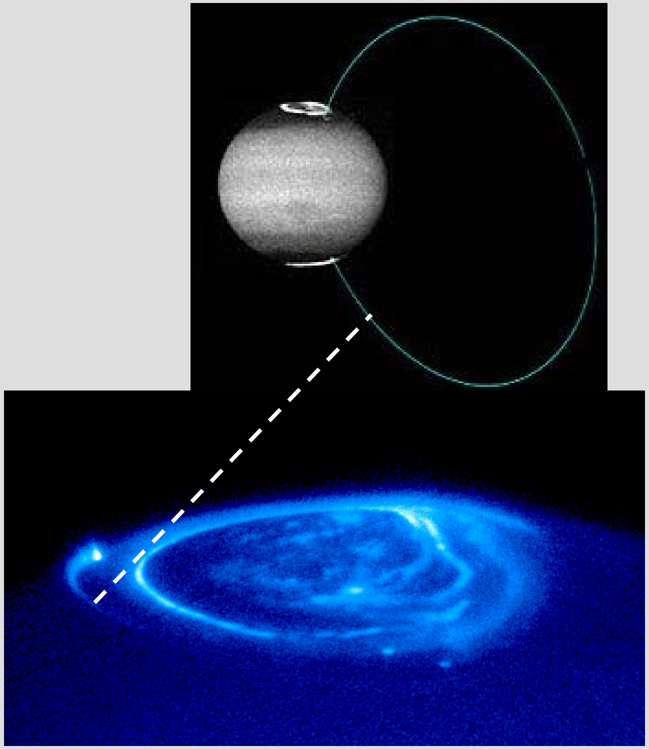
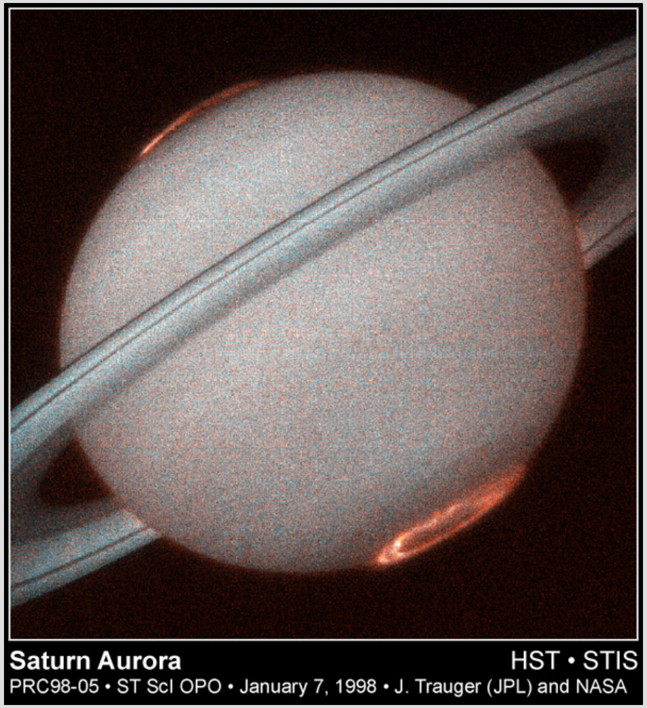


Foto från Hubble Space Telescope



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.)

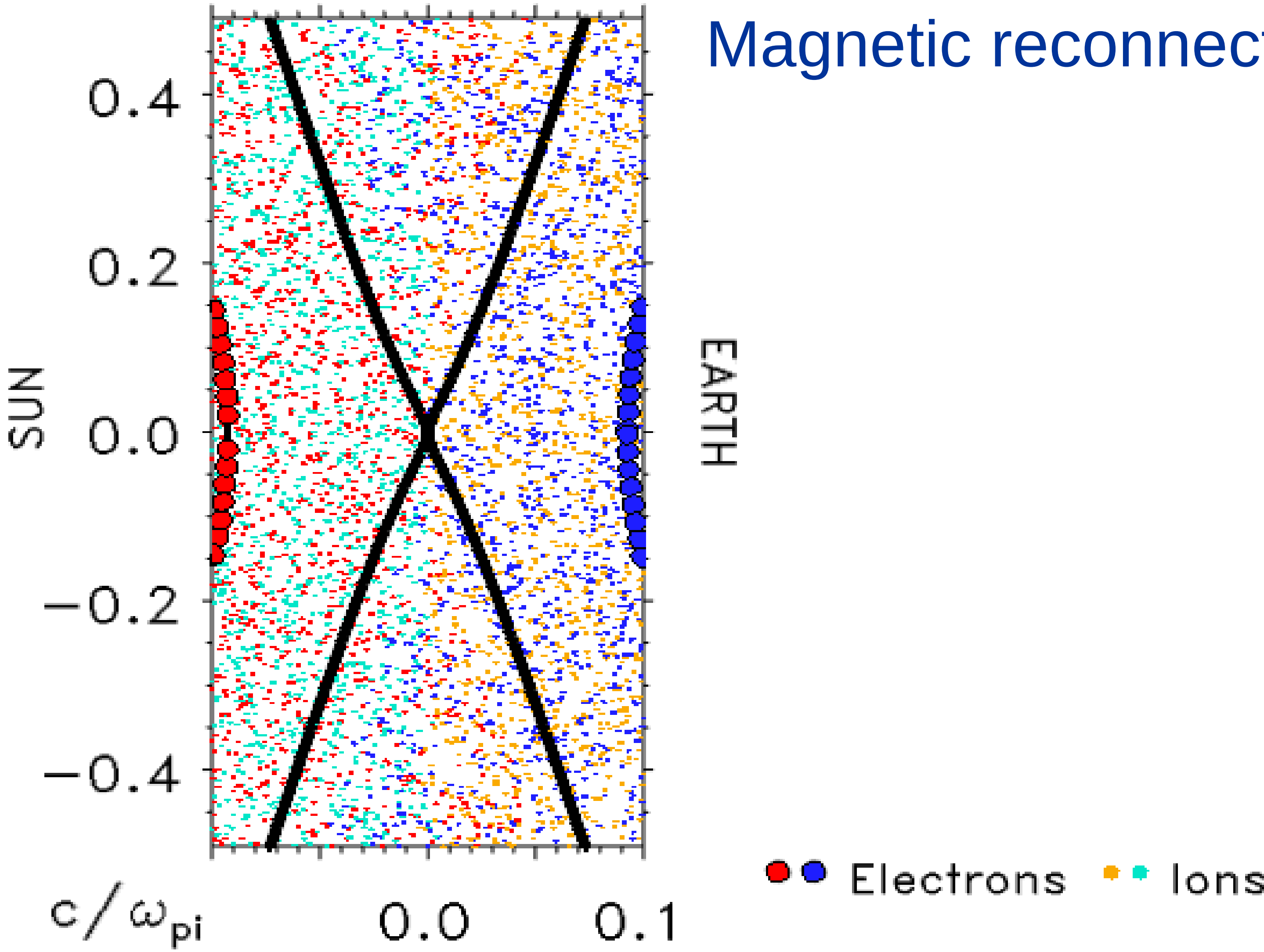
Uranus: *Auora detected in UV. Probably associated with Uranus' ring current/radiotion belts and not very dynamic.*

Neptunus: *weak UV aurora detected.*

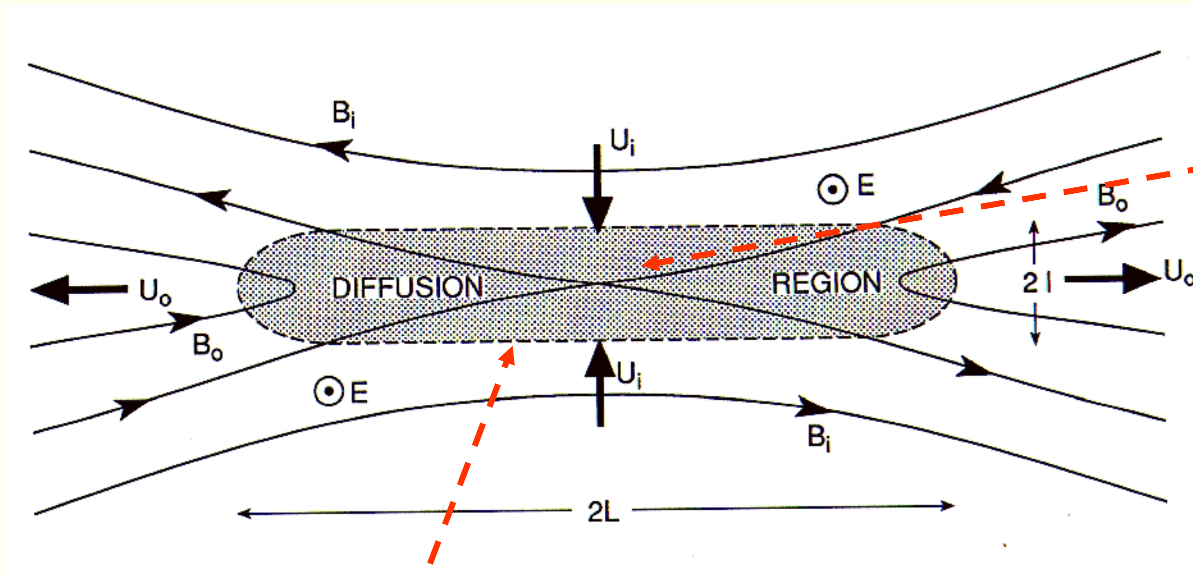
Mars, Venus: *No aurora.*

Space weather, geomagnetic storms, geomagnetic activity

Magnetic reconnection



Reconnection



In 'diffusion region':

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

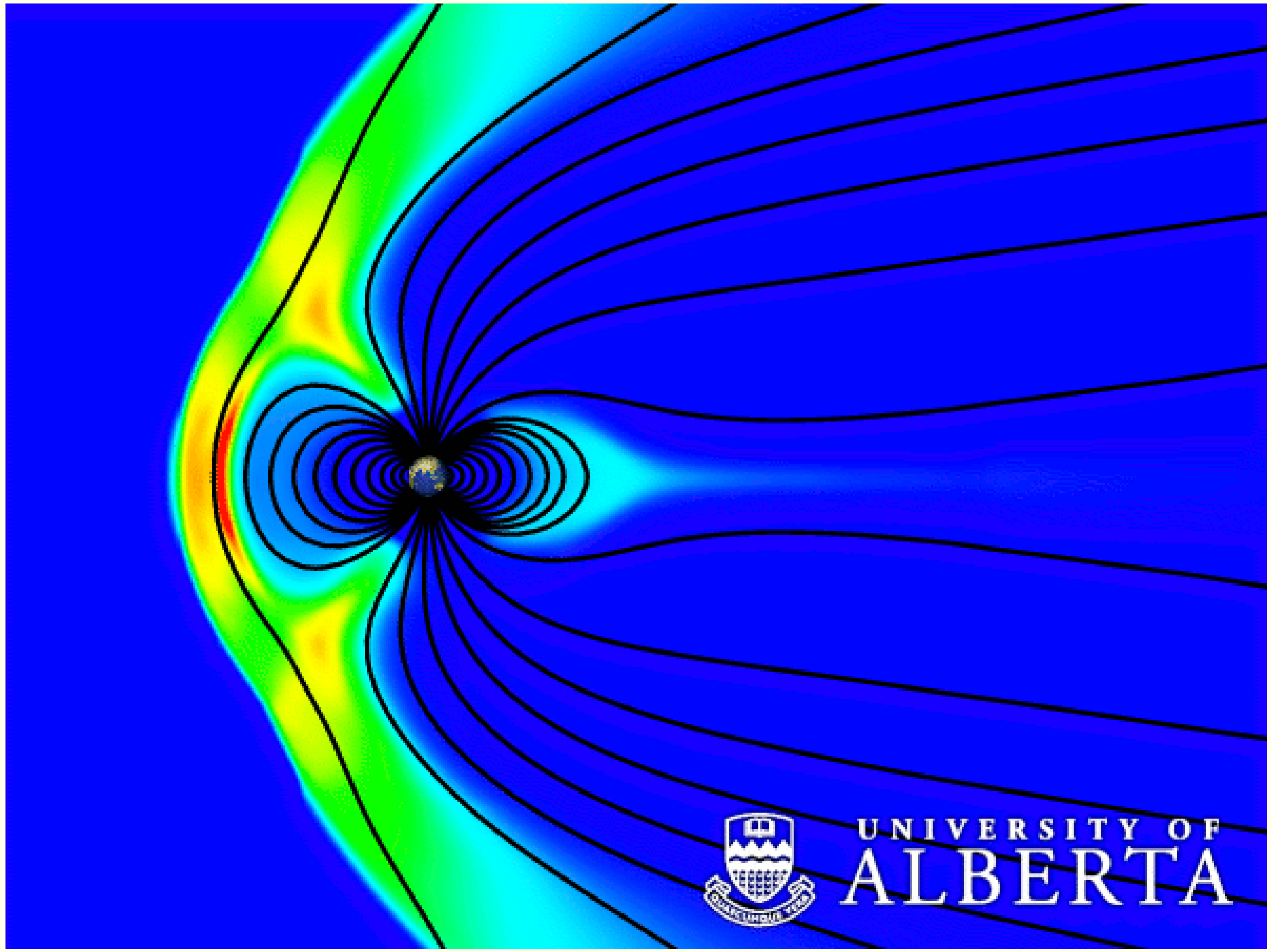
Thus: condition for frozen-in magnetic field breaks down.

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**

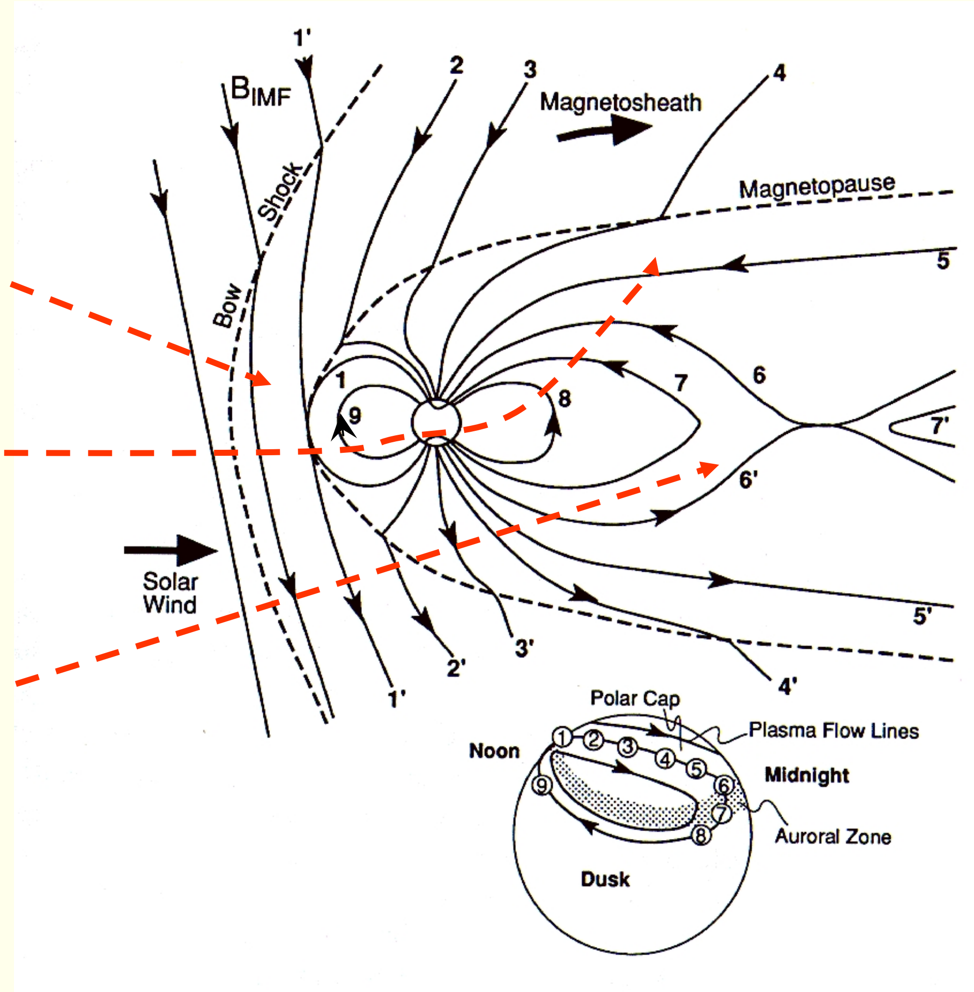
Reconnection and plasma convection

Solar wind

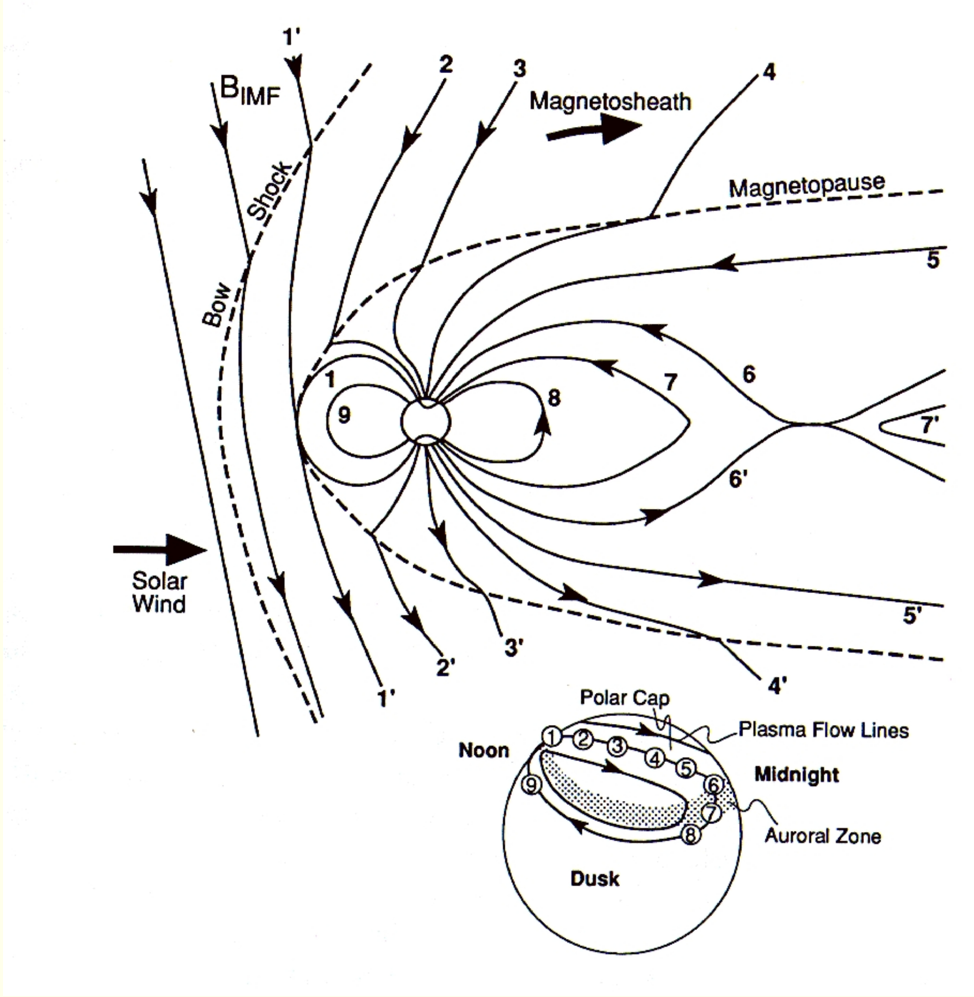


Reconnection och plasma convection

- 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.

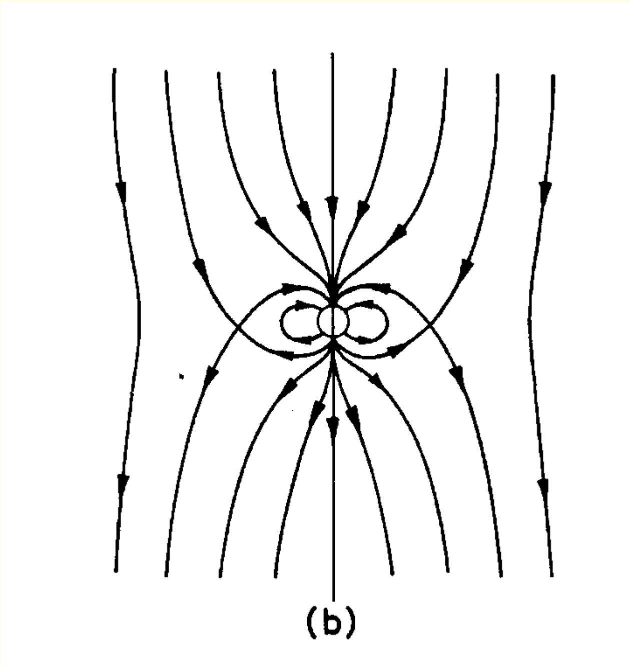


What happens if IMF is northward instead?

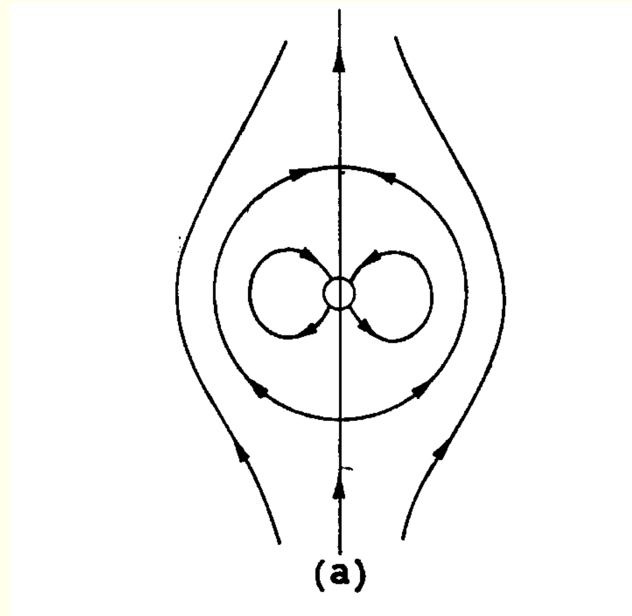


Magnetospheric dynamics

open magnetosphere



closed magnetosphere



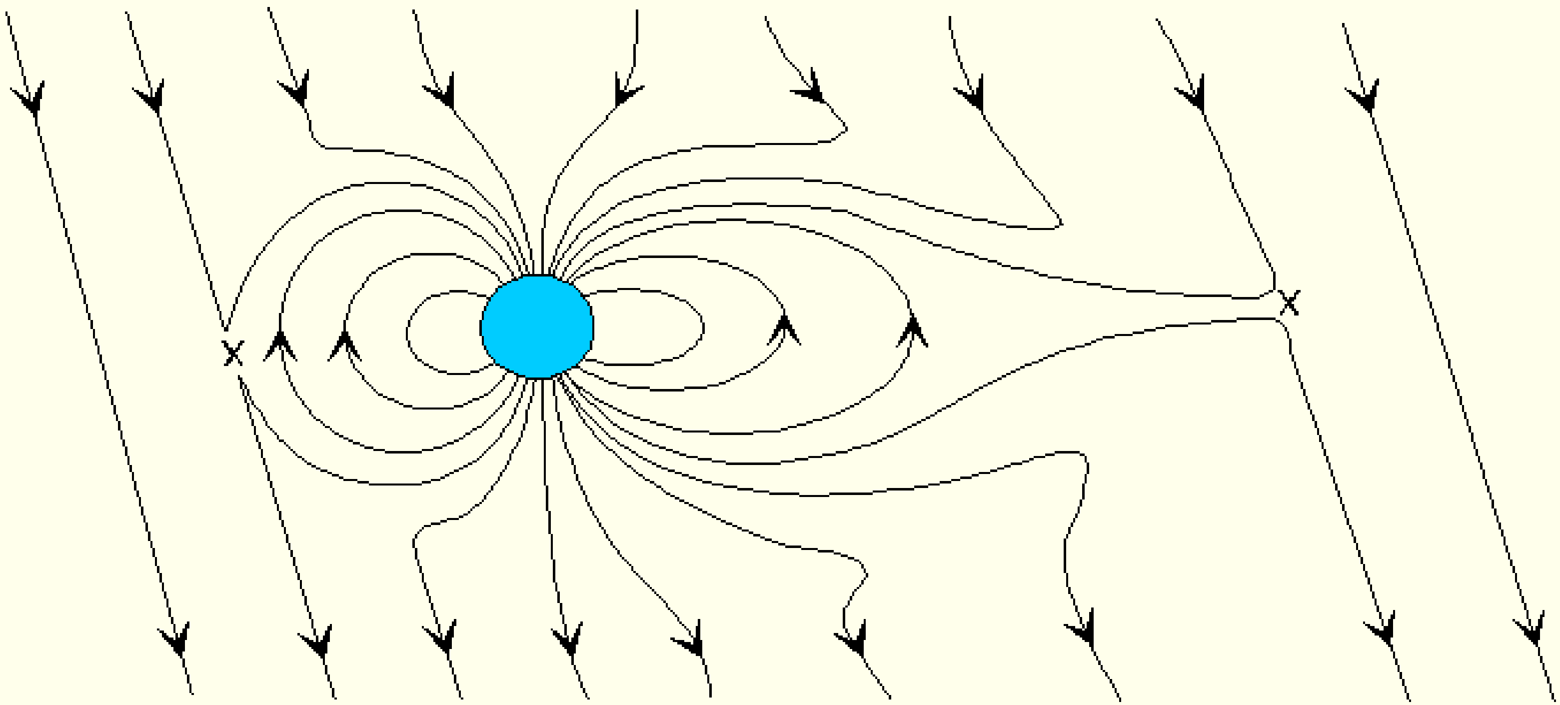
southward

Interplanetary
magnetic field (IMF)

northward

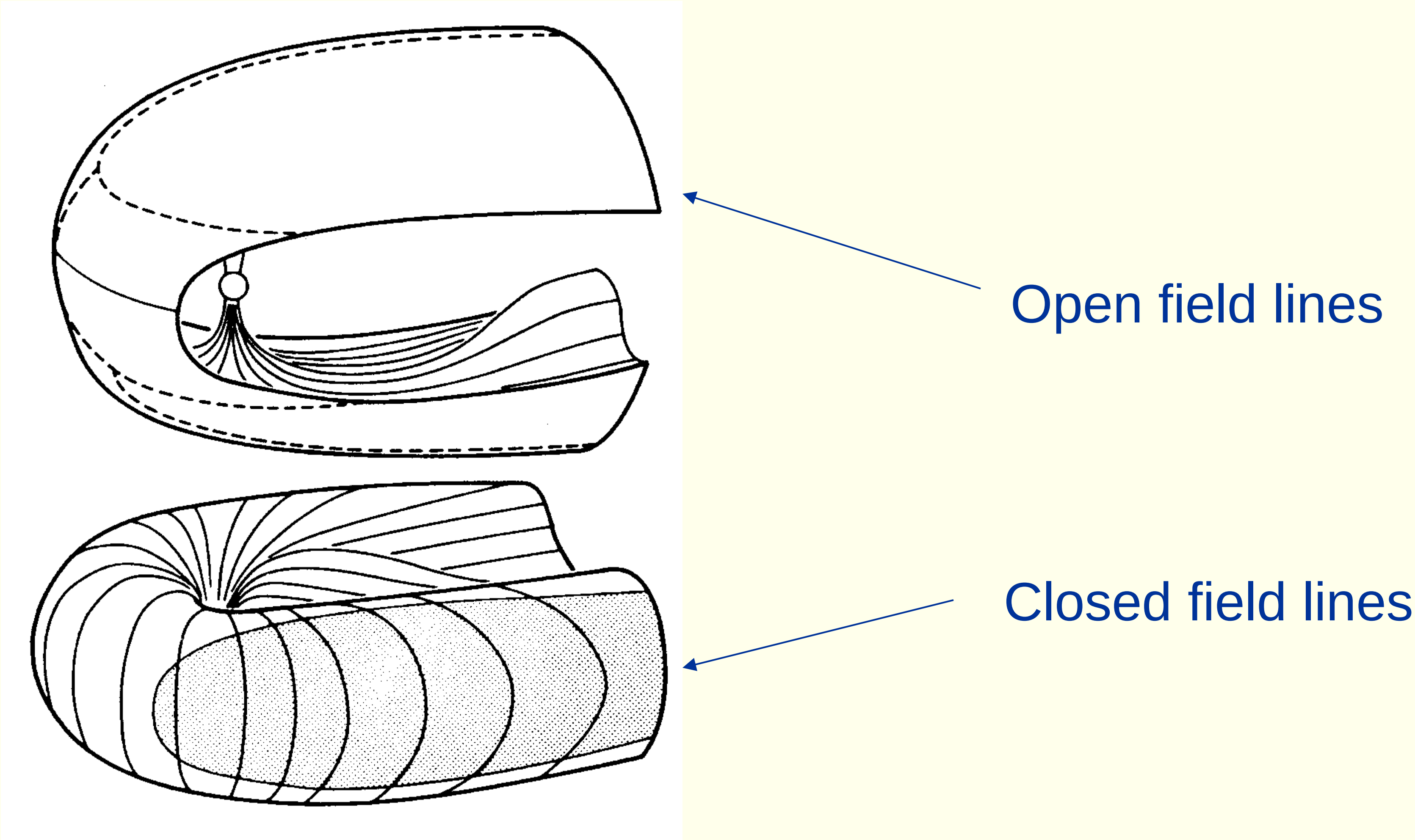
Magnetospheric dynamics

open magnetosphere

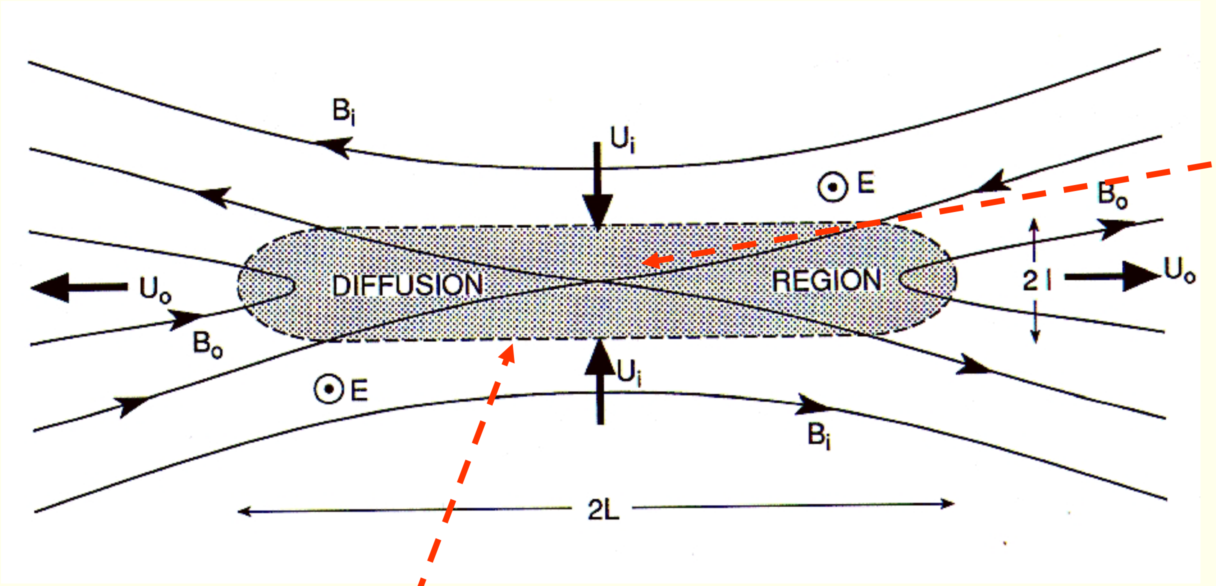


Southward IMF

Magnetospheric topology



Reconnection



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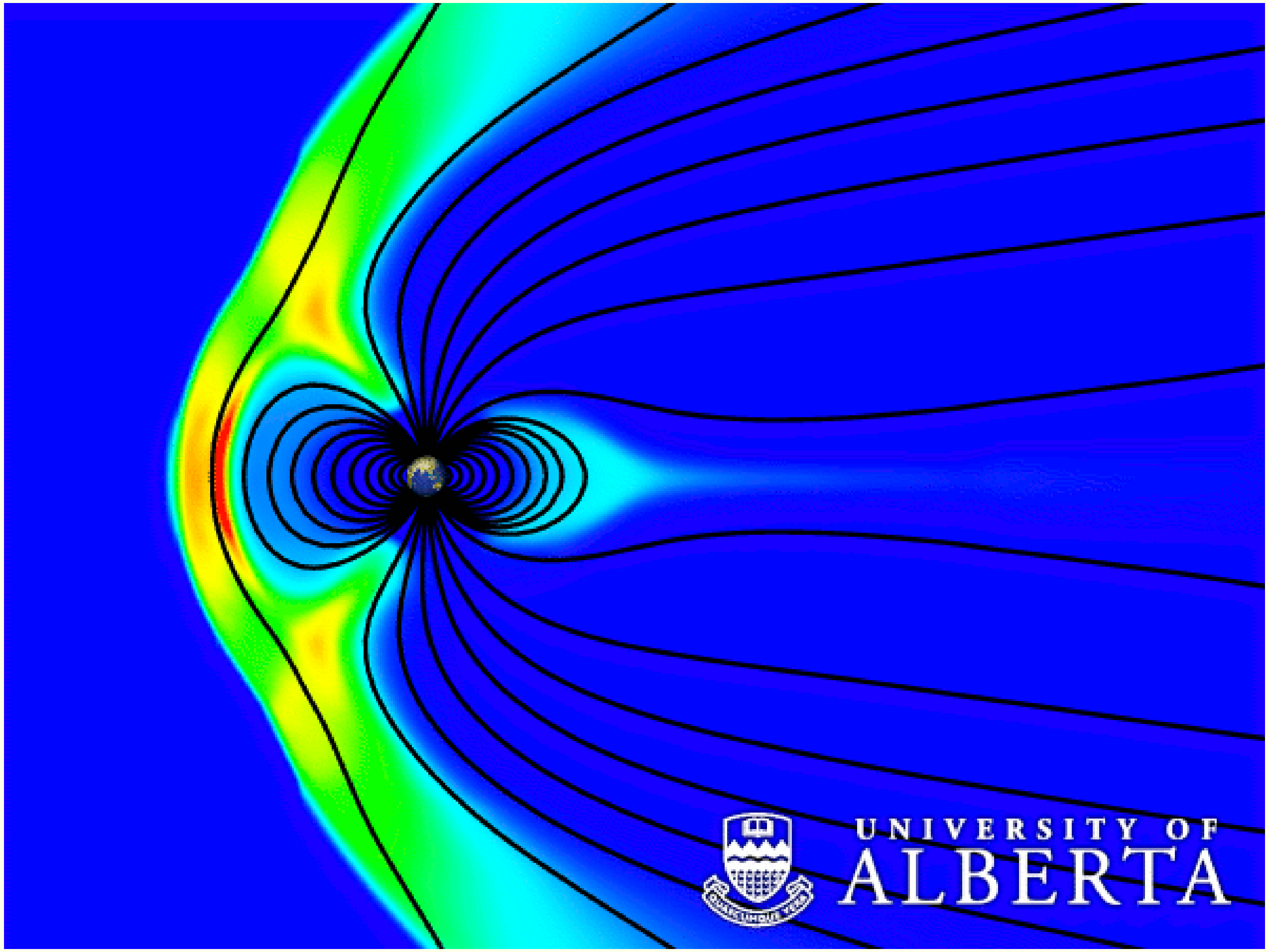
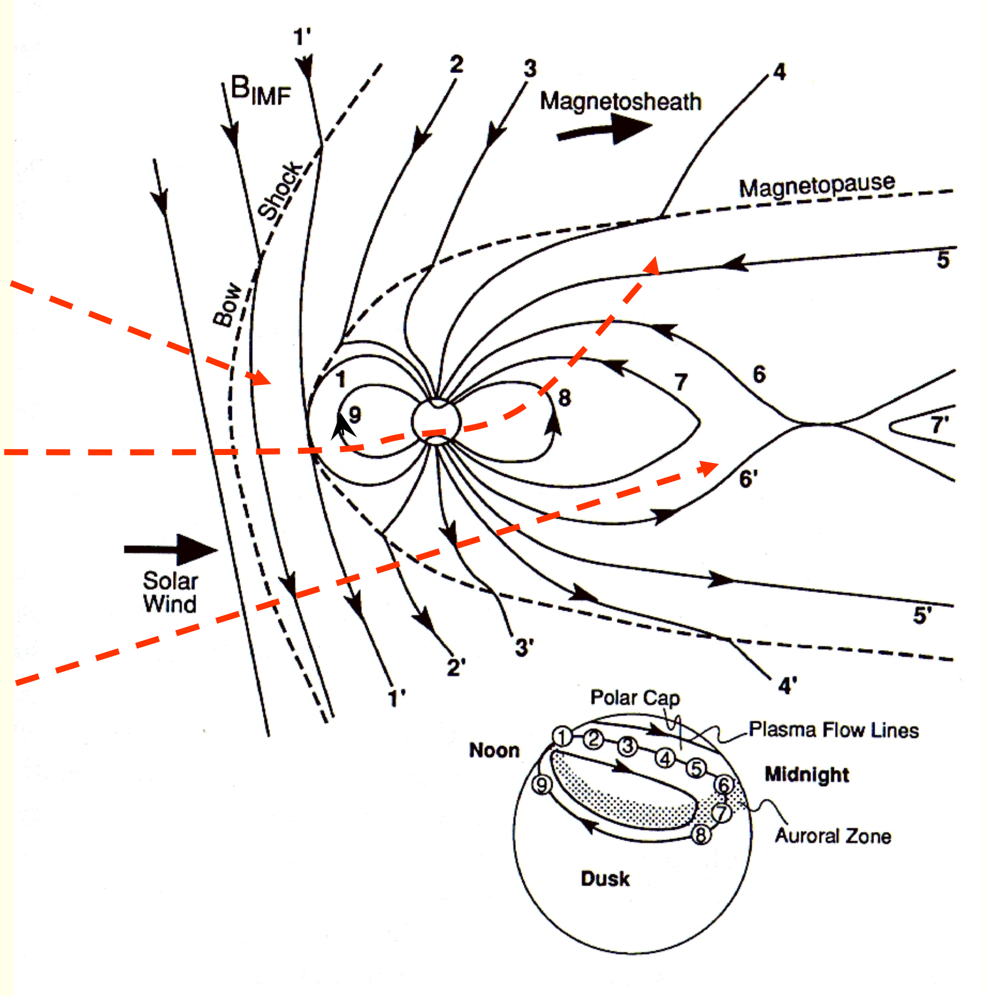
Reconnection and plasma convection

Solar wind

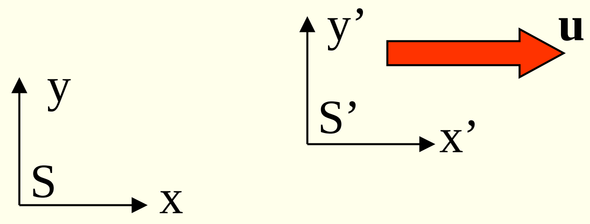


Reconnection och plasma convection

- 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 $u << c$*:*

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

induced electric field

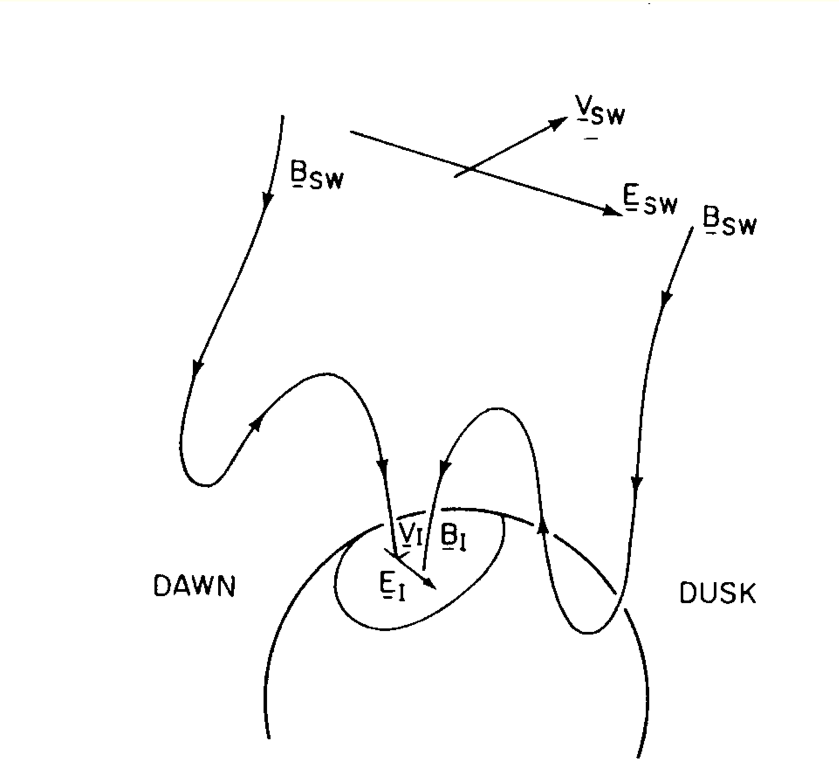
$$\mathbf{E} = \mathbf{E}' - \mathbf{u} \times \mathbf{B}$$

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 1



The solar wind generates an electric field

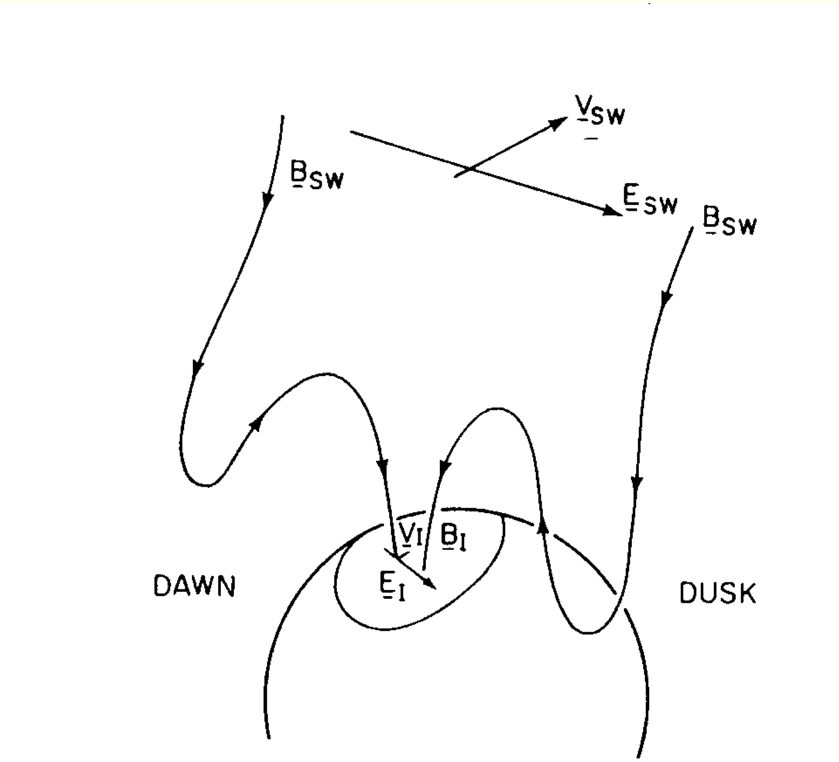
$$\mathbf{E}_{SW} = - \mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 2



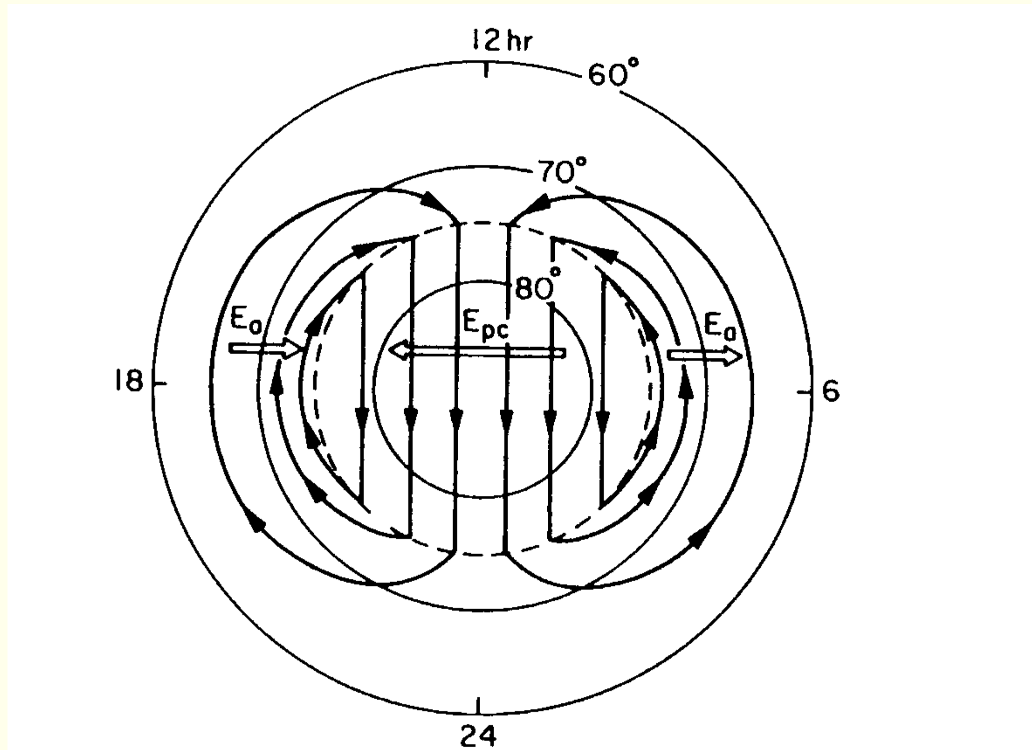
The solar wind magnetic field draws the ionospheric plasma with it, since the field is frozen into the plasma. This motion induces an ionospheric electric field

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

Magnetospheric dynamics

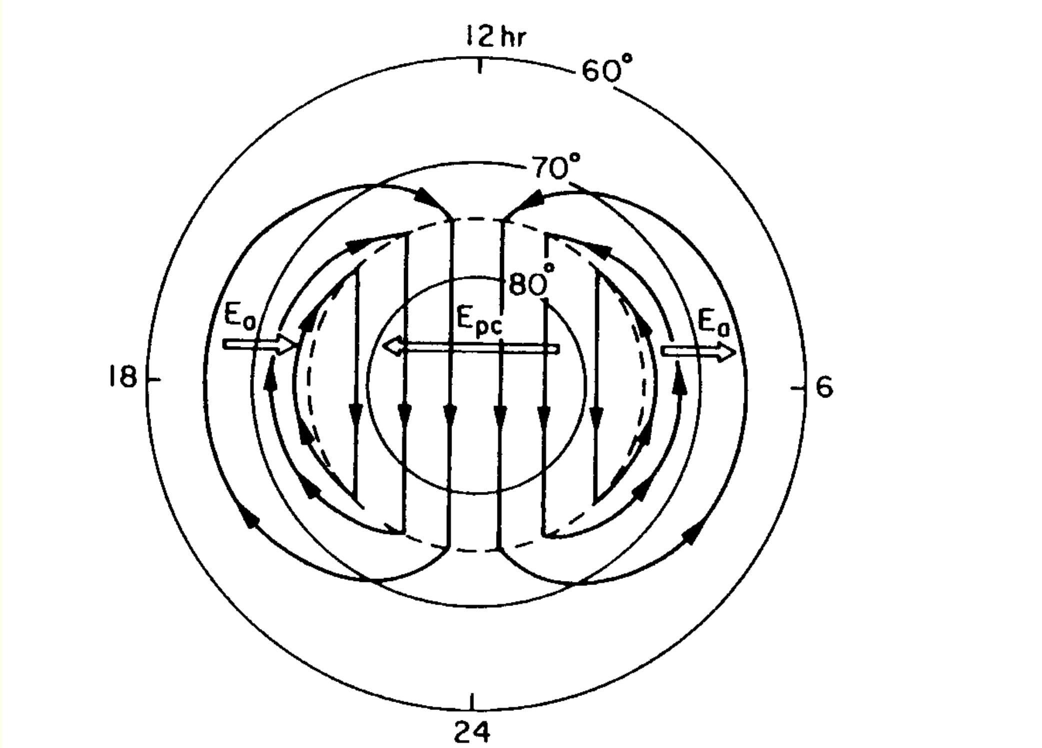
Plasma convection in the ionosphere

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



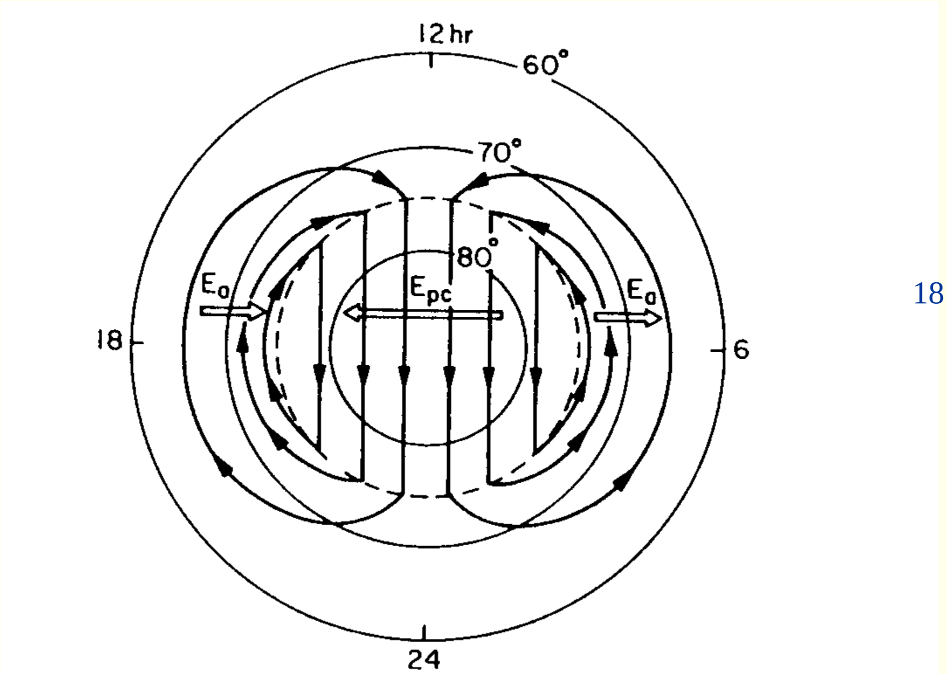
Do you recognize this pattern?

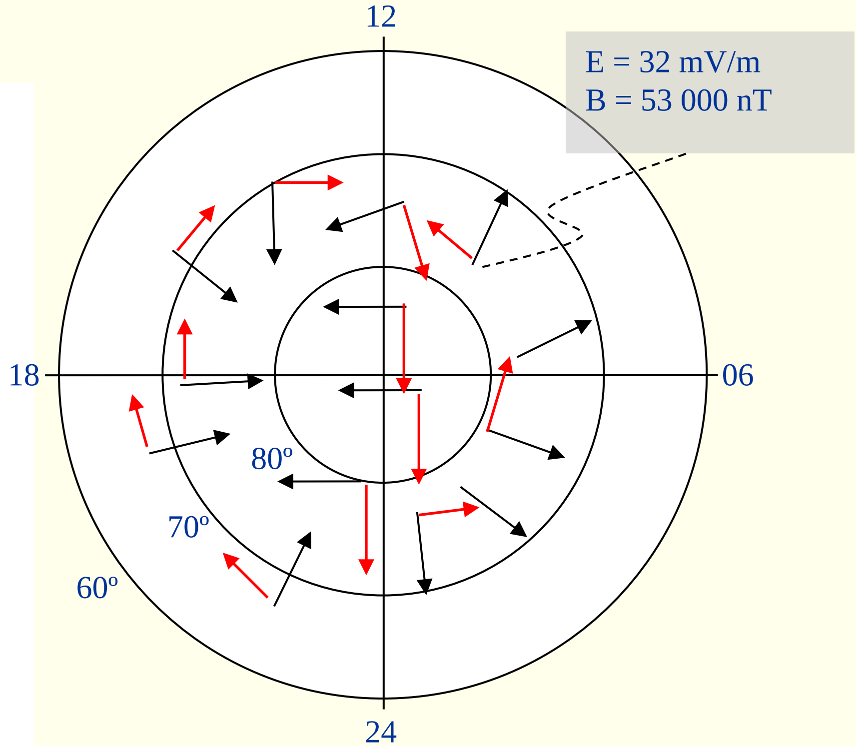
Plasma convection in the ionosphere



Do you recognize this pattern?

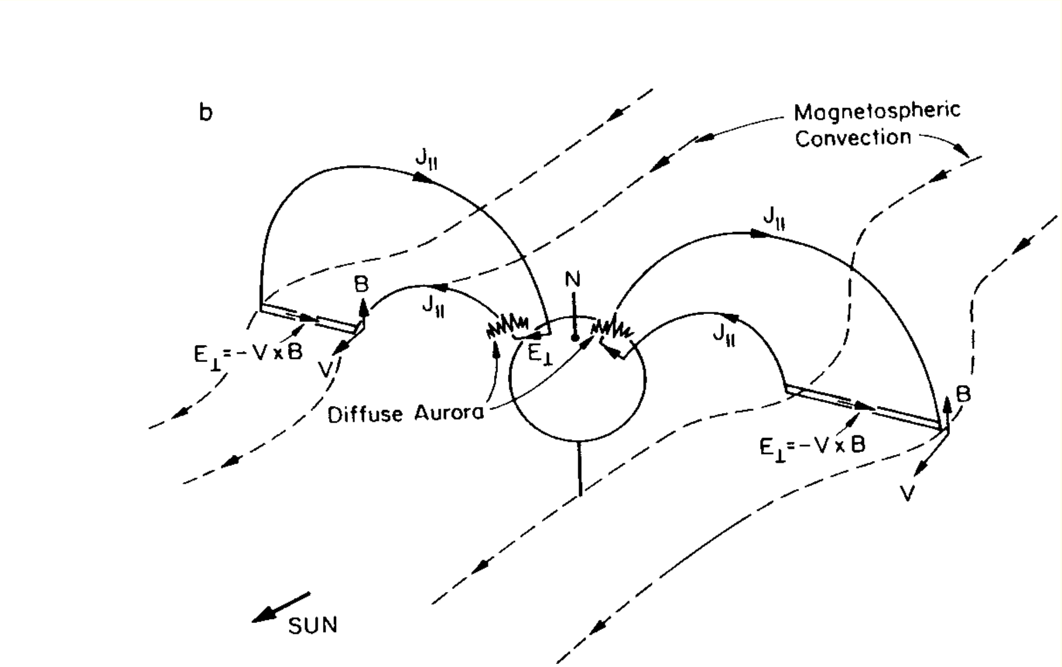
Plasma convection in the ionosphere





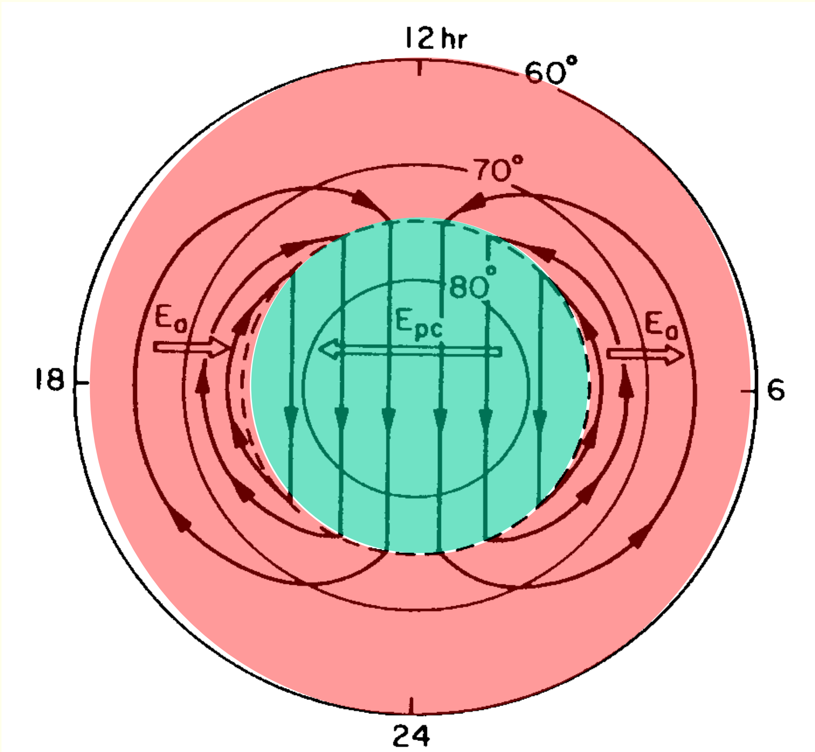
Static, large-scale MI-coupling

Magnetospheric and ionospheric convection

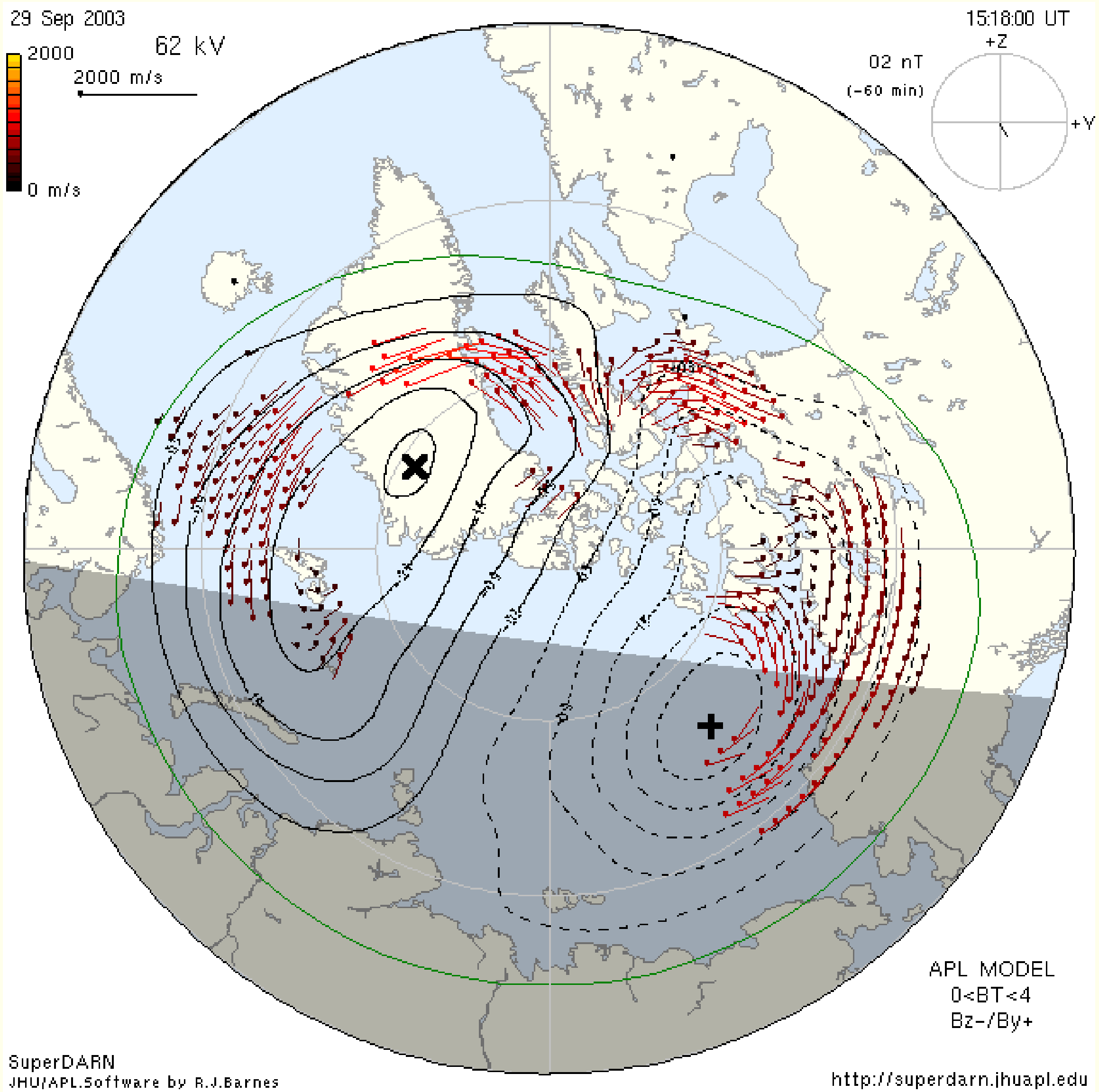


Kelley, 1989

Ionospheric convection

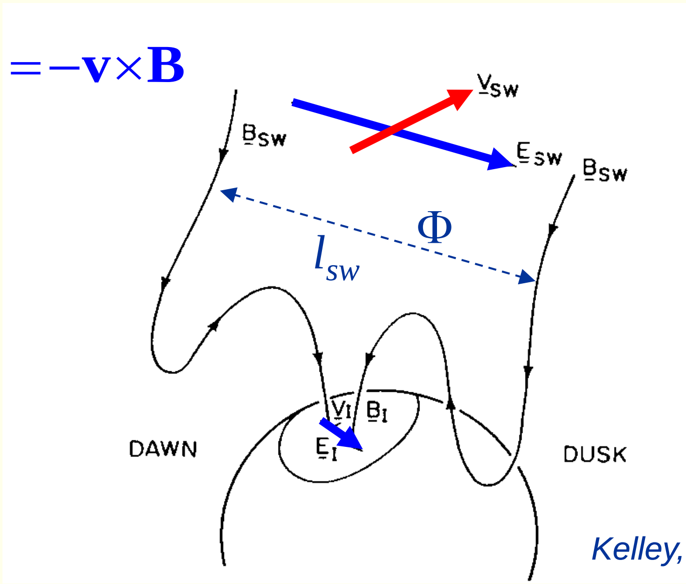


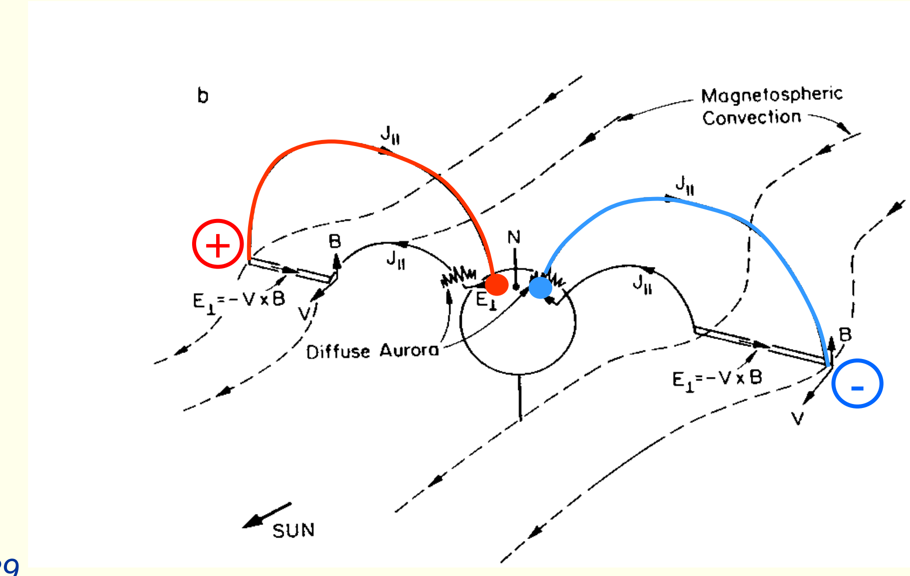
Measurements of plasma convection in the magnetosphere



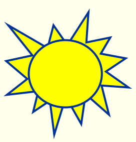
Magnetospheric plasma convection

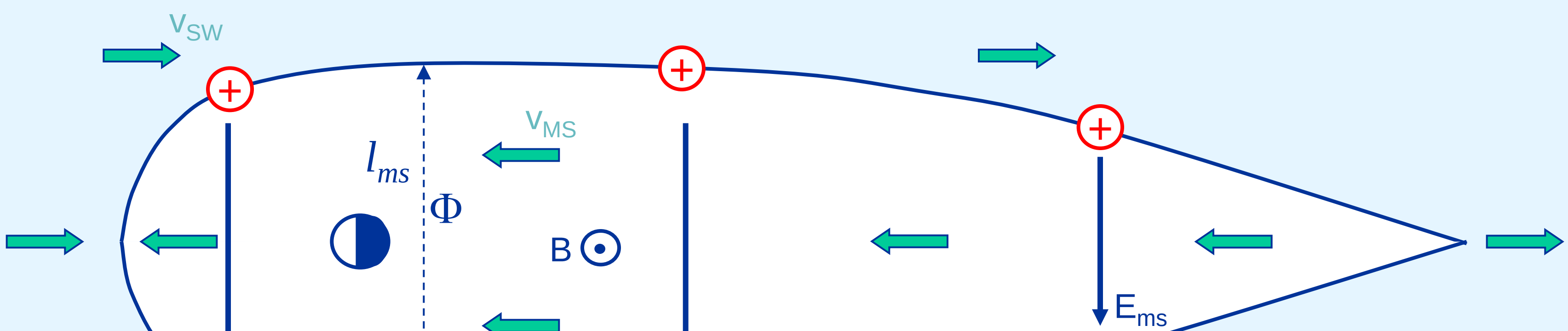
$$\mathbf{E}_{sw} = -\mathbf{v} \times \mathbf{B}$$





Kelley, 1989

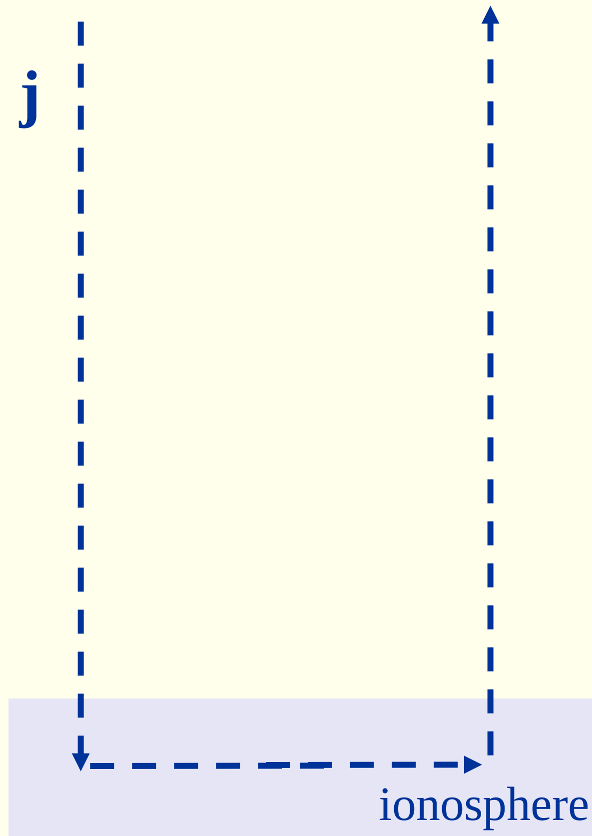




$$E_{ms} = \frac{l_{sw}}{l_{ms}} E_{sw}$$

Geomagnetic activity, definition

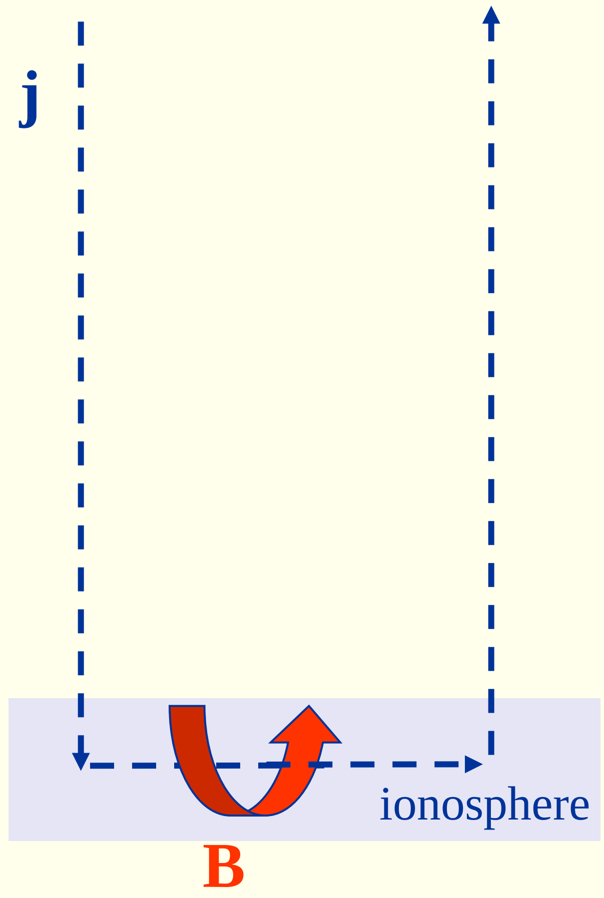
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.



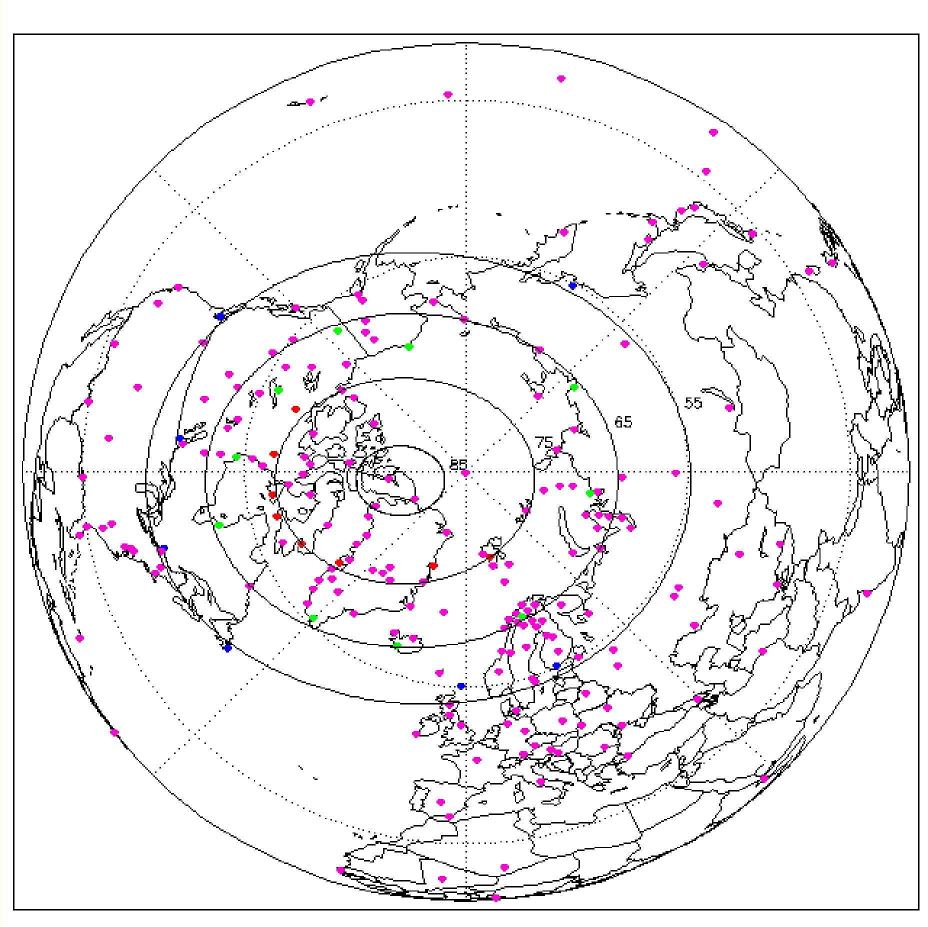
How can you observe these changing currents on Earth?

Geomagnetic activity, definition

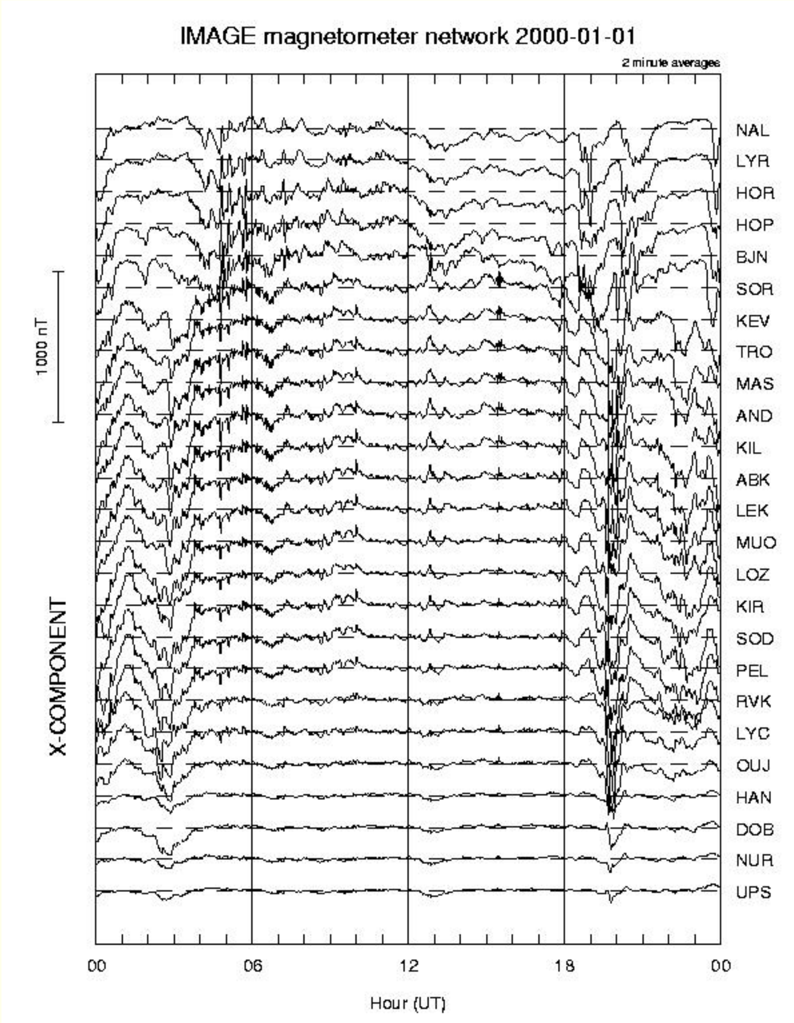
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.
- The variations are observed by geomagnetic observatories



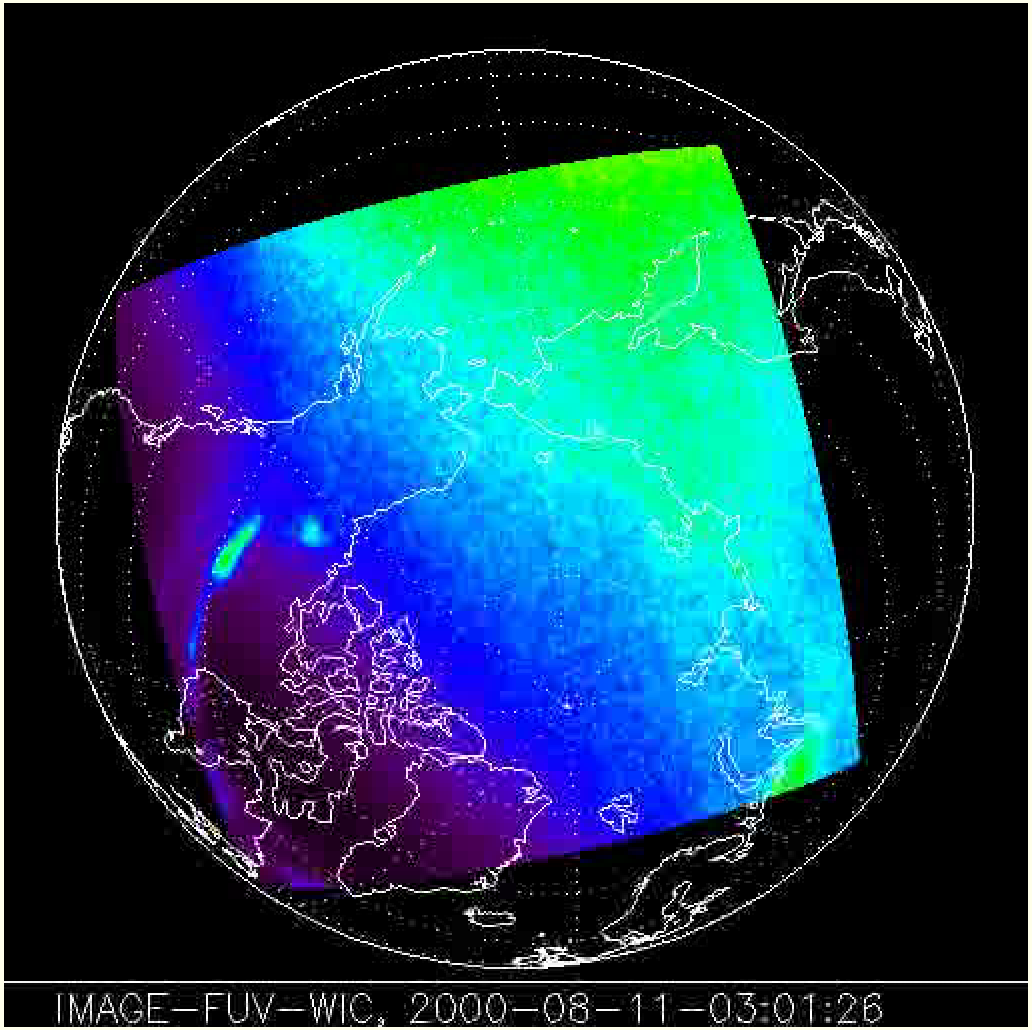
Magnetic observatories



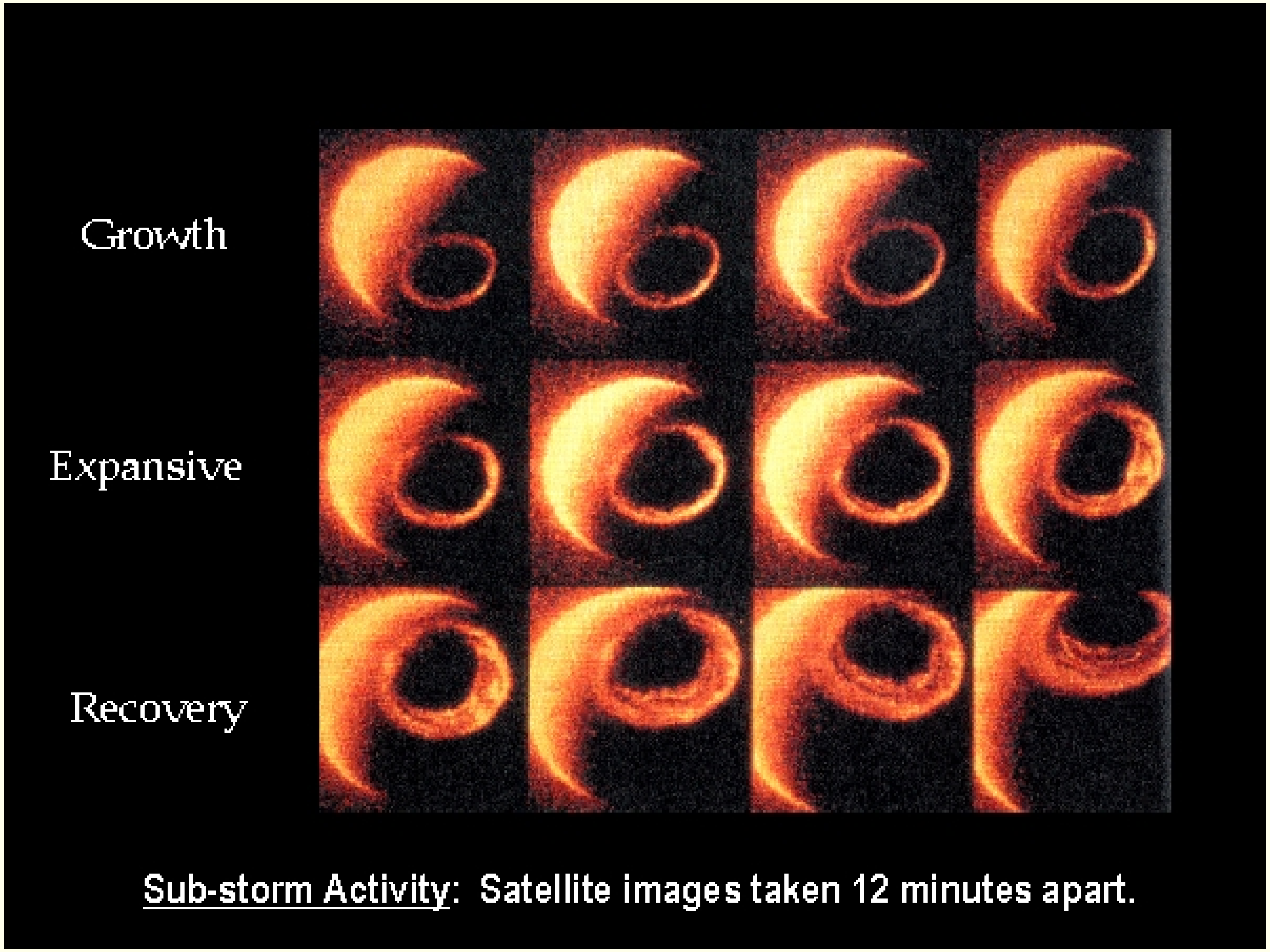
Magnetogram



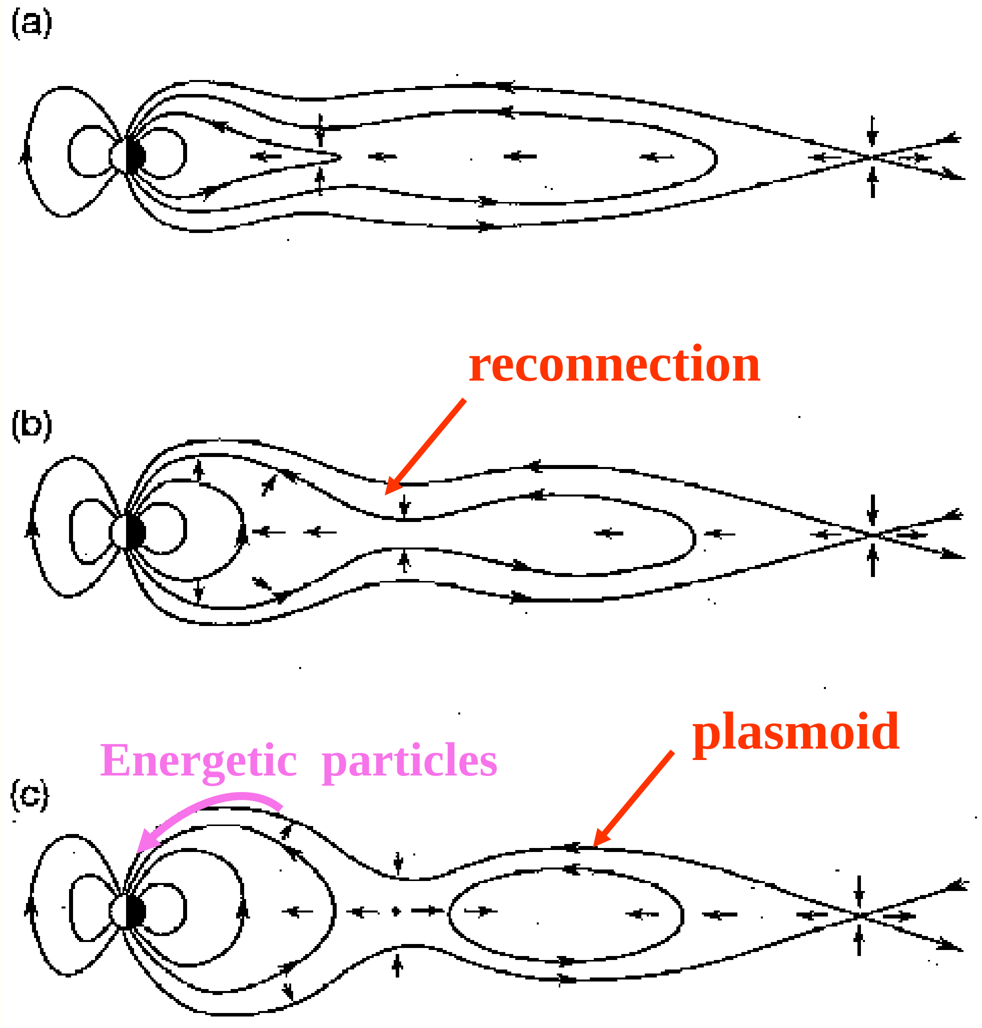
Aurora during substorm



Aurora during substorm

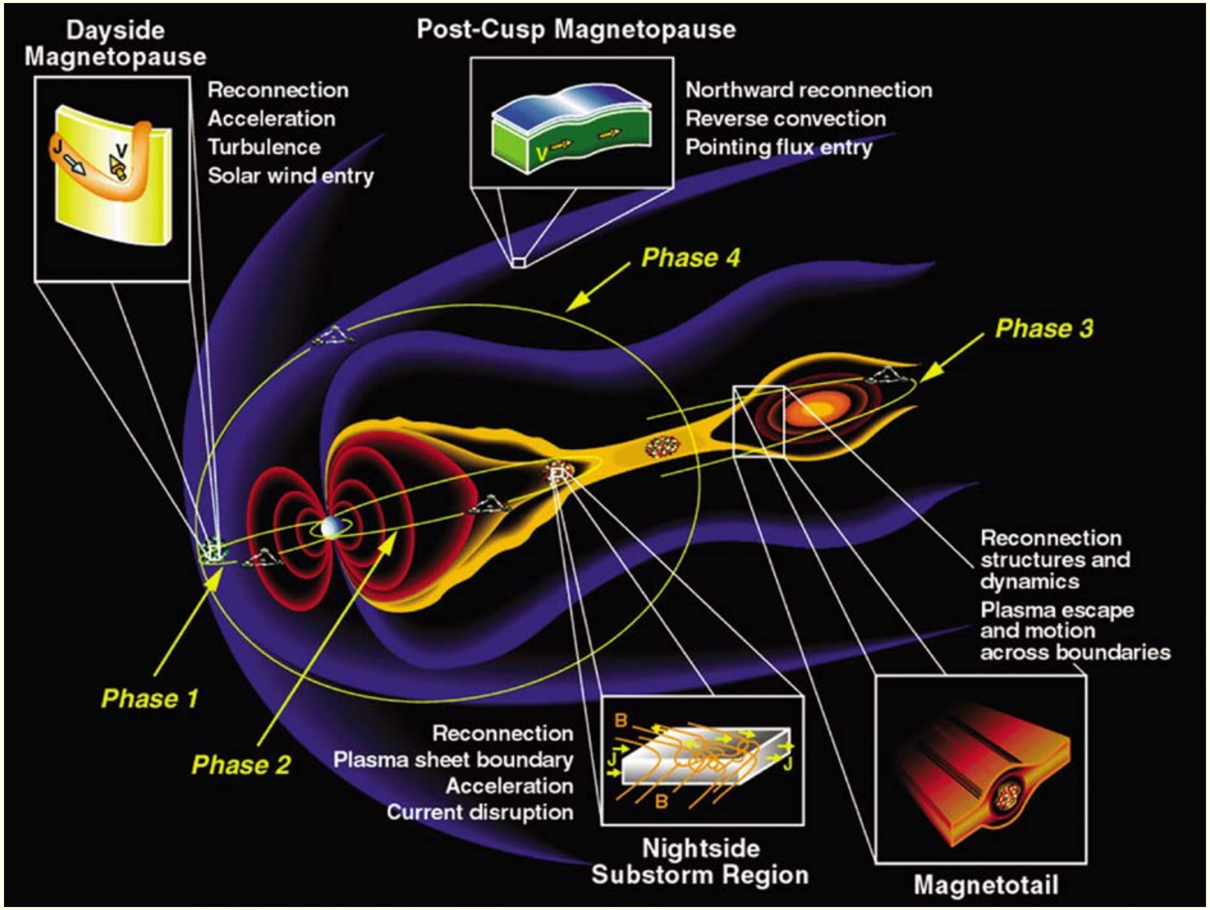


Substorms - magnetosphere



- **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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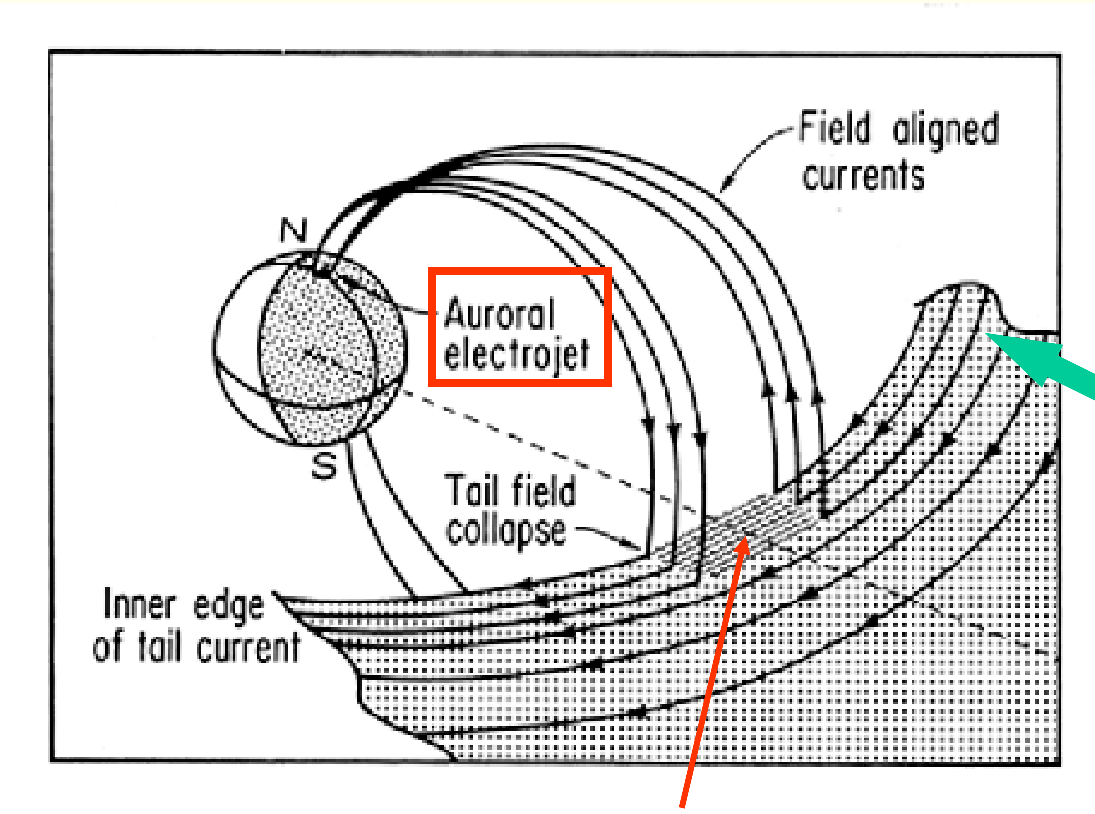
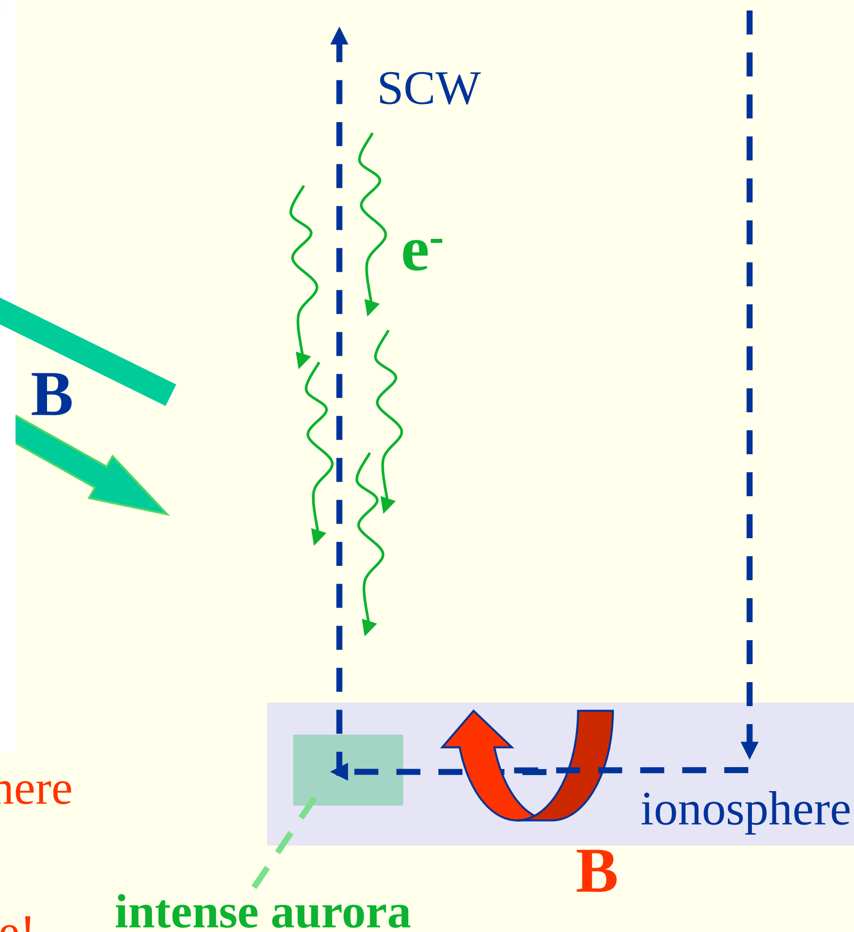
Substorm Current Wedge (SCW)



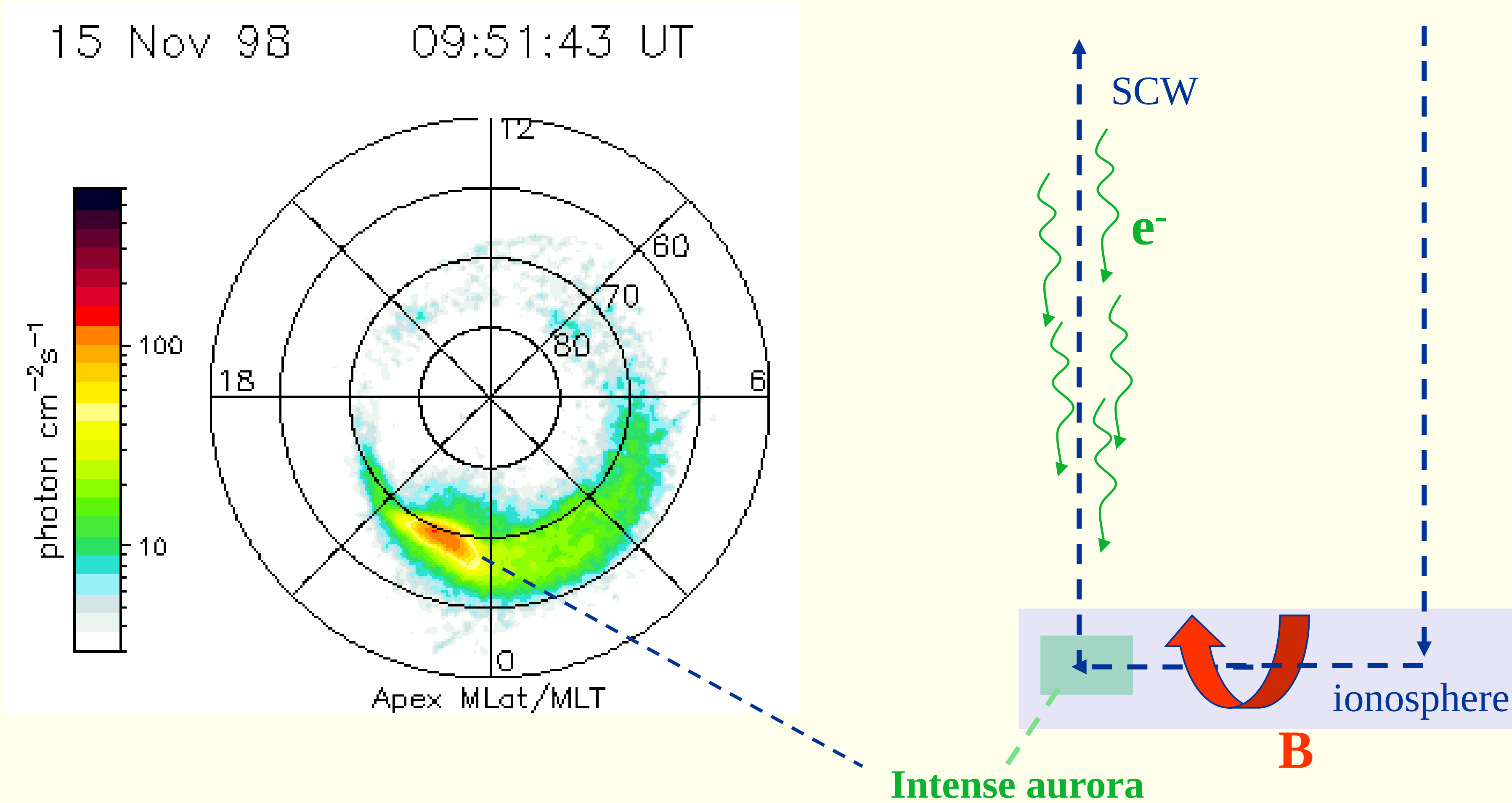


Due to reconnection processes the resistivity increases here

⇒

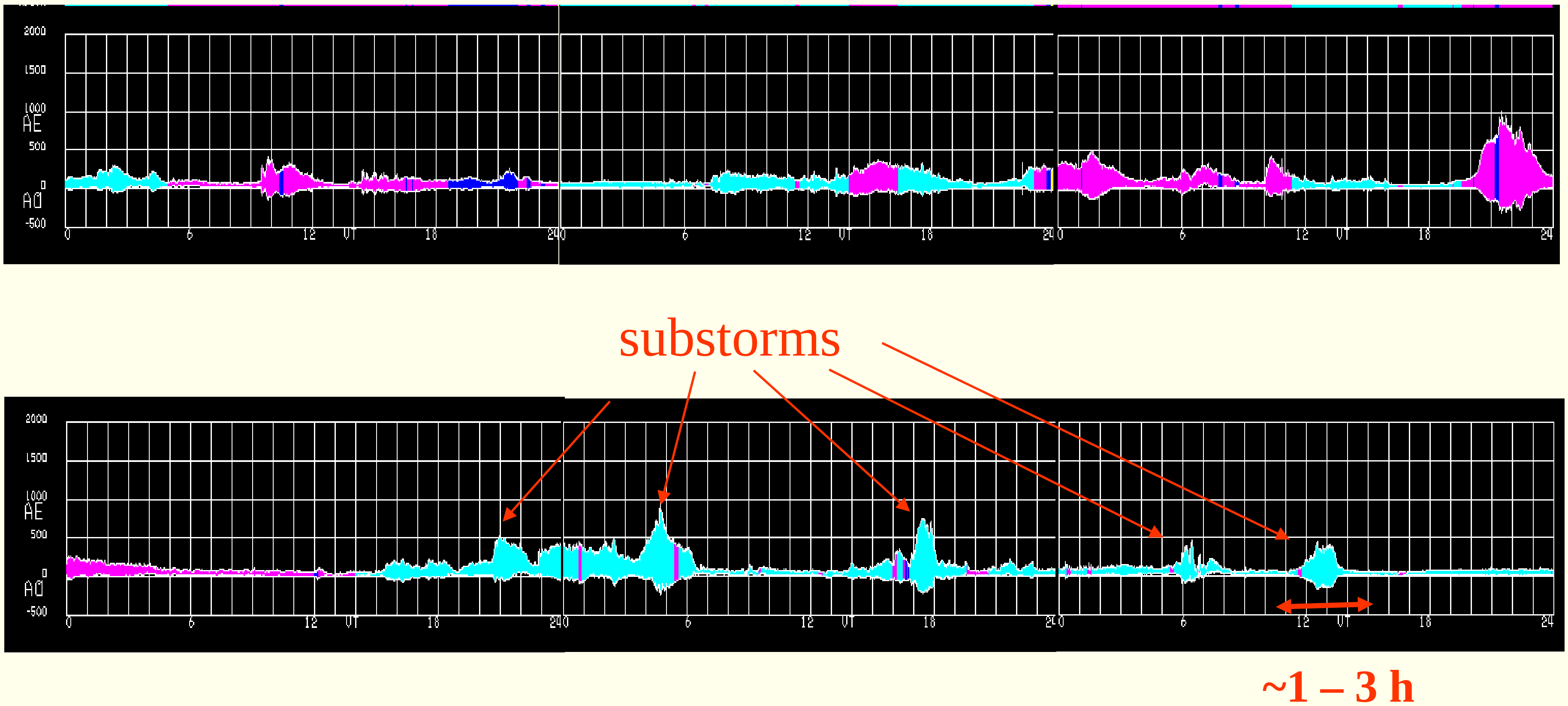
Current takes another direction – through the ionosphere!

Substorm Current Wedge (SCW)



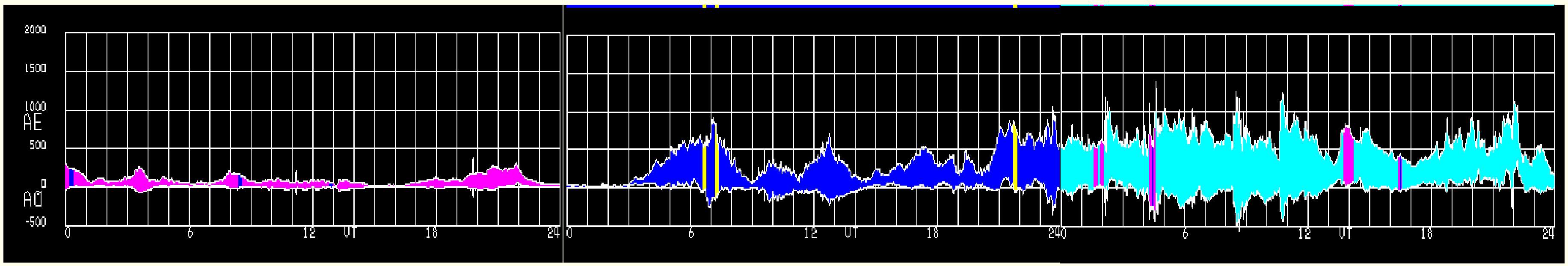
Auroral Electrojet (AE) index

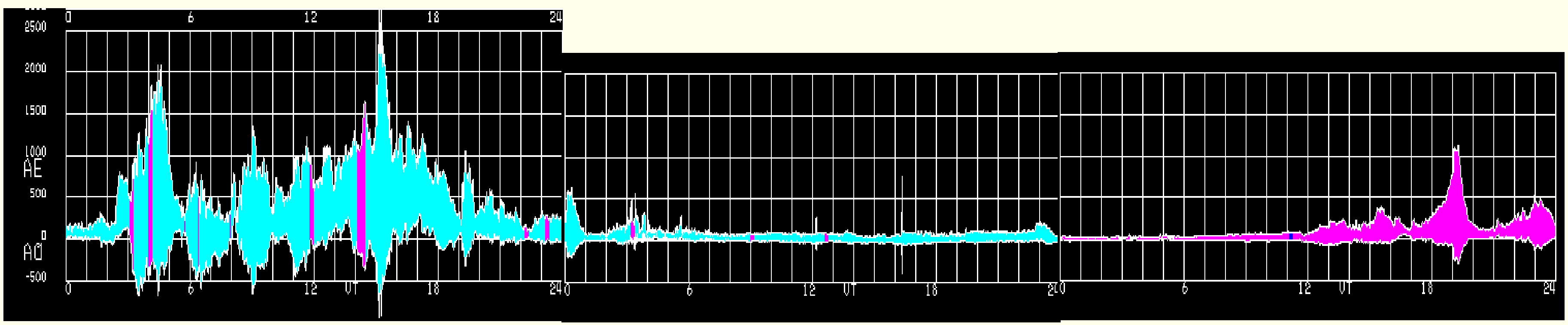
The AE index Measures the strength of the substorm current wedge (SCW), by using the information from several magnetic observatories.



Geomagnetic storms

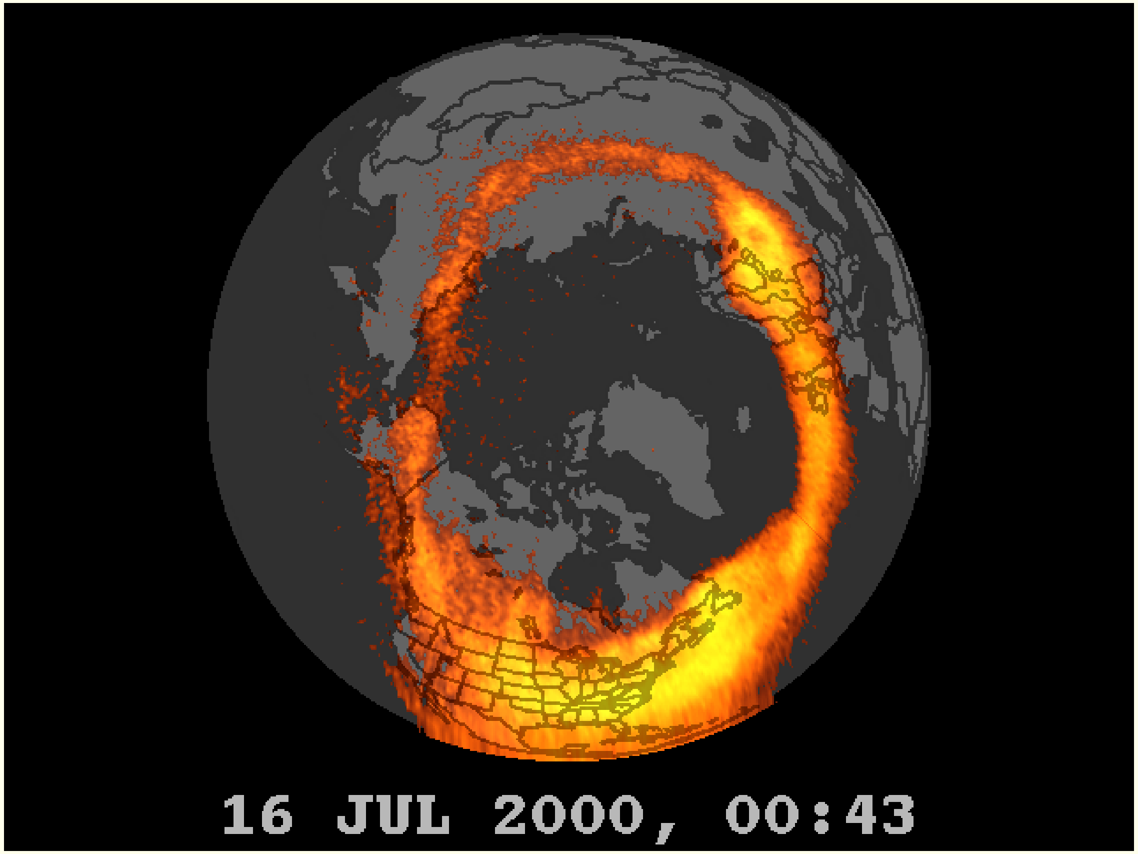
Geomagnetic storms are extended periods with southward interplanetary magnetic field (IMF) and a large energy input into the magnetosphere.



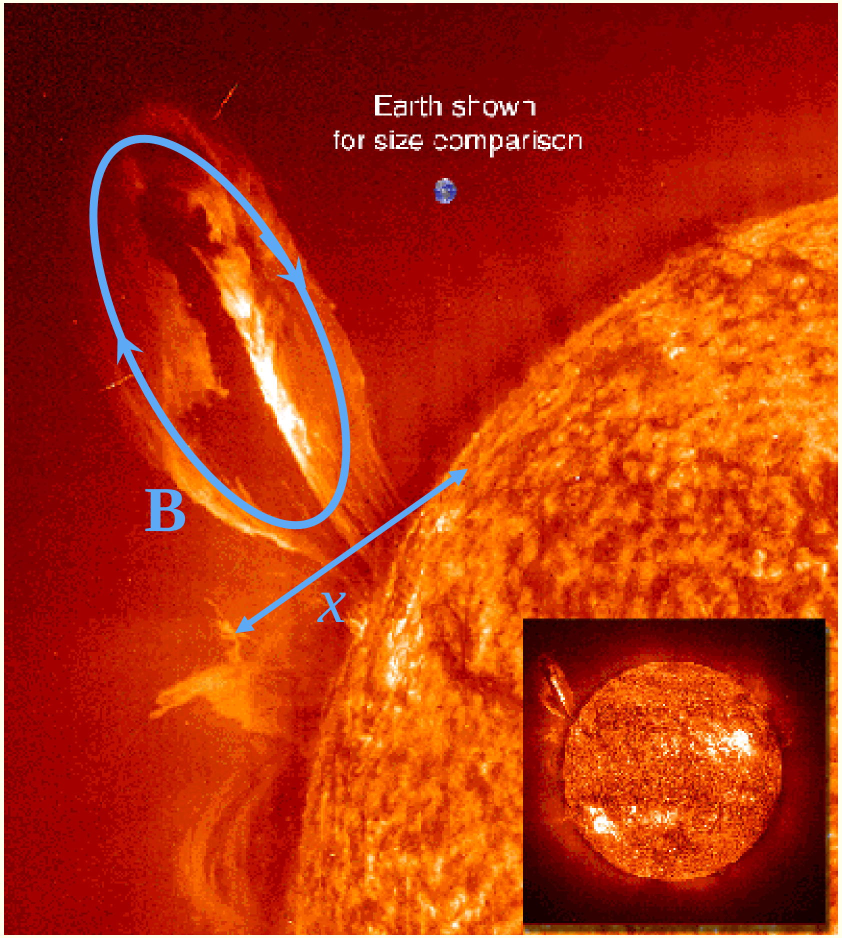


Geomagnetic storms

Auroral oval very extended

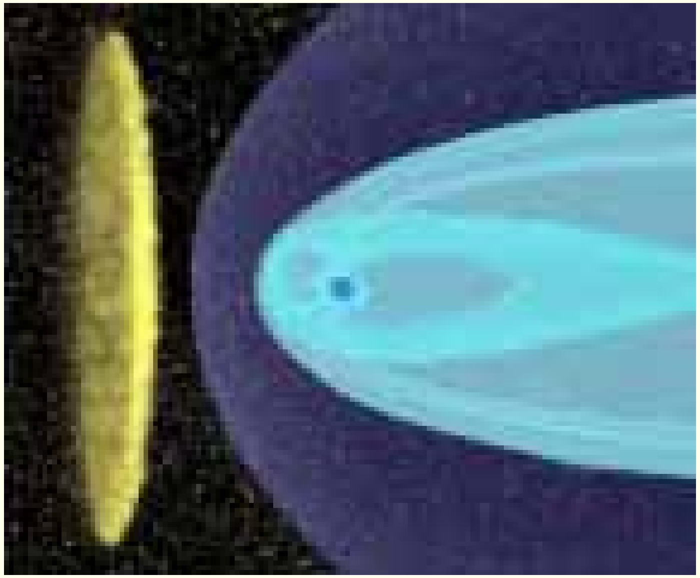


Geomagnetic storms and coronal mass ejections



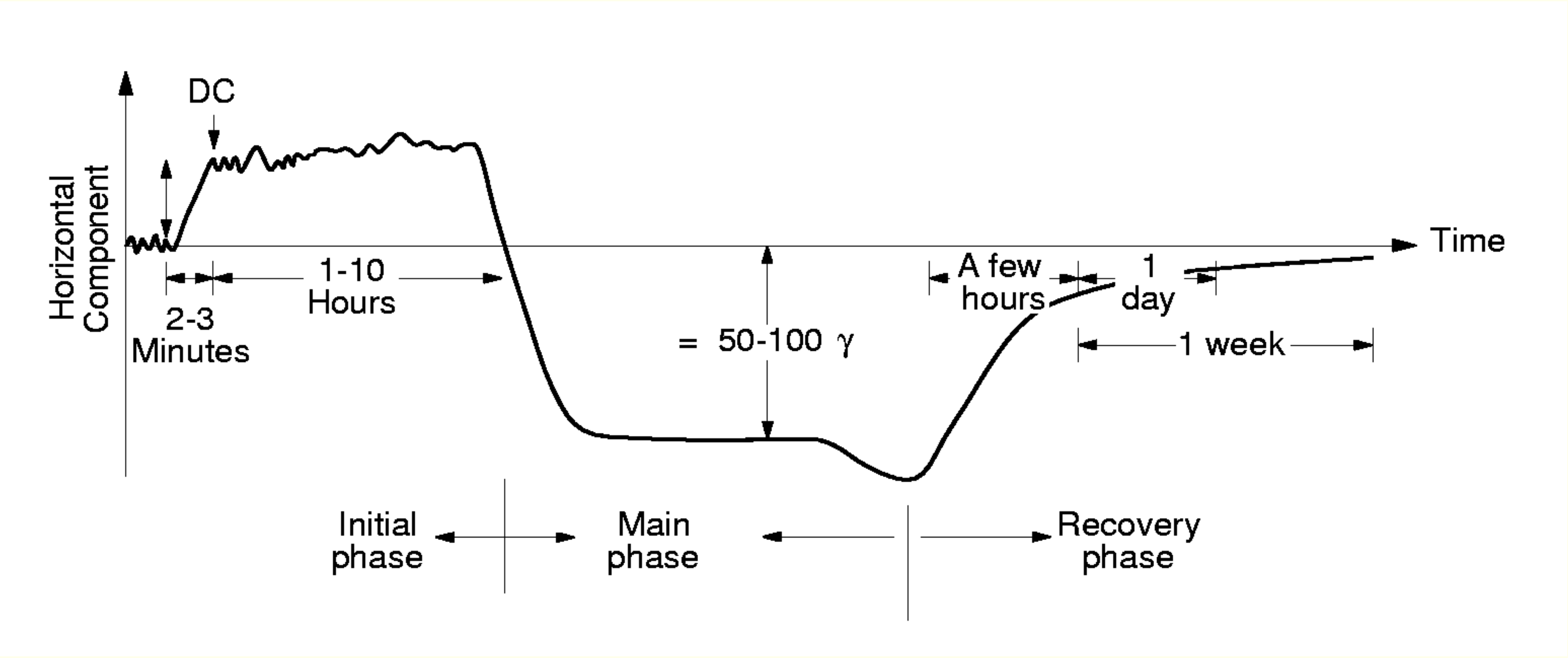
- Large geomagnetic storms are often associated with coronal mass ejections (CMEs)
- Because of their magnetic structure, they will give long periods with a constant IMF
- A typical time for a CME to pass Earth becomes $T = x/v \sim 10\ R_E/1000\ \text{kms}^{-1} \sim 60$ h

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

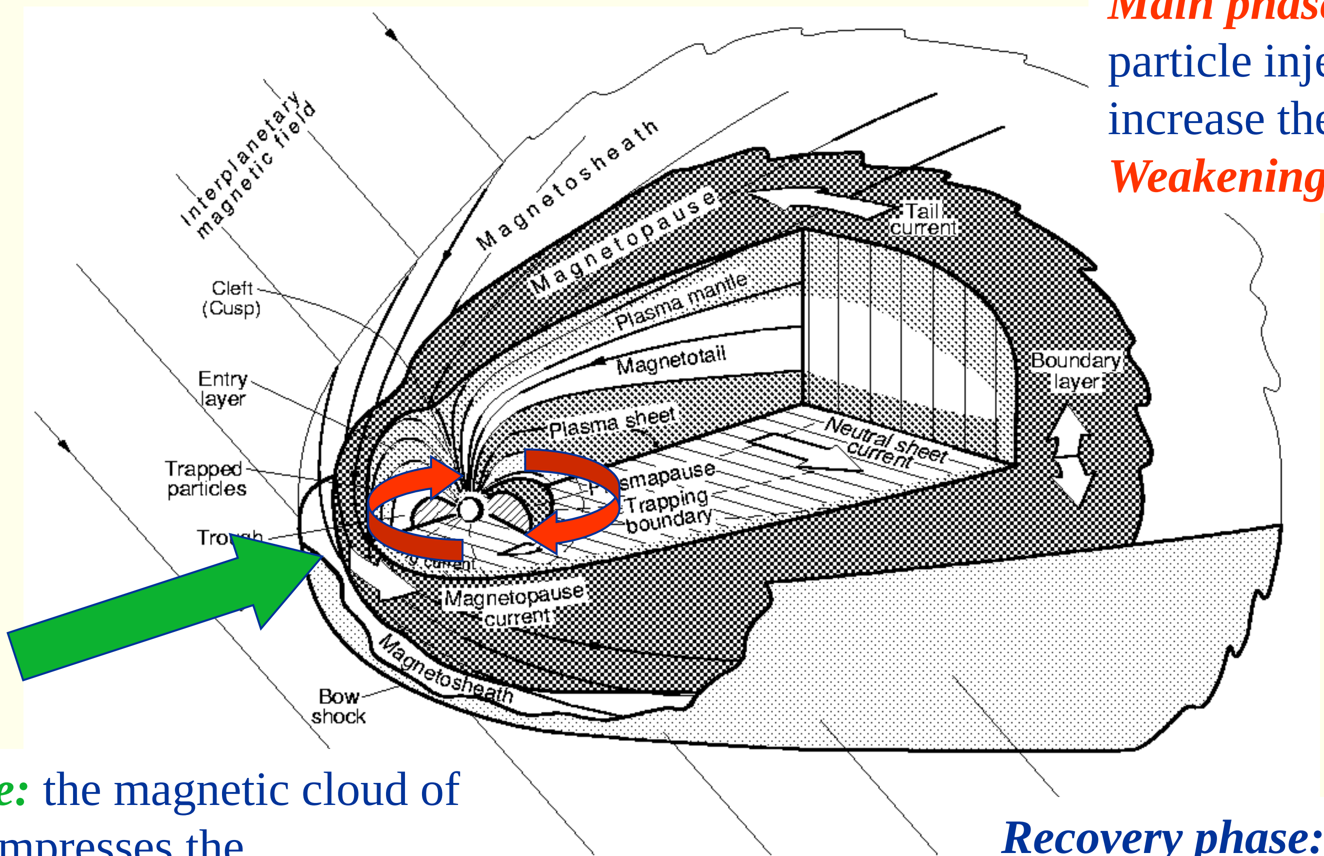


Geomagnetic storms - phases

Magnetogram



Geomagnetic storms - phases

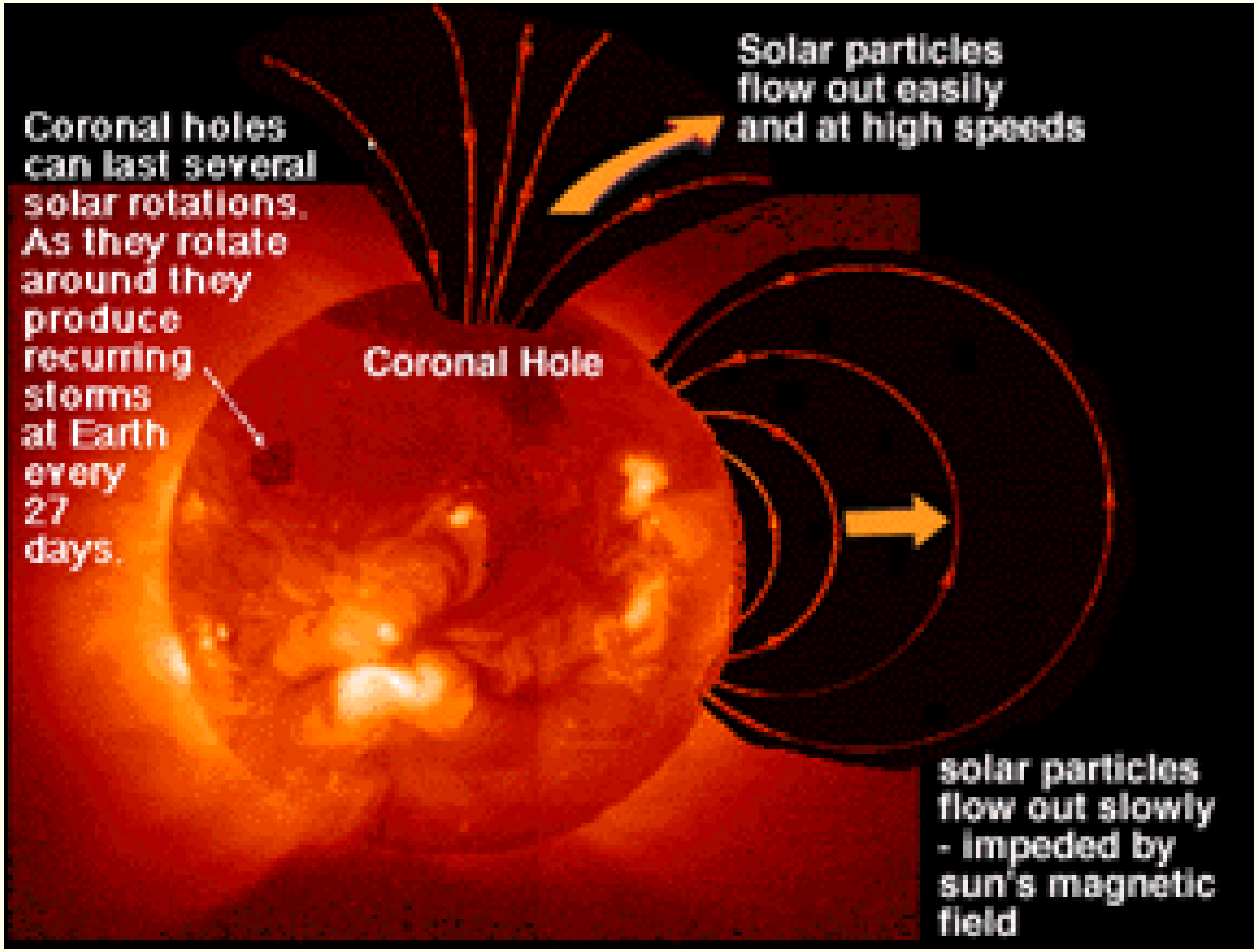


Main phase: Several particle injections increase the ring current.
Weakening of B

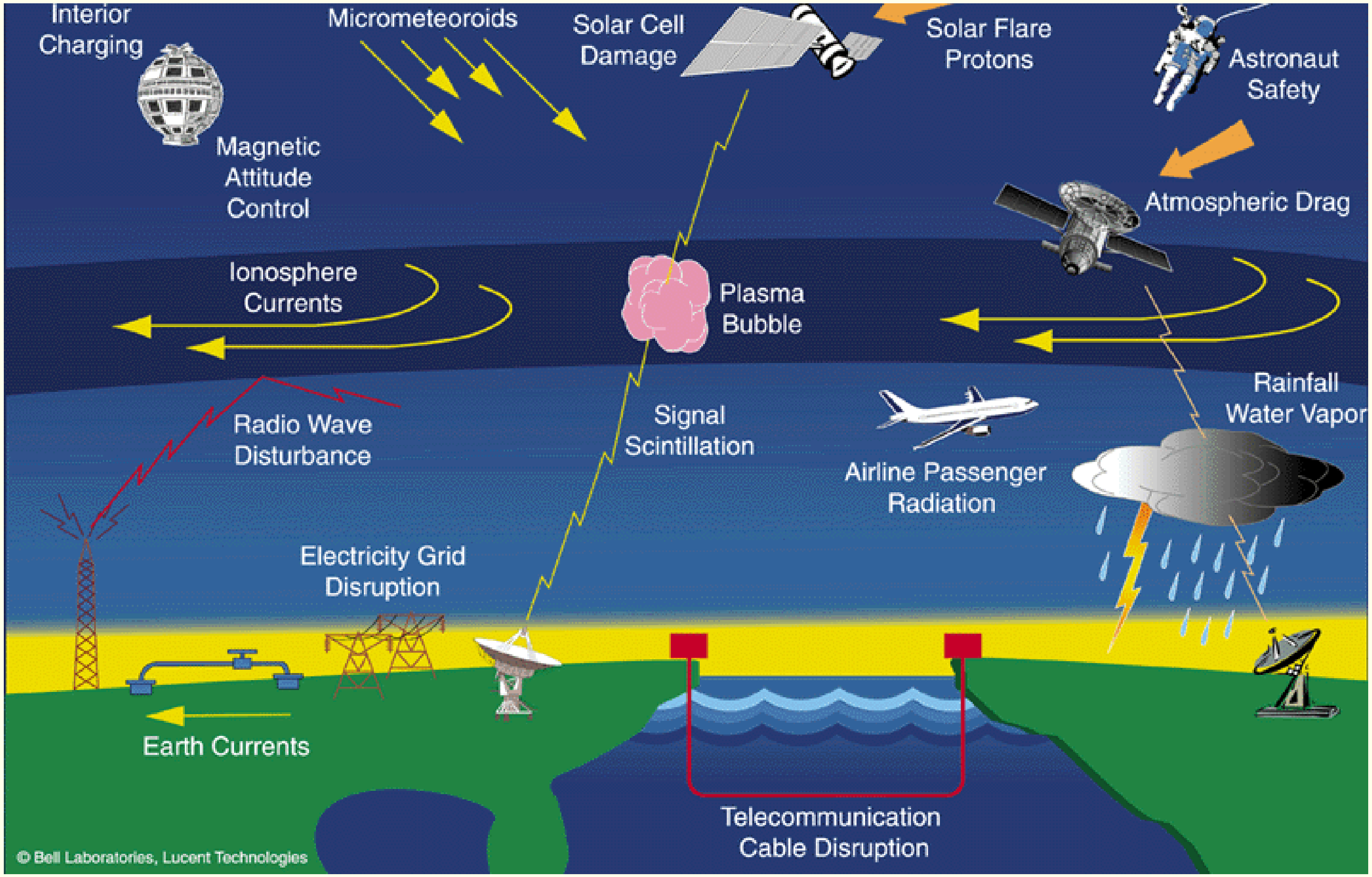
Initial phase: the magnetic cloud of the CME compresses the geomagnetic field.
Increase of B

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

Periodic geomagnetic activity

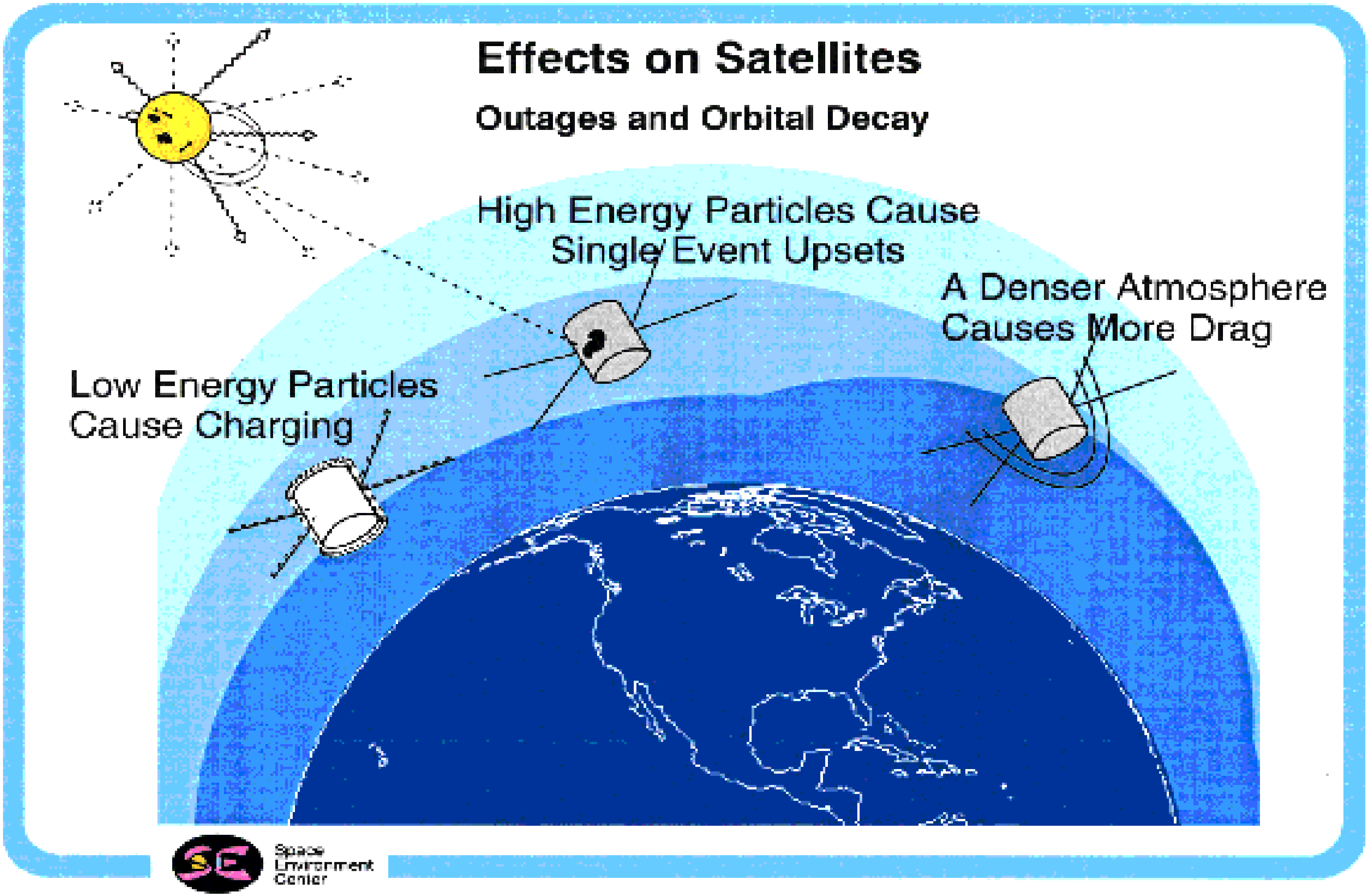


Space weather : consequences of solar and geomagnetic activity



"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

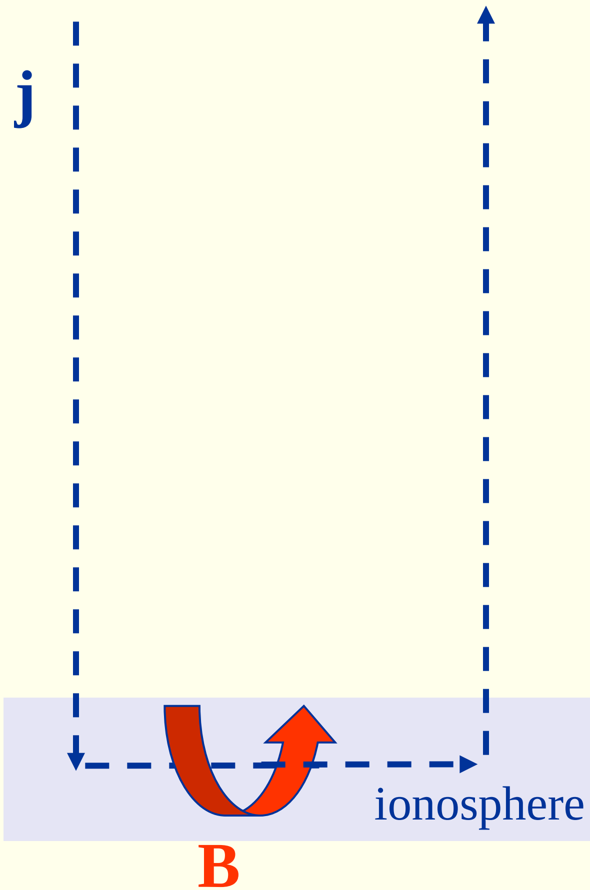

Effects on Satellites
Outages and Orbital Decay
High Energy Particles Cause
Single Event Upsets
A Denser Atmosphere
Causes More Drag
Low Energy Particles
Cause Charging
Space
Environment
Center

Damage To Solar Panels

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

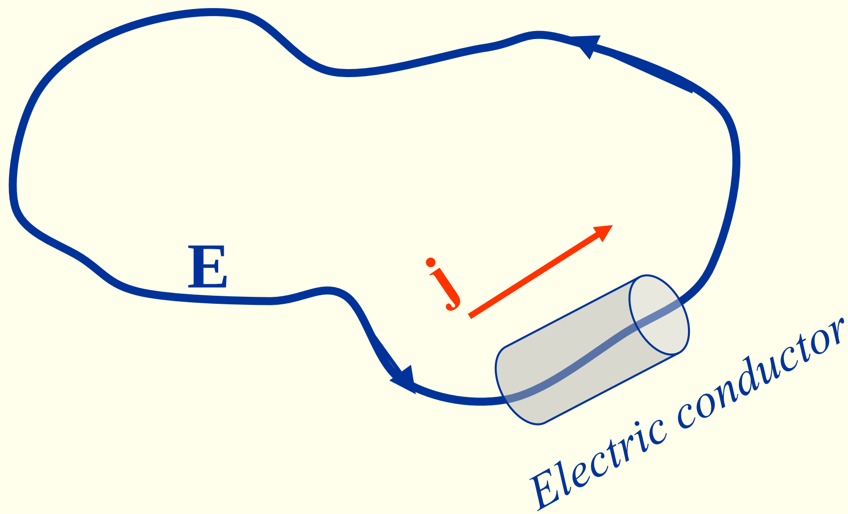
The damage is done by energetic particles which penetrate the surface of the panel and deposit a significant amount of energy inside the solar cells. This displaces the atoms within the cells and causes a loss in efficiency.

GIC – Geomagnetically Induced Currents



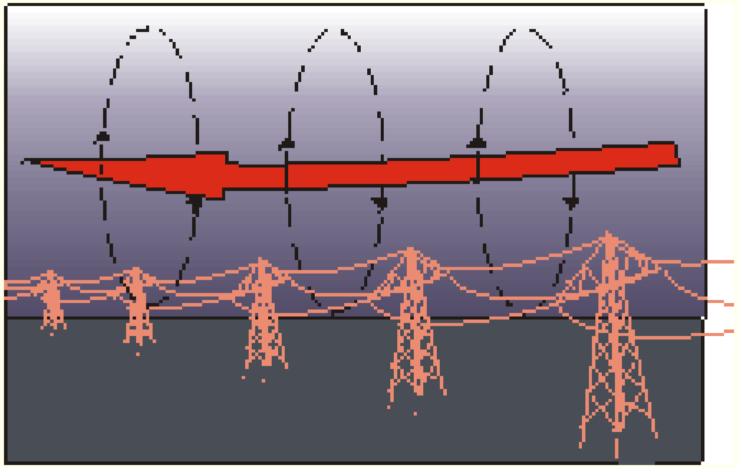
$$\frac{\partial B}{\partial t} = -\nabla \times \mathbf{E}$$

Faraday's law



GIC – Geomagnetically Induced Currents

Can damage electric power grids

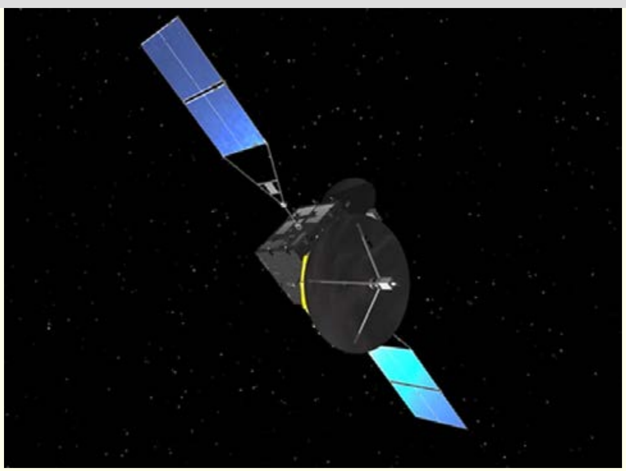


Induced currents is pipelines increase corrosion.

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?

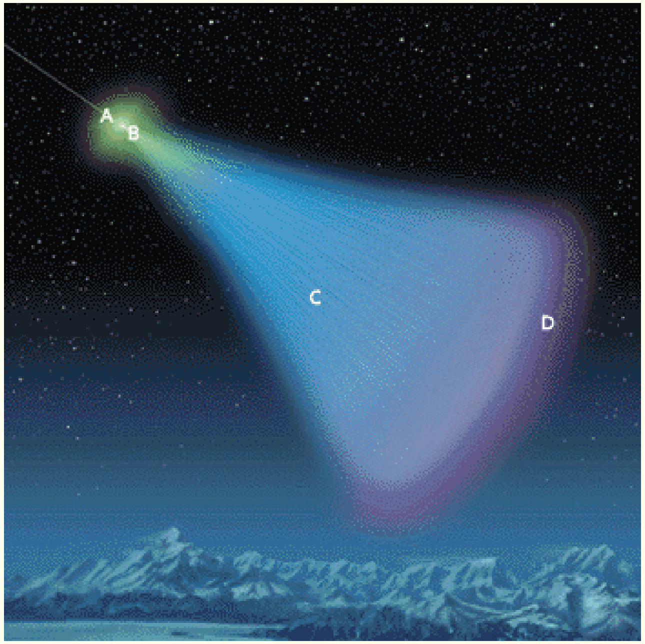
Cosmic rays (= cosmic radiation)

Primary cosmic radiation

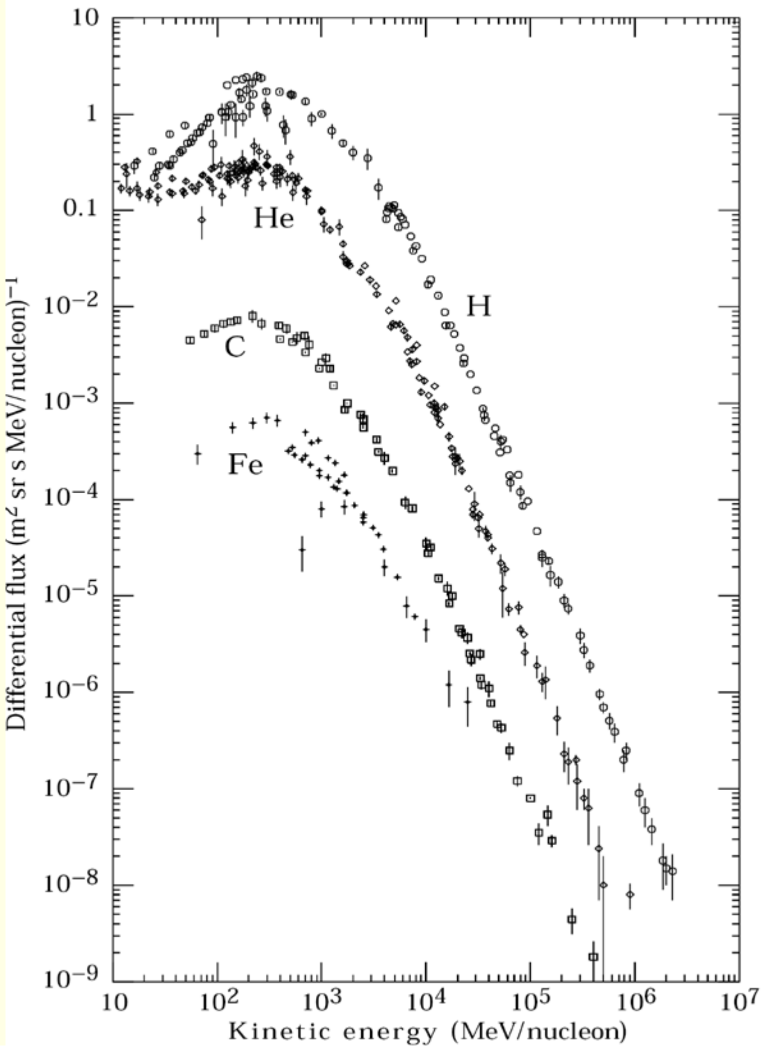
Extremely energetic particles ($>10^8$ eV)

- Galactic cosmic rays
- Solar ‘cosmic rays’ (Solar Energetic Particles)

Secondary cosmic radiation



Composition and spectrum of galactic cosmic radiation

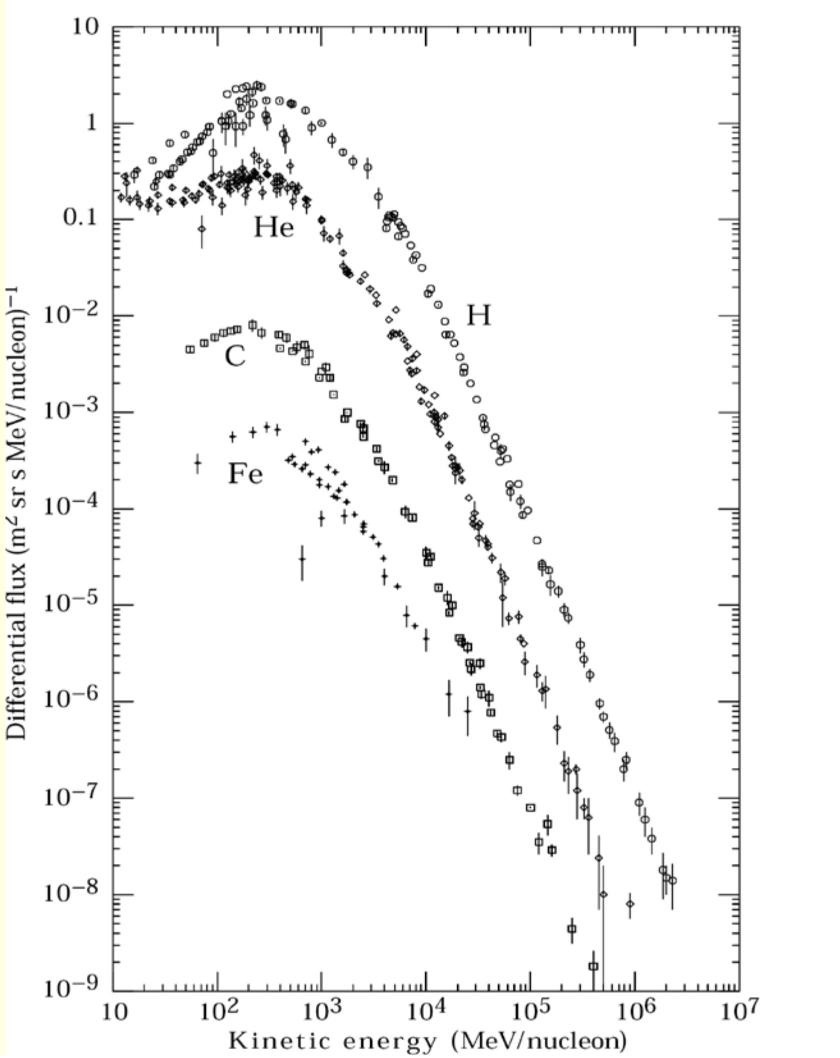


Simpson, 1983.

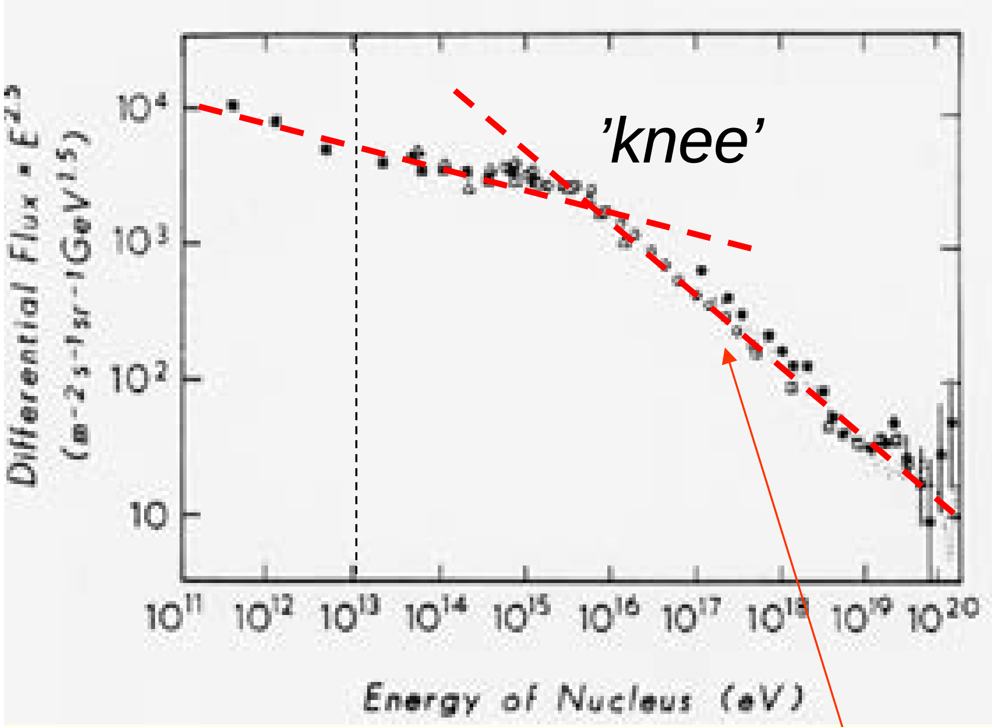
83 % protons
13 % alpha particles
3 % electrons
1 % other nuclei

All cosmic ray particles are fully ionized

Spectrum of galactic cosmic radiation

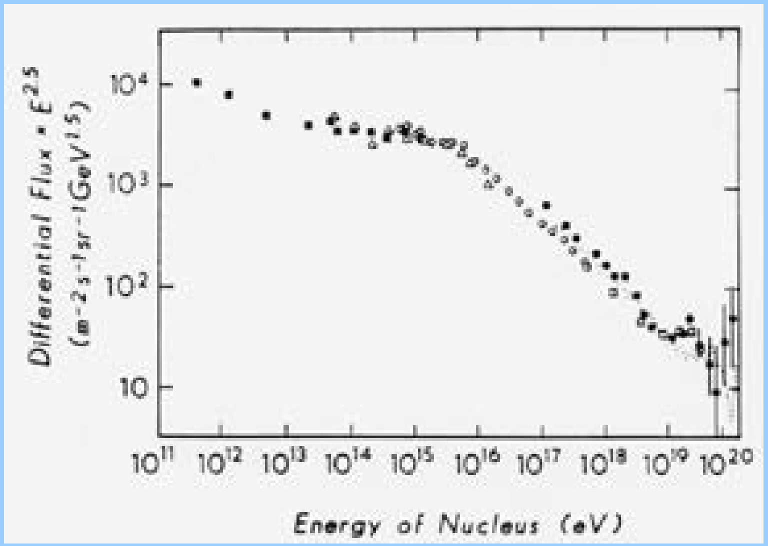


Simpson, 1983.



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