Last lecture (6)

- Particle motion in the magnetosphere
- Magnetospheric size (standoff distance)

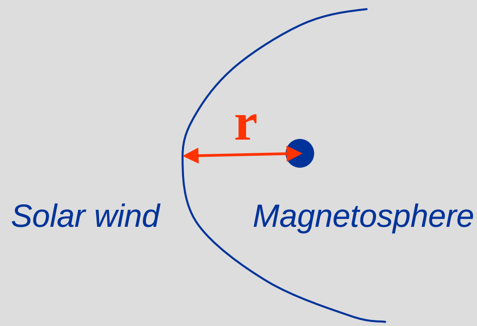
Today's lecture (7)

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

Today

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

Magnetopause "stand-off distance"



Dynamic pressure: $p_d = \rho_{SW} v_{SW}^2$

Magnetic pressure: $p_B = \dfrac{1}{2\mu_0} B^2$

Dipole field strength (in equatorial plane): $B = \dfrac{\mu_0 a}{4\pi} \dfrac{1}{r^3}$

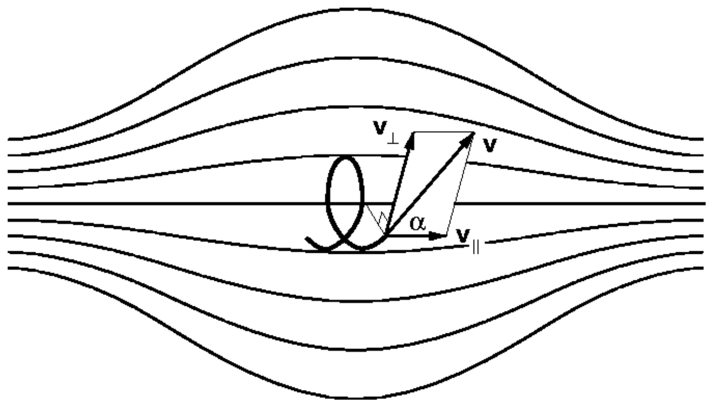
$$p_d = p_B \Rightarrow \qquad \rho_{SW} v_{SW}^2 = \left[\frac{\mu_0 a}{4\pi} \frac{1}{r^3} \right]^2 / 2\mu_0 \Rightarrow$$

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

$a = 8 \times 10^{22}$ Am^2, $v = 500$ km/s, $\rho_{SW} = 10^7 \times 1.7 \times 10^{-27}$ kg/m^3:

r = 7 R_e (1 R_e = 6378 km)

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

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

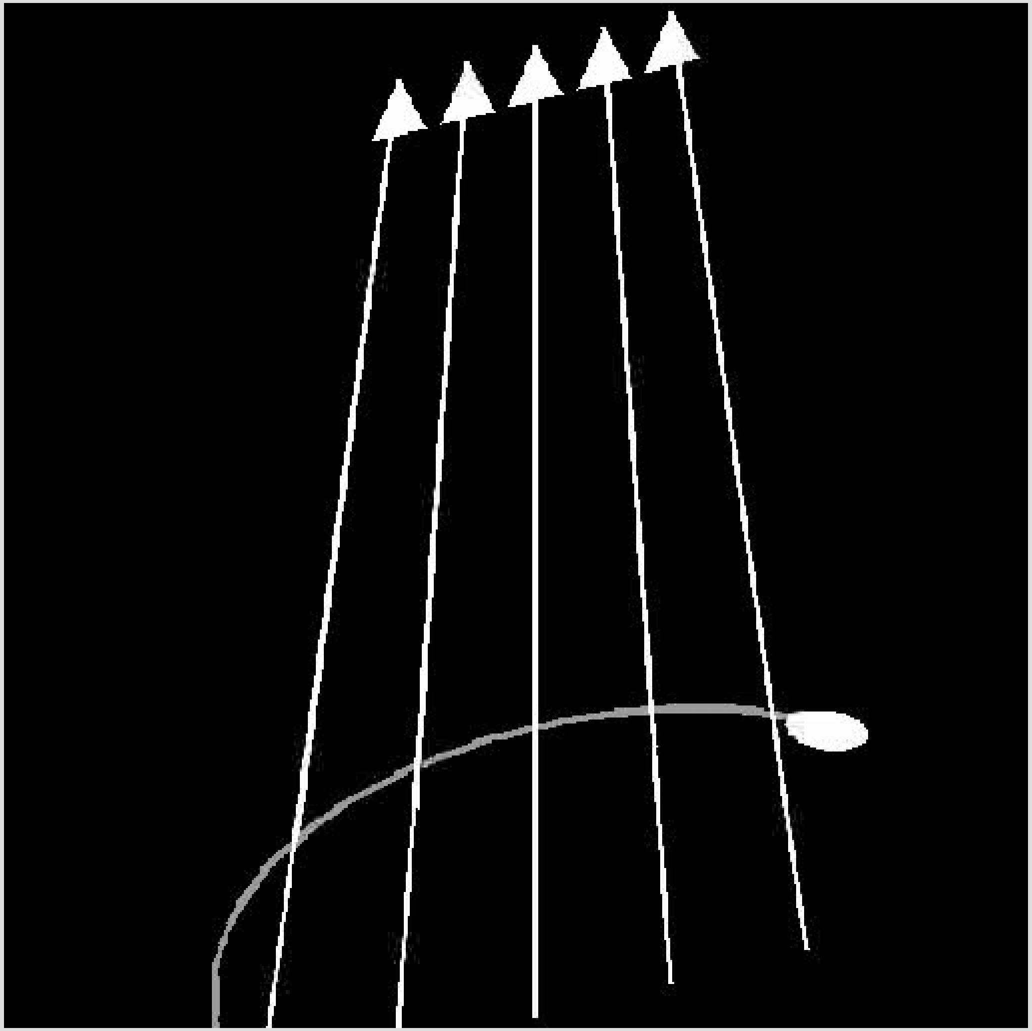
$$\alpha > \alpha_{lc} = \arcsin\sqrt{B/B_{max}}$$

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

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

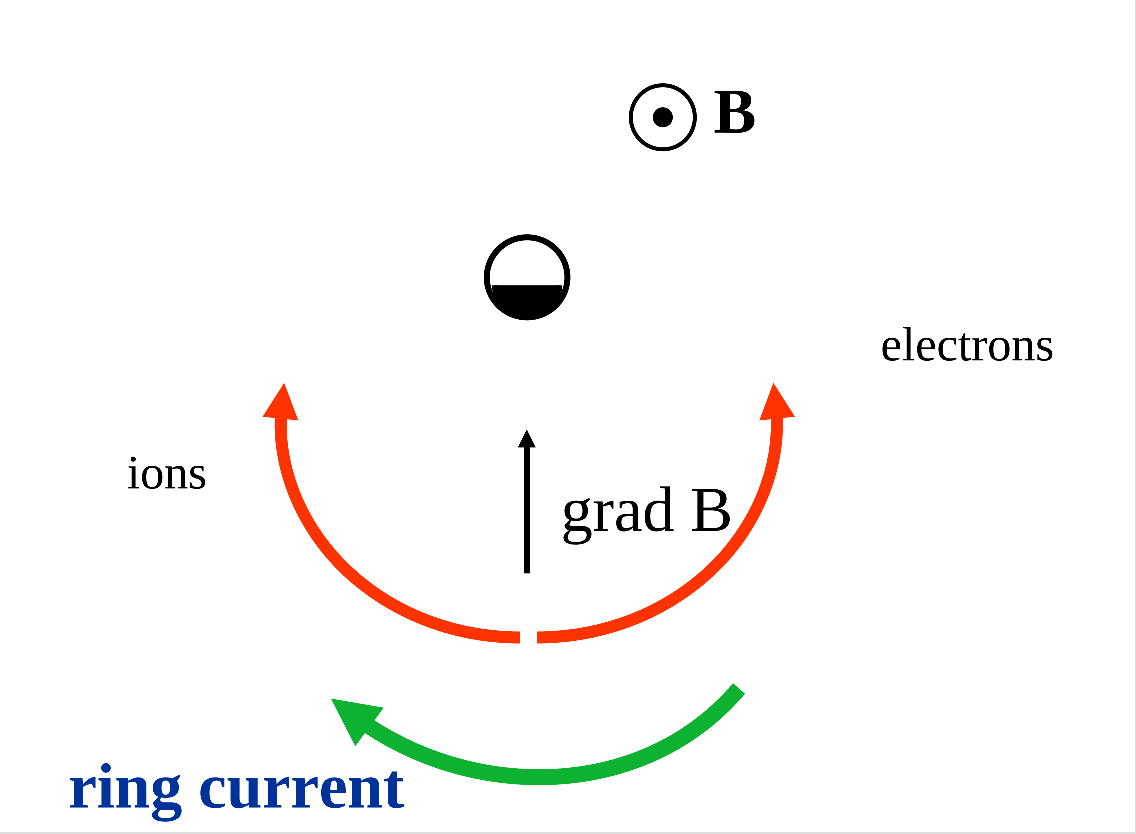
Particles in ***loss cone*** : $\alpha < \alpha_{lc}$

Magnetic mirror

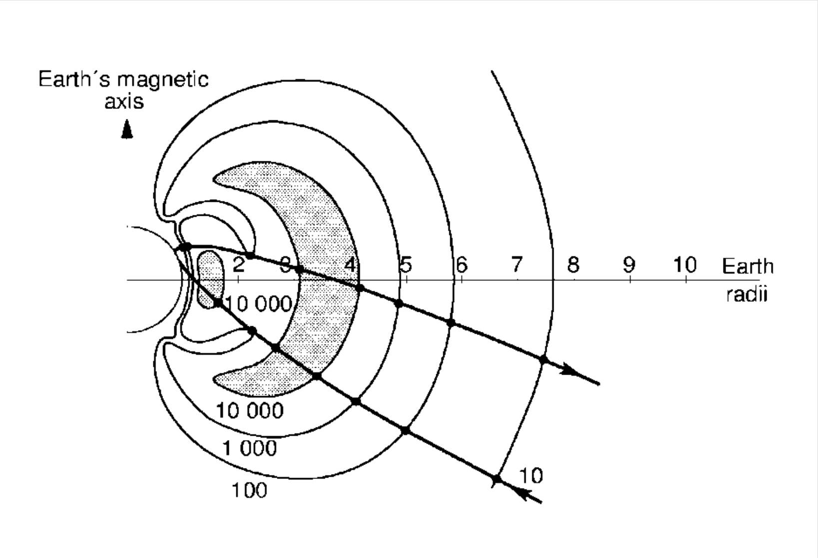


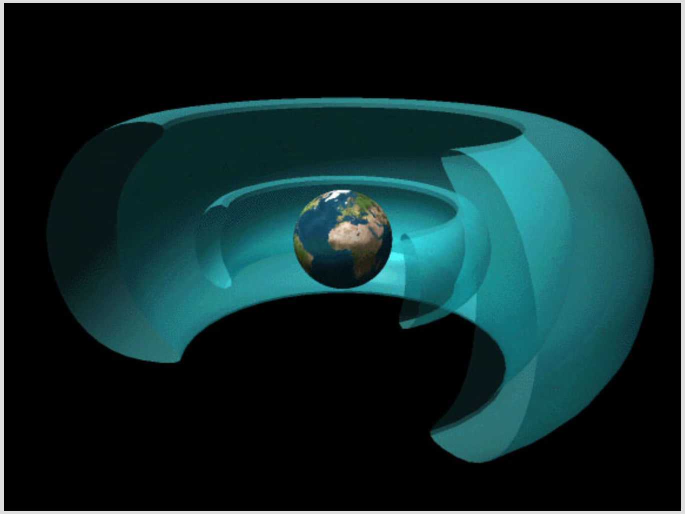
Ring current and particle motion

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



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

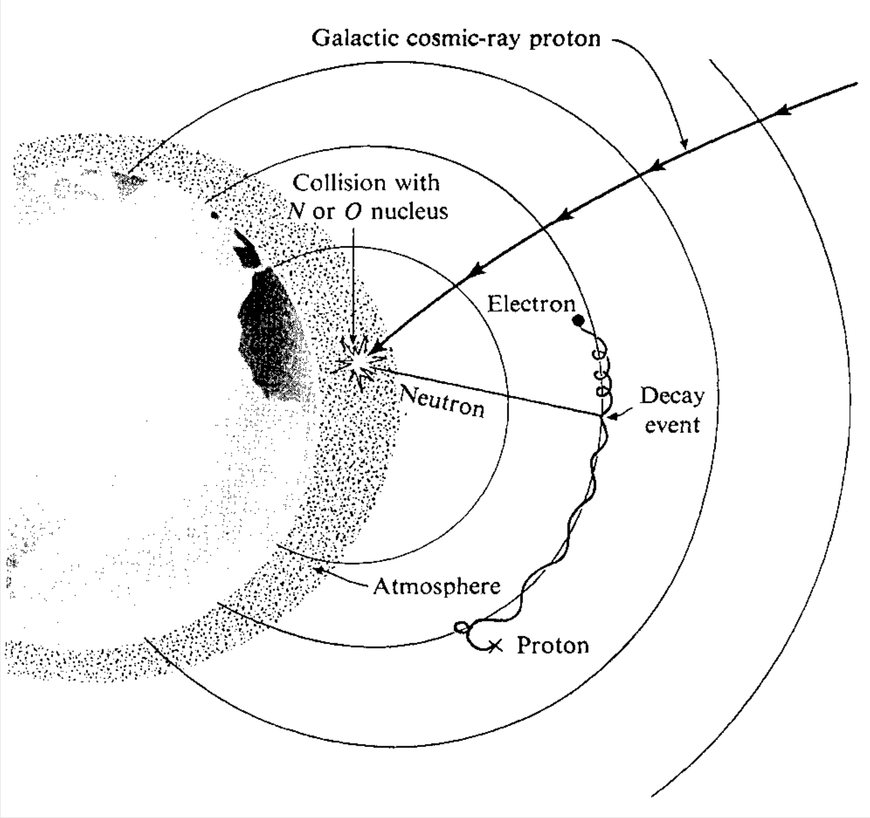


Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

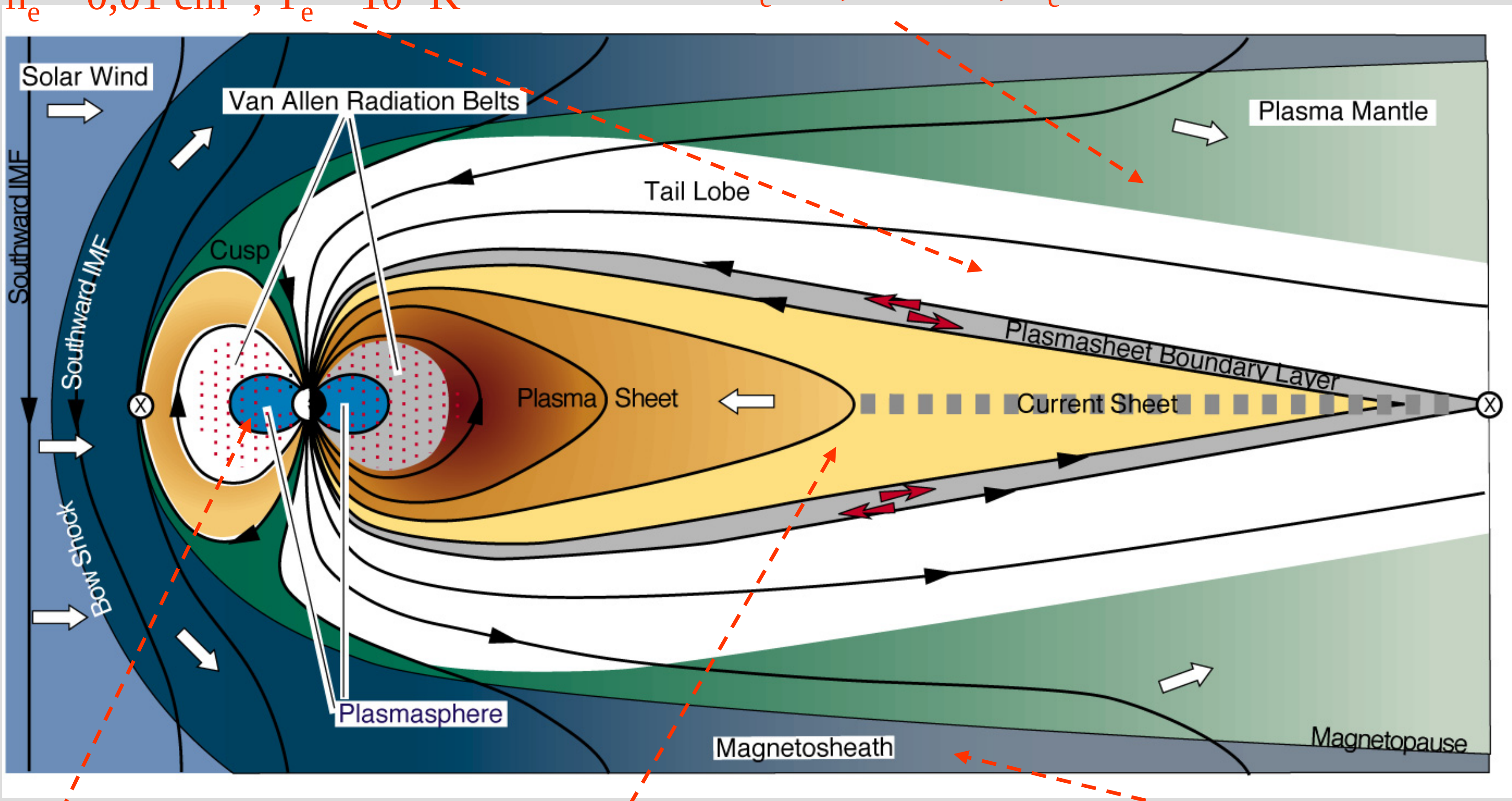
Collisions between cosmic ray particles and the Earth create new particles. Among these are neutrons, that are not affected by the magnetic field. They decay, soom eof them when they happen to be in the radiation belts. The resulting protons and electrons are trapped in the radiation belts.

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

Magnetospheric structure

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

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

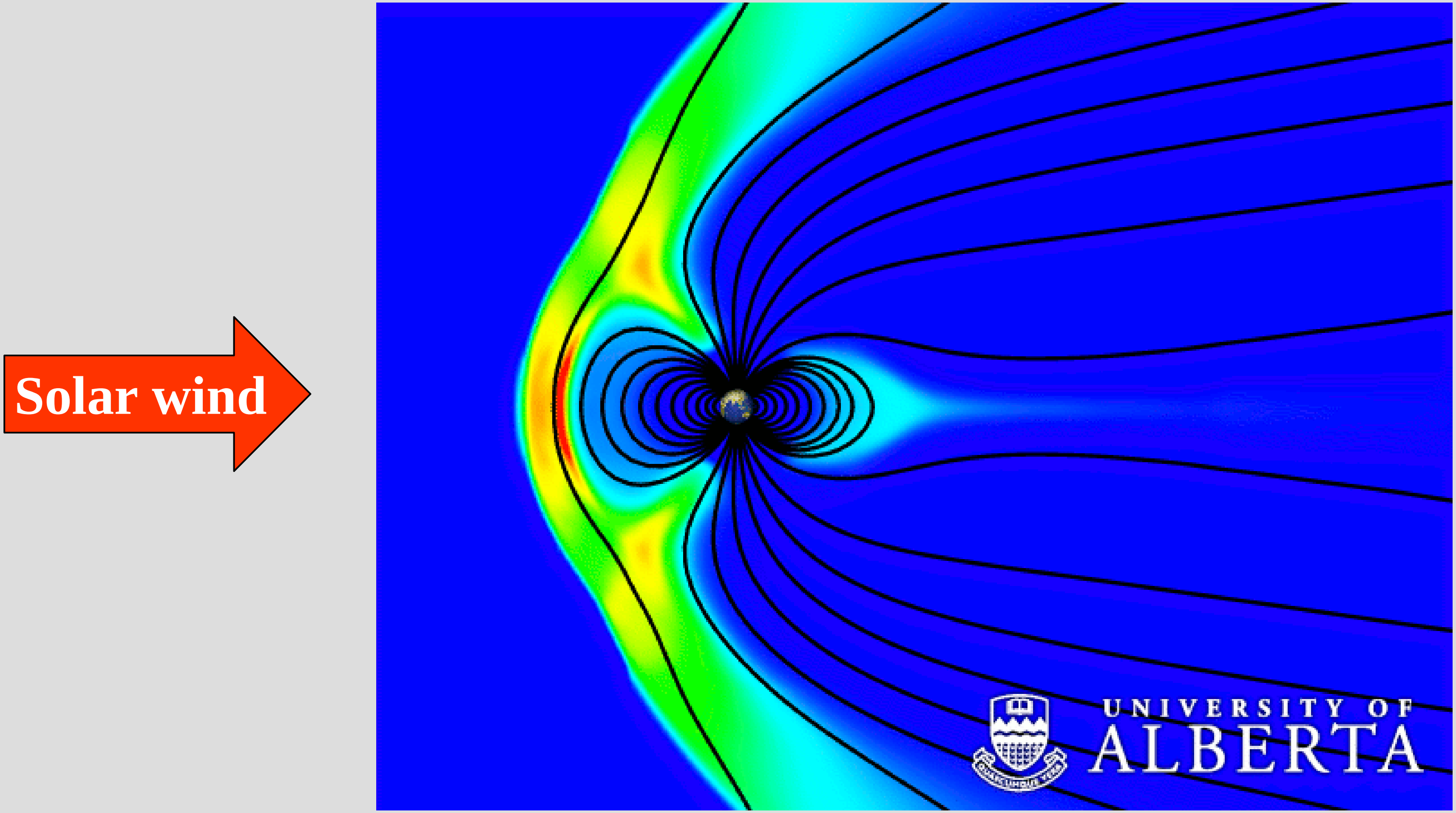


plasmasphere:
$n_e \sim 10\text{-}100\ cm^{-3}$, $T_e \sim 1000$ K

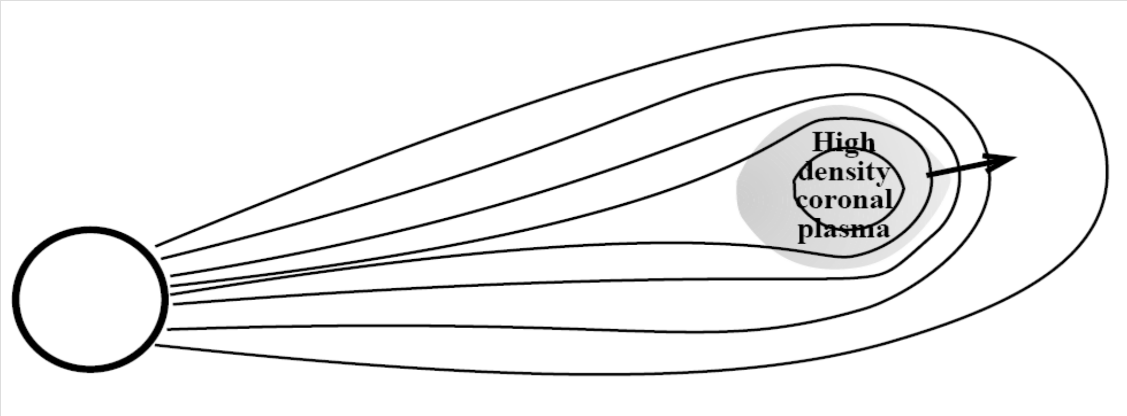
plasma sheet:
$n_e \sim 1\ cm^{-3}$, $T_e \sim 10^7$ K

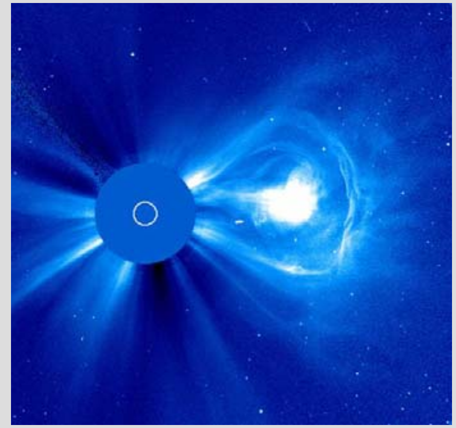
magnetosheath:
$n_e \sim 5\ cm^{-3}$, $T_e \sim 10^6$ K

Reconnection and plasma convection

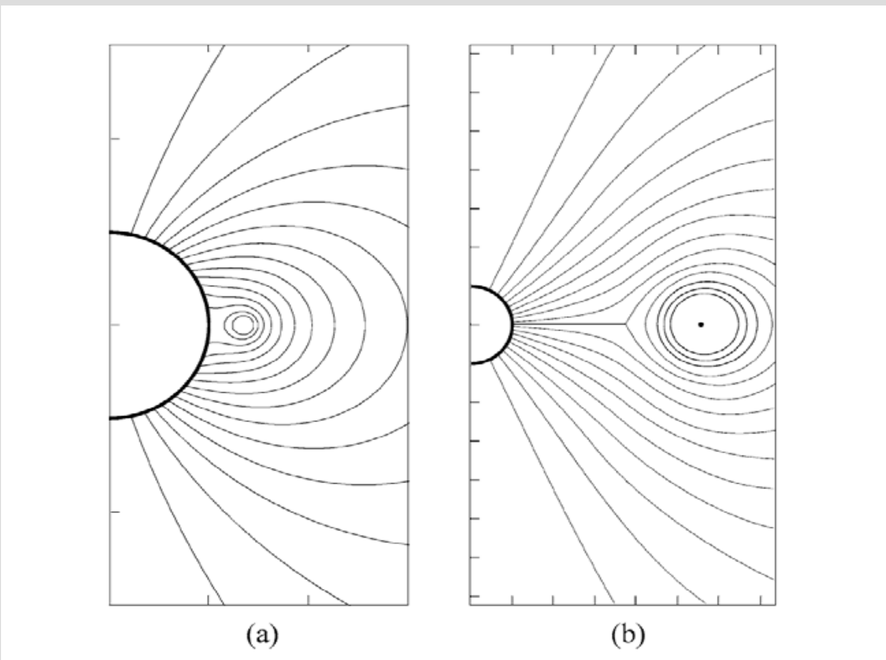


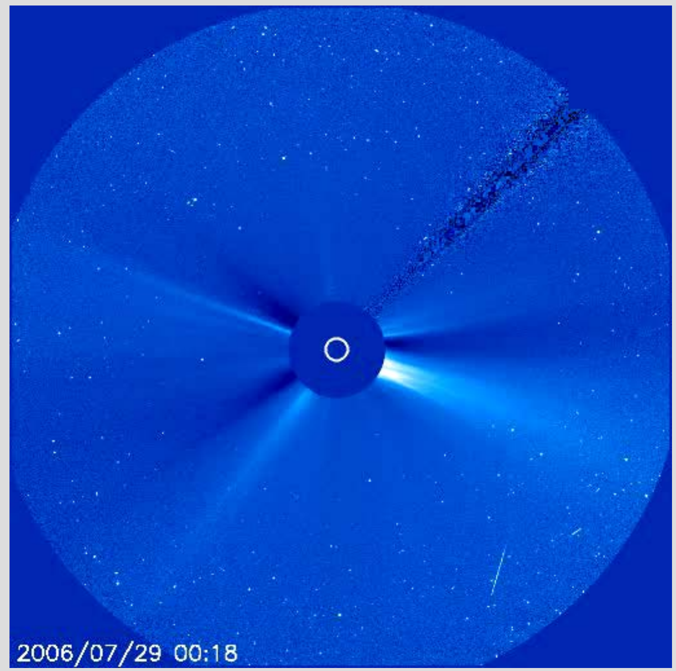
CME - magnetic connection to sun





flux rope CME

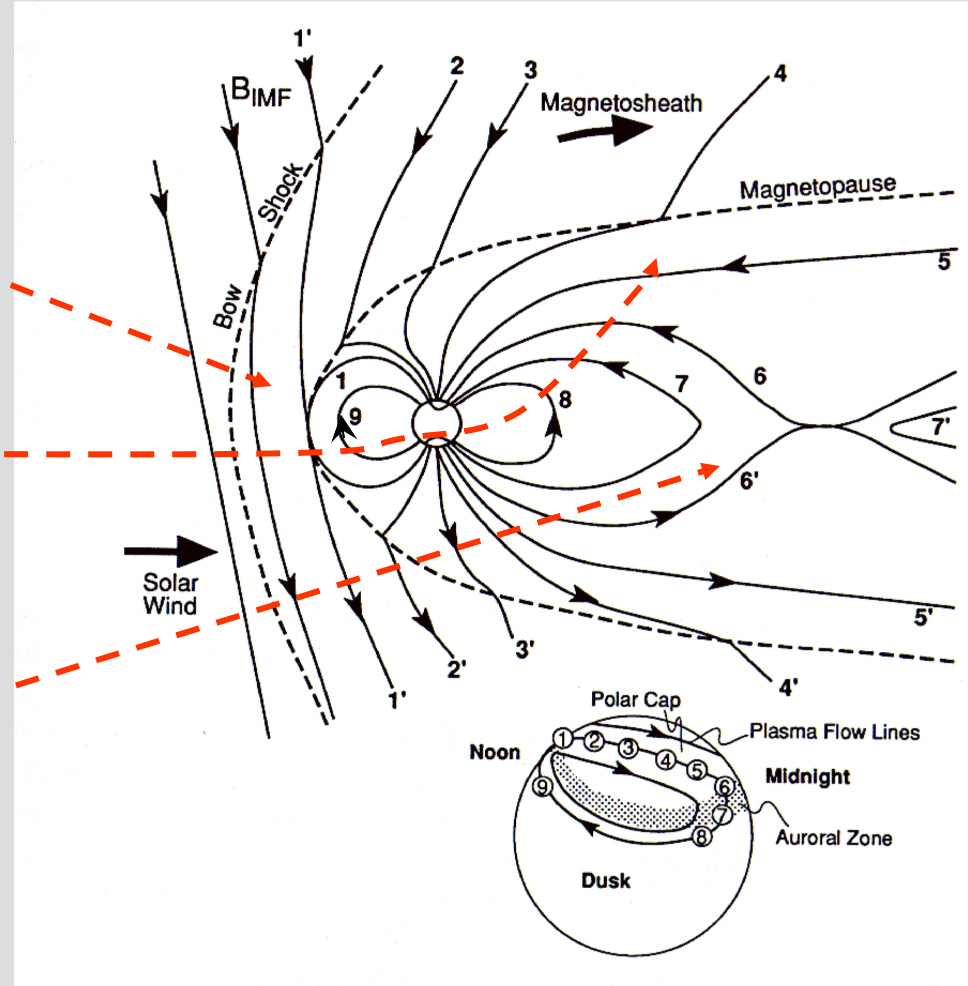




'smoke ring' CME

Reconnection and 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 do the magnetospheres of the other planets look like?

Planetary magnetospheres

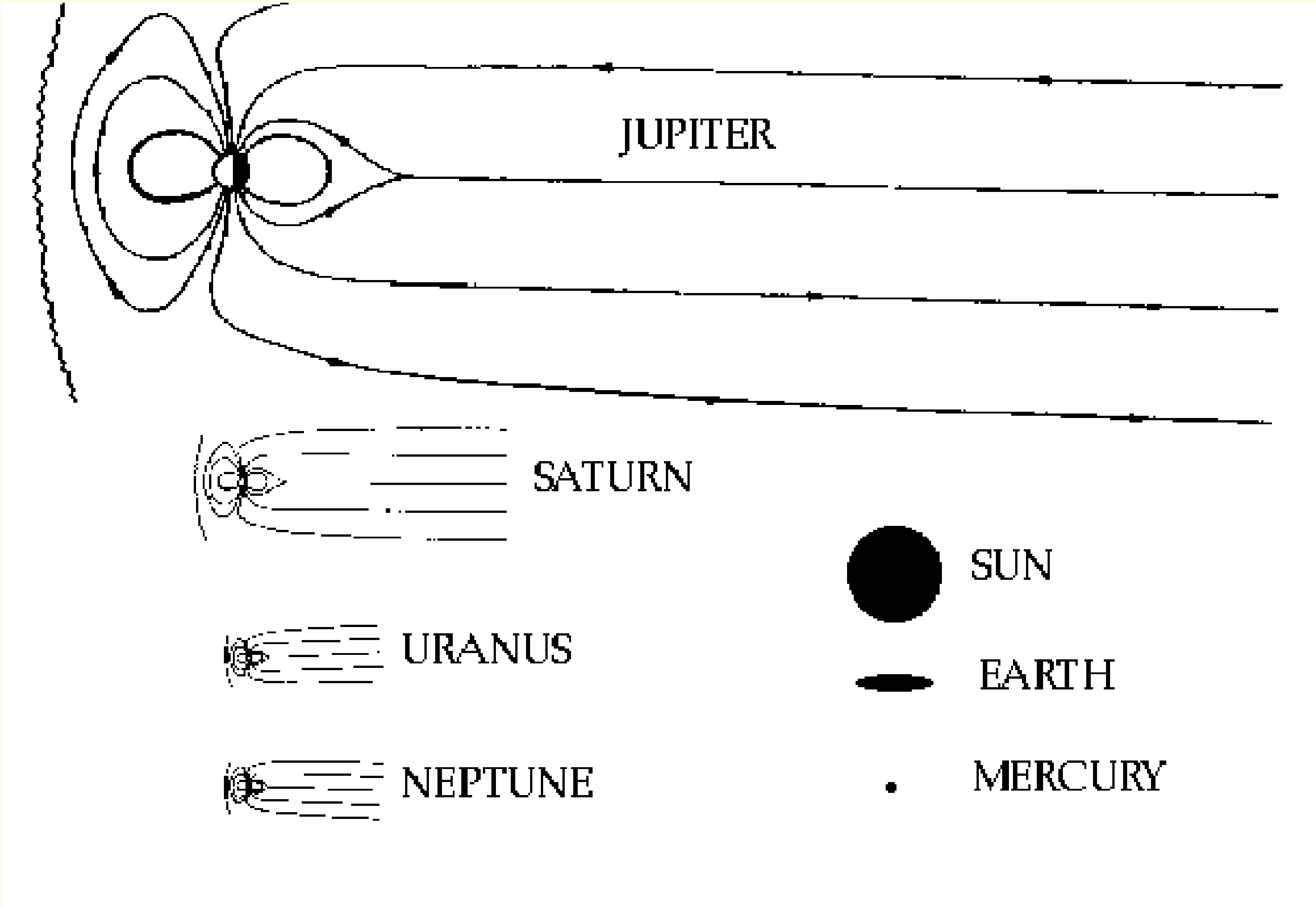
	Radius Earth radii	Spin period (days)	Equatorial field strength (μT)	Magnetic axis direction relative to spin axis	Polarity relative to Earth´s	Typical magneto-pause distance (planetary radii)
Mercury	0.38	58.6	0.35	10^{o}	Same	1.1
Venus	0.95	243	< 0.03	-	-	1.1
Earth	1.0	1	31	11.5^{o}	Same	10
Mars	0.53	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

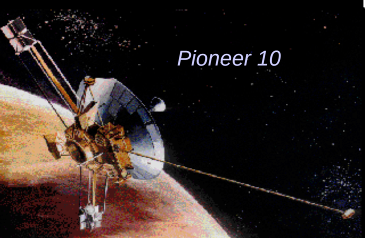
In situ observations

Space probe	Planets	Observations
Mariner 10	Mercury	*1974 – 1975*
*Messenger **	Mercury	*2008 –*
Pioneer 10,11	Jupiter, Saturn	*1973 – 1979*
Voyager 1,2	Jupiter, Saturn, Uranus, Neptune	*1977 – 1989*
Ulysses	Jupiter	*1992*
*Galileo**	Jupiter	*1995 – 2003*
*Cassini**	Jupiter, Saturn	*2004 –*
New Horizons	Jupiter	*2007*

** Orbiters*

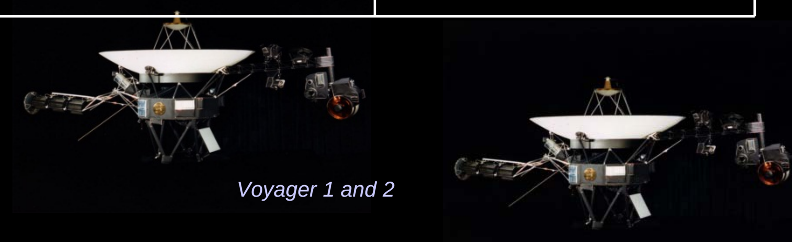
Mariner 10

Ulysses



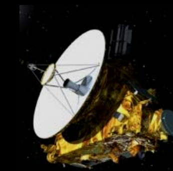
Pioneer 10

Pioneer 11



Voyager 1 and 2

Galileo



New Horizons

Messenger

Cassini

Mercury

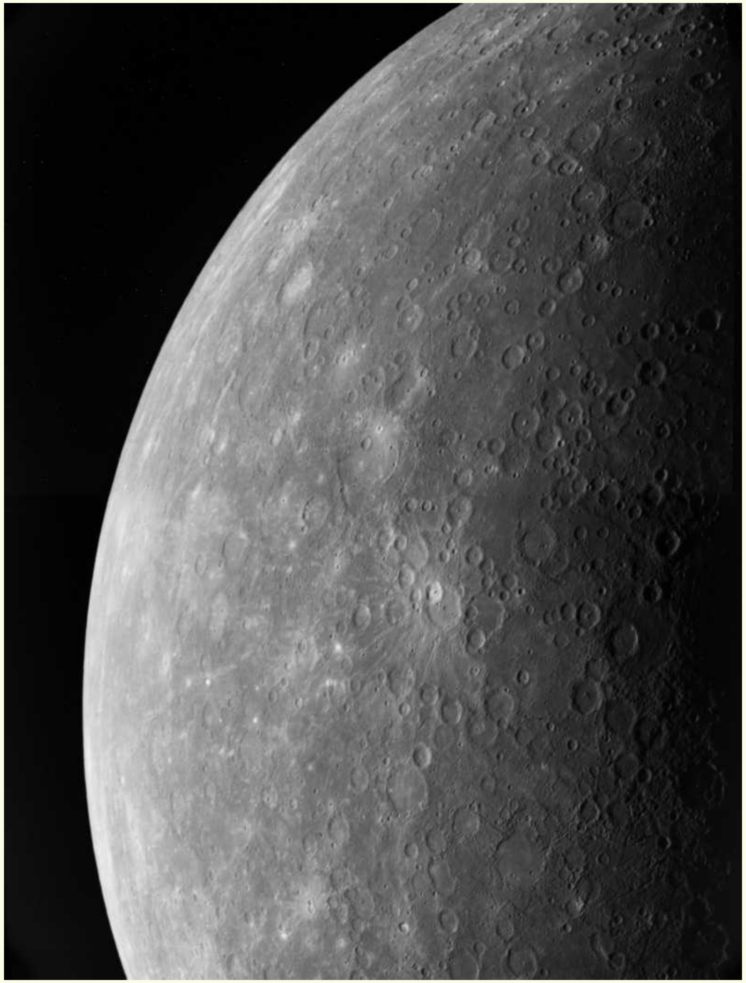
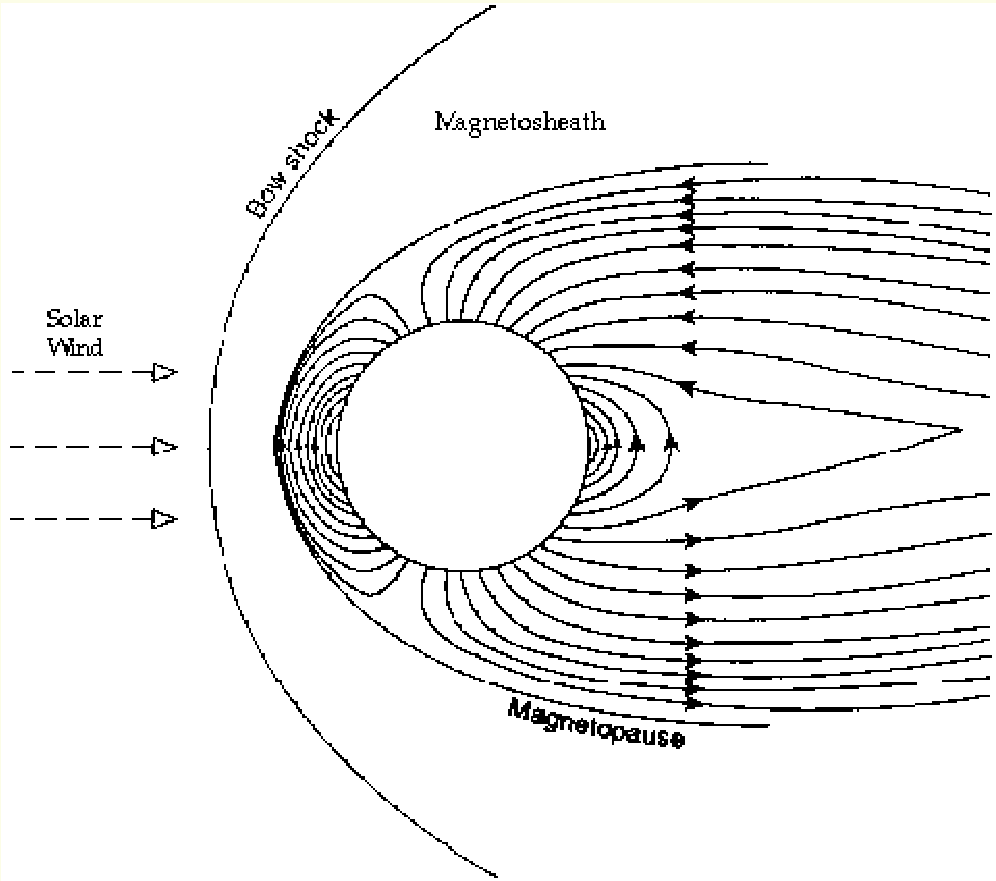


Photo from Mariner 10

- $r_M = 0{,}38\ r_E$
- $m_M = 0{,}06\ m_E$
- distance from sun: 0,39 AU
- no or extremely thin atmosphere

Mercury's magnetosphere



- rather large magnetic field
- the high solar wind density close to the sun makes the magneto-sphere very small
- no ionosphere

Venus

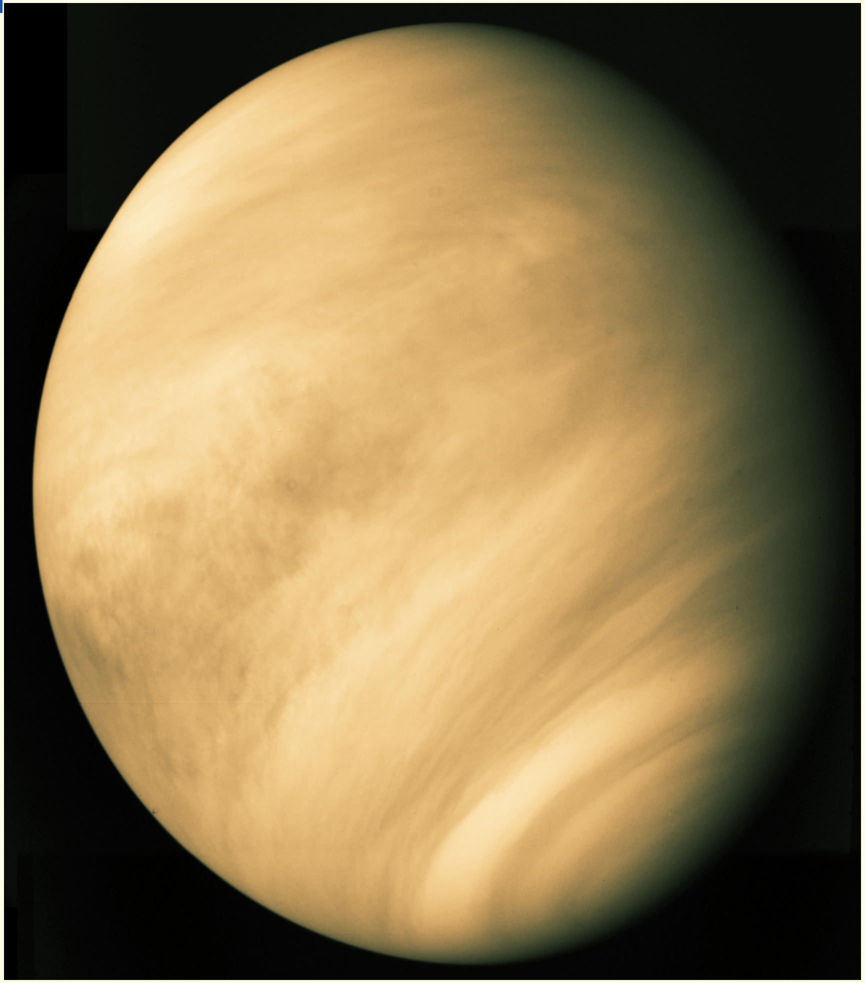
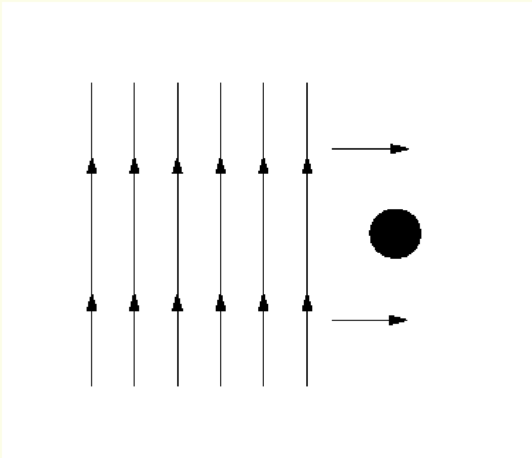


Photo from Galileo

- $r_V = 0{,}95\ r_E$
- $m_V = 0{,}82\ m_E$
- distance from sun : 0,72 AU
- very dense atmosphere
  - ~ 90 atm
  - 96% CO_2
- very weak magnetic field

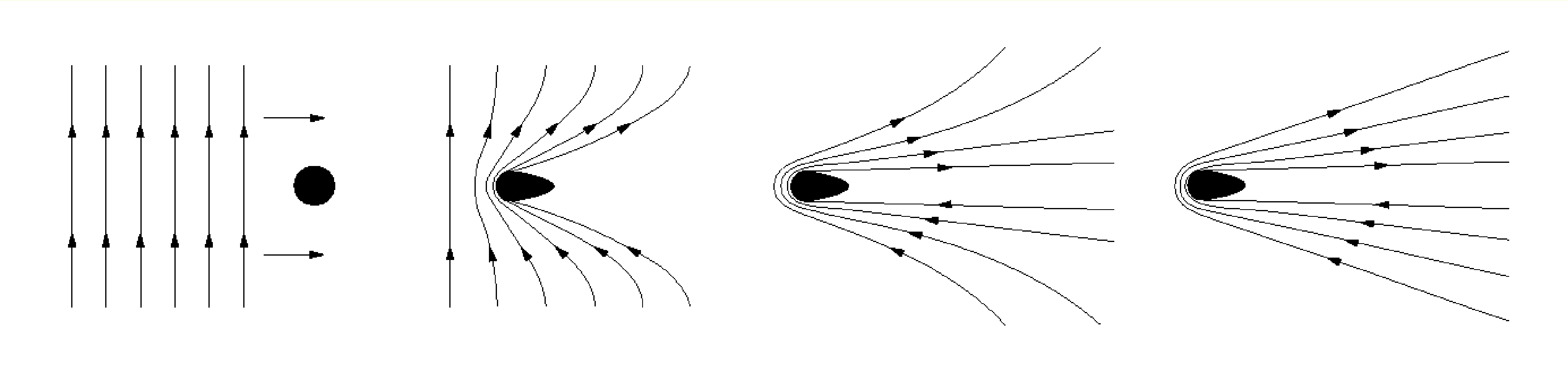
Comets, induced magnetotail



- The ***coma*** of the comet is ionized when the comet gets close to sun

What will happen when the interplanetary magnetic field (which is frozen into the solar wind) hits the coma?

Comets, induced magnetotail



- The ***coma*** of the comet is ionized when the comet gets close to sun
- This plasma stops the field lines from passing the comet, due to the frozen-in magnetic field
- Venus and Mars have similar induced, weak ”magnetospheres”

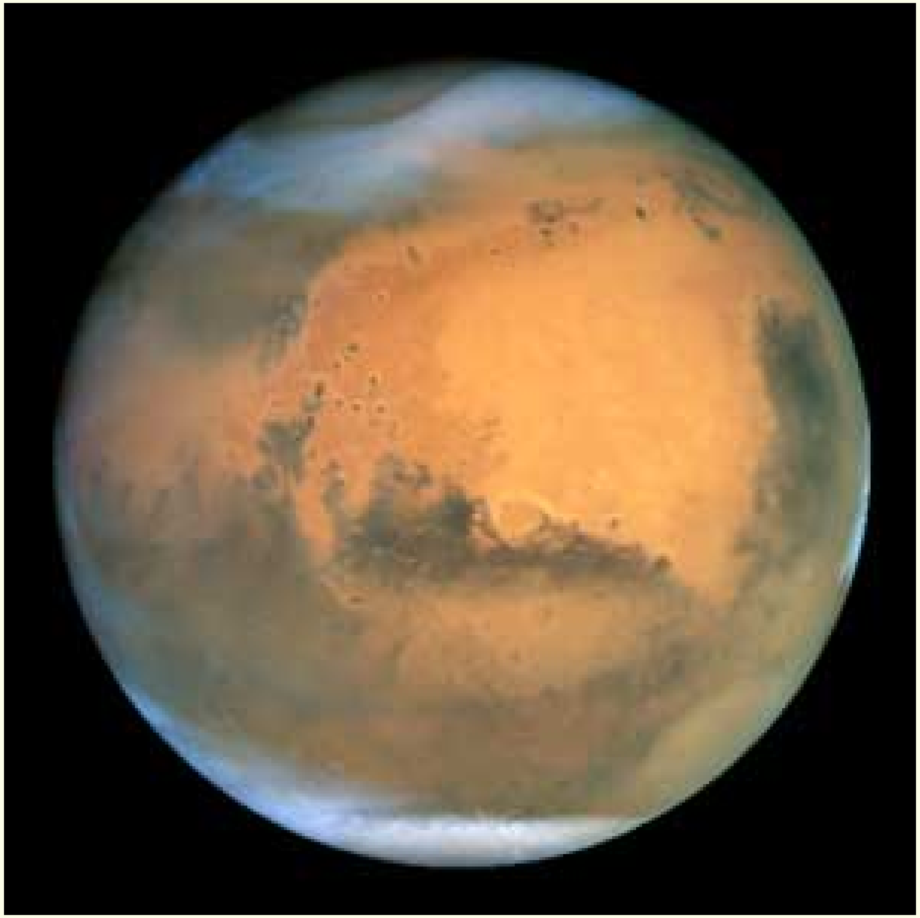


Photo from Hubble Space Telescope

Mars

- $r_M = 0{,}53\ r_E$
- $m_M = 0{,}11\ m_E$
- distance from sun : 1,52 AU
- very thin atmosphere
  - ~ 0.01 atm.
  - 95% CO_2
- very weak magnetic field

Jupiter

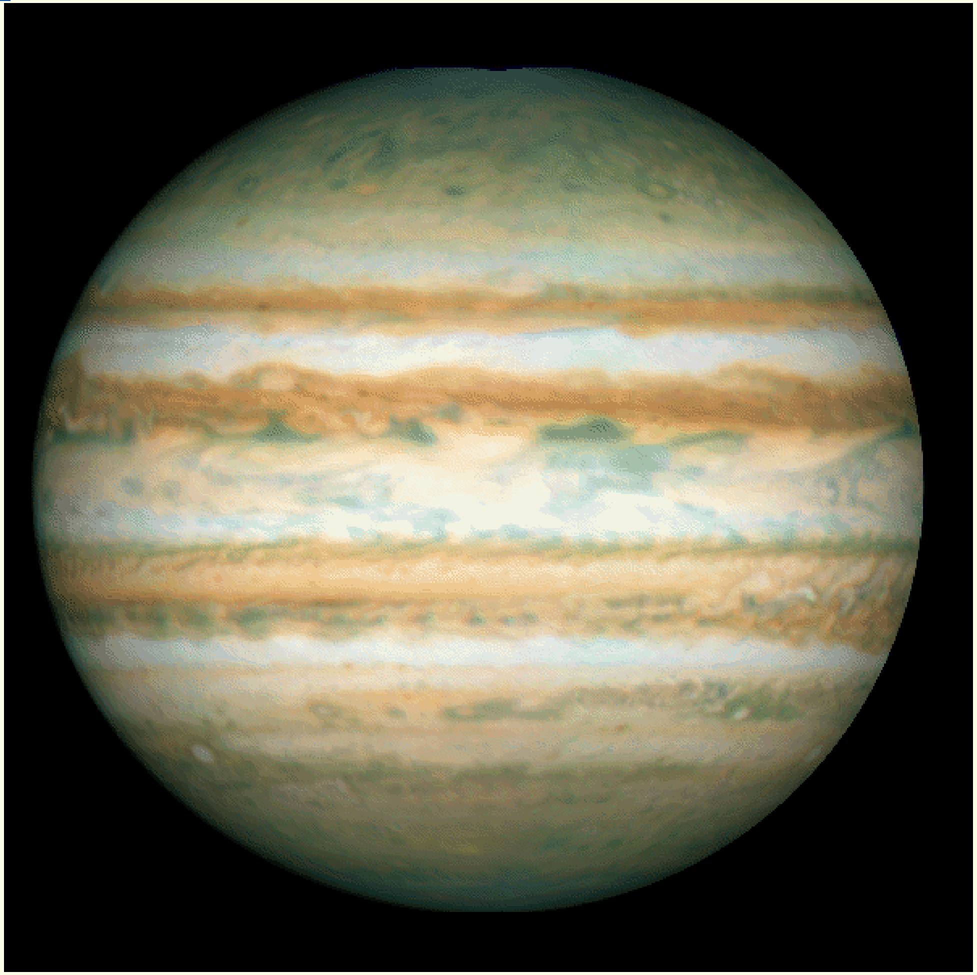
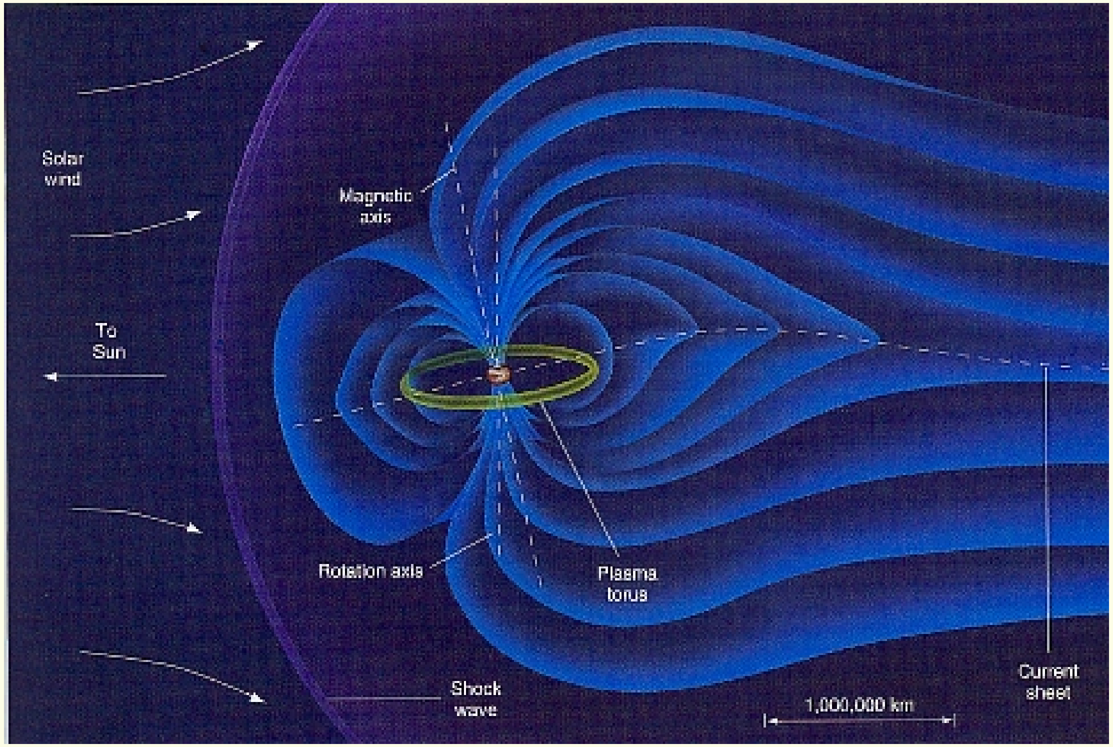


Photo from Hubble Space Telescope

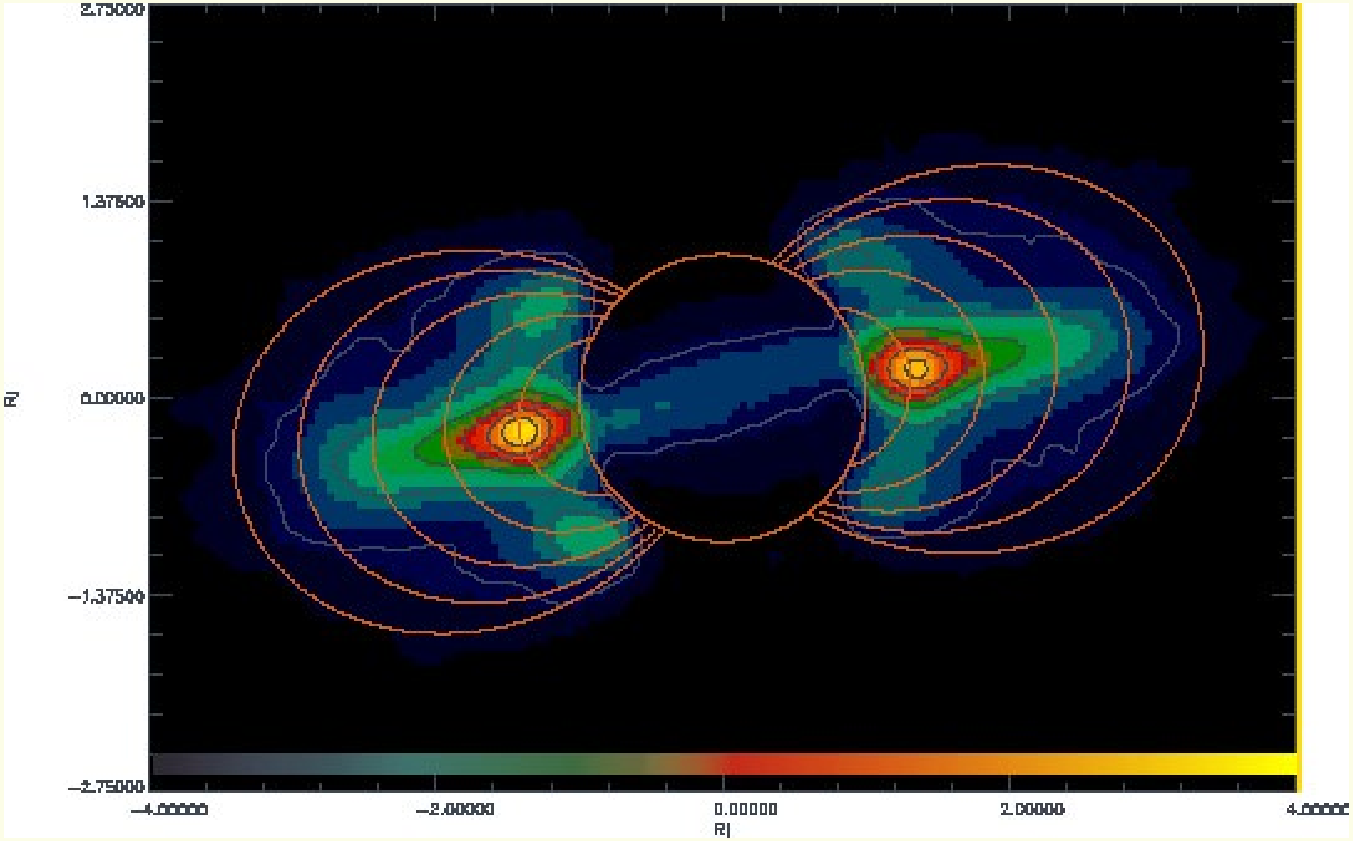
- $r_J = 11{,}2\ r_E$
- $m_J = 318\ m_E$
- distance from sun: 5,20 AU
- gas giant with very dense atmosphere containing hydrogen, helium, ammonium, methane, etc.
- ~ 60 moons (+ weak ring system)

Jupiter's magnetosphere



- high plasma density, Io is an important source
- plasma pressure thus becomes an important factor for balancing the solar wind pressure
- the plasma co-rotates with Jupiter, which gives the magnetosphere a flattened look

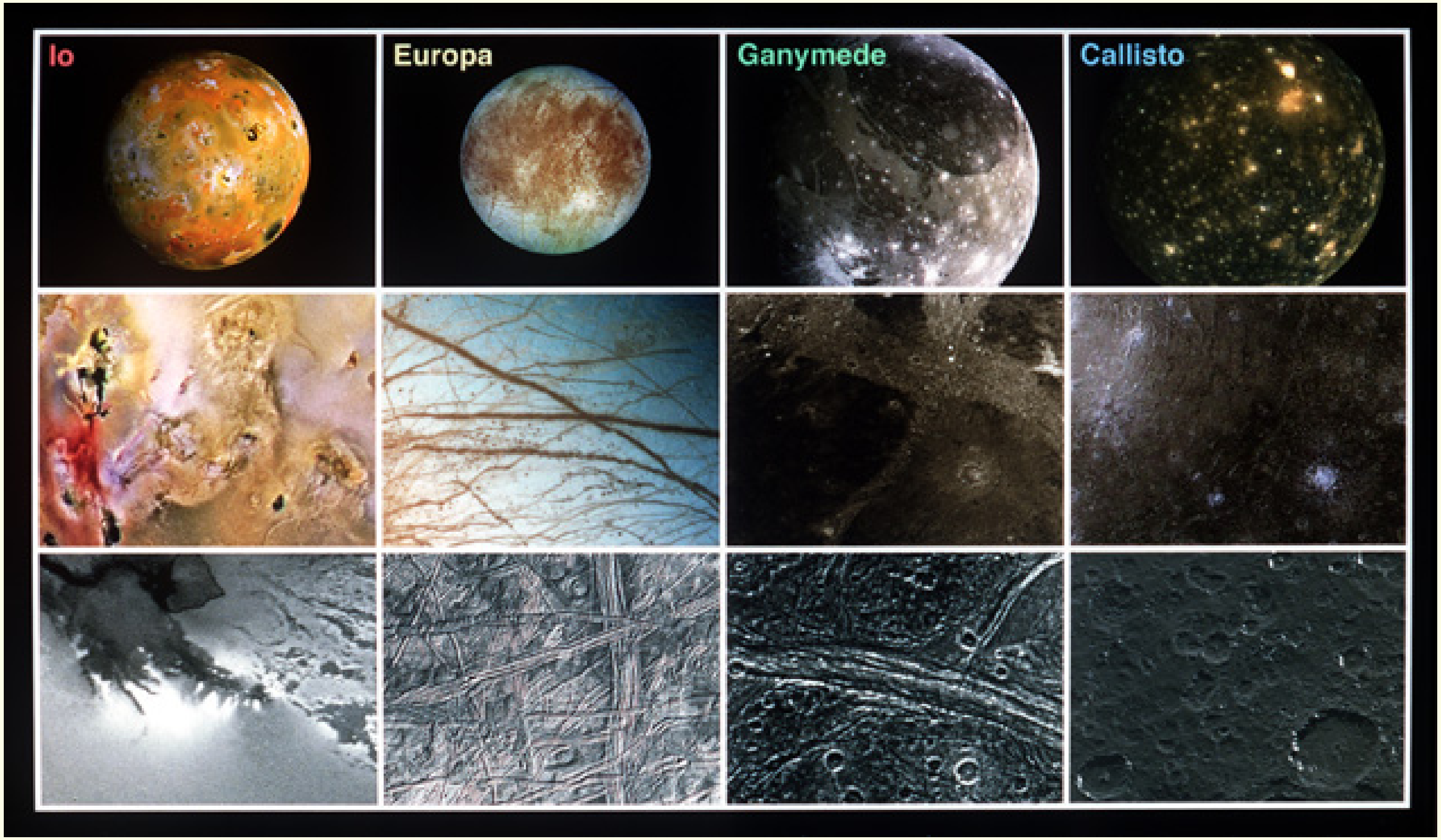
Syncrotron radiation from Jupiter's radiation belts



- Gyrating electrons emit "syncrotron radiation" with frequencies ~ $f_{ce} = eB/(2\pi m_e)$
- The emitted power is proportional to the electron temperature:

  $P = CT_e$
- In this way you can get a picture of the radiation belts

Galilean satellites



Volcanic activity, source for plasma.

Oceans under the ice?

Has its own magnetosphere the size of Mercury's

Weak magnetic field

Saturn

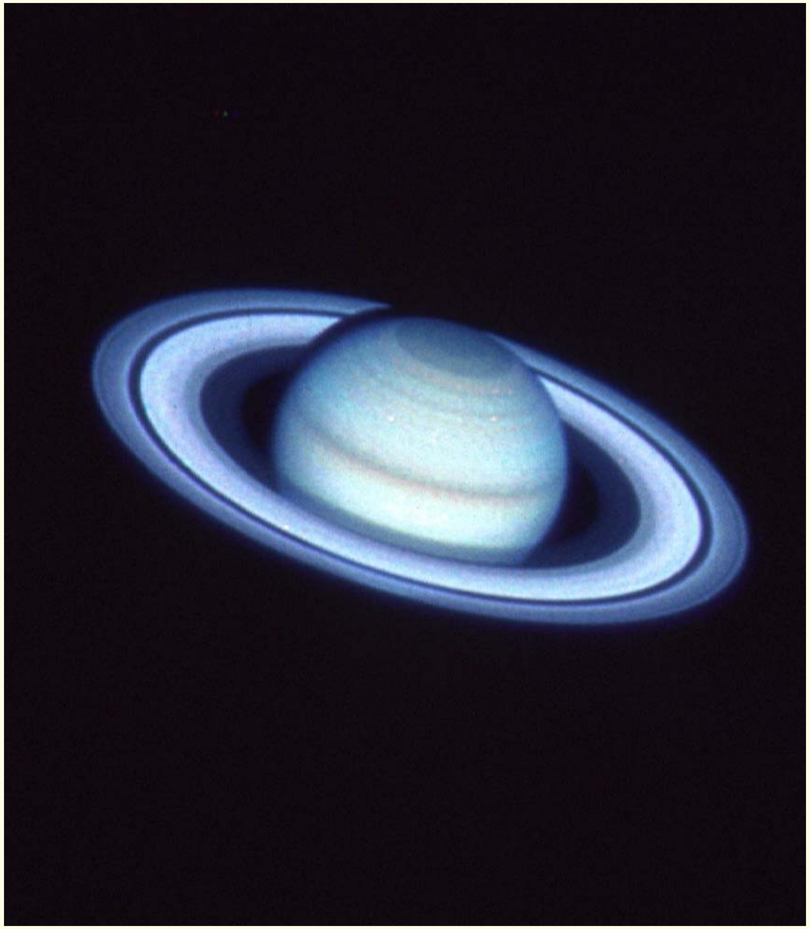
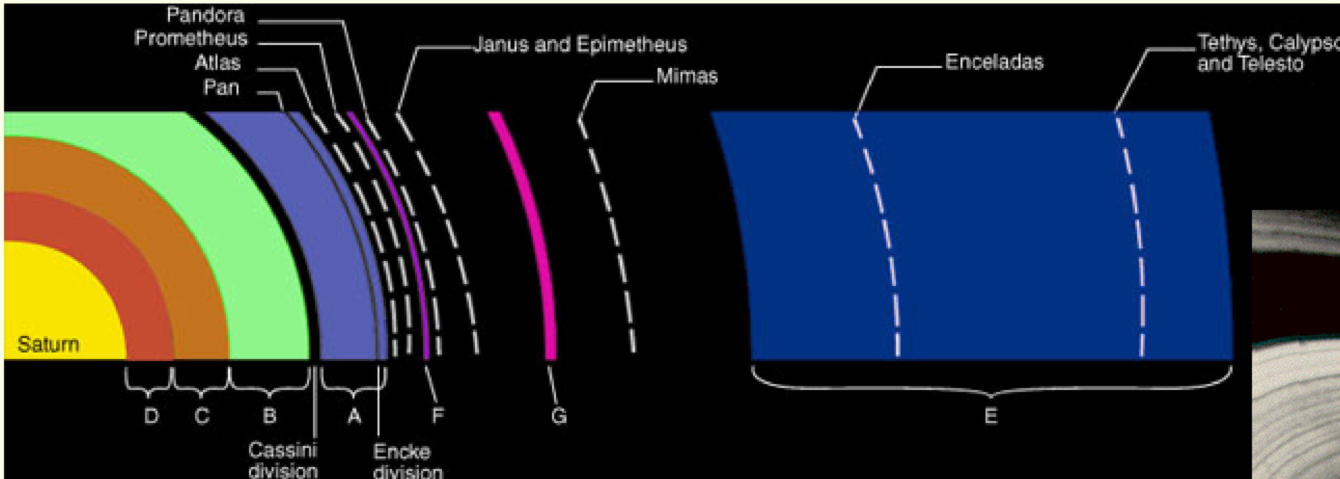
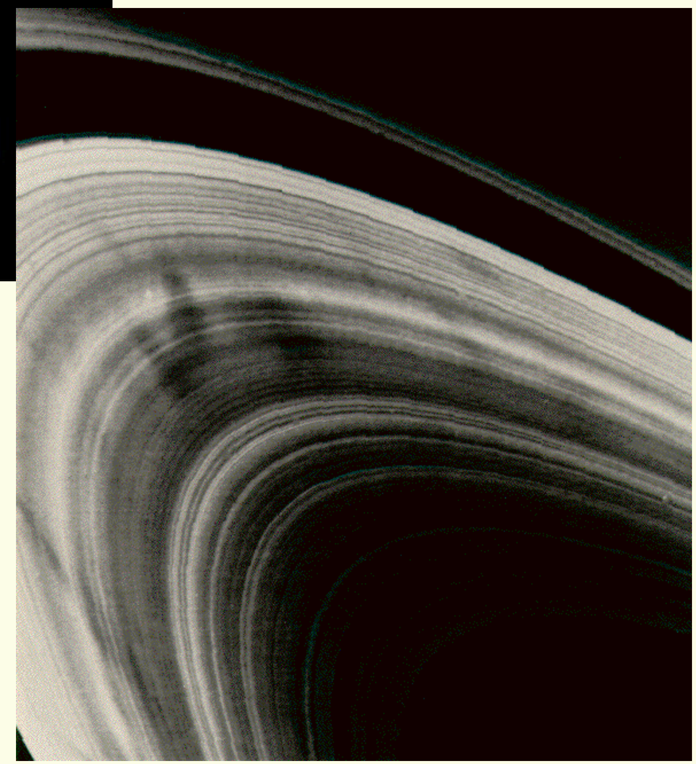


Photo from Hubble Space Telescope

- $r_s = 9{,}42\ r_E$
- $m_S = 95\ m_E$
- distance from sun: 9.53 AU
- gas giant with very dense atmosphere containing sulphur, hydrogen, helium, ammonium, methane, etc.
- ~ 31 moons + ring system

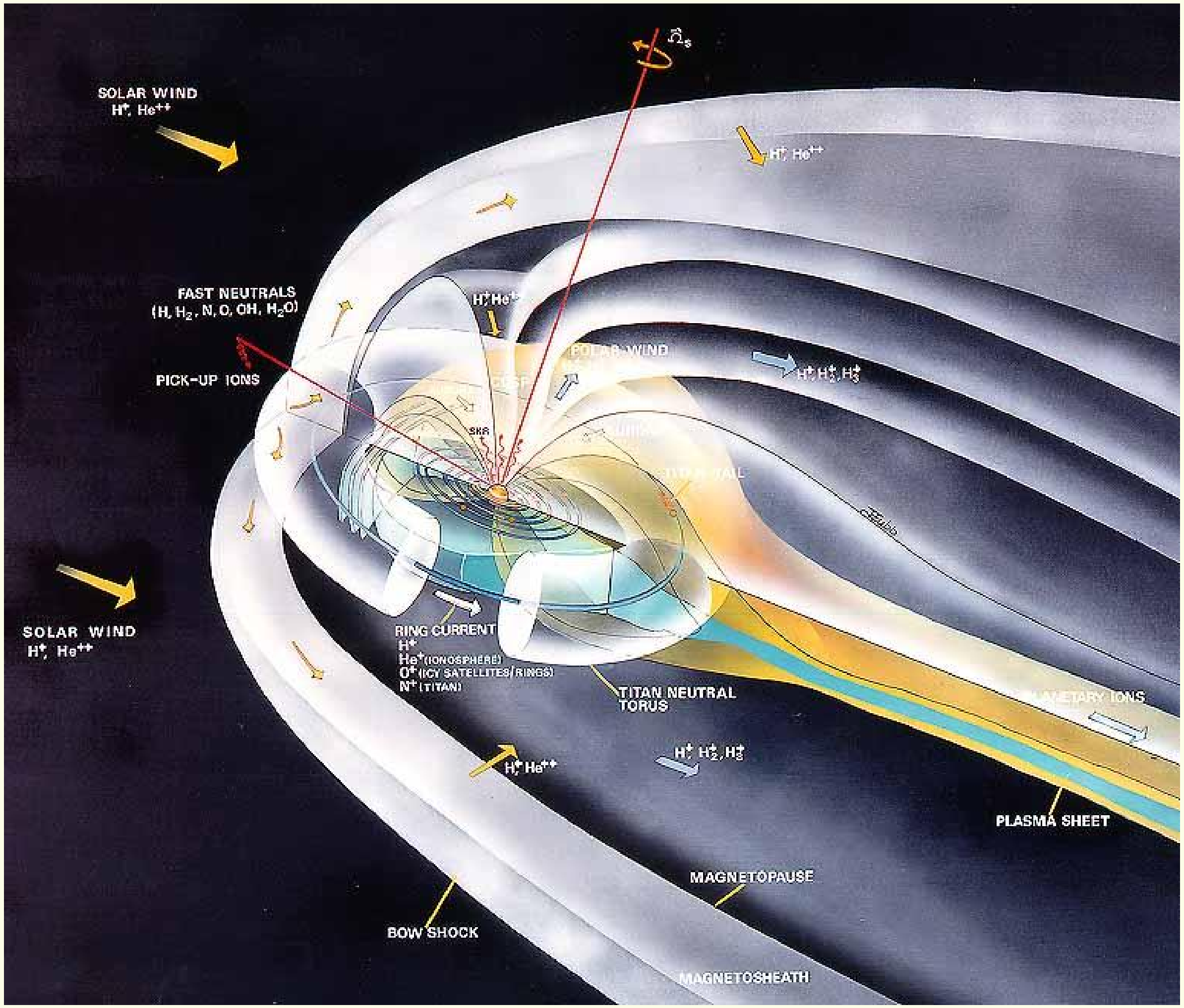
Saturn's rings



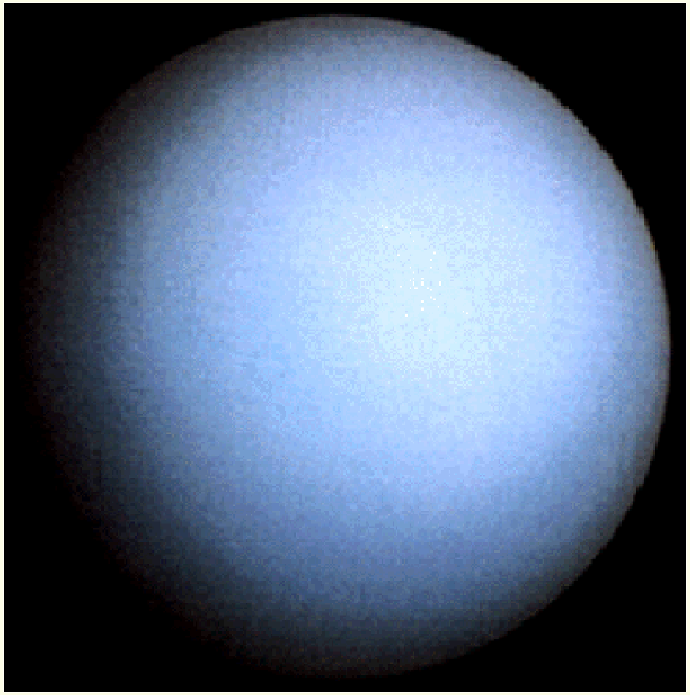


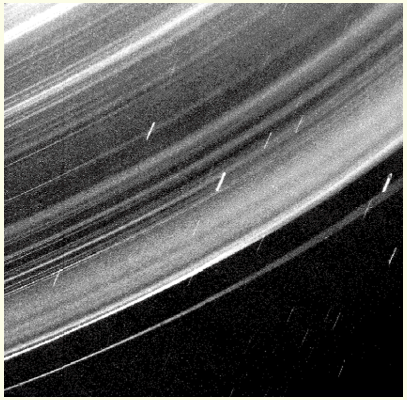
- ring systemet is made up of ice and mineral particles from ~ 1 cm to ~ 1 km
- rings are only 1.5 km thick

Saturn's magnetosphere



- ring systemet is both source and sink for plasma and limits the size of the plasmasphere
- plasma pressure important for balancing solar wind pressure, just as for Jupiter
- Intense radiation belt with 50 MeV protons

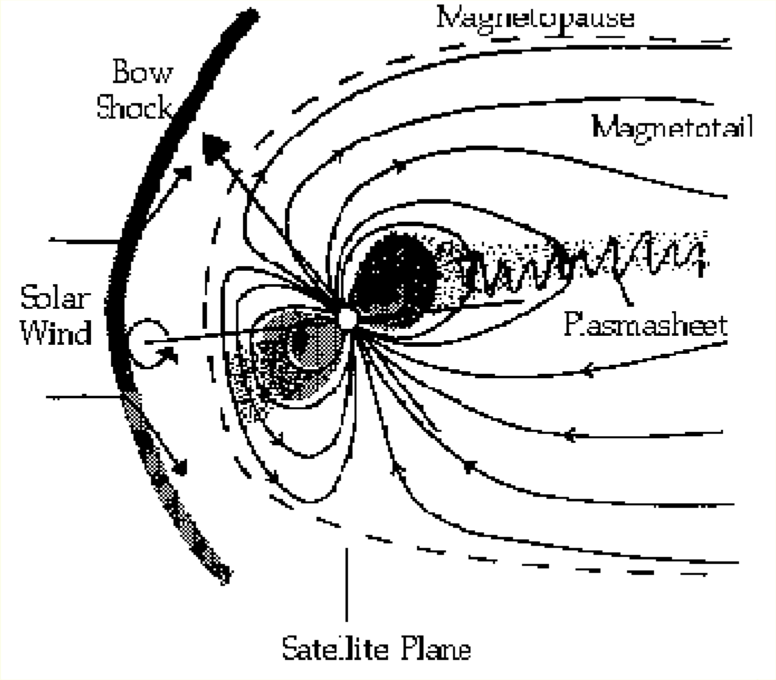


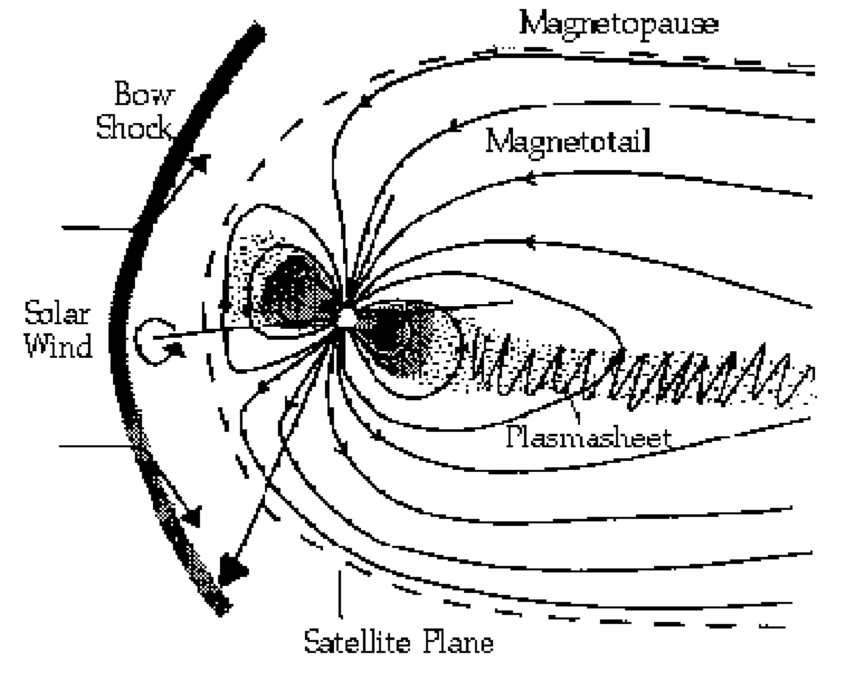


Uranus

- $r_U = 3{,}84\ r_E$
- $m_U = 14{,}5\ m_E$
- distance from sun: 19,2 AU
- gas giant with very dense atmosphere containing mainly methane
- 20 moons + ring system

Uranus





- Uranus' rotational axis almost in ecliptic plane
- magnetic field axis makes an angle of around 60° with rotational axis
- this gives enourmous daily variations of the structure of the magnetosphere

Neptune

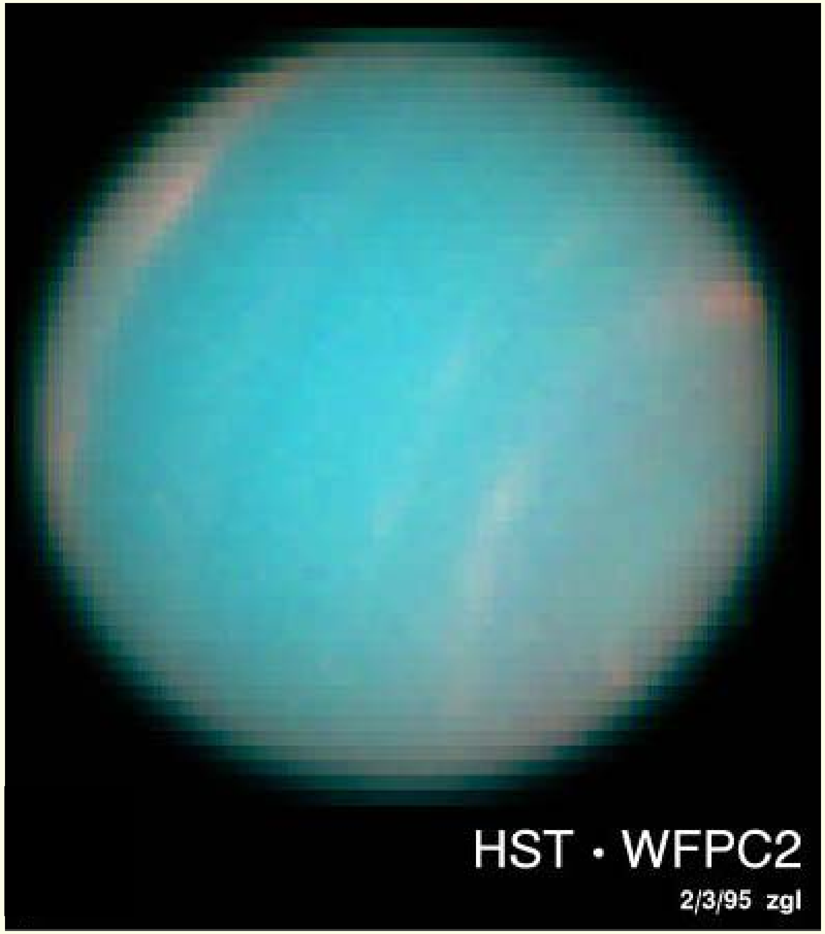
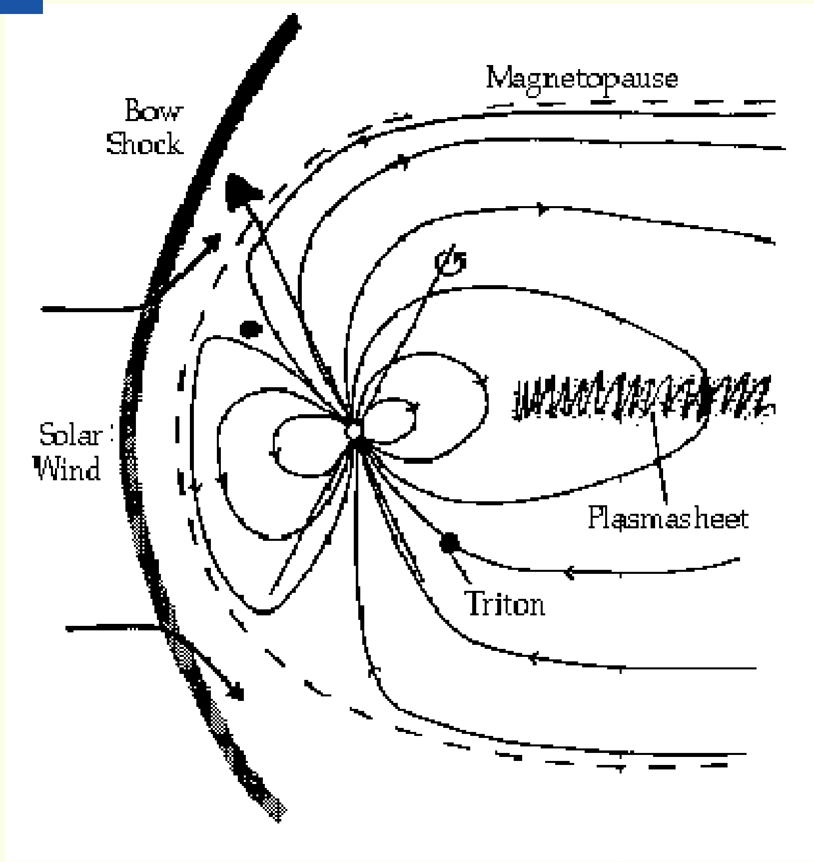
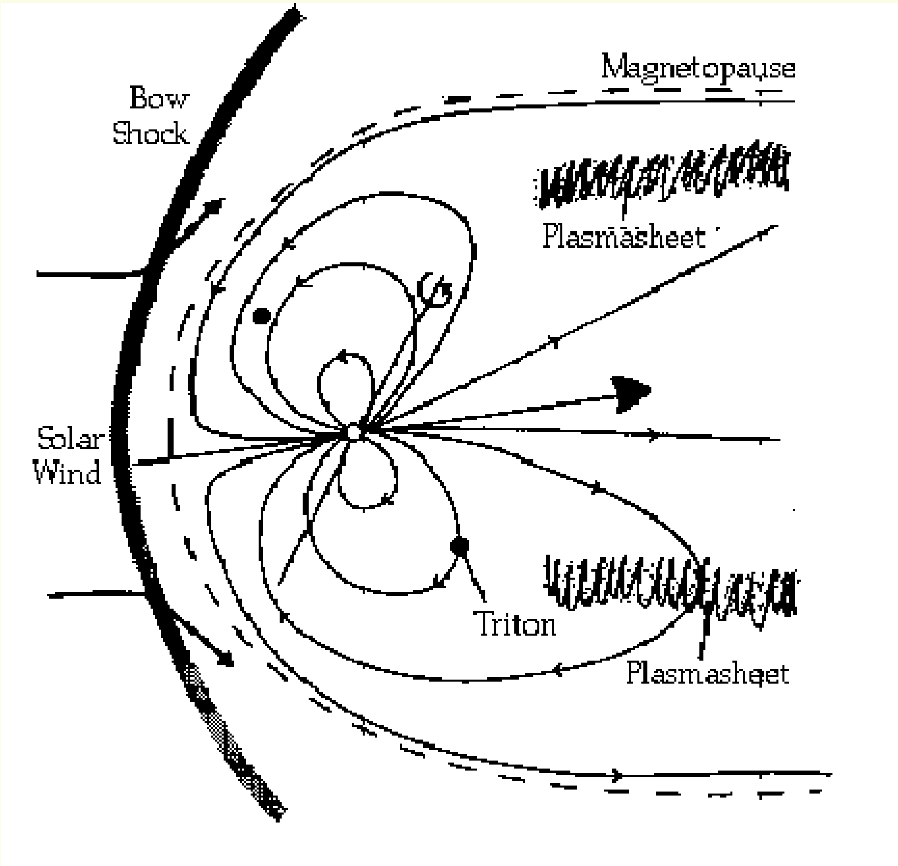


Photo from Hubble Space Telescope

- $r_N = 3{,}93\ r_E$
- $m_N = 17{,}2\ m_E$
- distance from sun : 30.1 AU
- gas giant with very dense atmosphere containing mainly methane
- 11 moons + ring system

Neptune

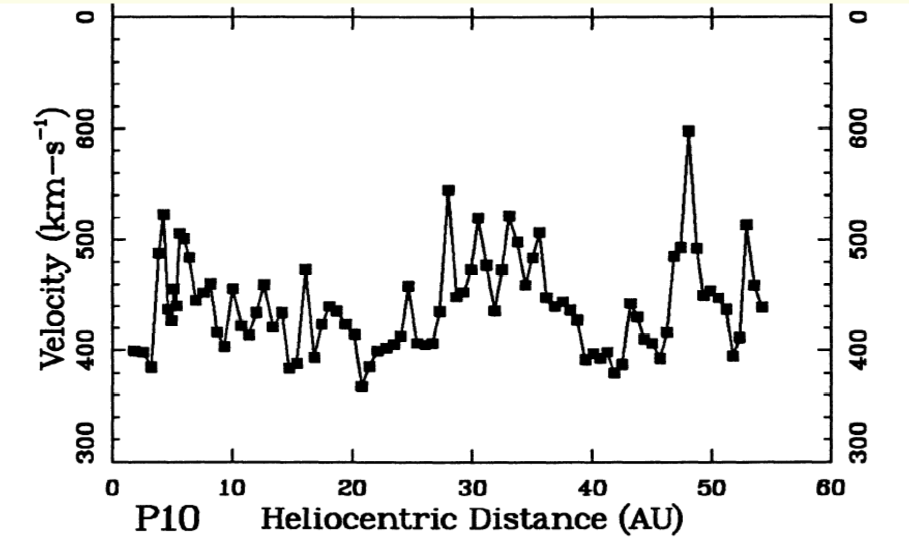




- magnetic field axis makes an angle of around 43° with rotational axis
- this gives enourmous daily variations of the structure of the magnetosphere also for Neptune

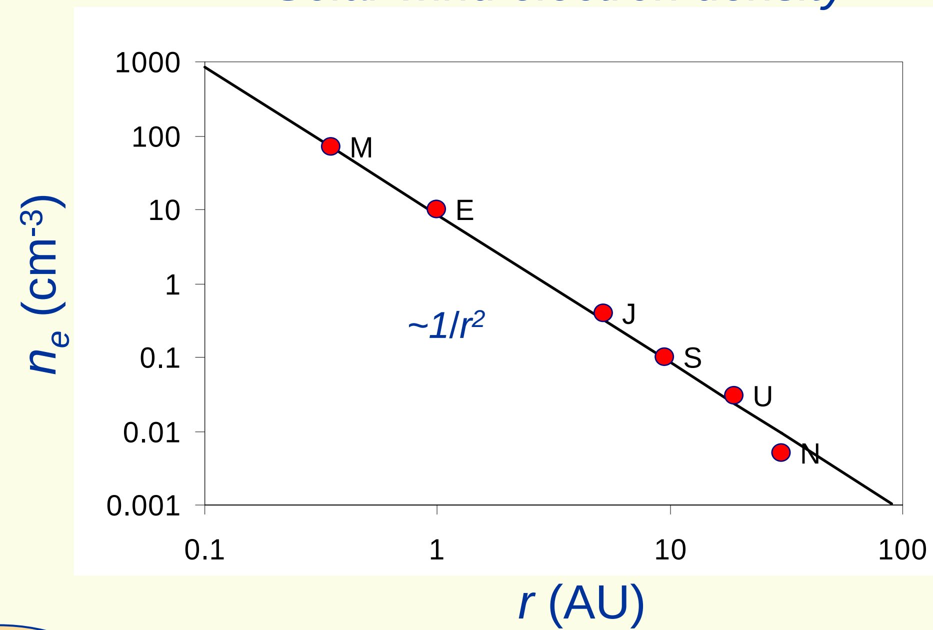
Comparative magnetospheres
Solar wind properties

Solar wind velocity

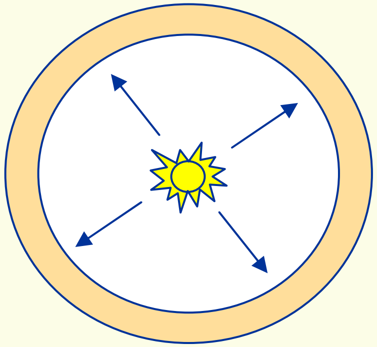


Pioneer 10, measurements
[Grazin et al., 1994]

Solar wind electron density



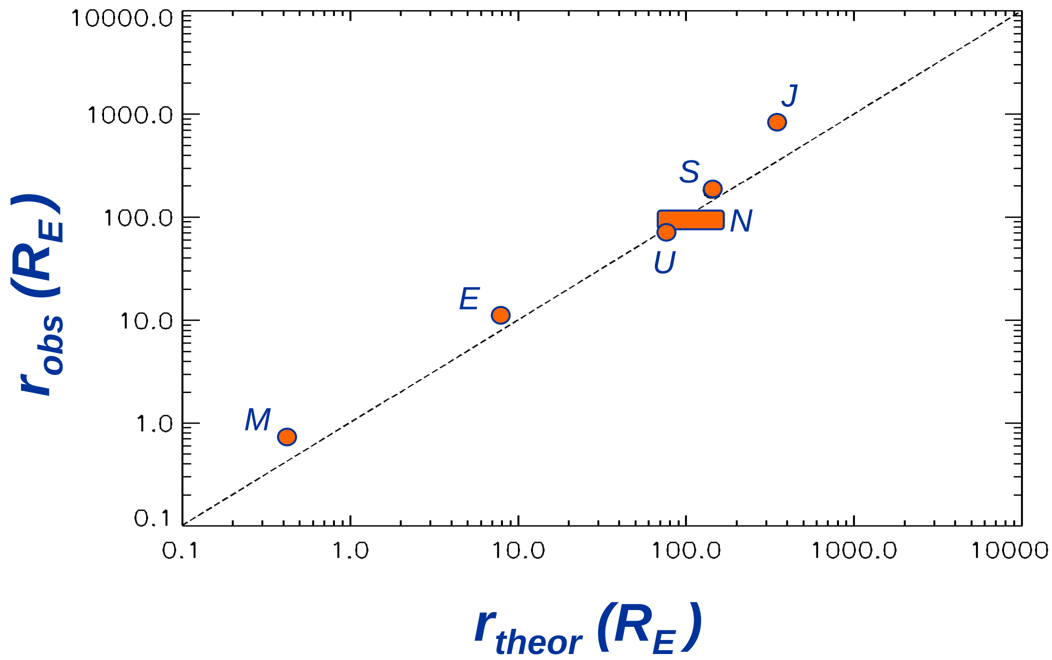
[Blanc et al., 2005]



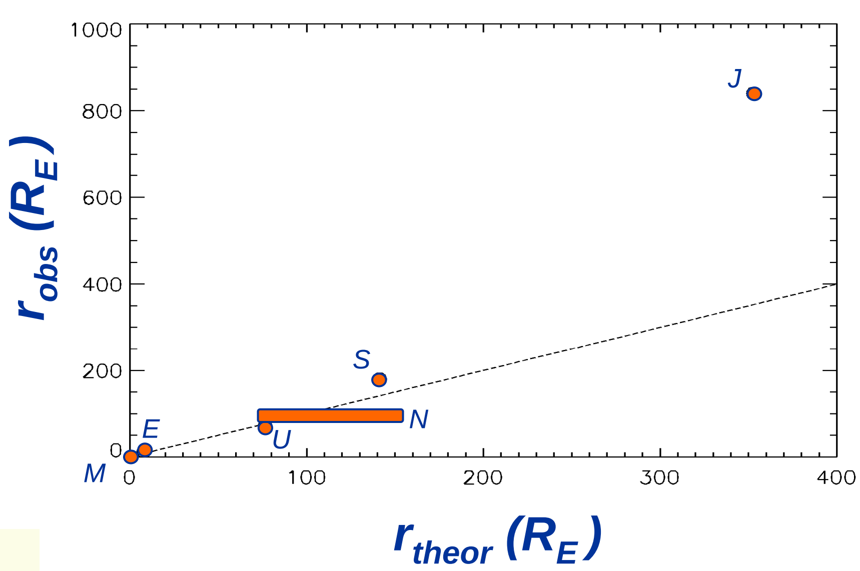
$$dV = 4\pi r^2 dr$$

Comparative magnetospheres

Observed vs. theoretical standoff-distance



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

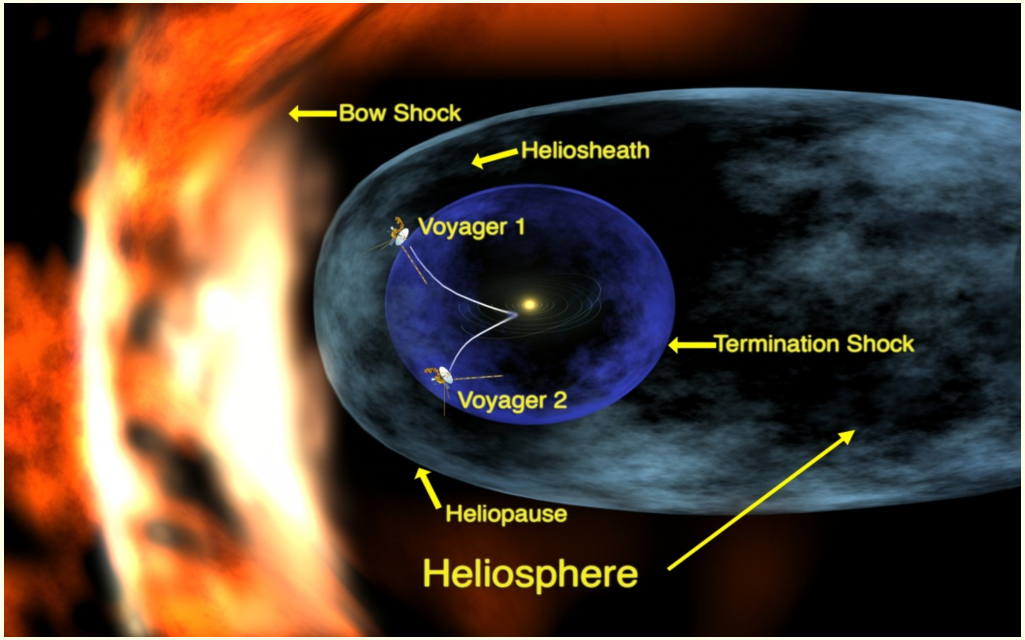


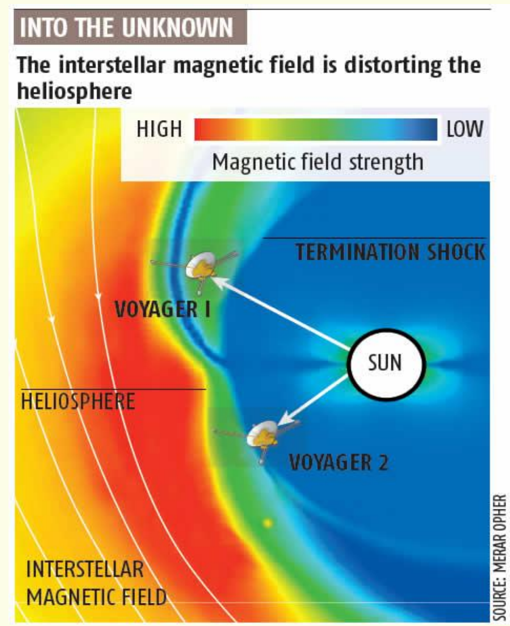
- *Model reasonably valid over three orders of magnitude*
- *Size of Jupiter's (and maybe Saturn's) magnetosphere underestimated*

Other other magnetospheres

Heliosphere

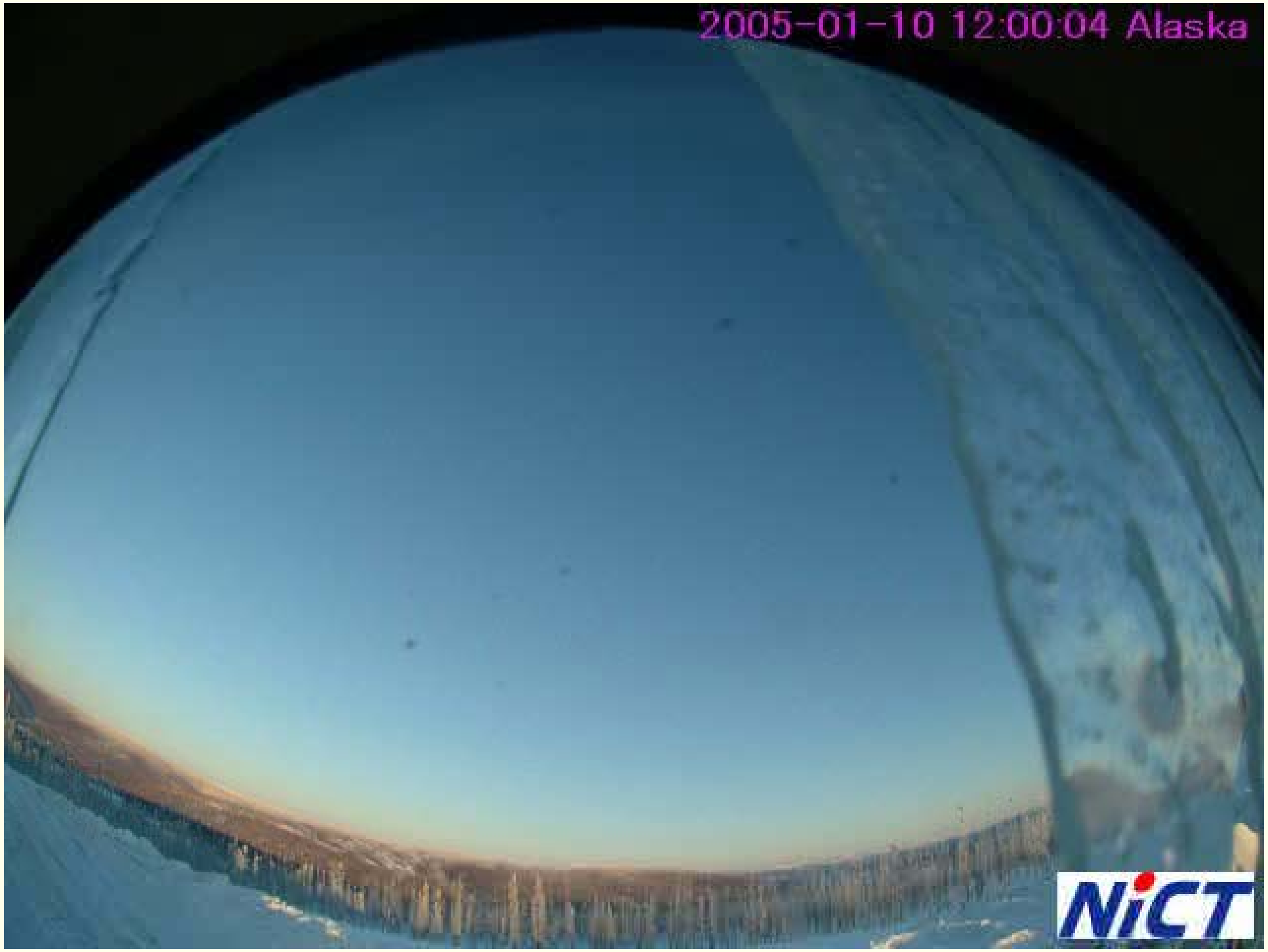
Interstellar wind





[Opher, 2007]

The aurora

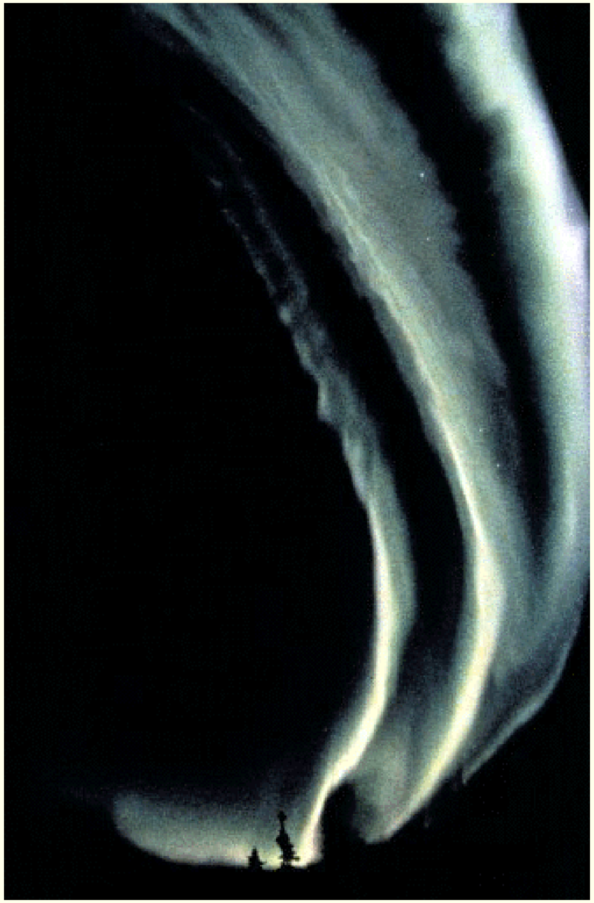


The aurora

The aurora

External movie

Homogenous auroral arcs

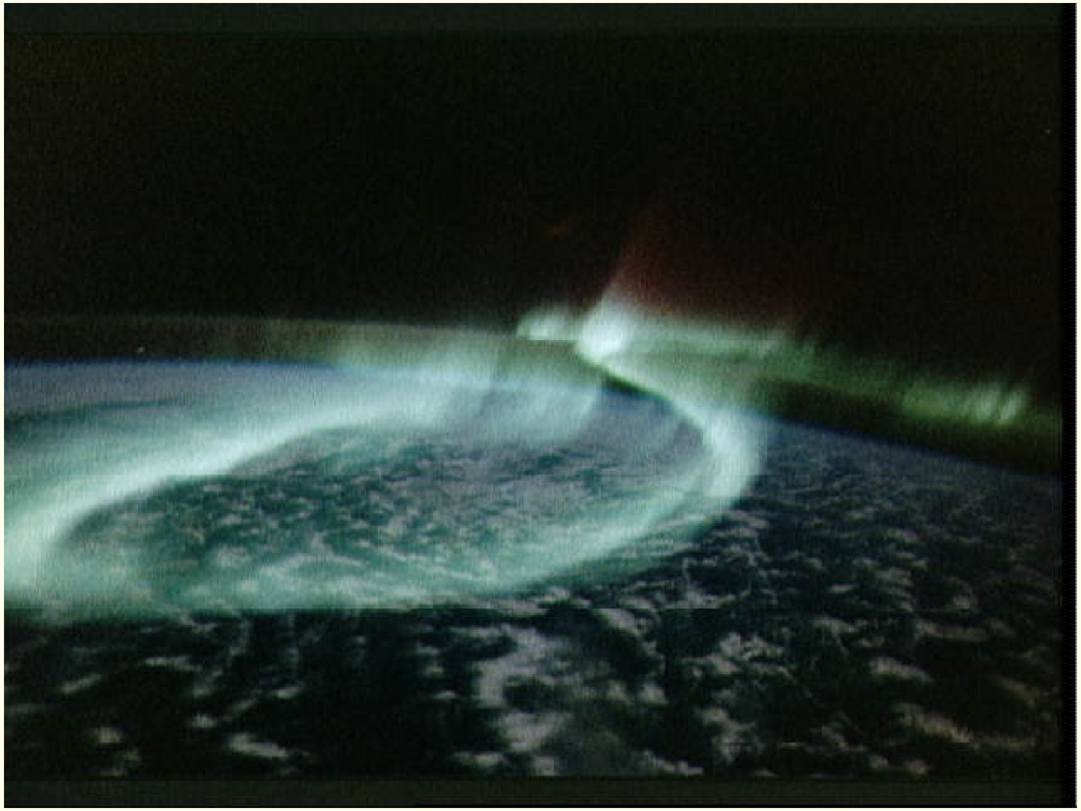


Rays, curtains

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

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

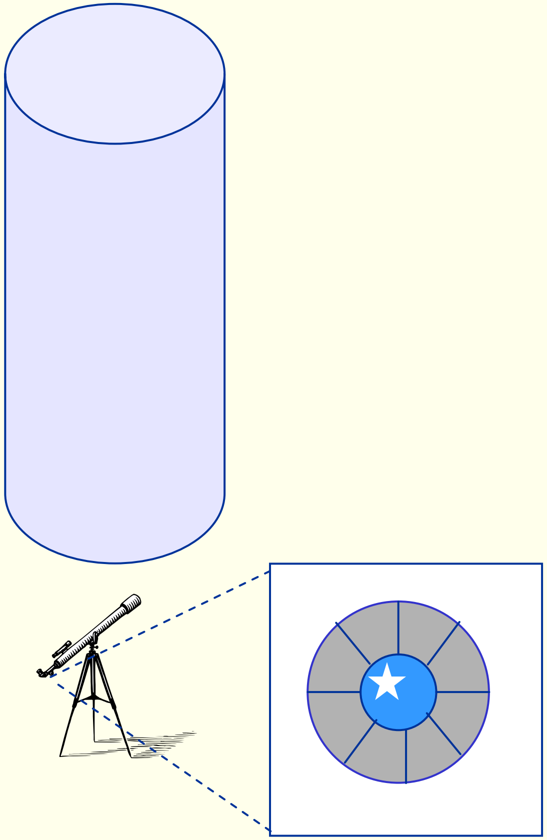
Auroral spirals



Develop when arcs become unstable

Auroral corona

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



Aurora - altitude

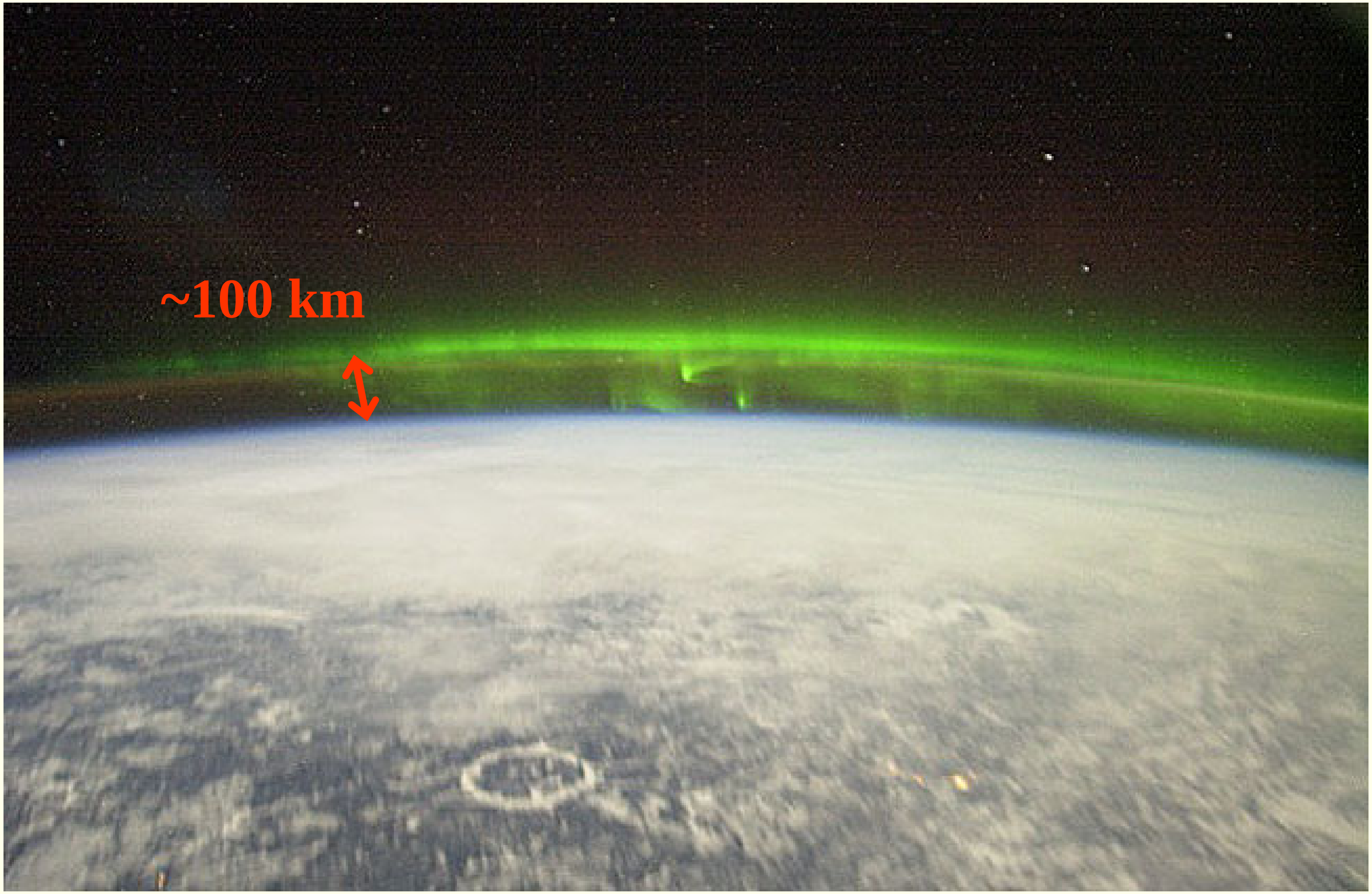


Foto from International Space Station

Early notions

Woodcut from Böhmen 1570.

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

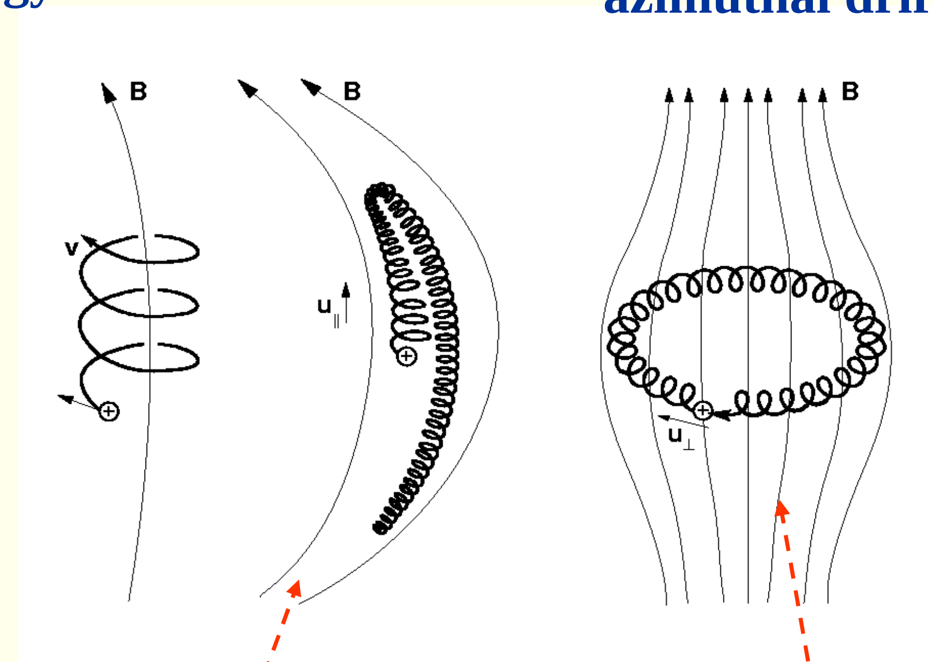
What causes the aurora?

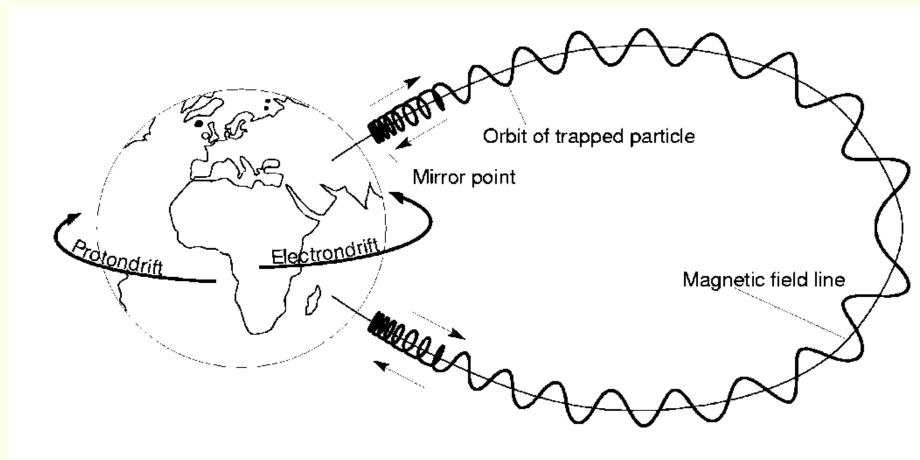
Particle motion in geomagnetic field

longitudinal oscillation

gyration

azimuthal drift

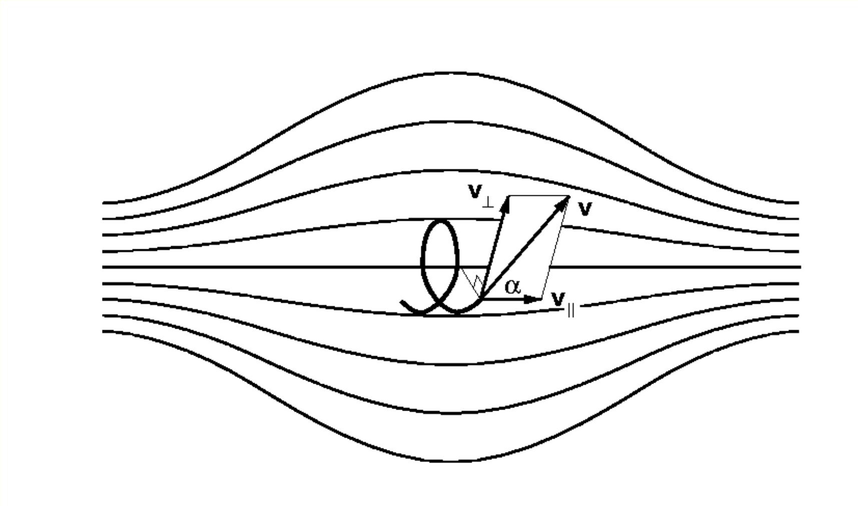




Magnetic mirror

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

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

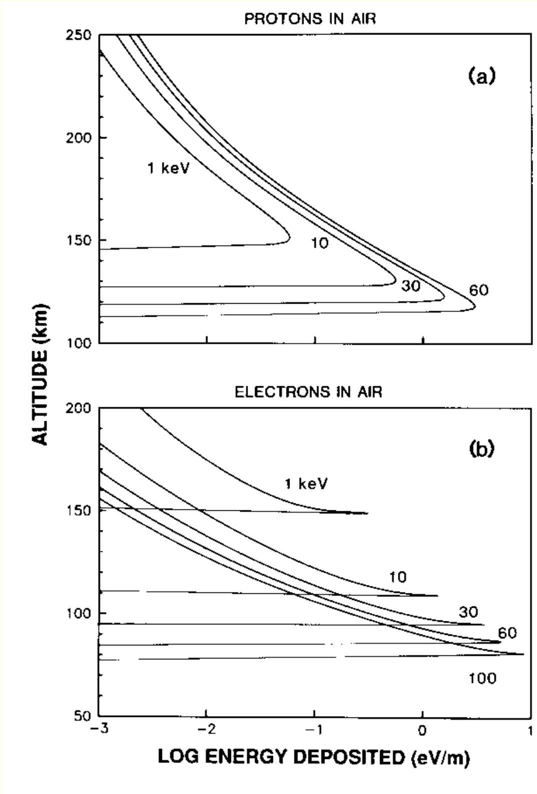
$$\alpha > \alpha_{lc} = \arcsin\sqrt{B/B_{max}}$$

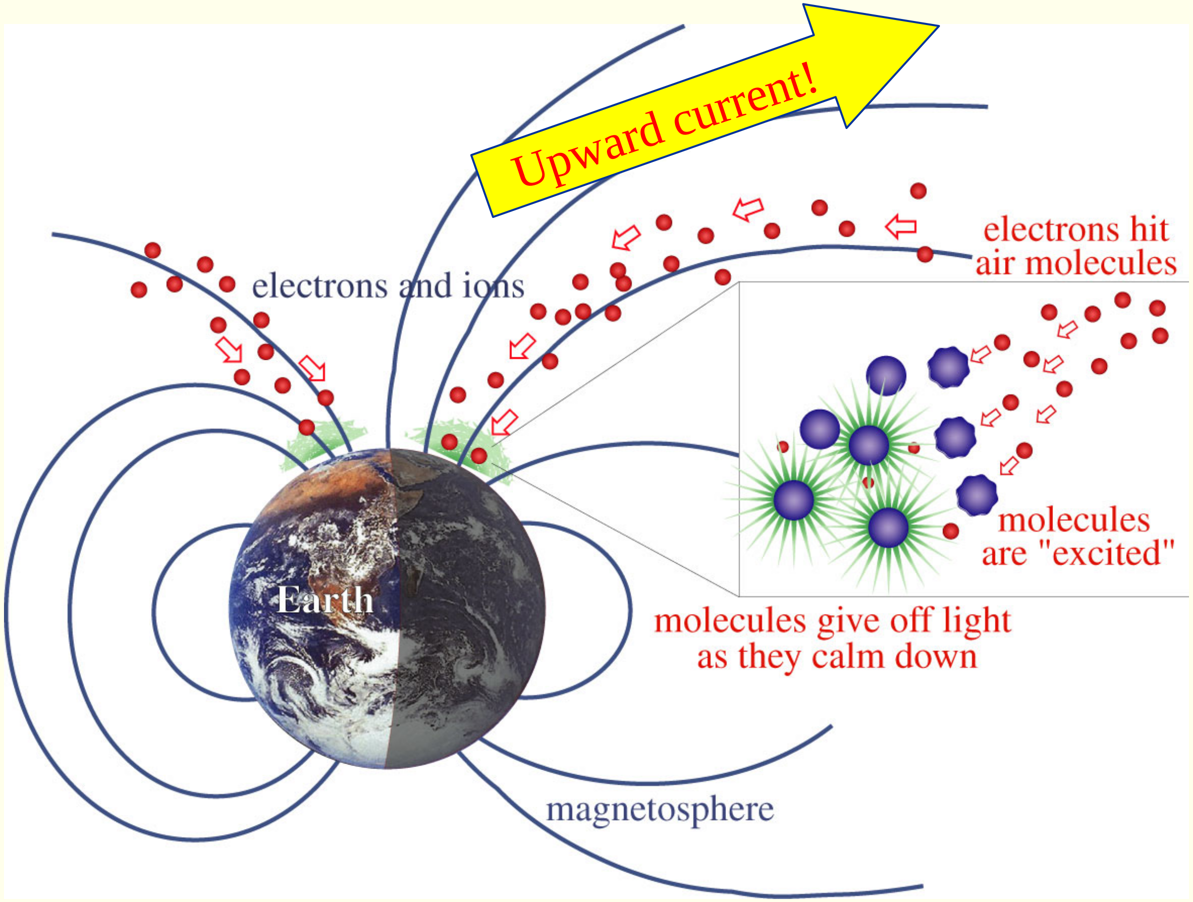
Particles in ***loss cone*** : $\alpha < \alpha_{lc}$

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

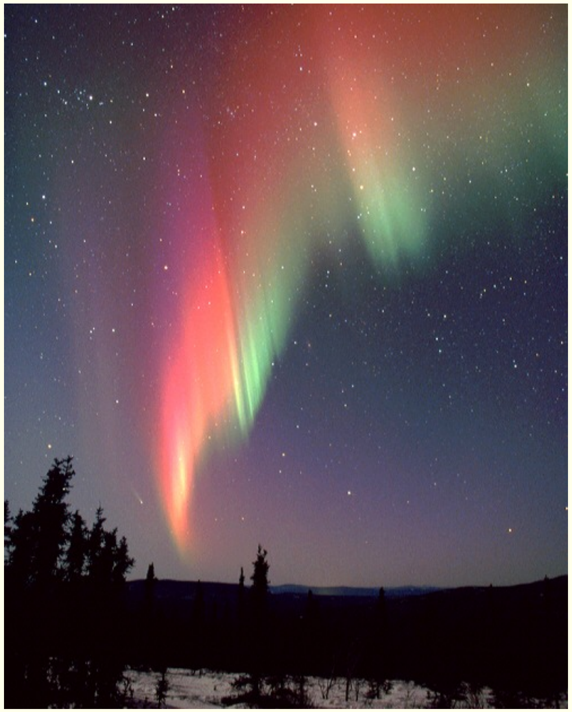
$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2\sin^2\alpha}{2B}$$

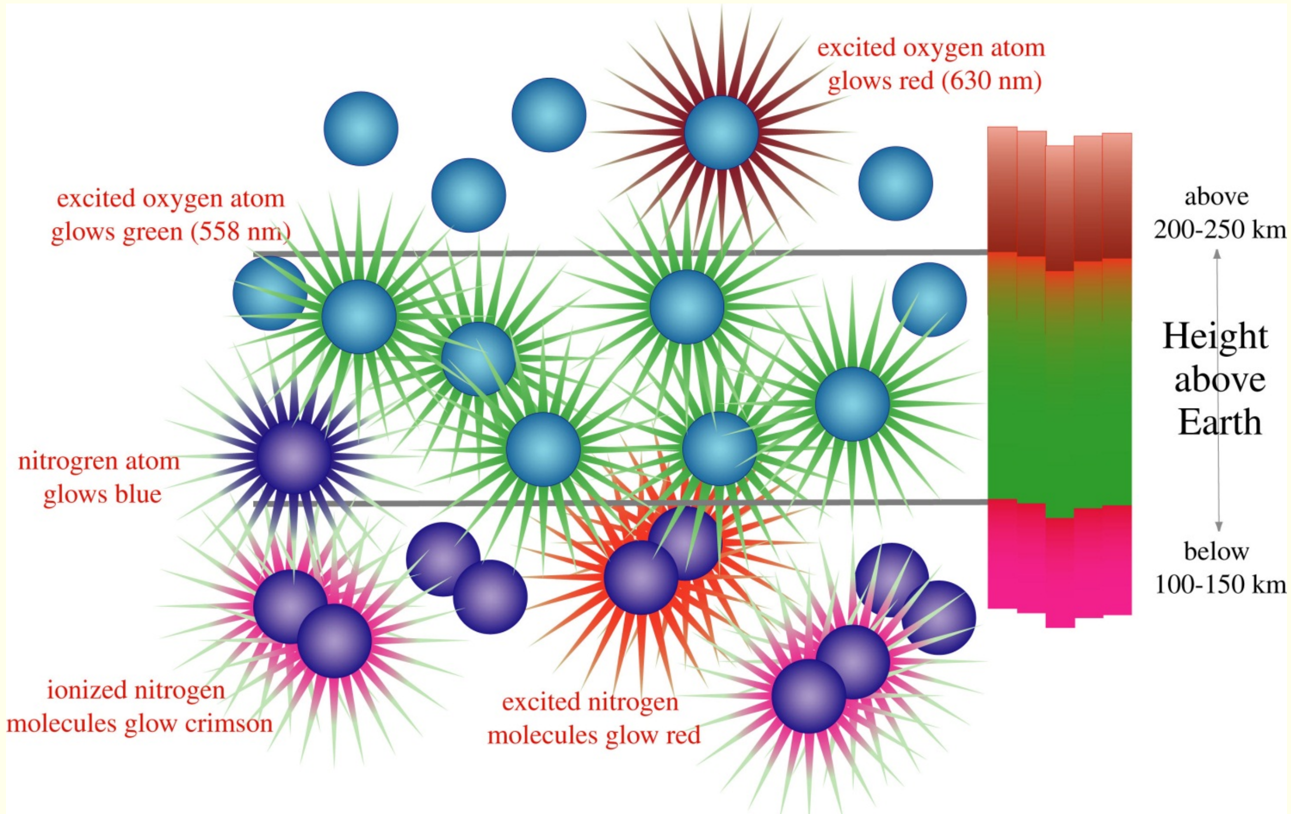
Collisions - emissions





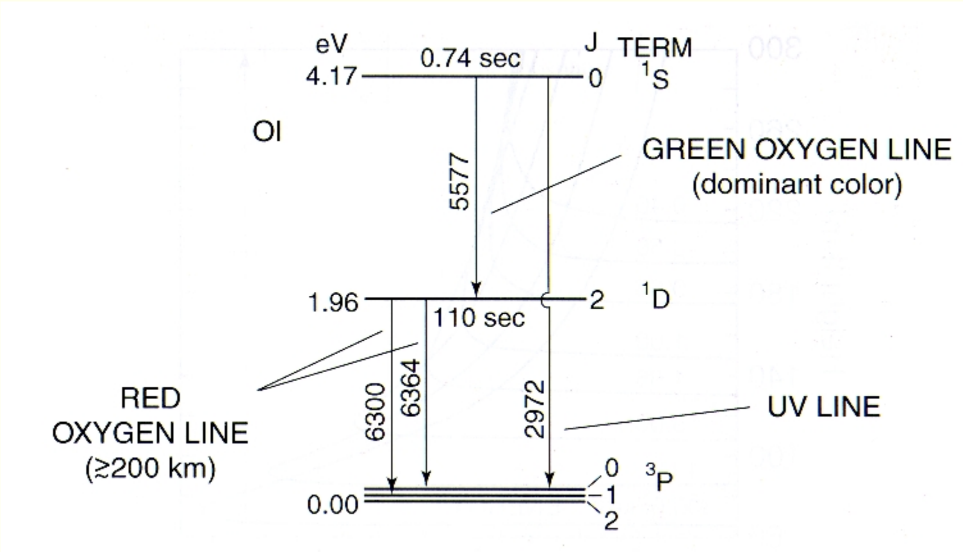
Emissions

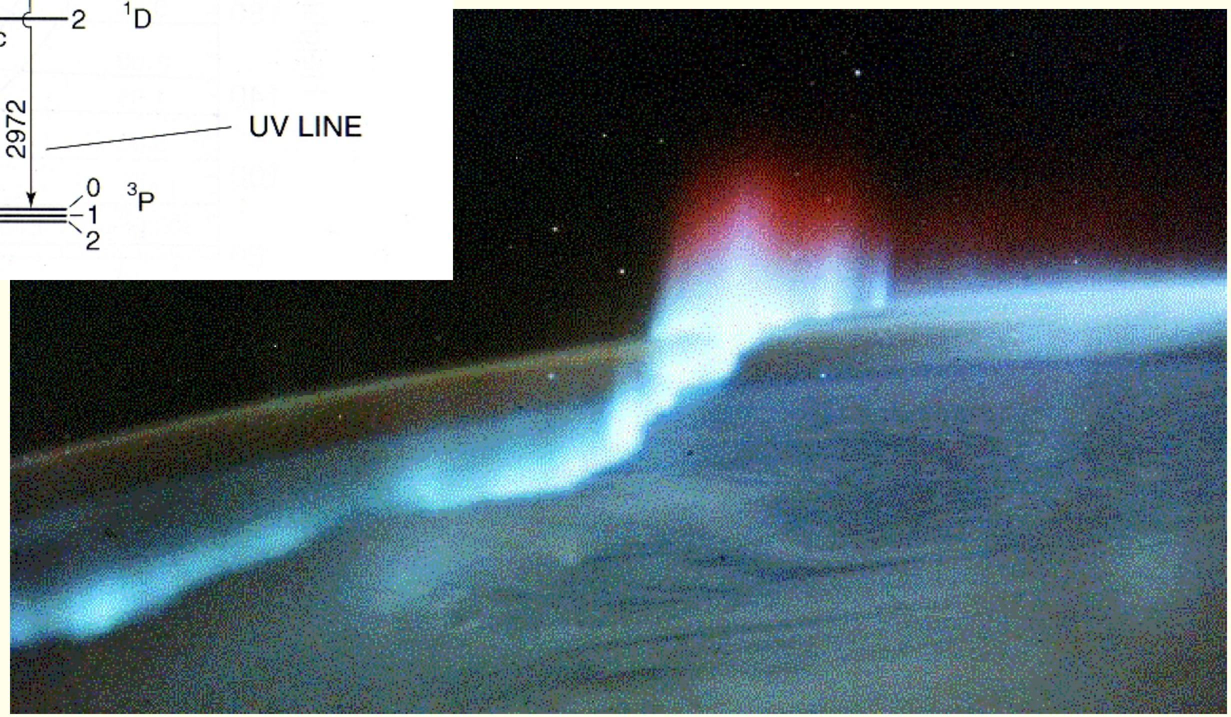




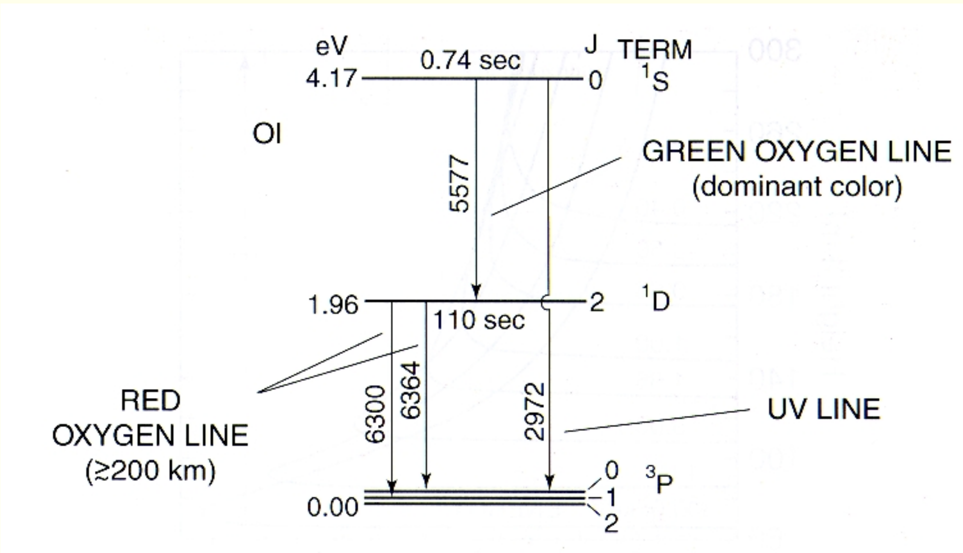
excited oxygen atom
glows red (630 nm)
excited oxygen atom
glows green (558 nm)
nitrogren atom
glows blue
ionized nitrogen
molecules glow crimson
excited nitrogen
molecules glow red
above
200-250 km
Height
above
Earth
below
100-150 km

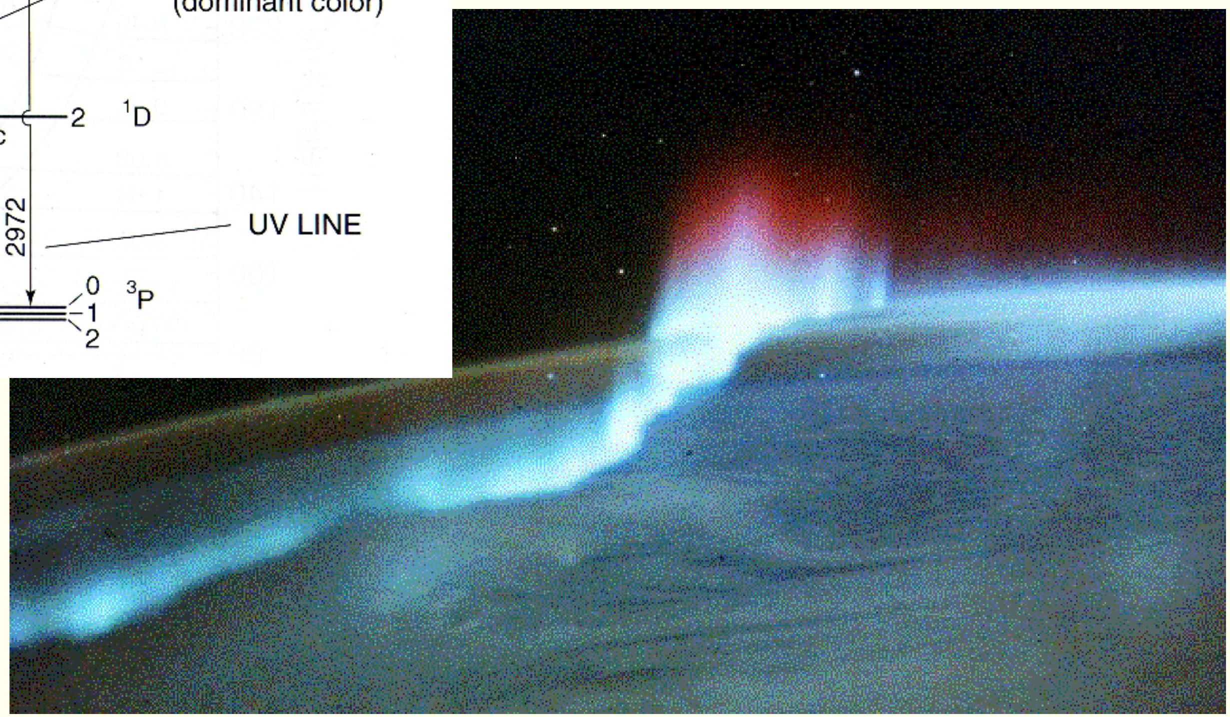
Oxygen emissions



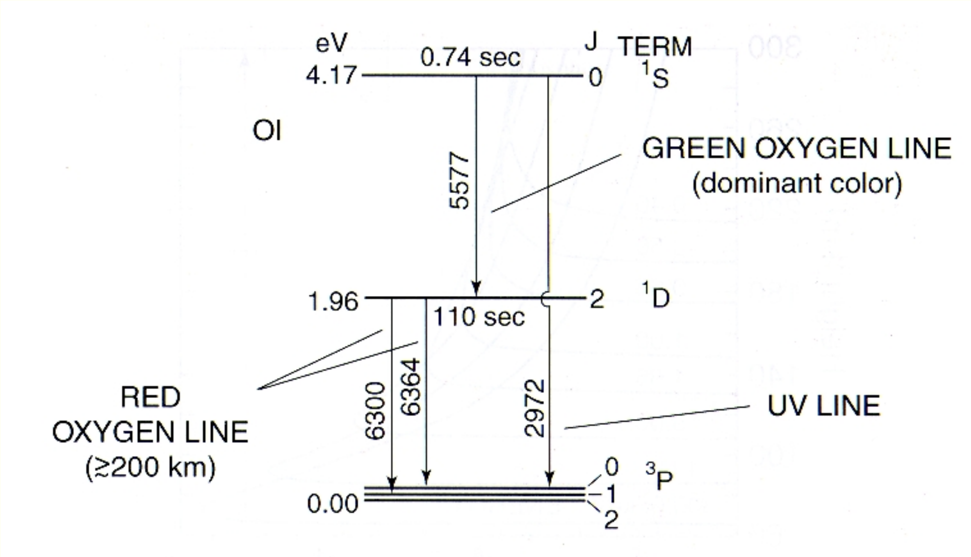


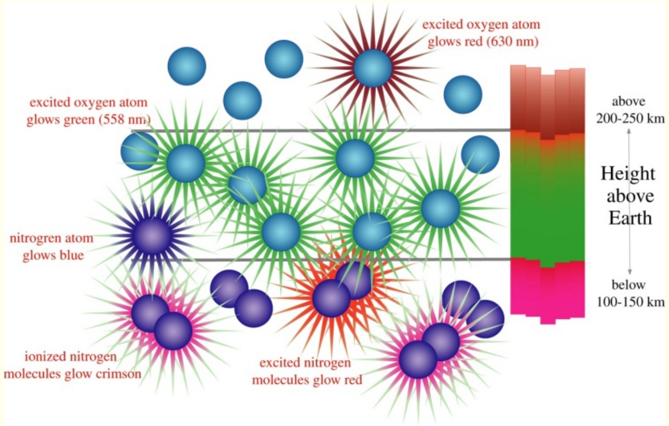
Why is there no red emissions at lower altitude?



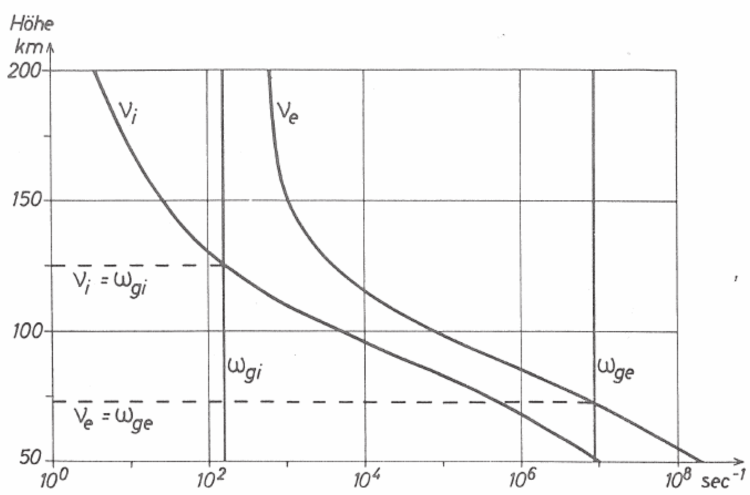


Oxygen emissions





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

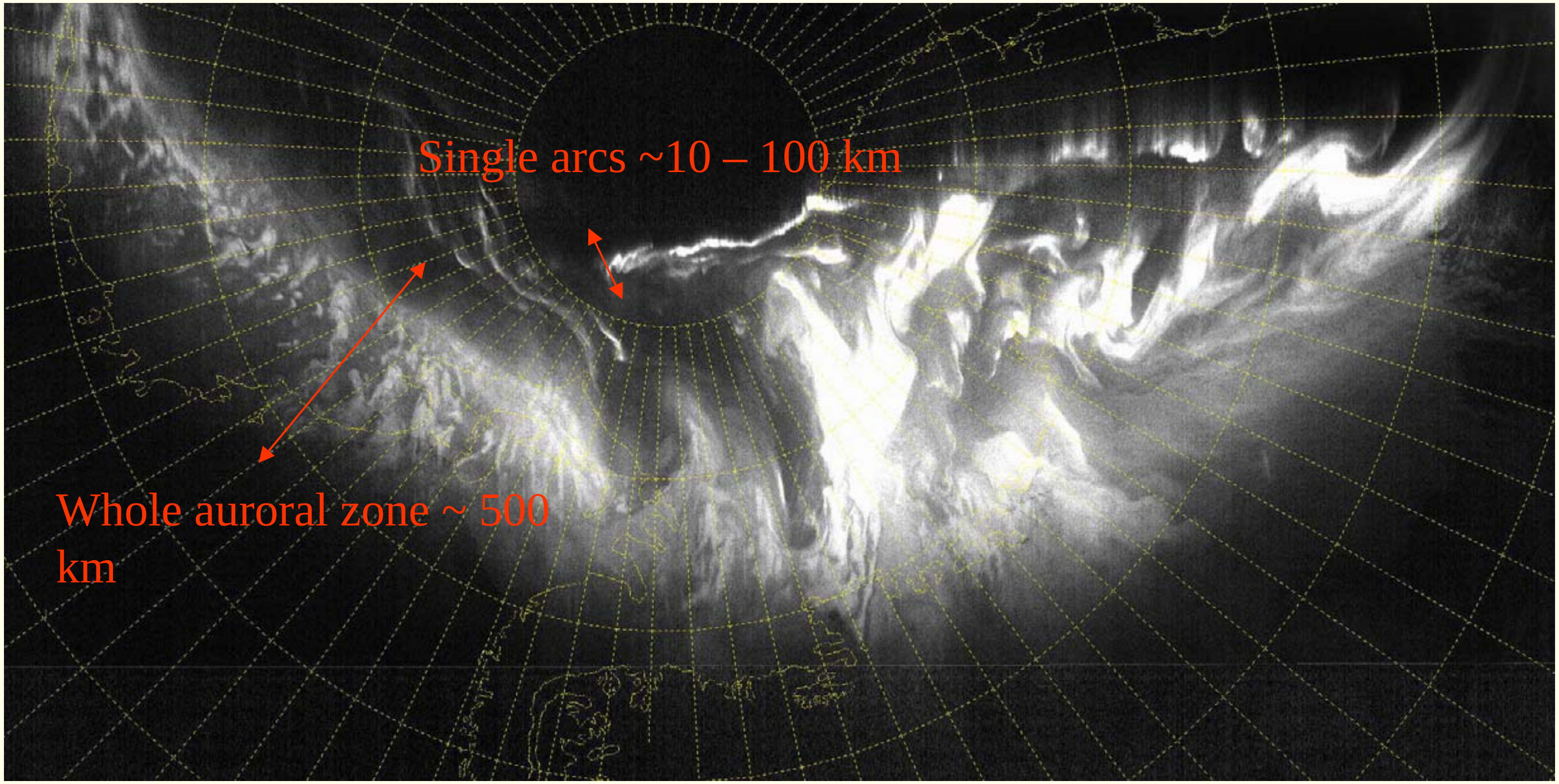
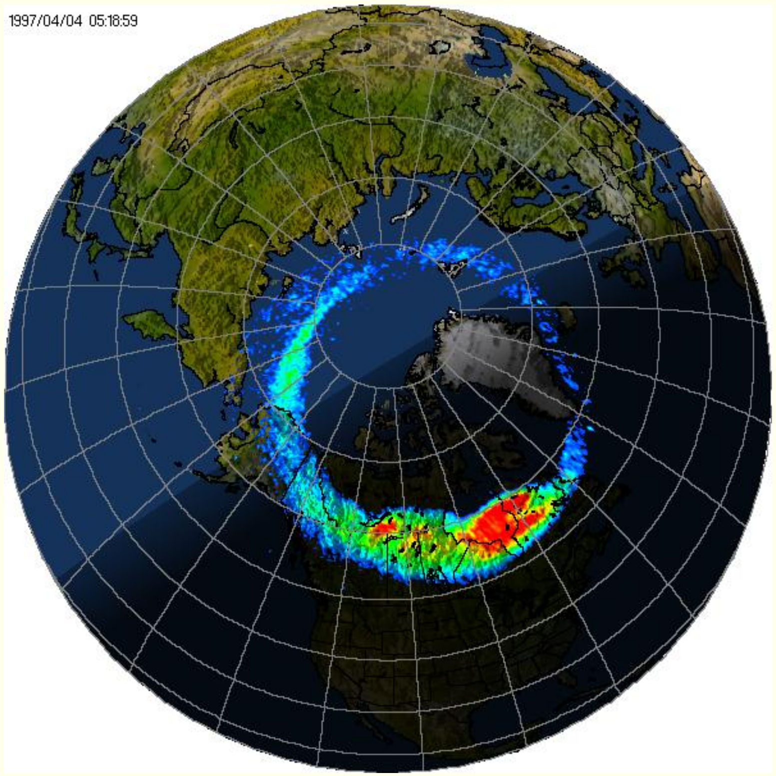
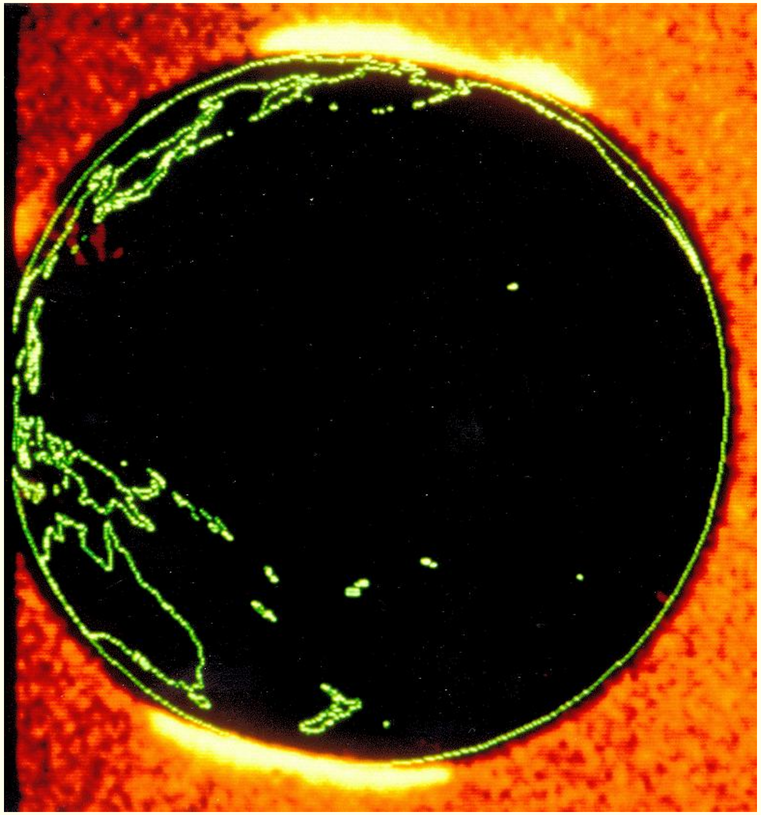


Foto från DMSP-satelliten

Auroral ovals



Polar

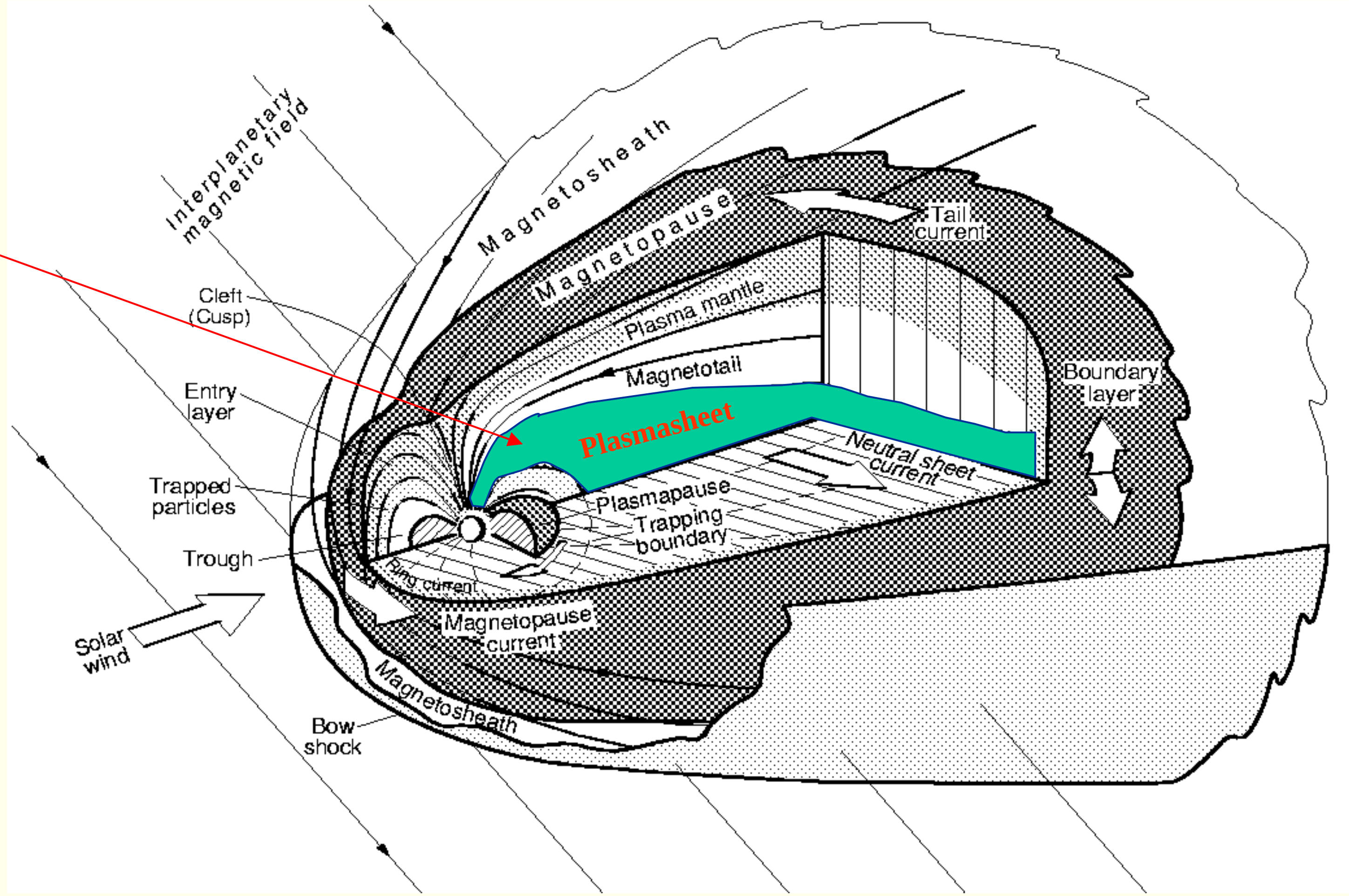


Dynamics Explorer

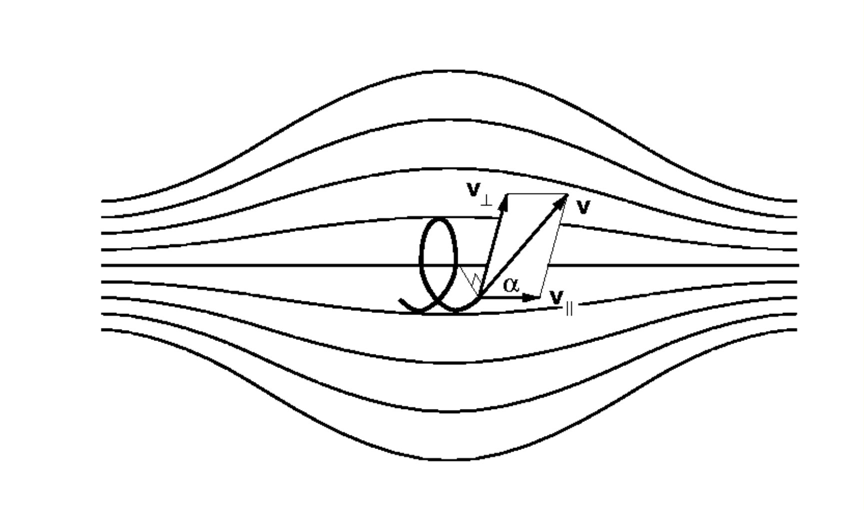
The auroral oval is the projection of the plasmasheet onto the atmosphere

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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particle turns when α = 90° ➡

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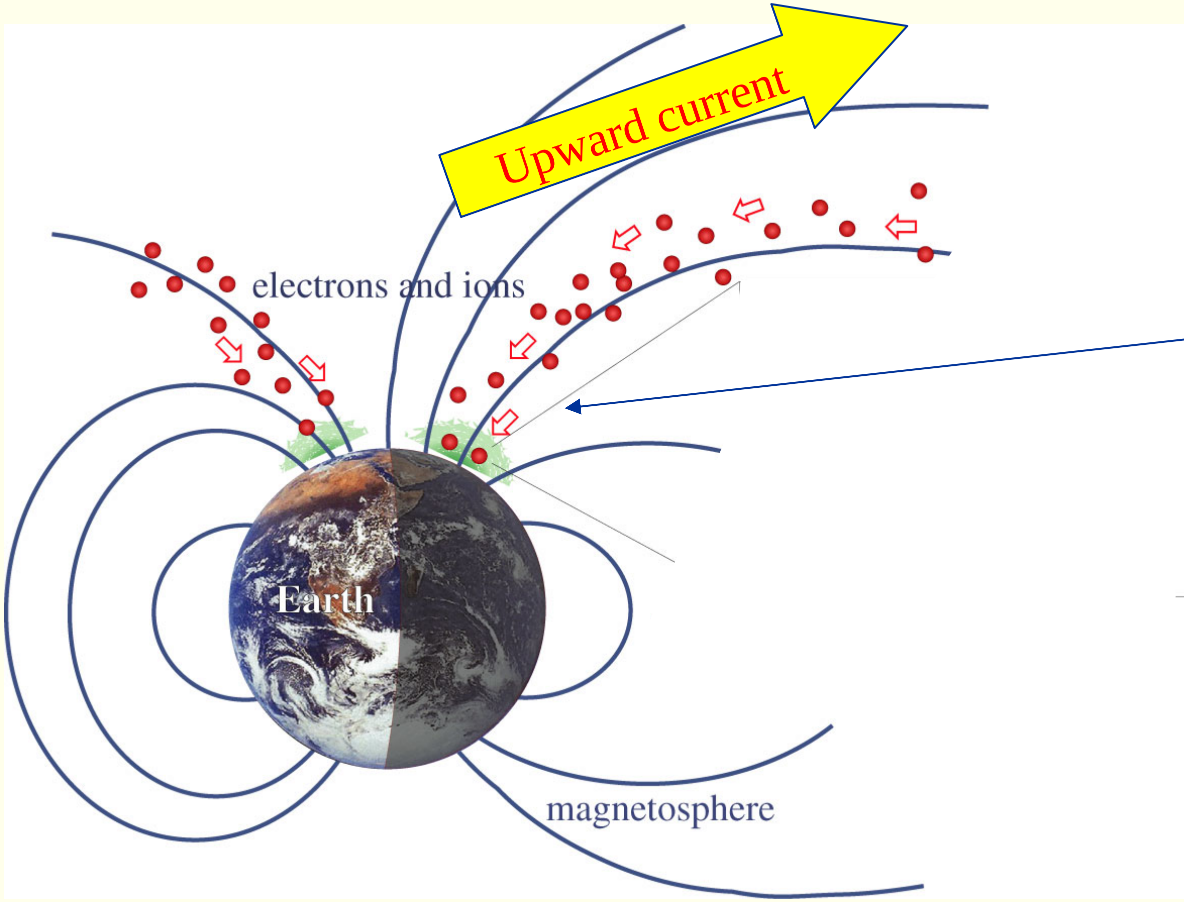
$$\mu = \frac{mv_\perp^2}{2B} = \frac{mv^2\sin^2\alpha}{2B}$$

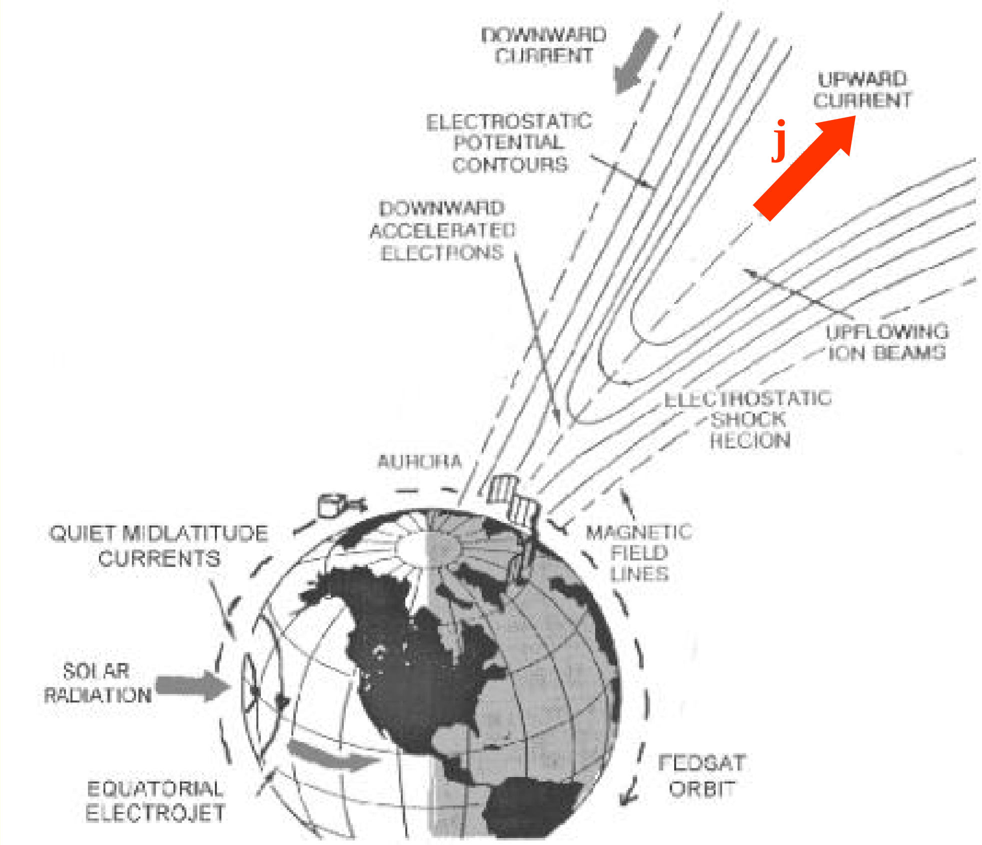
Particles in ***loss cone*** : $\alpha < \alpha_{fl}$

Why particle acceleration?



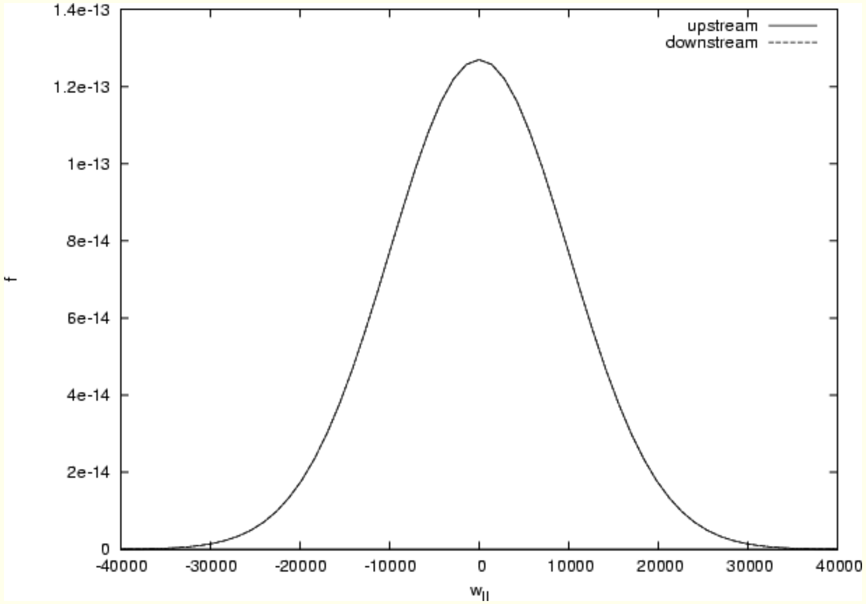
- The magnetosphere often seems to act as a current generator.
- The lower down you are on the field line, the more particles have been reflected by the magnetic mirror.
- At low altitudes there are not enough electrons to carry the current.

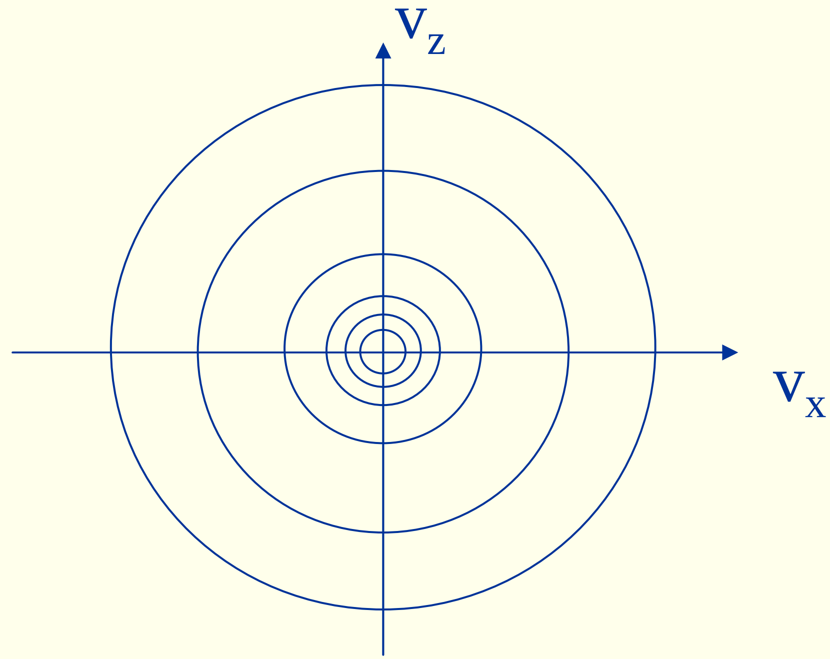
Why particle acceleration?



- 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

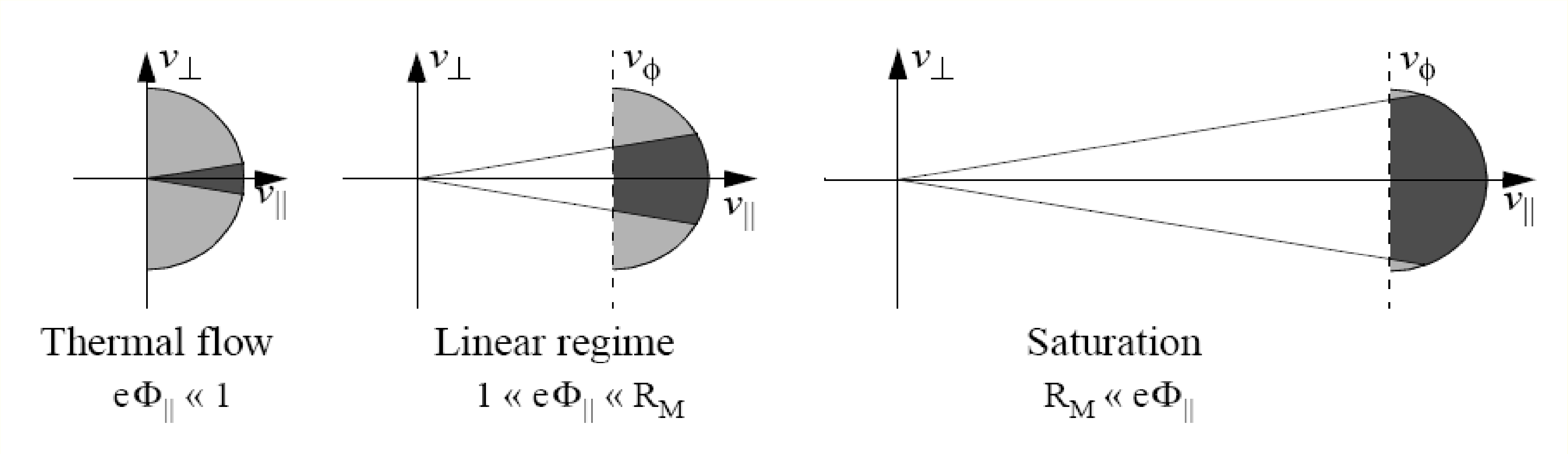




Example:
Maxwellian distribution

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

Why particle acceleration?



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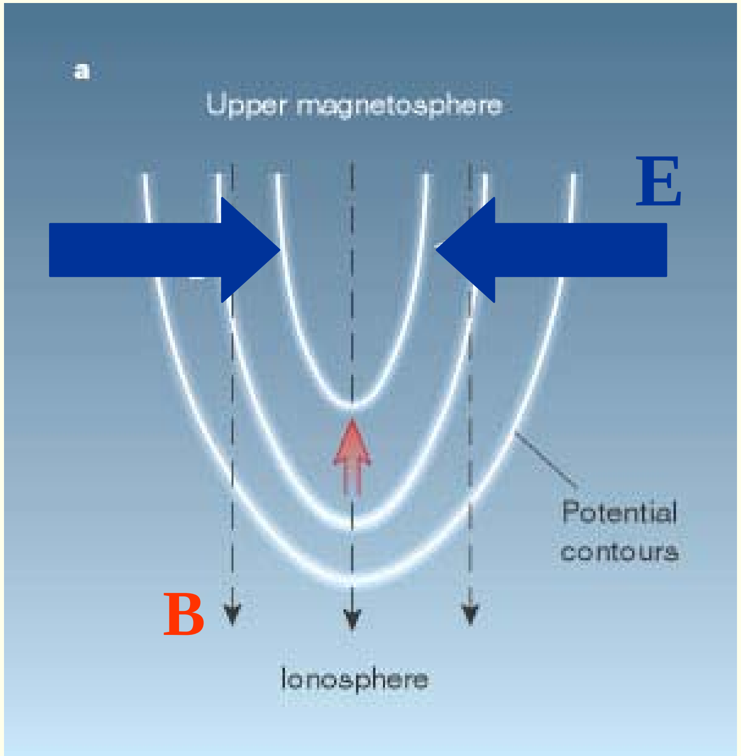
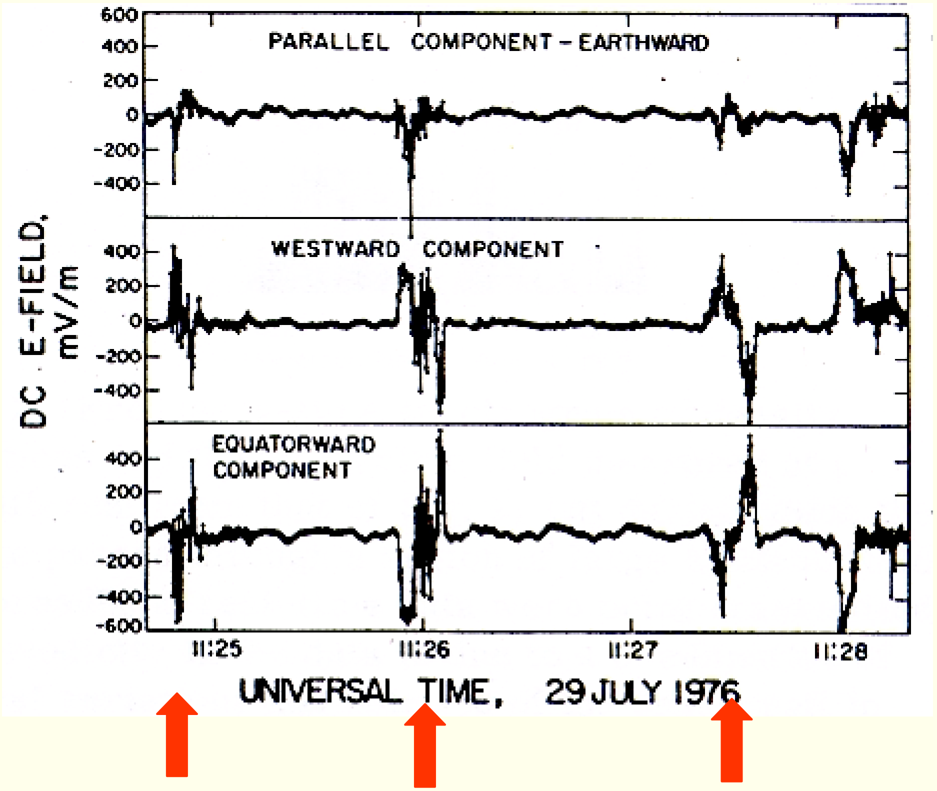
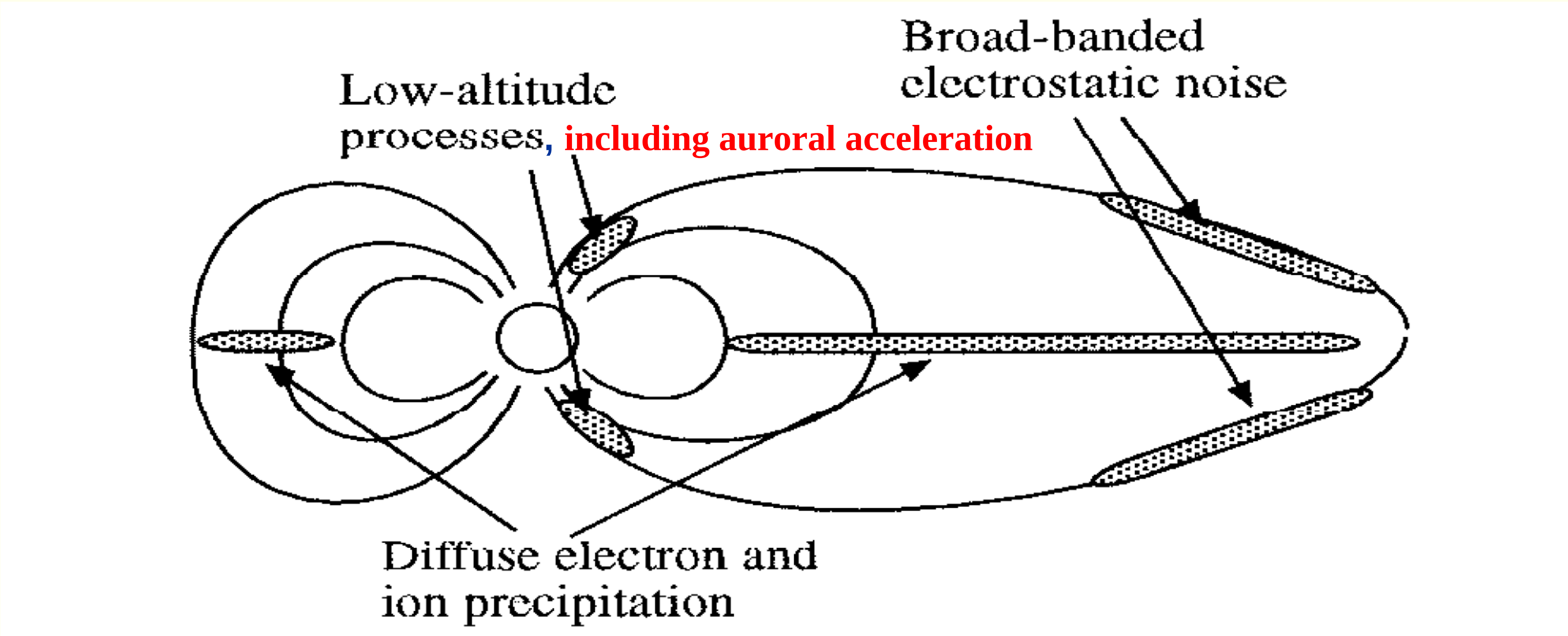
Satellite signatures of U potential





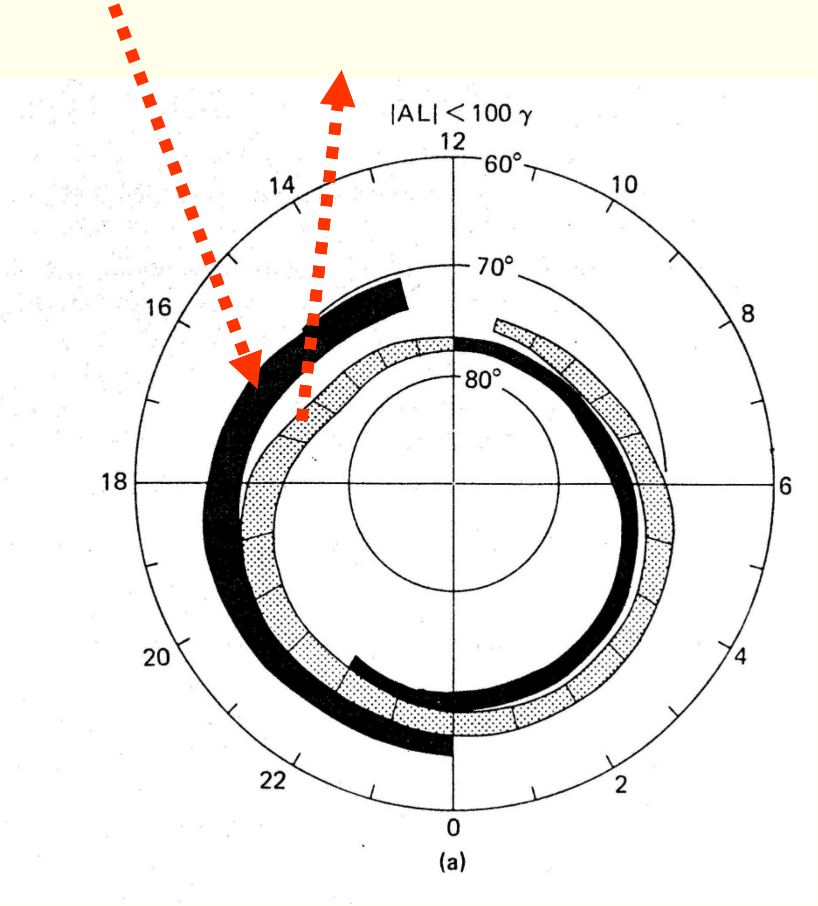
Measurements made by the ISEE satellite
(Mozer et al., 1977)

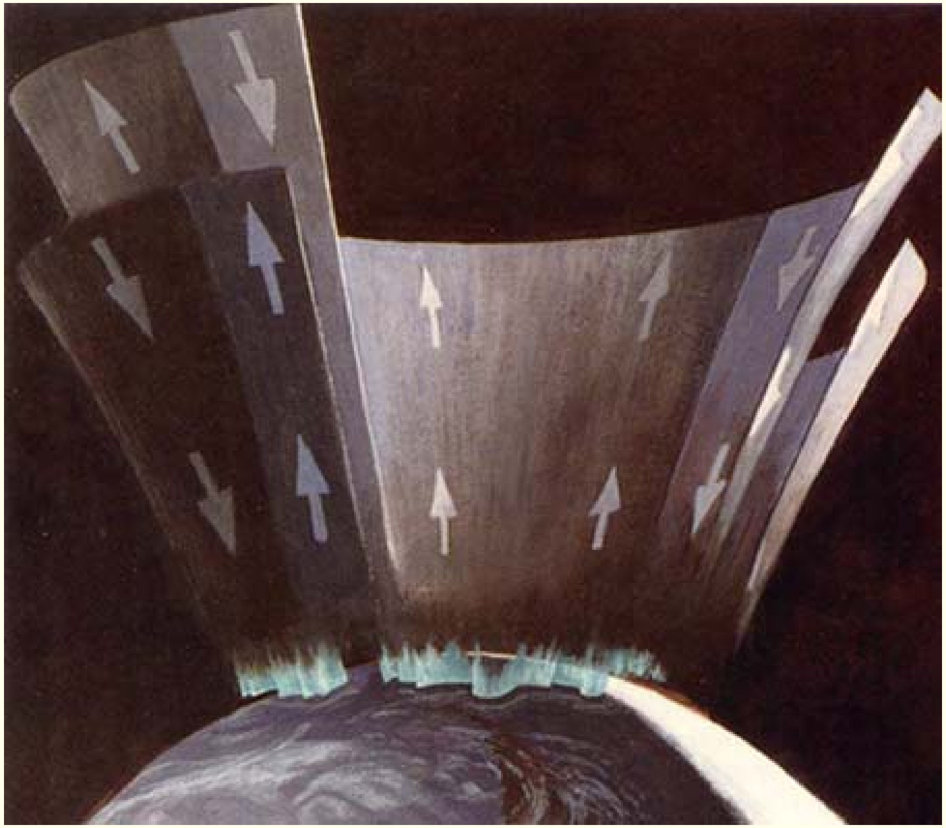
Acceleration regions



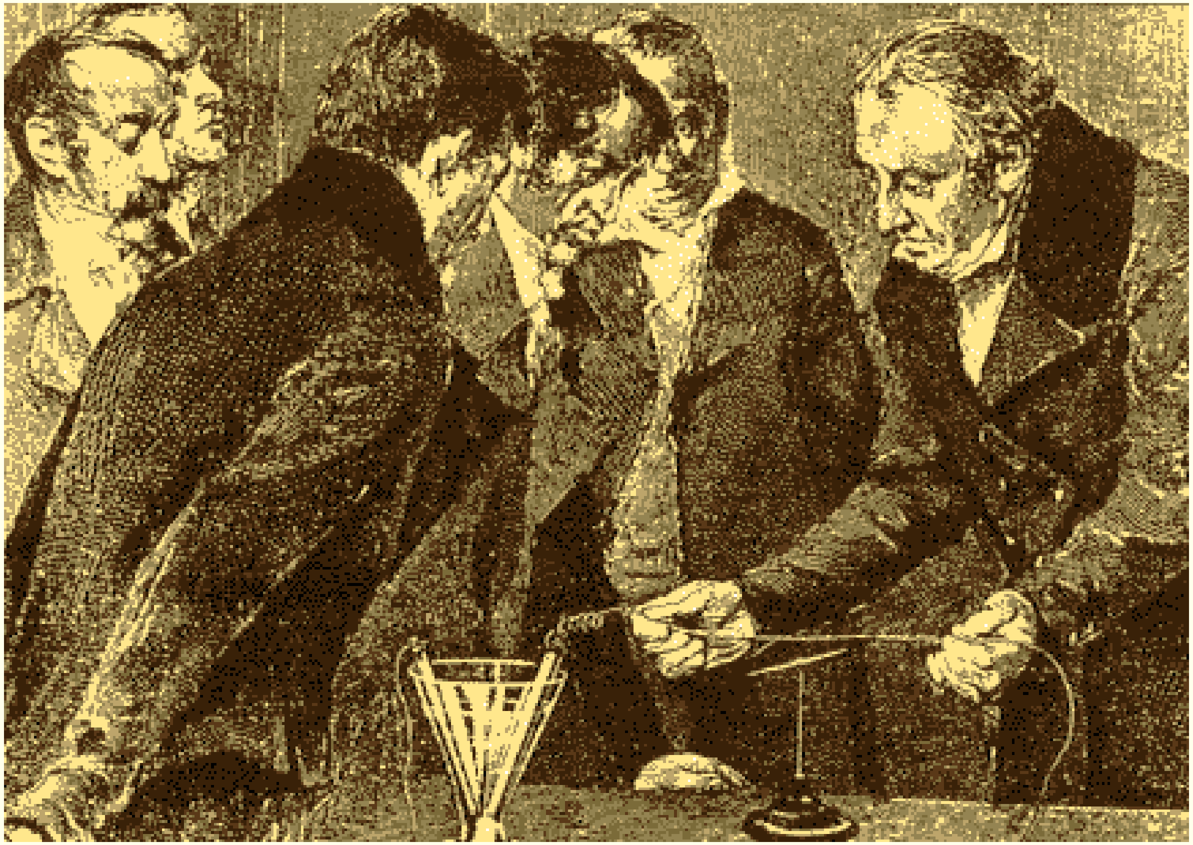
Auroral acceleration region typically situated at altitude of 1-3 R_E

Birkeland currents in the auroral oval

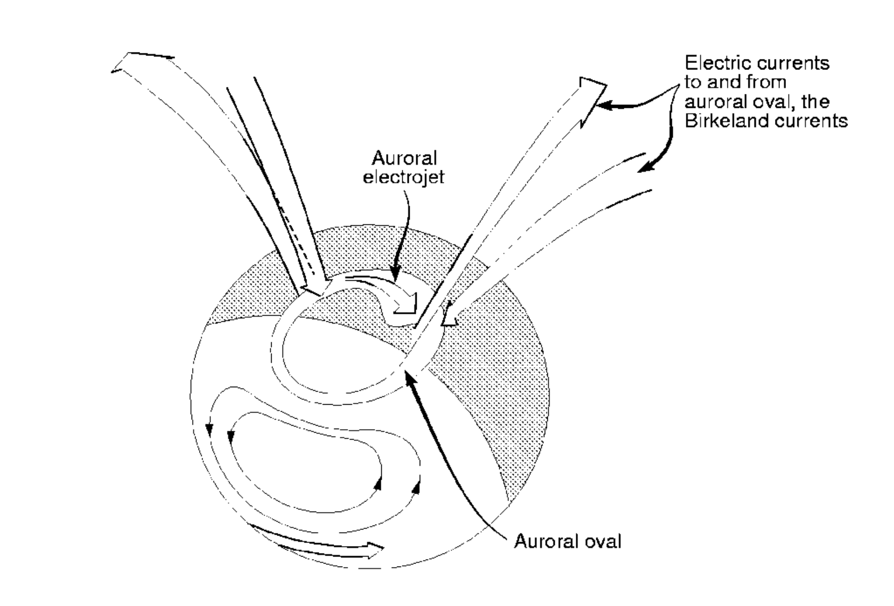




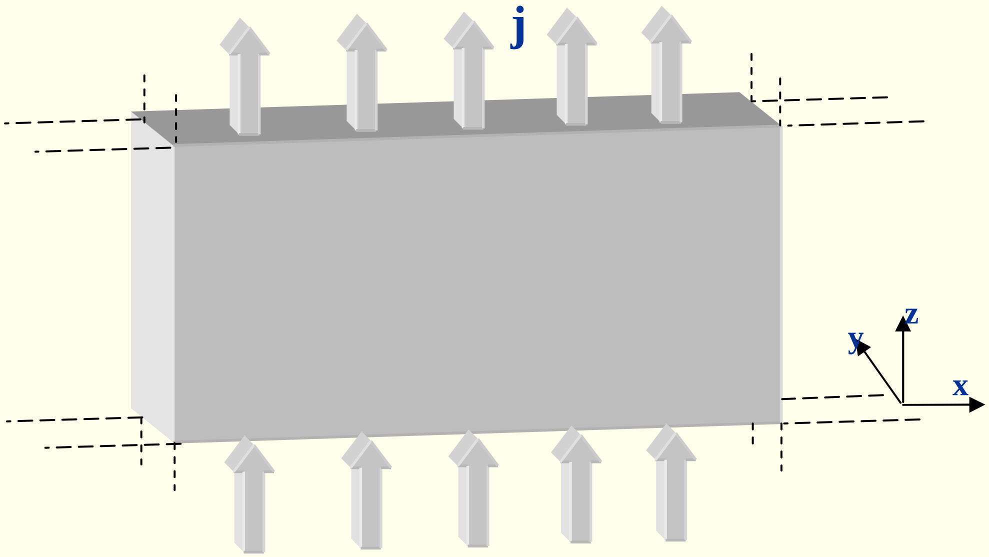
How can you measure currents in space?



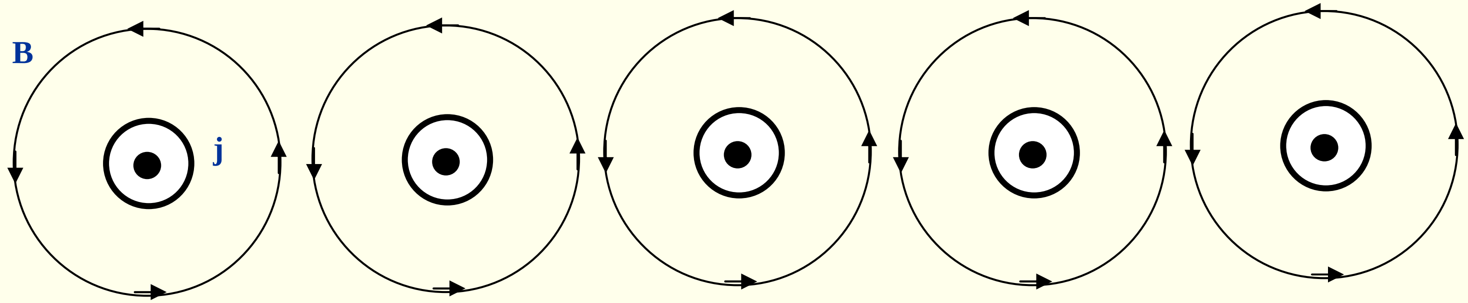
Current sheet approximation



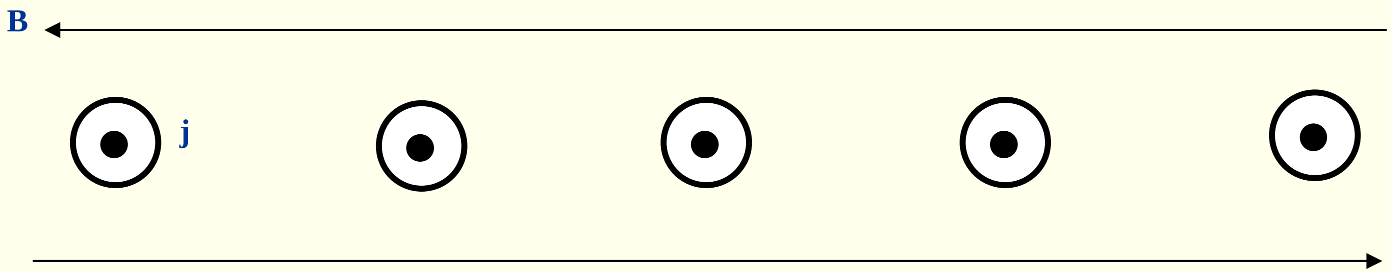
Approximate currents by thin current sheets with infinite size in the x- och z-directions.



Current sheet approximation

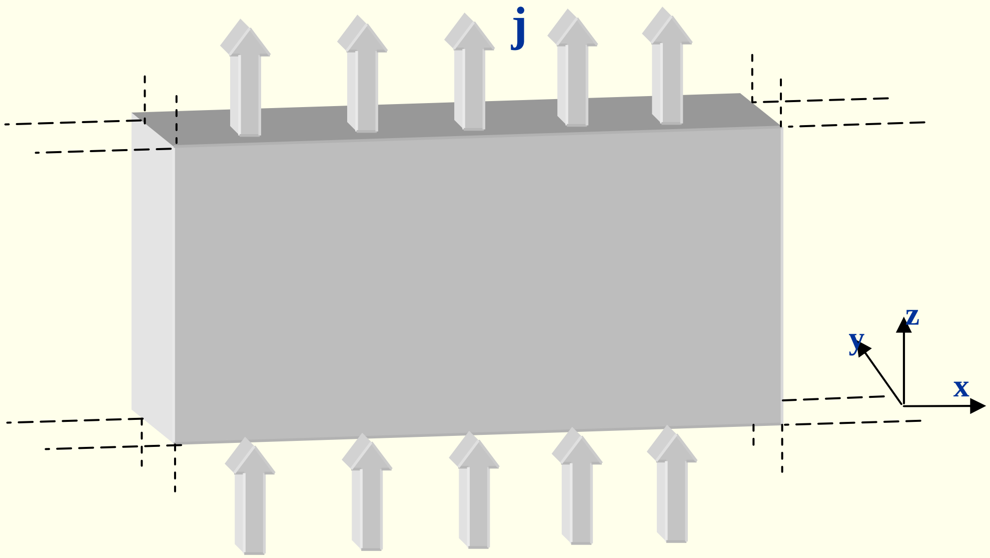


What will the magnetic field around such a current configuration be? Start by approximating with line currents to get a qualitative picture.



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

Current sheet approximation and Ampére's law



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

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

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

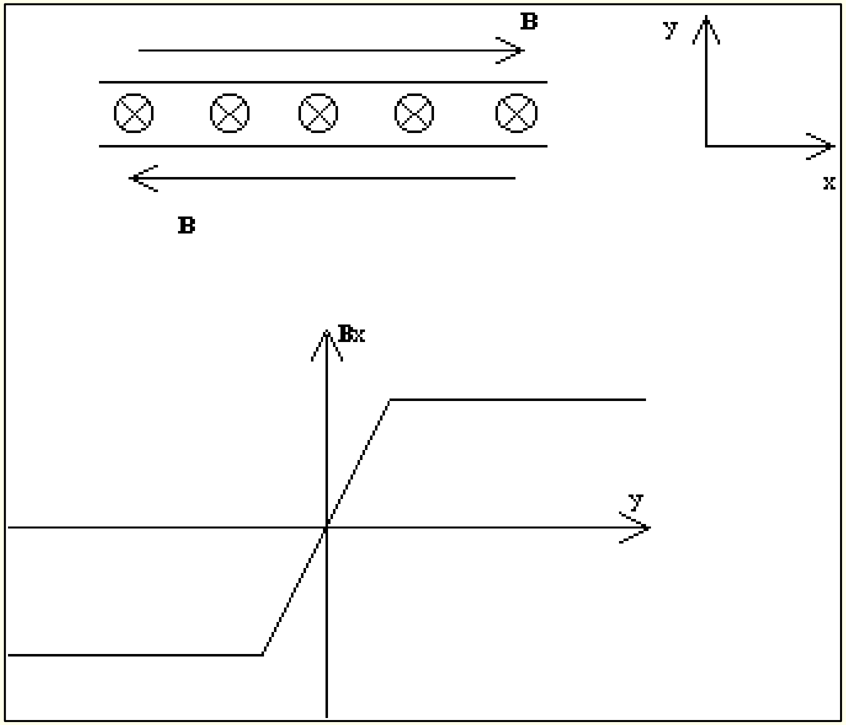
eller

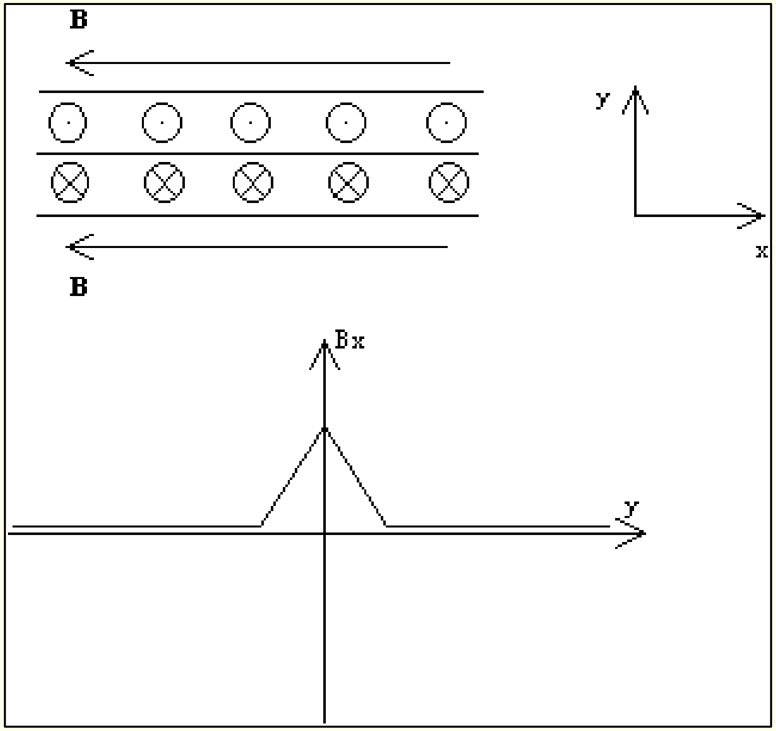
Ampére's law (no time dependence):

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

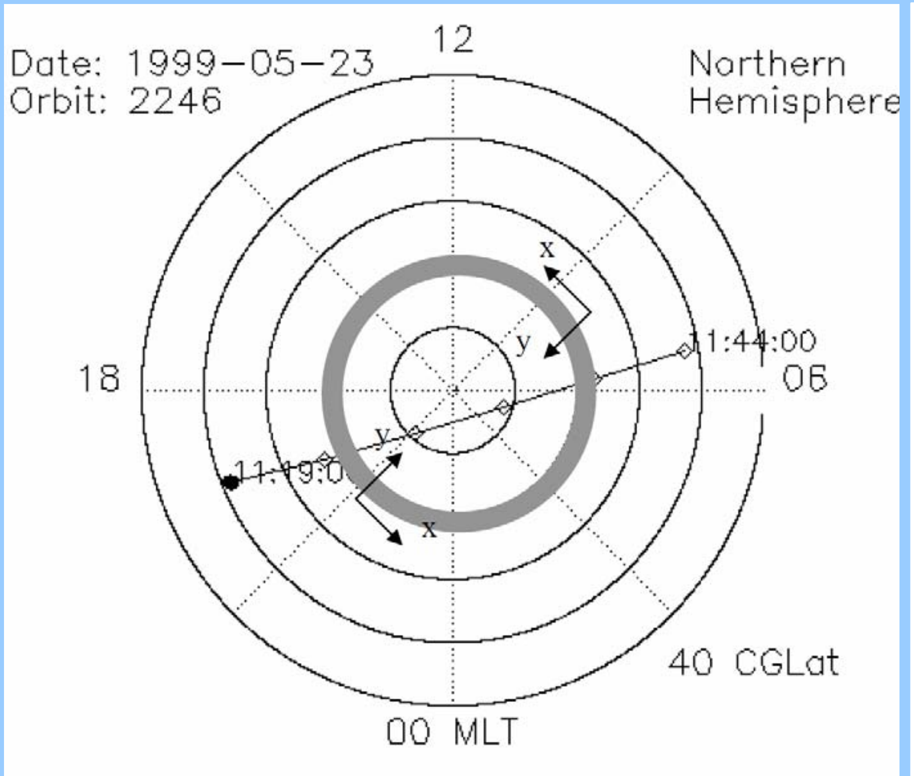
$$j_z=-\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

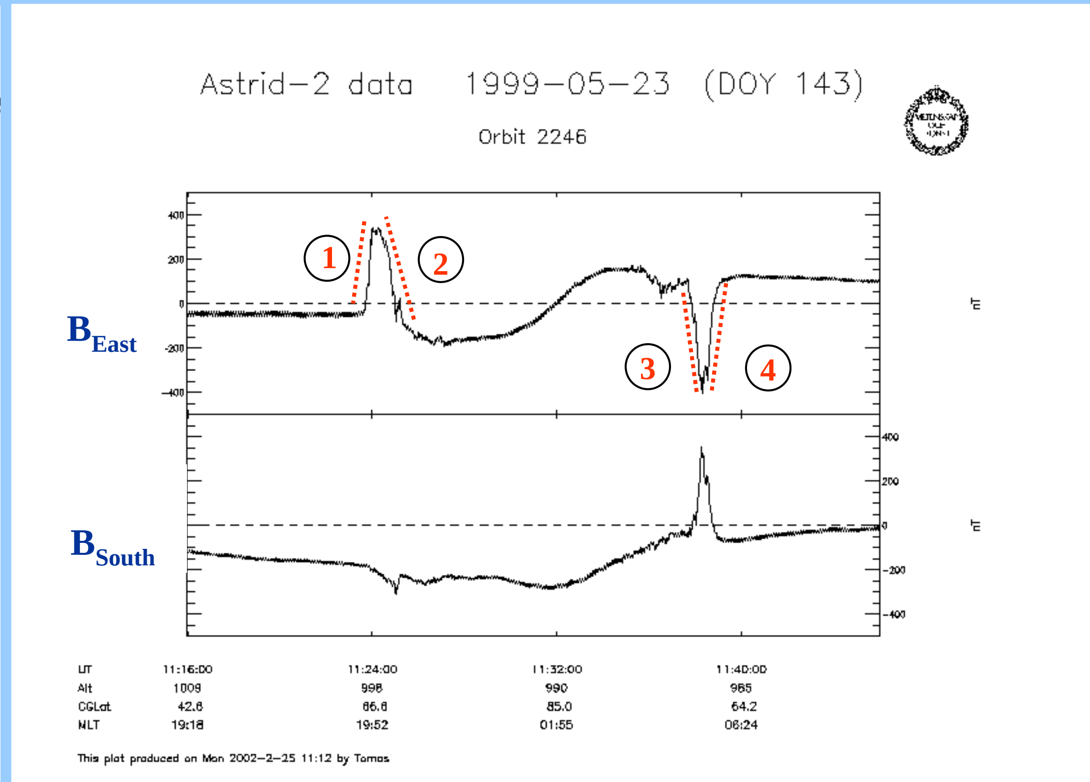
Current sheet - example





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

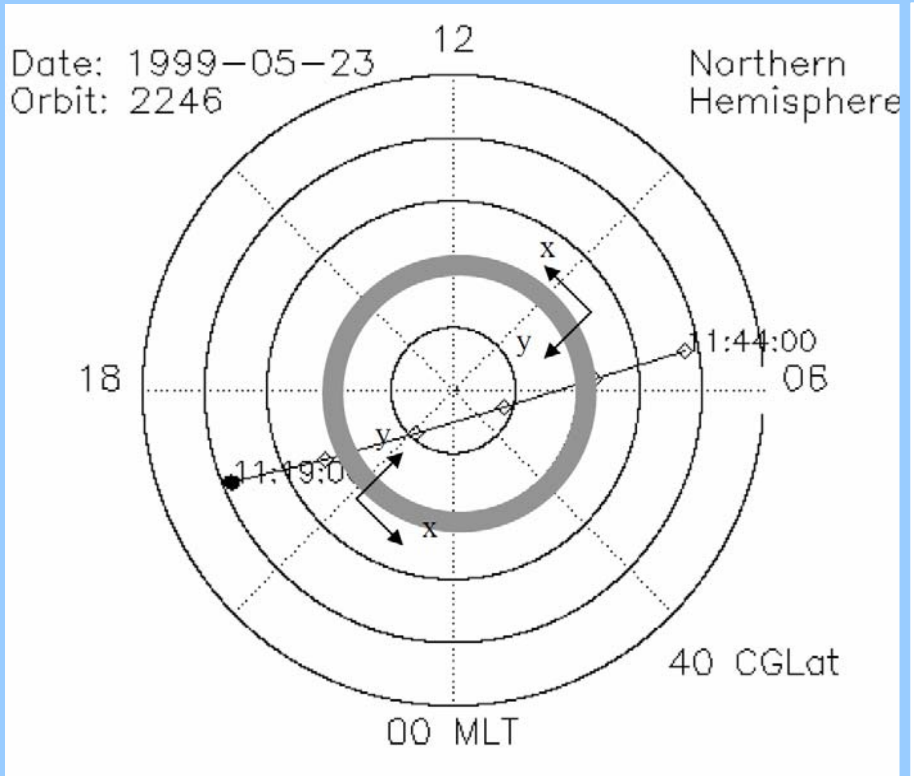


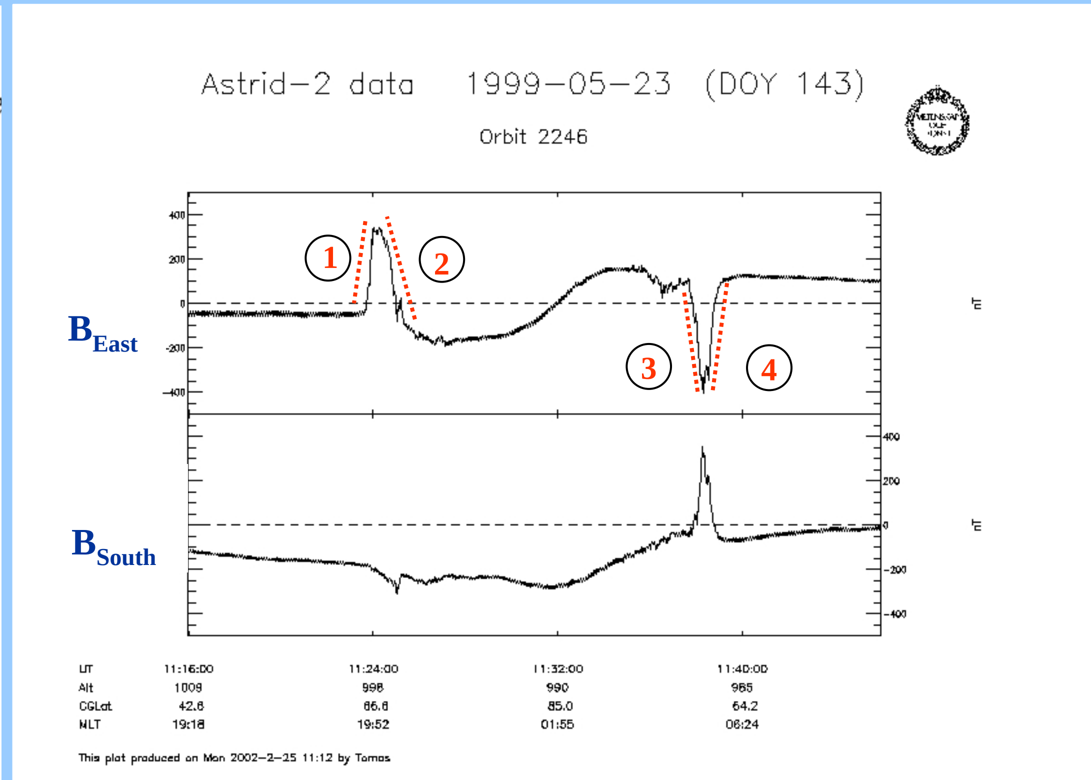


What is the direction of the current in current sheet 1?

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

Blue	Into the ionosphere
Red	Out of the ionosphere





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

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

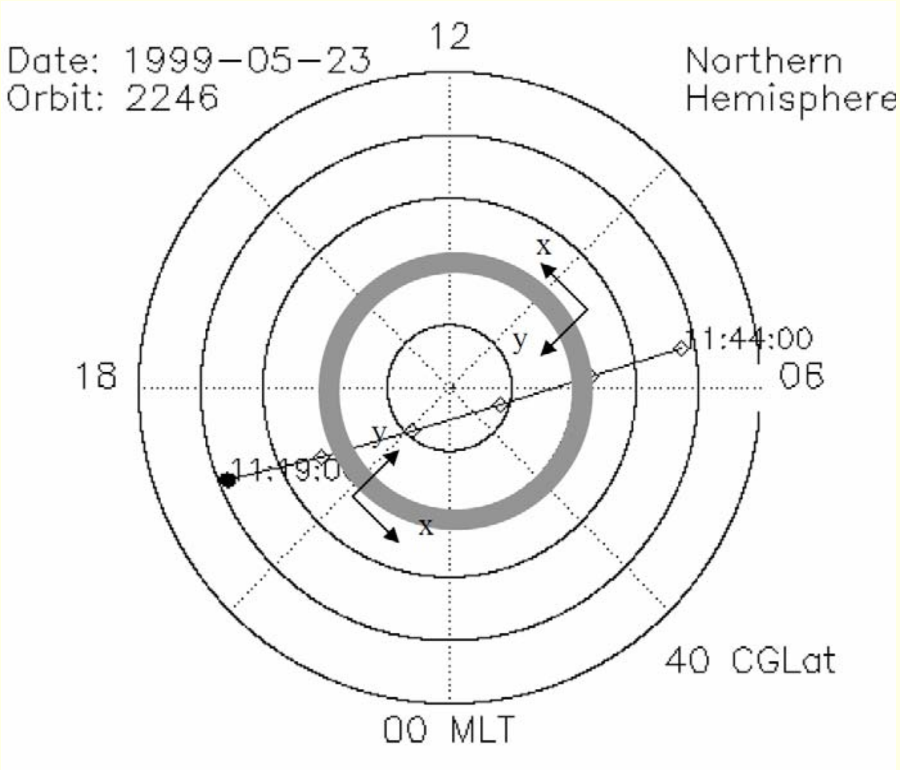
$$\frac{\partial B_x}{\partial y} = \frac{\partial B_{East}}{\partial y} > 0$$

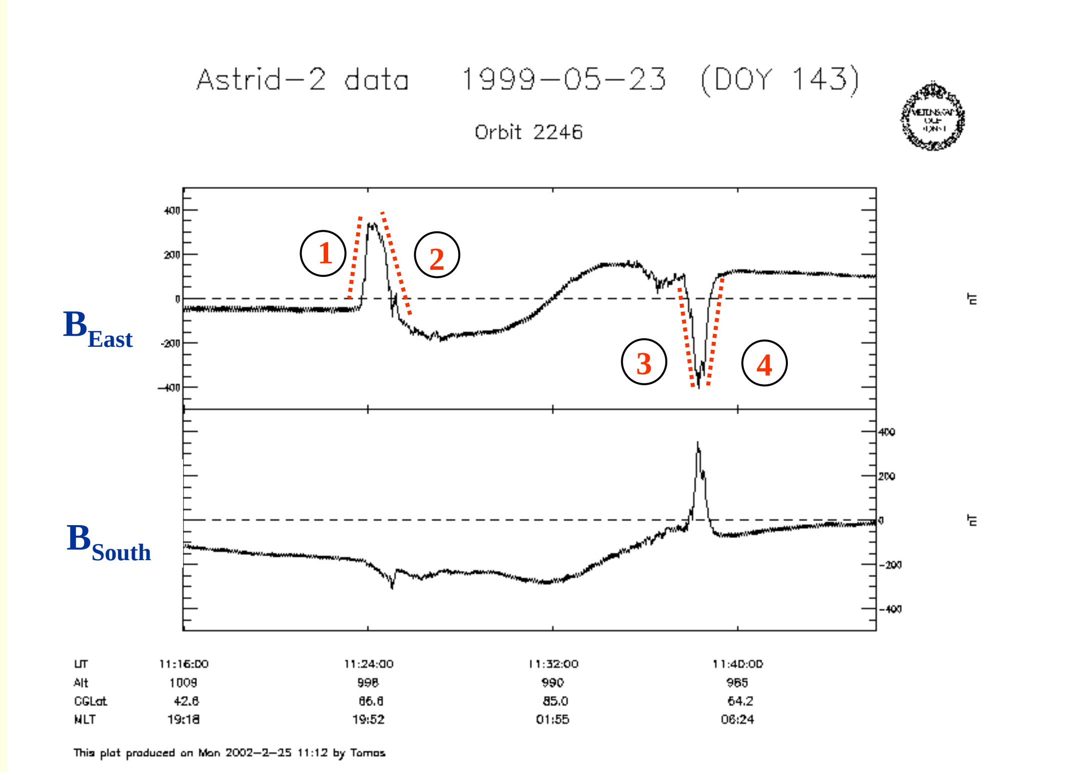
$$\Rightarrow$$

$$j_z < 0$$

Blue

Into the ionosphere

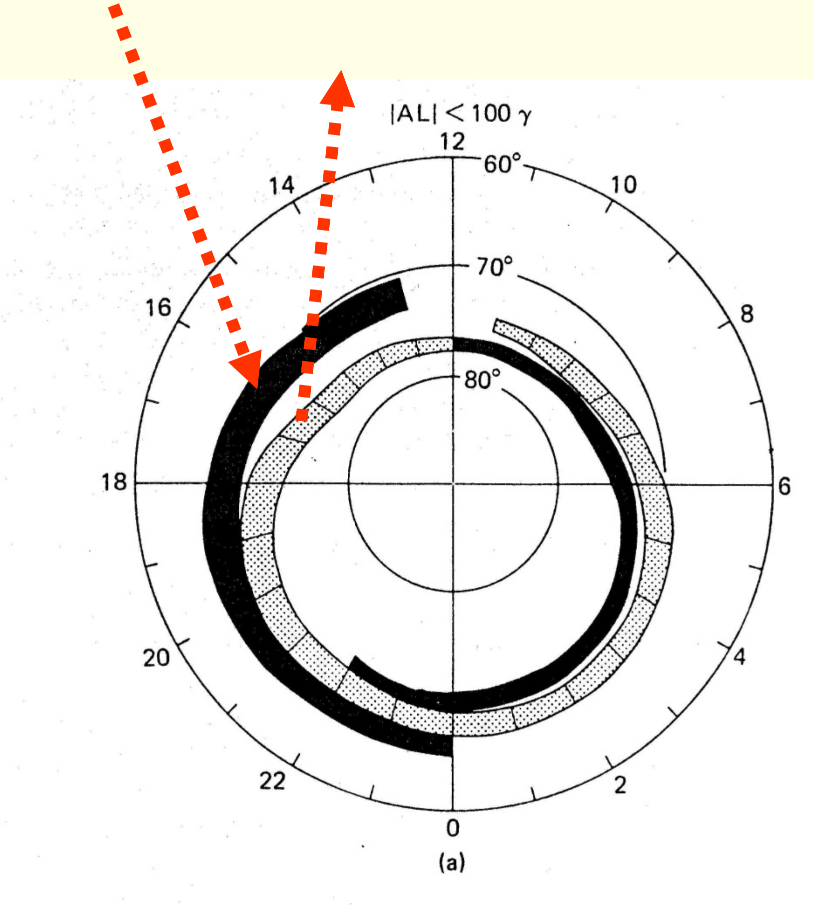


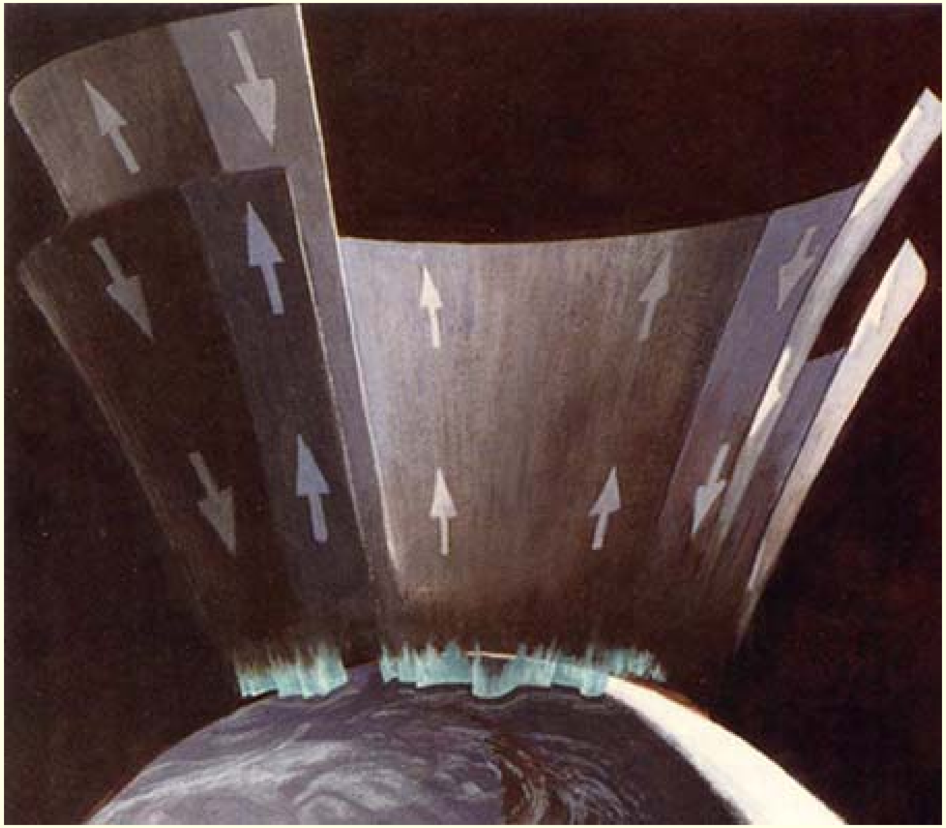


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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?

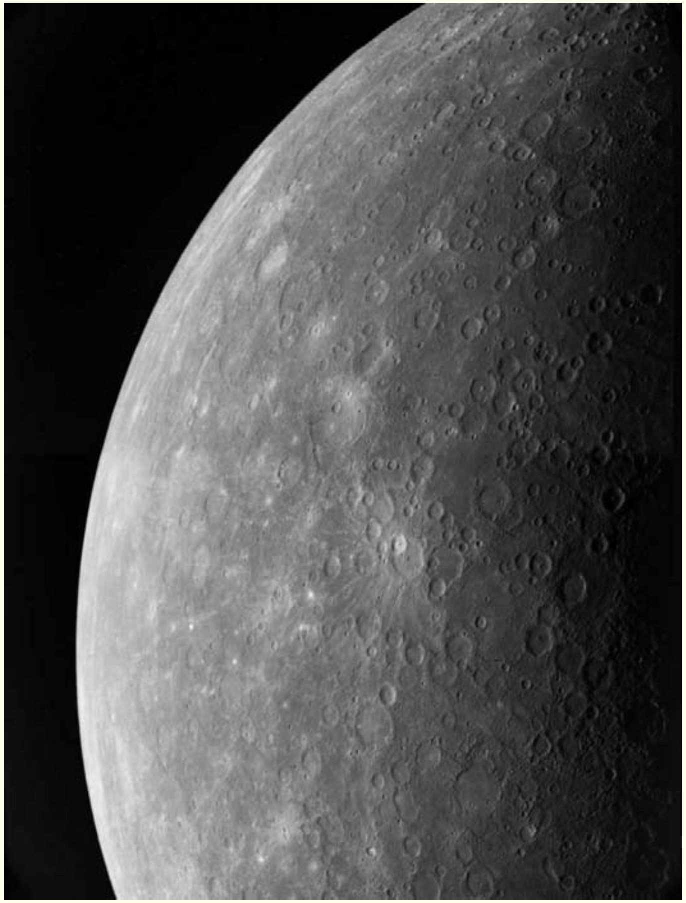
- Magnetic field (to guide the plasma particles towards the planet)
- Atmosphere (to create emissions)

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!

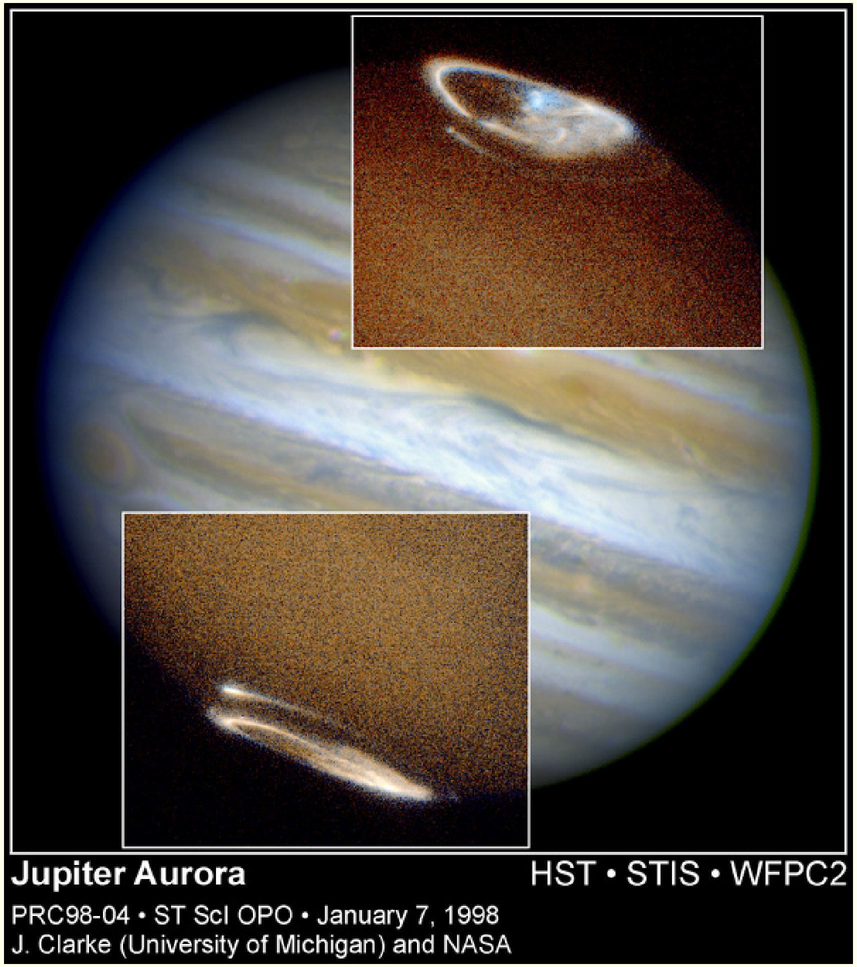
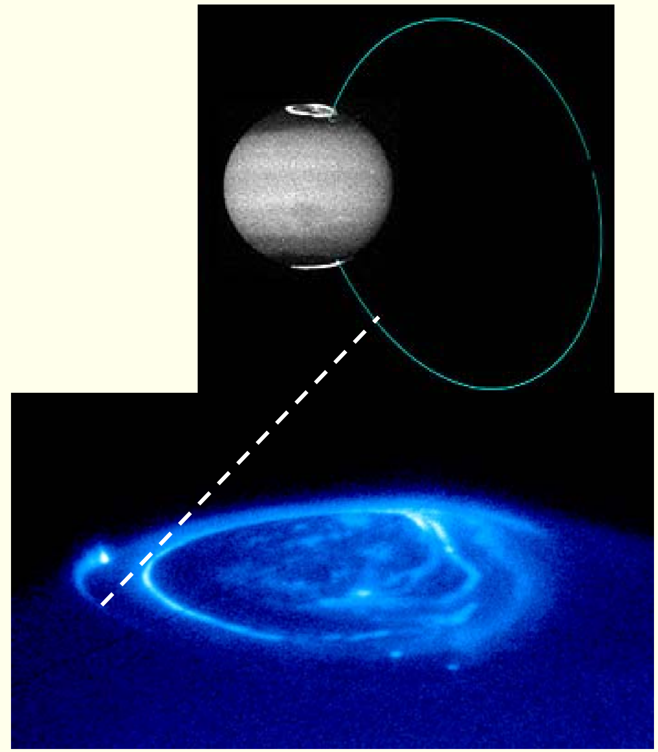
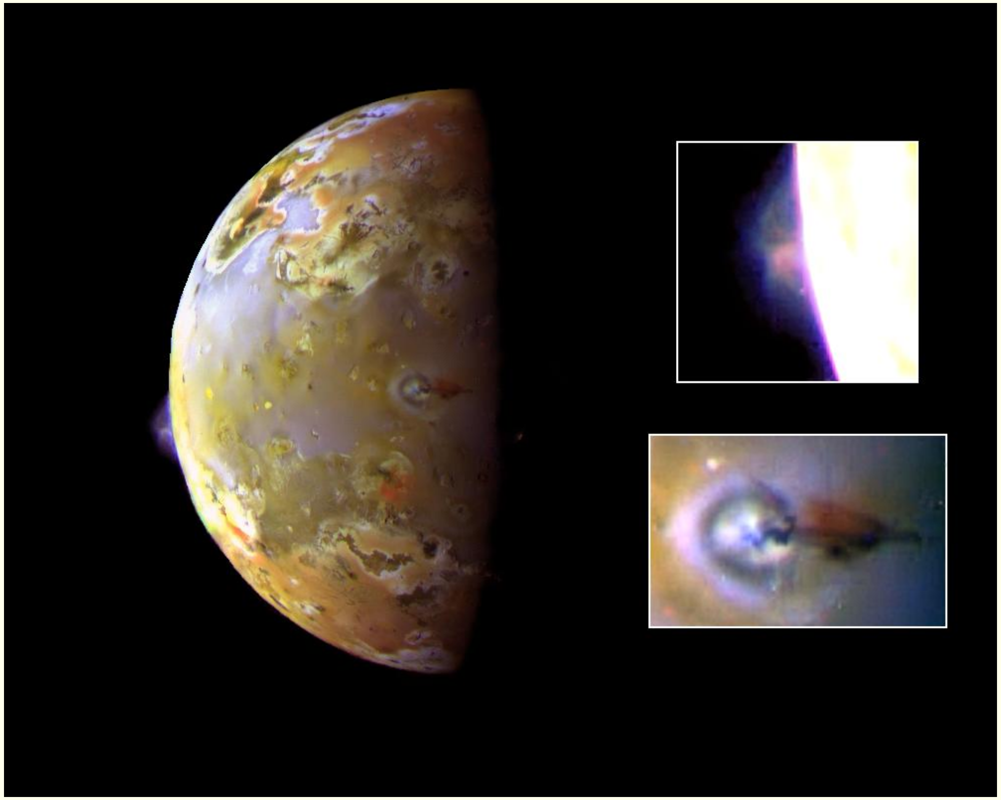


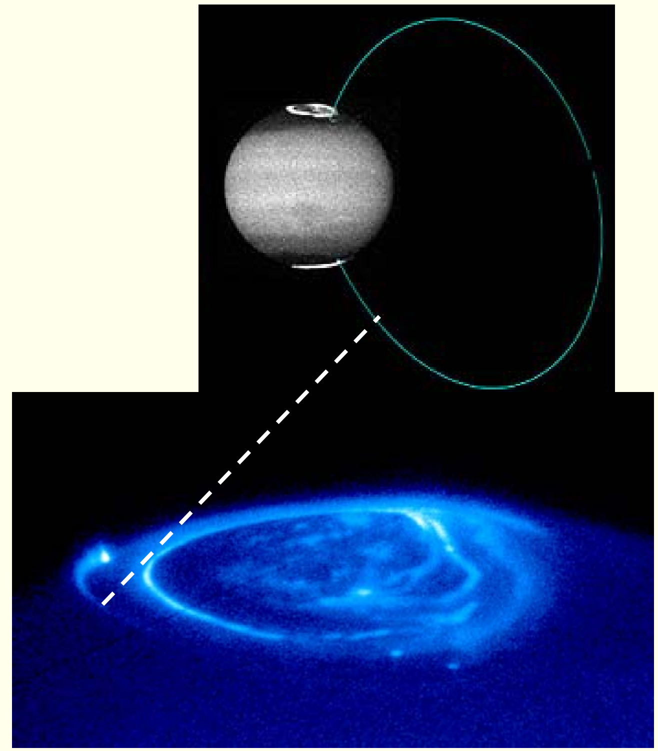
Foto från Hubble Space Telescope



Jupiter and Io

Photo from rymdsonden Galileo

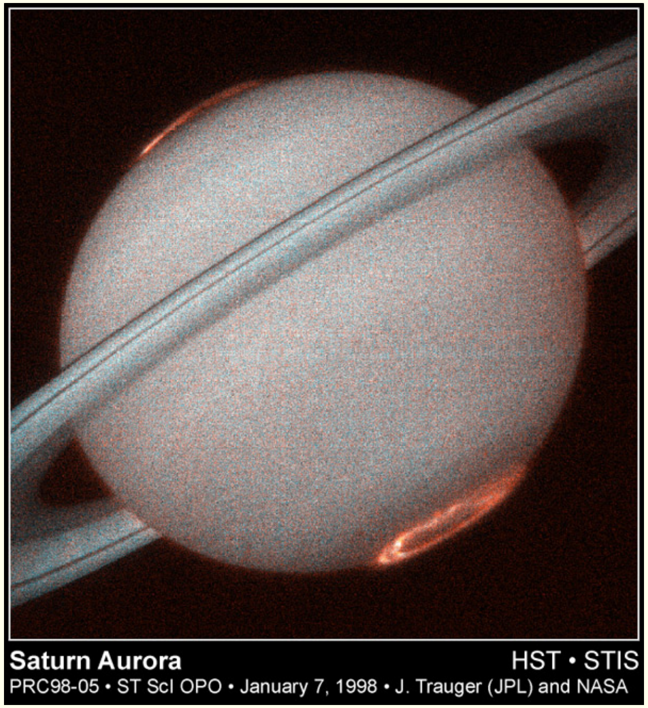




The Jupiter moon Io is very volcanically active, and deposes large amounts of dust and gas in Jupiter's magnetosphere. This is ionized by the sunlight, and the charged plasma partícles follow Jupiter's magnetic field lines towards the atmosphere and cause auroral emissions.

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

Last Minute!