Last lecture (8)

- Aurora
- Magnetospheric dynamics

Today's lecture (9)

- Cosmic radiation
- Interstellar plasma

Today

Activity	Date	Time	Room	Subject	Litterature
L1	31/8	13-15	V22	Course description, Introduction, The Sun 1, Plasma physics 1	CGF Ch 1, 5, (p 110-113)
L2	3/9	15-17	Q36	The Sun 2, Plasma physics 2	CGF Ch 5 (p 114-121), 6.3
L3	7/9	13-15	Q36	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	10/9	15-17	Q36	Mini-group work 1	
L4	14/9	13-15	E2	The ionosphere 2, Plasma physics 4	CGF Ch 3.4, 3.7, 3.8
T2	17/9	8-10	Q31	Mini-group work 2	
L5	17/9	15-17	L52	The Earth's magnetosphere 1, Plasma physics 5	CGF 4.1-4.3, LL Ch I, II, IV.A
L6	21/9	13-15	L52	The Earth's magnetosphere 2, Other magnetospheres	CGF Ch 4.6-4.9, LL Ch V.
T3	24/9	16-18	Q36	Mini-group work 3	
L7	28/9	13-15	Q36	Aurora, Measurement methods in space plasmas and data analysis 1	CGF Ch 4.5, 10, LL Ch VI, Extra material
T4	1/10	15-17	V22	Mini-group work 4	
L8	5/10	13-15	M33	Space weather and geomagnetic storms	CGF Ch 4.4, LL Ch IV.B-C, VII.A-C
L9	6/10	8-10	Q36	Interstellar and intergalactic plasma, Cosmic radiation.	CGF Ch 7-9
T5	8/10	15-17	Q34	Mini-group work 5	
L10	12/10	13-15	Q36	Swedish and international space physics research.	
T6	15/10	15-17	Q33	Round-up.	
Written examination	28/10	8-13	Q21, Q26		

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 3, 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*), 30/10

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)

(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.)

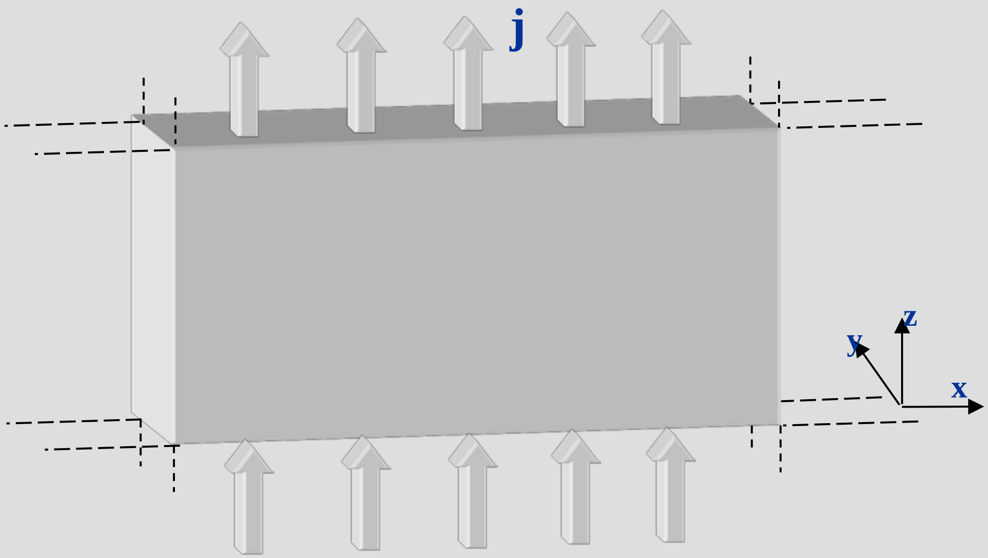
Approx. 5 different problems (which may contain sub-problems).

About the exam

Motivate your answers!

Be careful with units and numerical calculations!

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

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

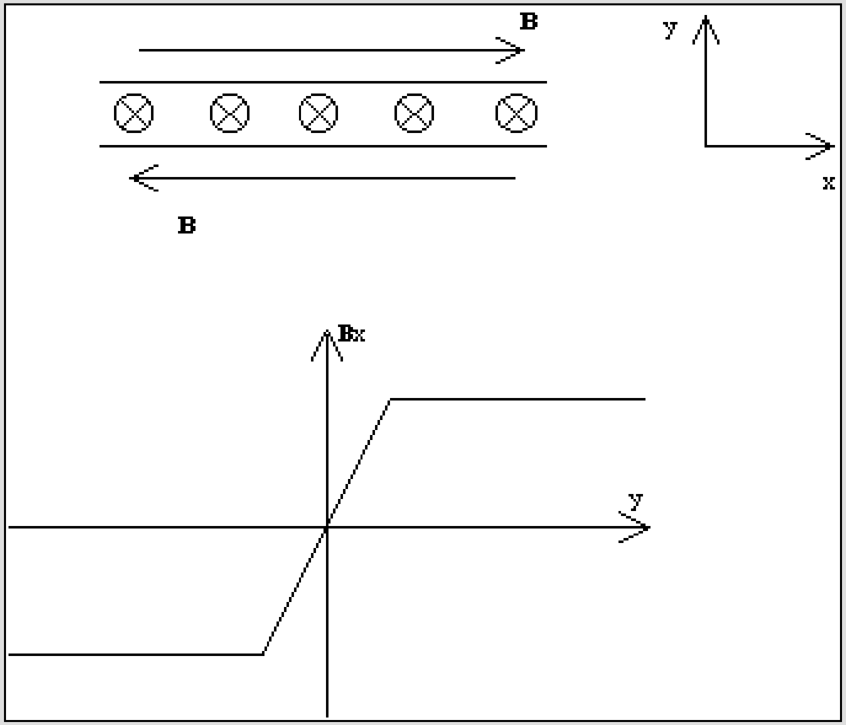
eller

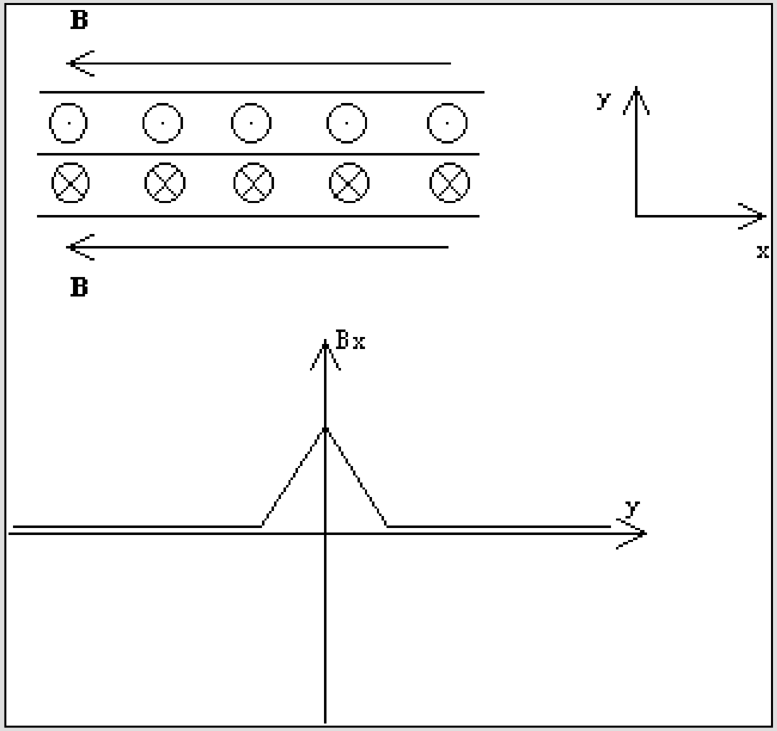
Ampére's law (no time dependence):

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

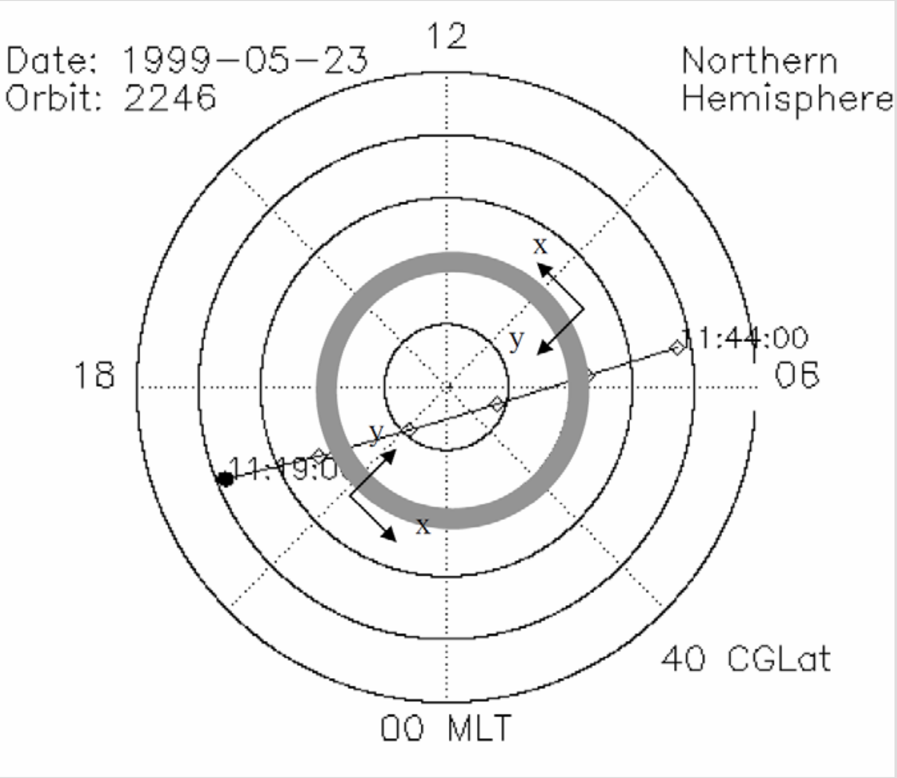
$$j_z=-\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

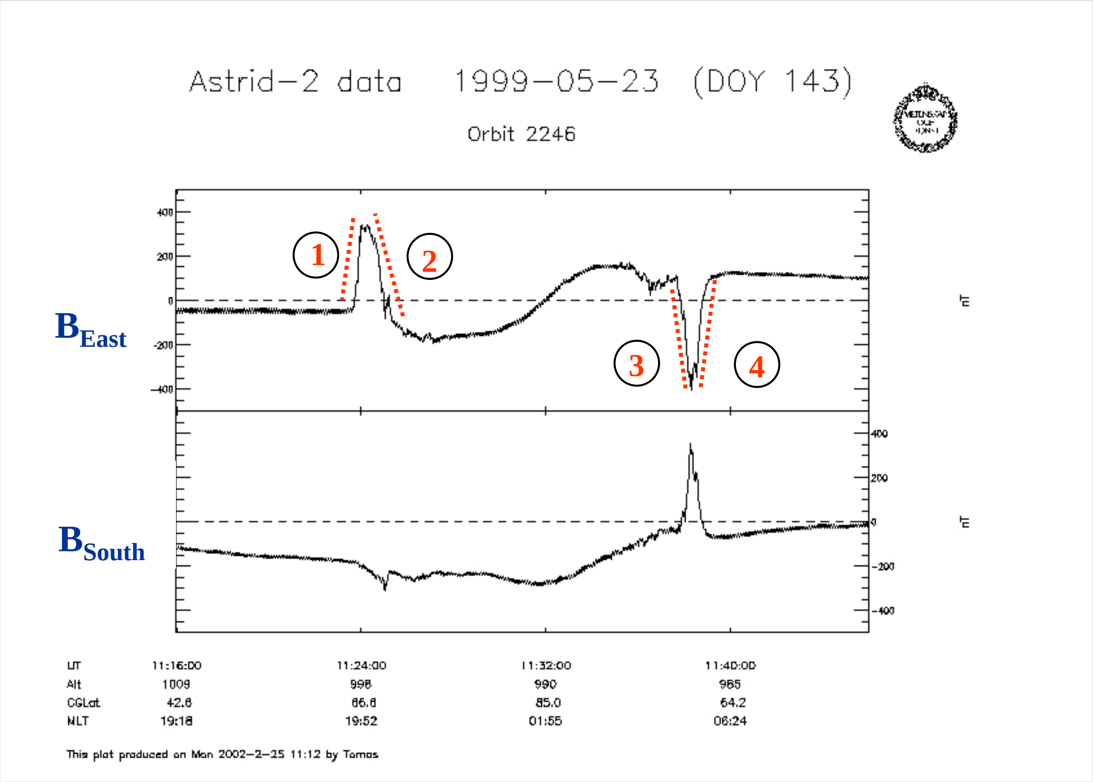
Current sheet - example





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

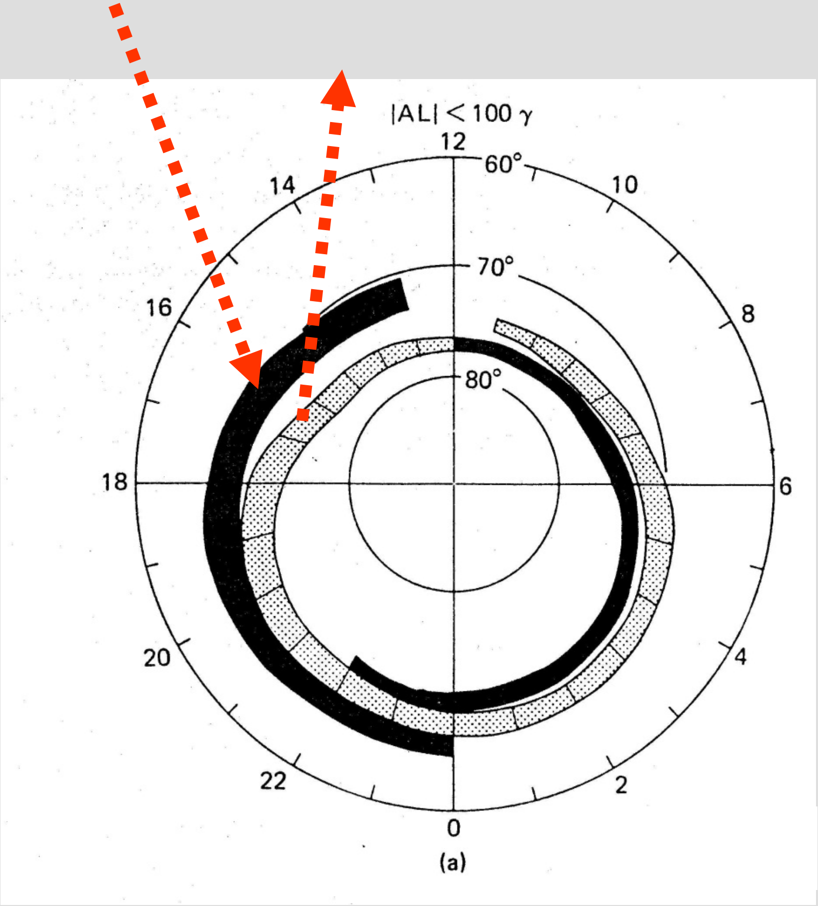


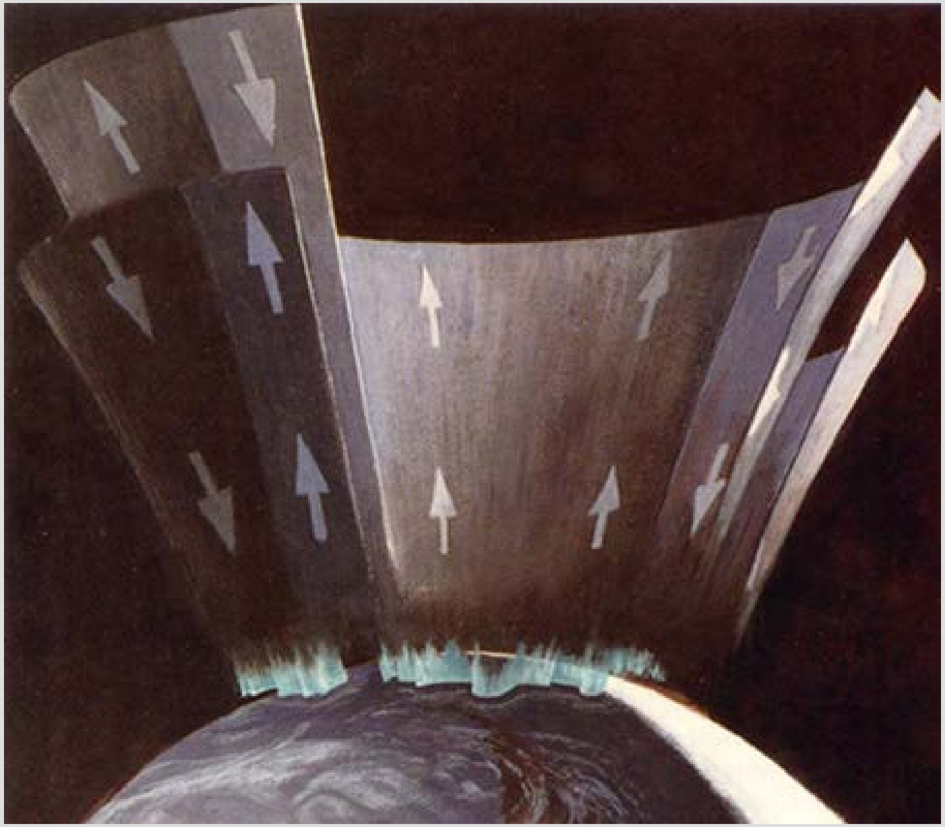


$$j_z = -\frac{1}{\mu_0}\frac{\partial B_x}{\partial y}$$

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

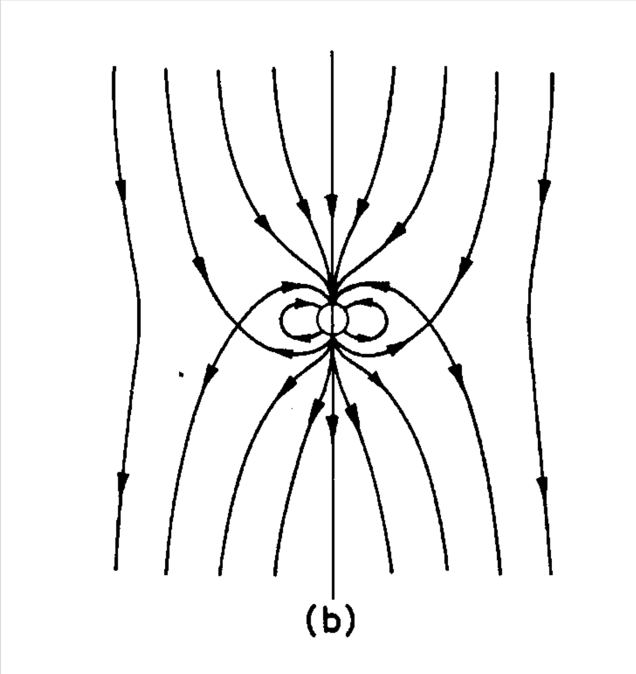
Birkeland currents in the auroral oval



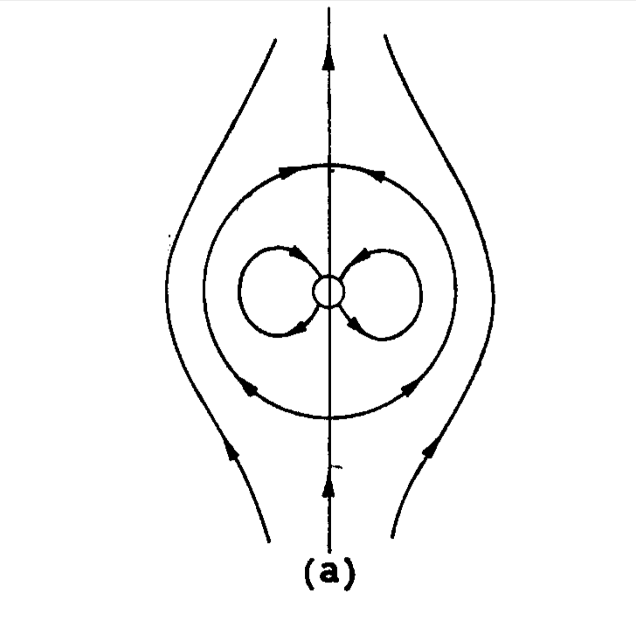


Magnetospheric dynamics

open magnetosphere



closed magnetosphere



southward

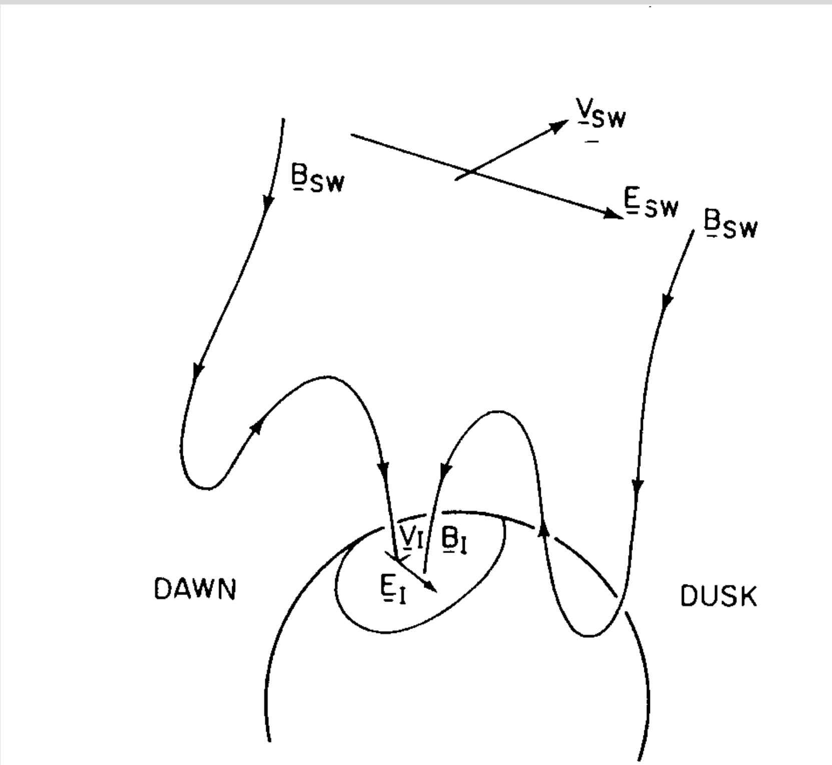
Interplanetary magnetic field (IMF)

northward

Magnetospheric dynamics

open magnetosphere

Viewpoint 1



The solar wind generates an electric field

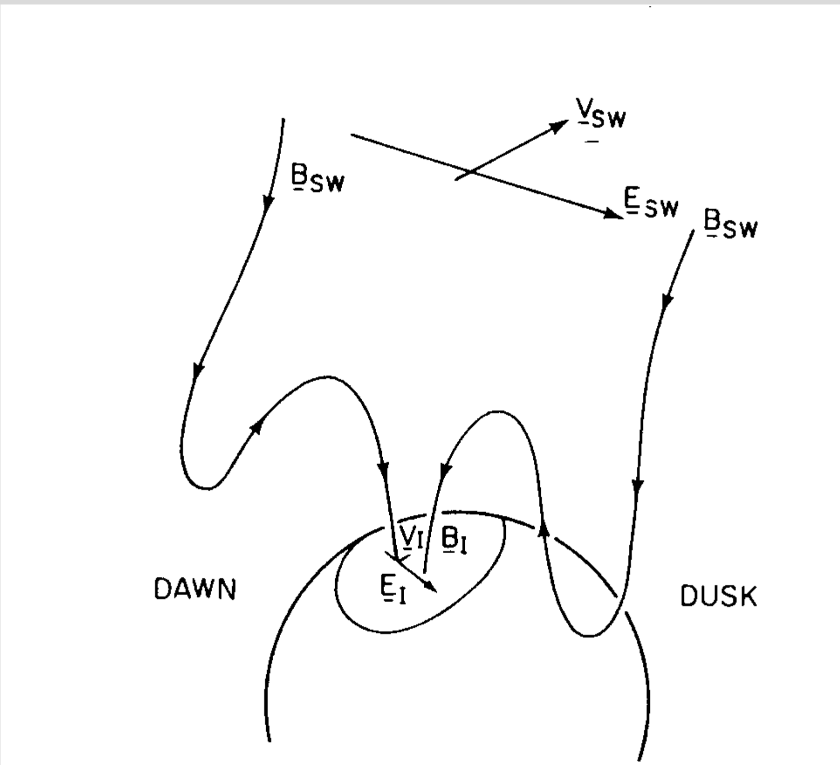
$$\mathbf{E}_{SW} = -\,\mathbf{v}_{SW} \times \mathbf{B}_{SW}$$

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

Magnetospheric dynamics

open magnetosphere

Viewpoint 2



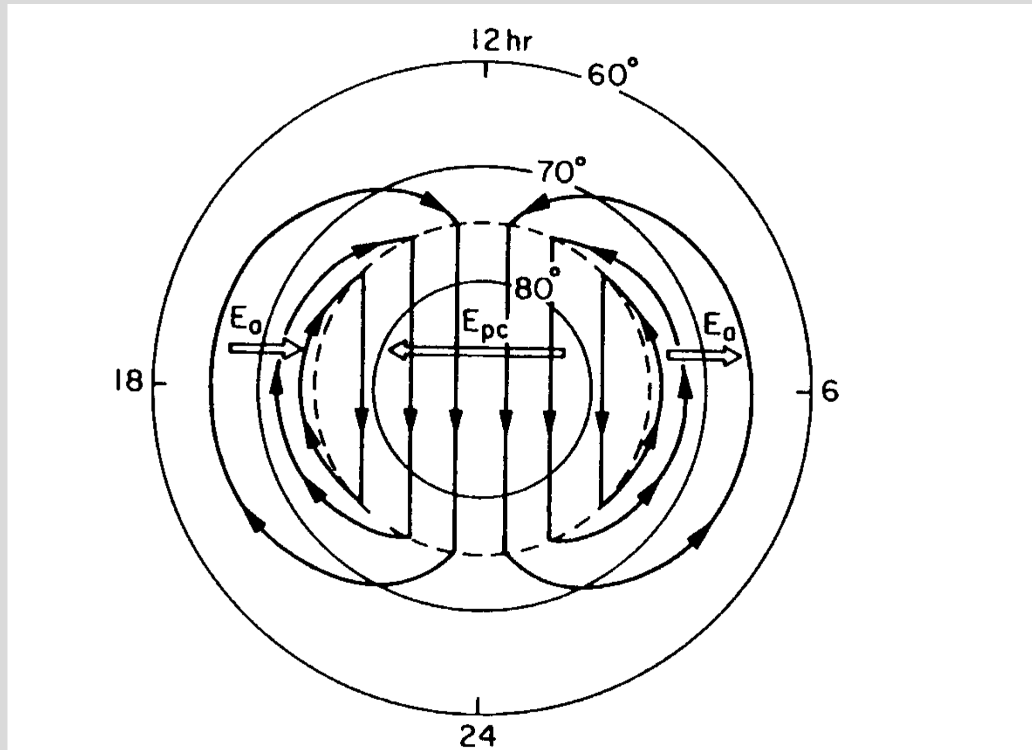
The solar wind magnetic field draws the ionospheric plasma with it, since the field is frozen into the plasma. This motion induces an ionospheric electric field

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

Magnetospheric dynamics

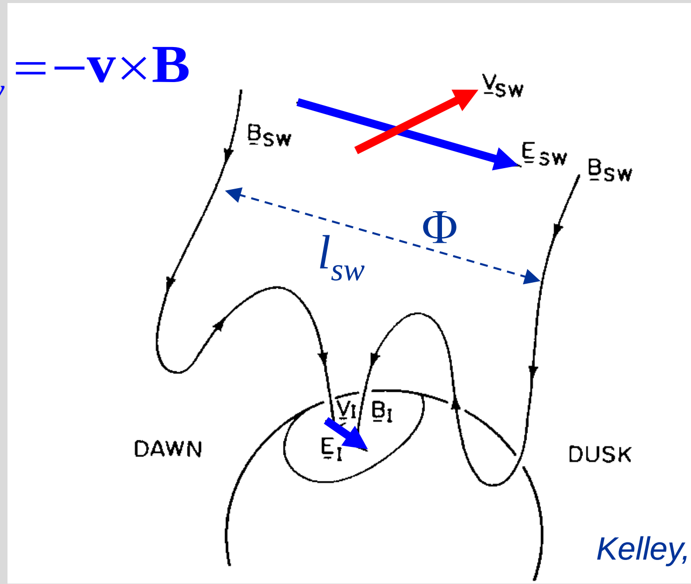
Plasma convection in the ionosphere

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

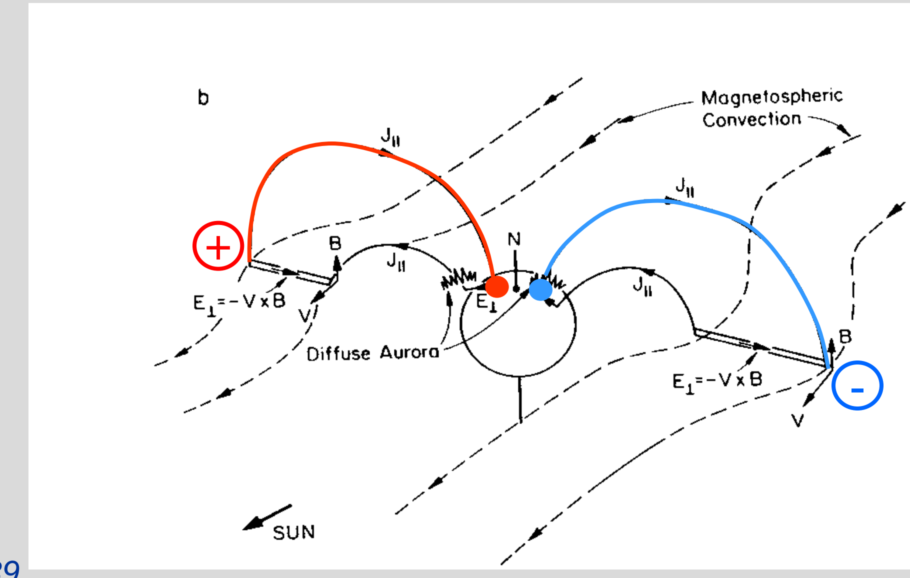


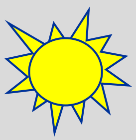
Magnetospheric plasma convection

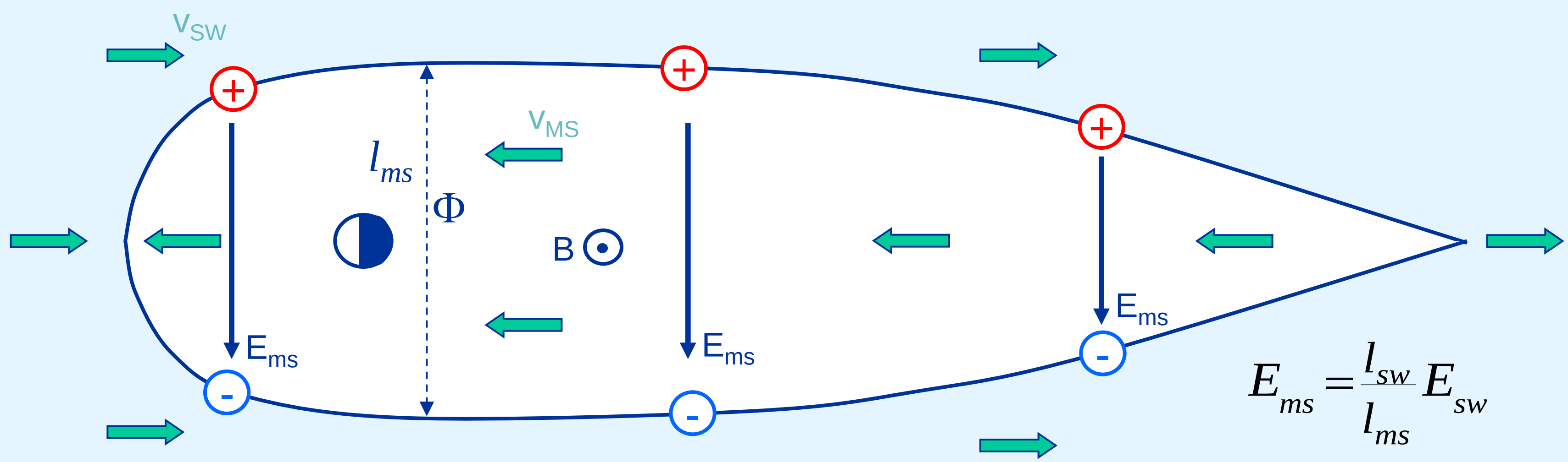
$$\mathbf{E}_{sw} = -\mathbf{v} \times \mathbf{B}$$



Kelley, 1989



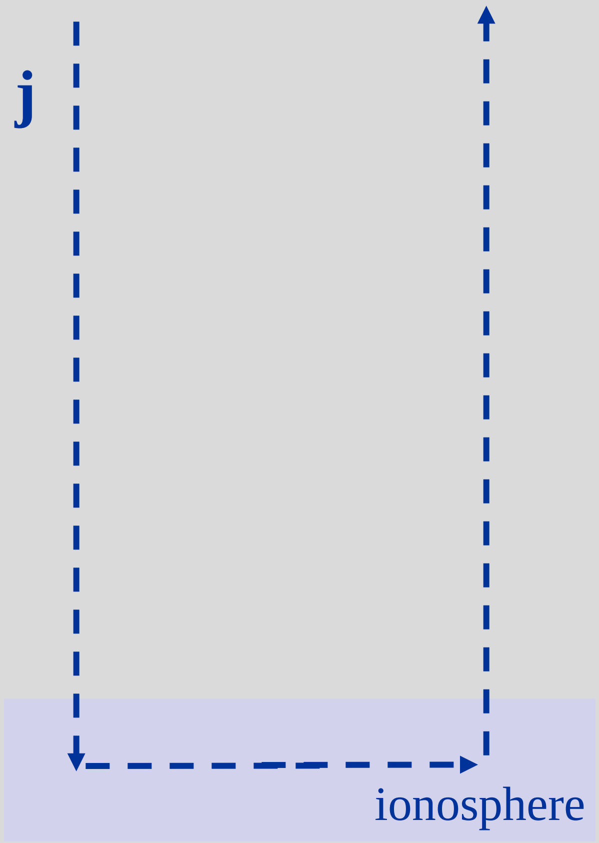




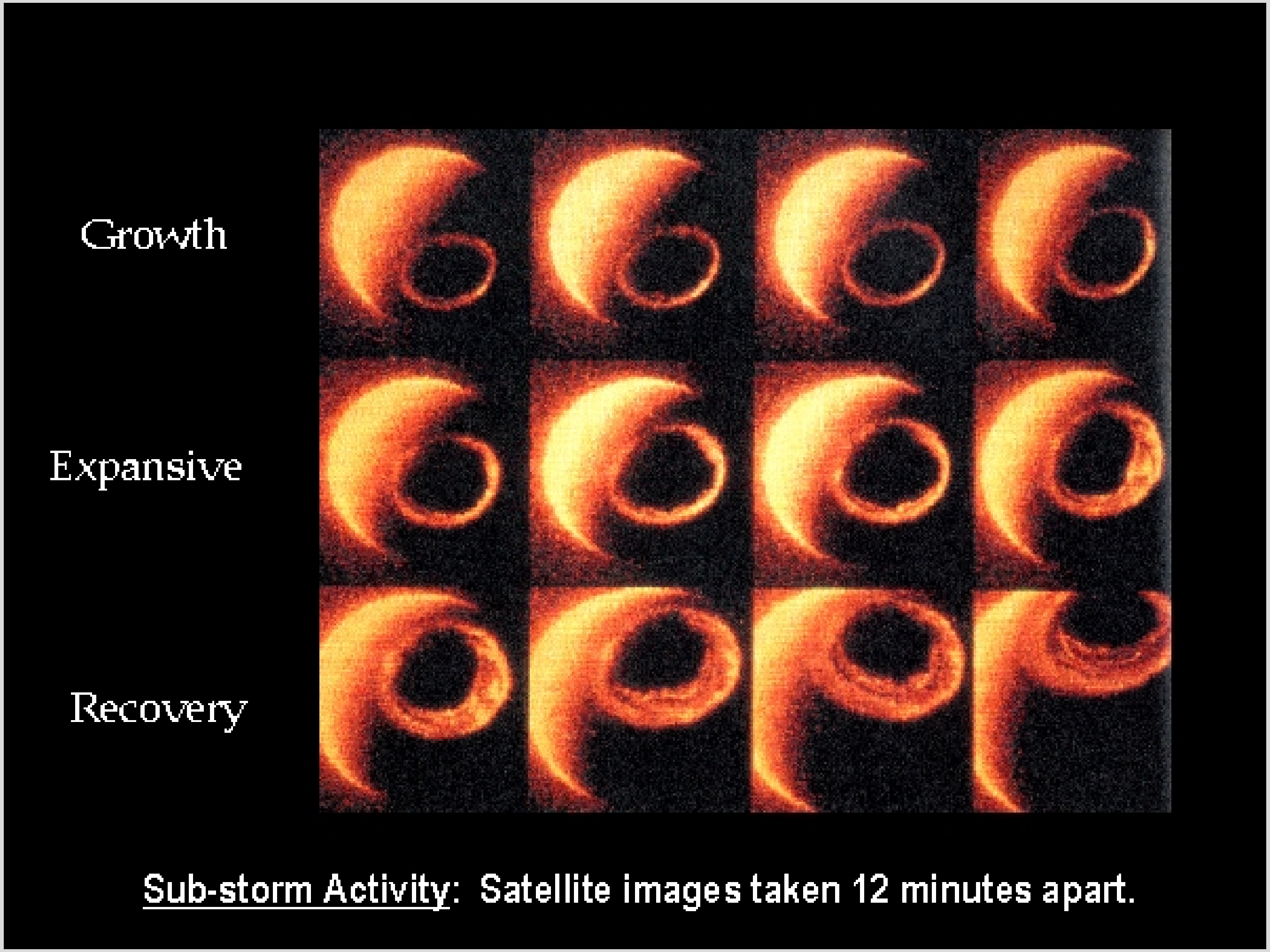
$$E_{ms} = \frac{l_{sw}}{l_{ms}} E_{sw}$$

Geomagnetic activity, definition

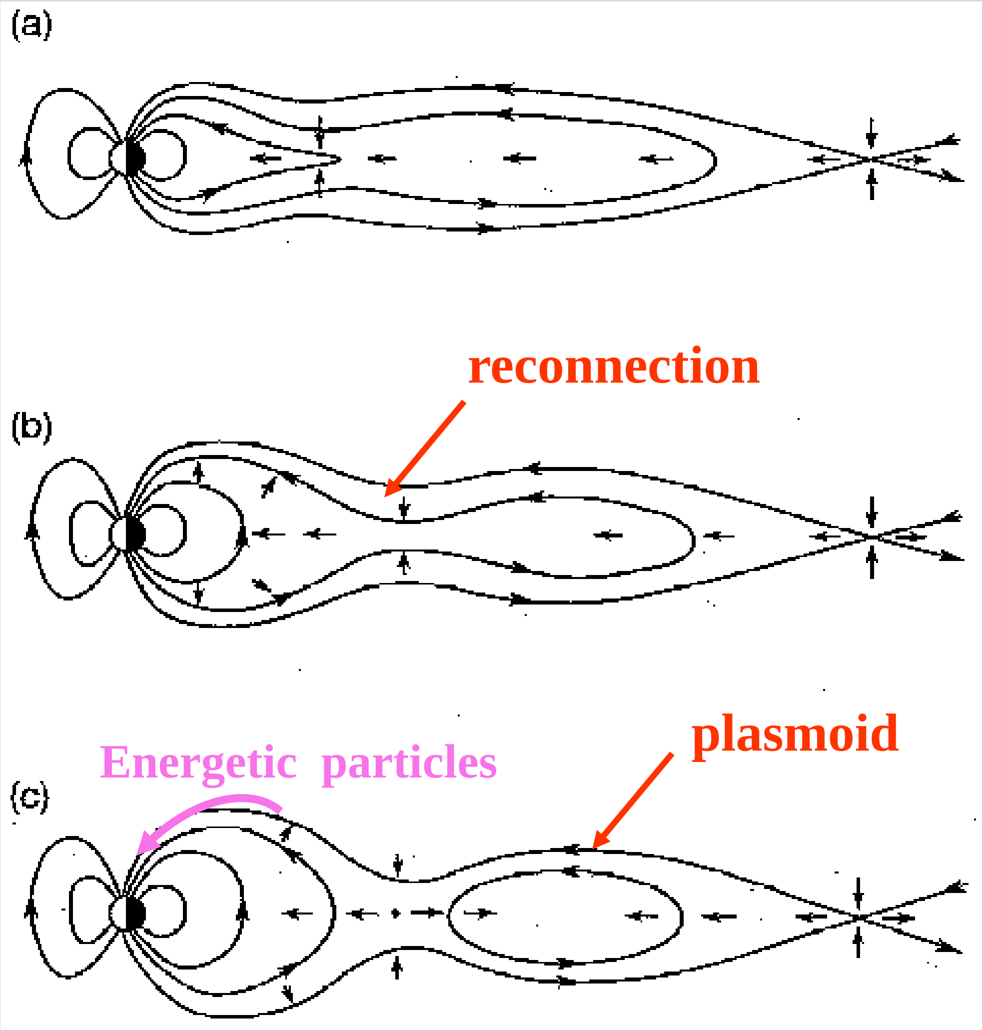
- Geomagnetic activity = temporal variations in the geomagnetic field.
- These variations are caused by temporal variations in the currents in the magnetosphere and ionosphere.



Aurora during substorm

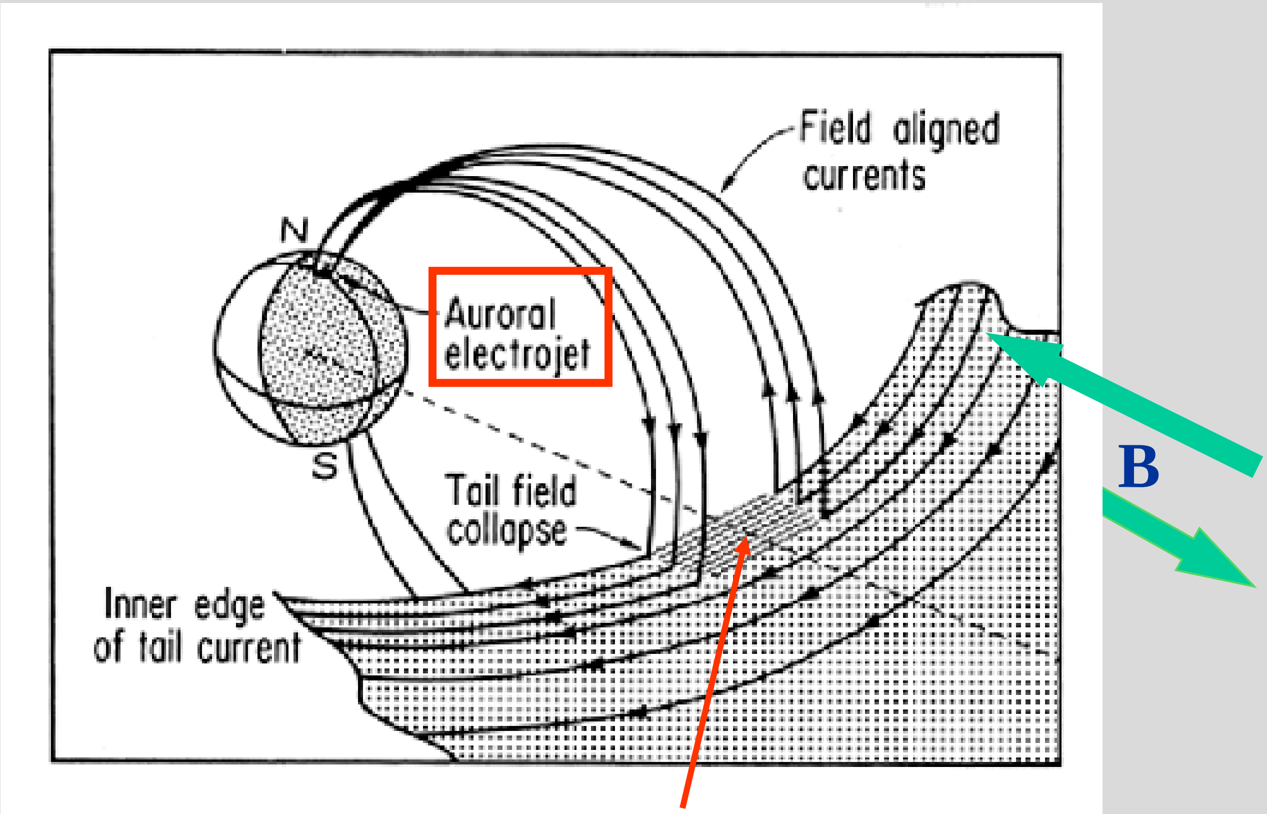


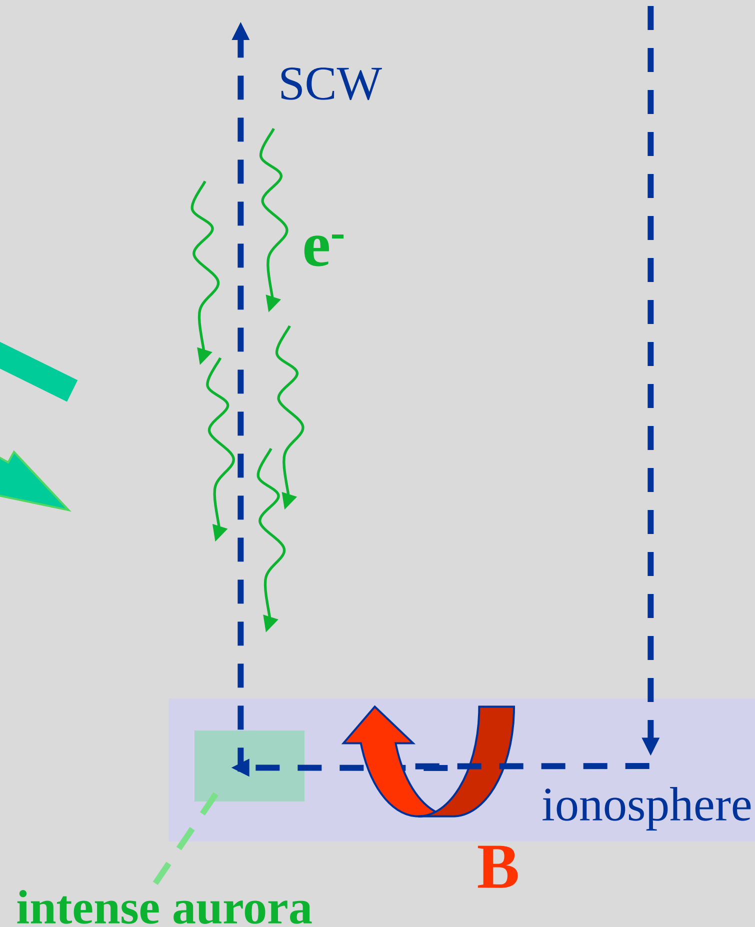
Substorms - magnetosphere



- **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.

Substorm Current Wedge (SCW)



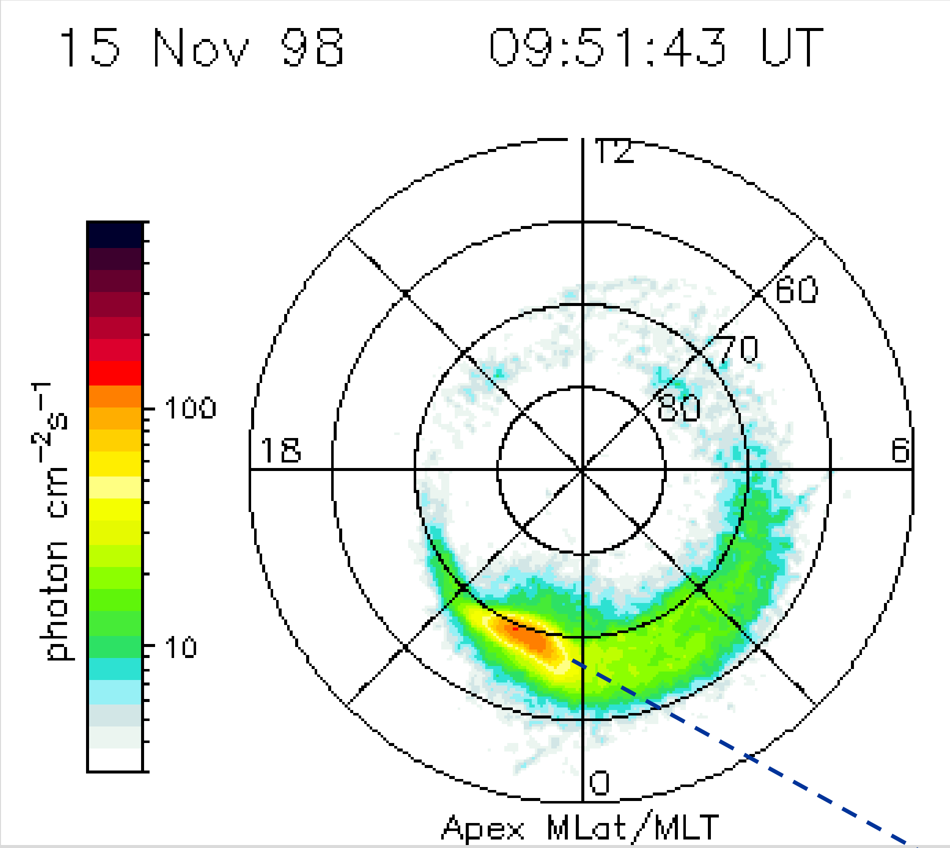


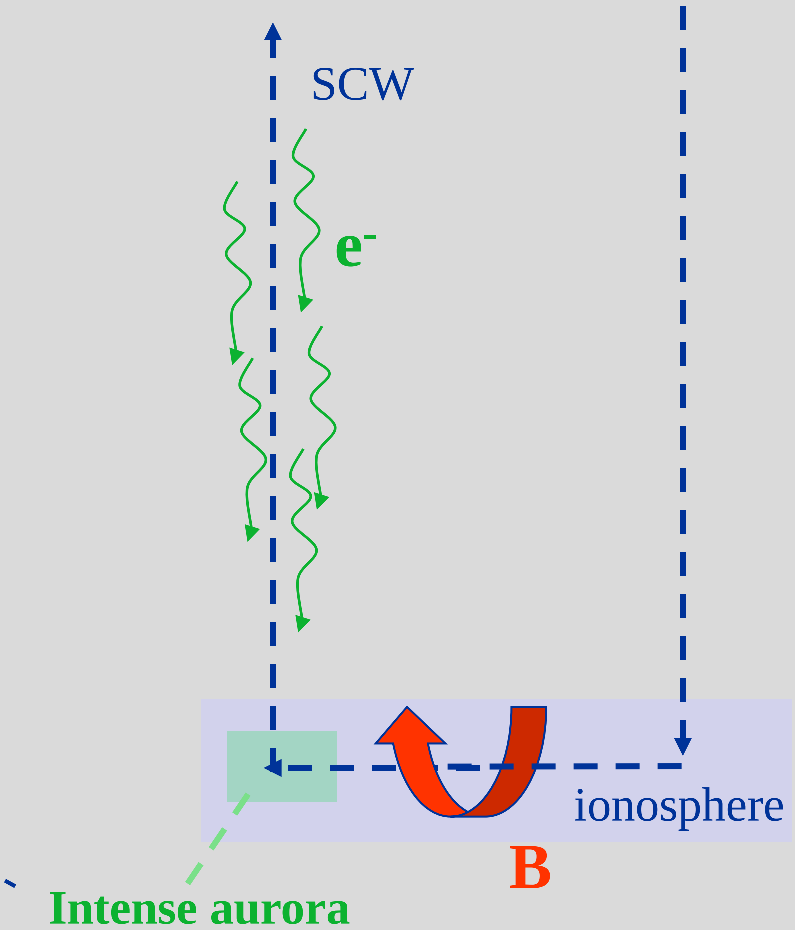
Due to reconnection processes the resistivity increases here

⇒

Current takes another direction – through the ionosphere!

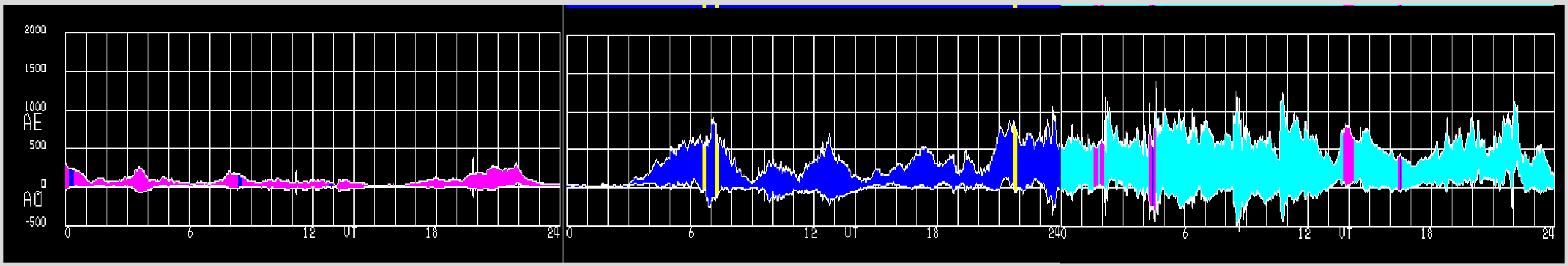
Substorm Current Wedge (SCW)

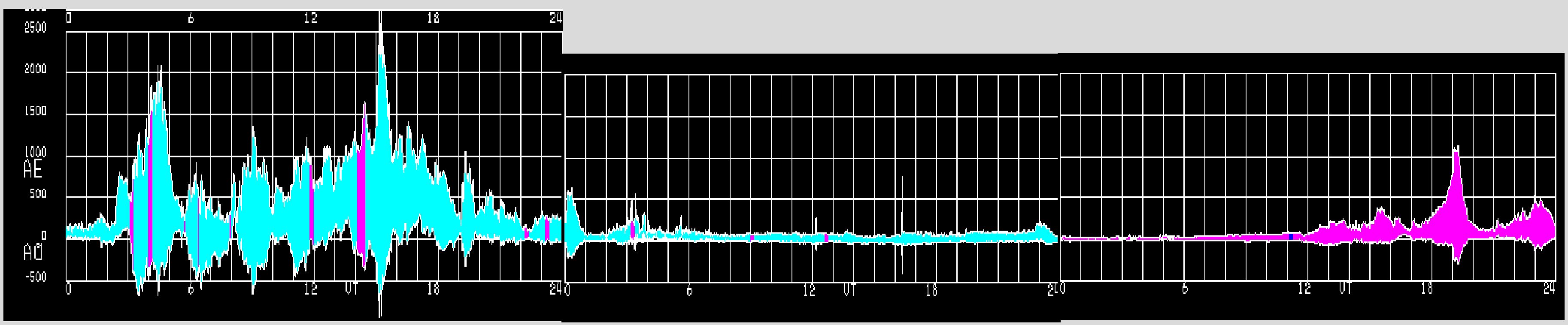




Geomagnetic storms

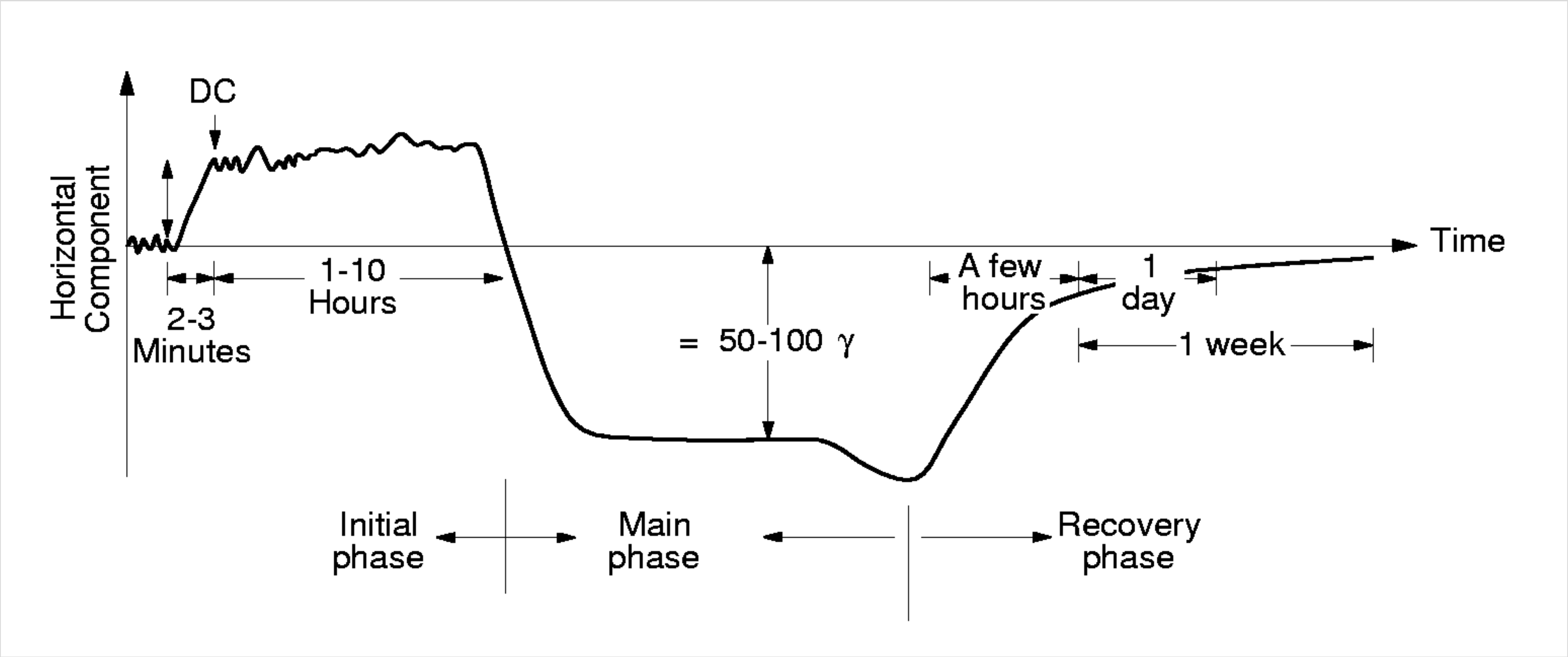
Geomagnetic storms are extended periods with southward interplanetary magnetic field (IMF) and a large energy input into the magnetosphere.



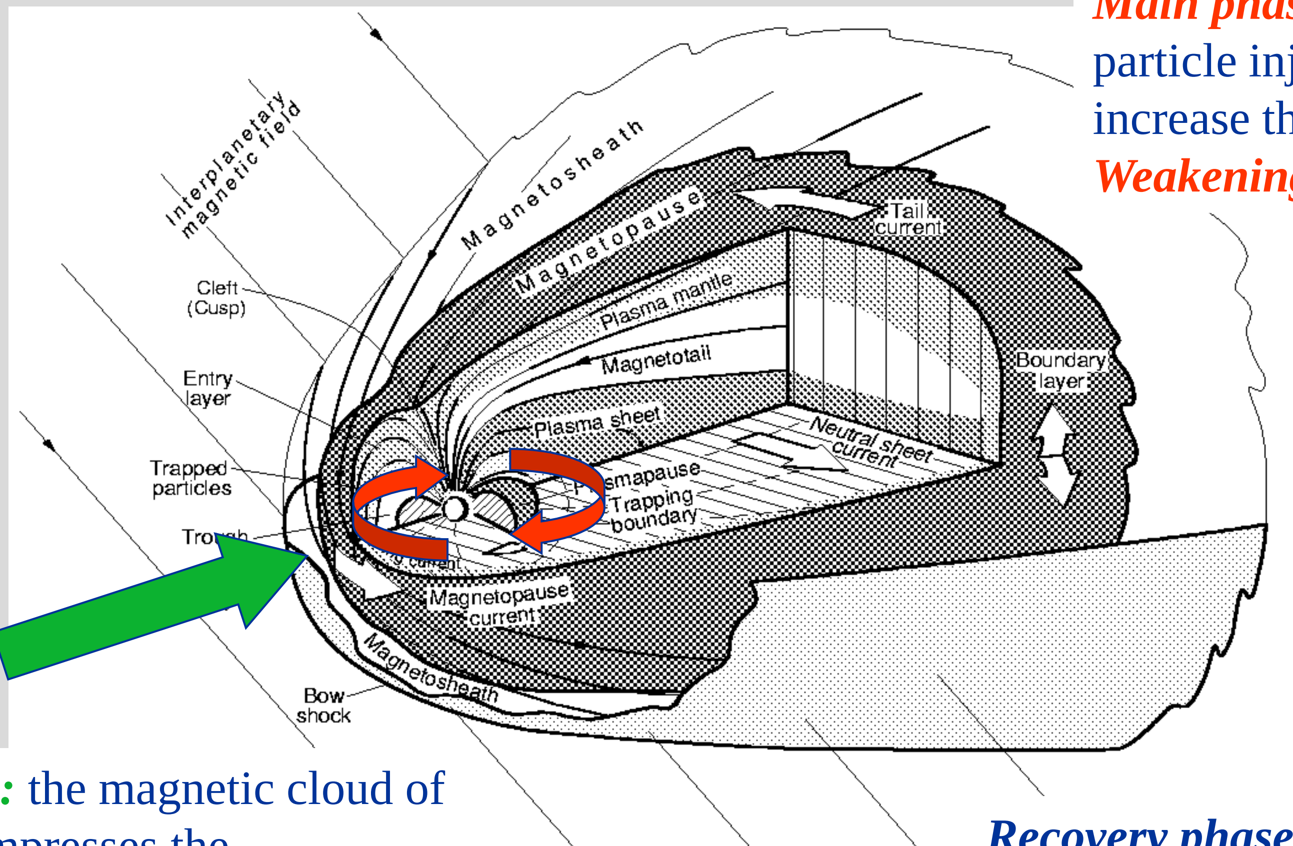


Geomagnetic storms - phases

Magnetogram



Geomagnetic storms - phases

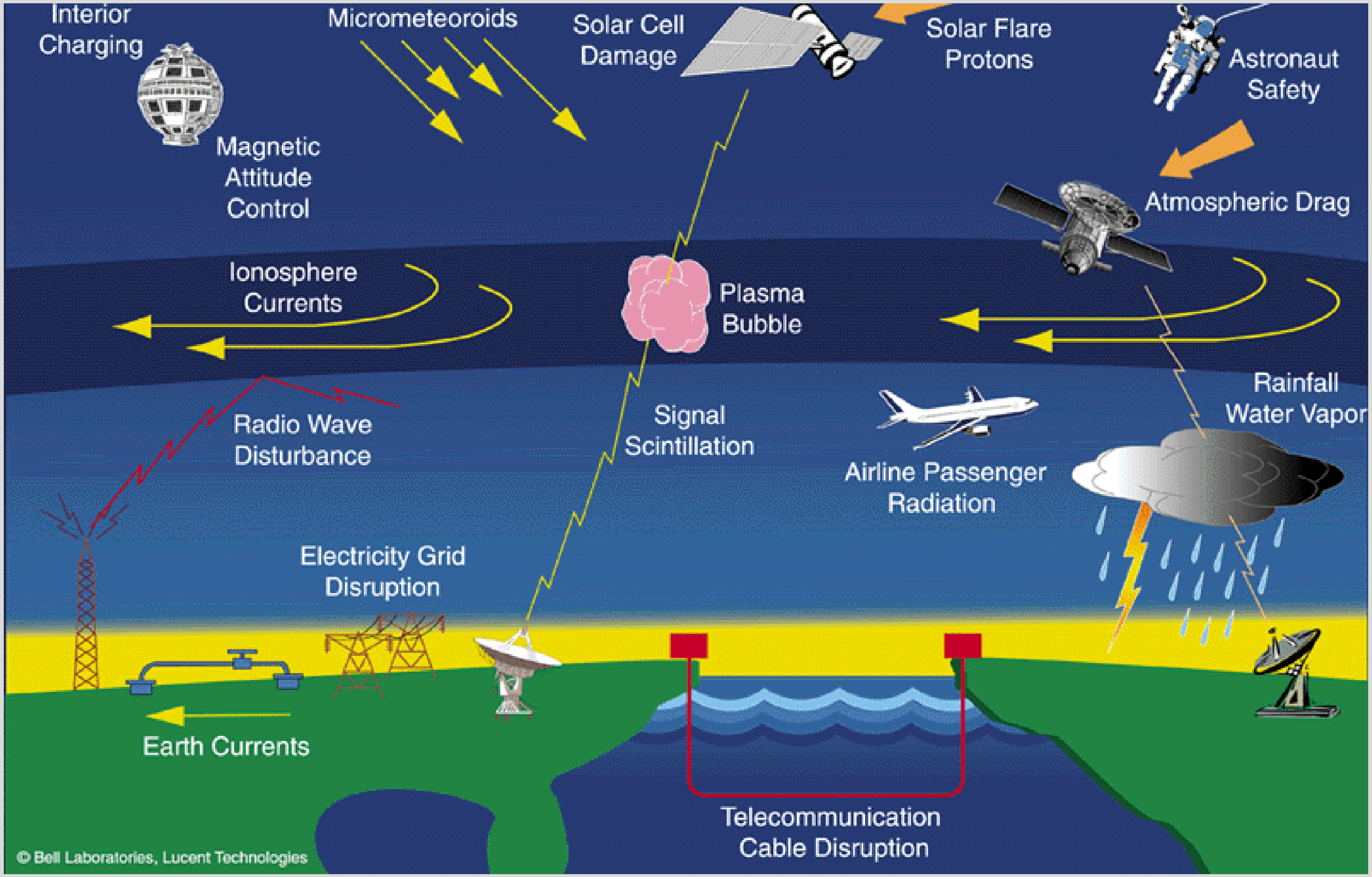


Main phase: Several particle injections increase the ring current.
Weakening of B

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

Space weather : consequences of solar and geomagnetic activity

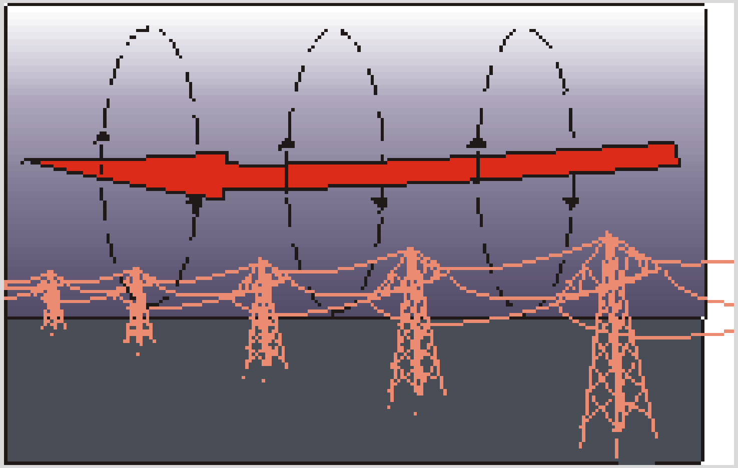


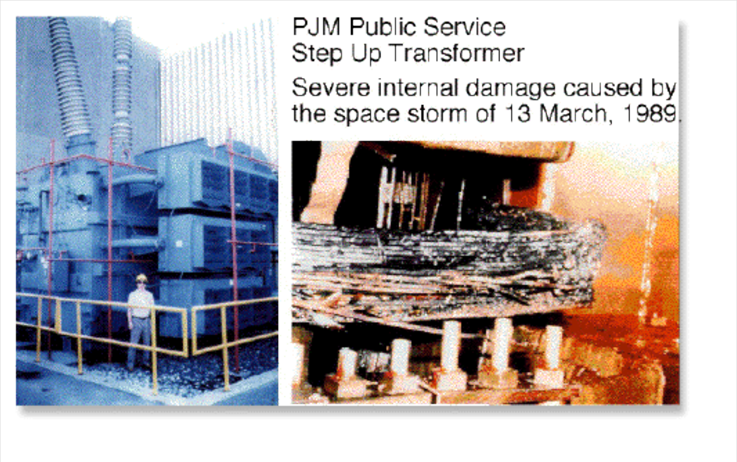
"conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health."

US National Space Weather Programme

GIC – Geomagnetically Induced Currents

Can damage electric power grids



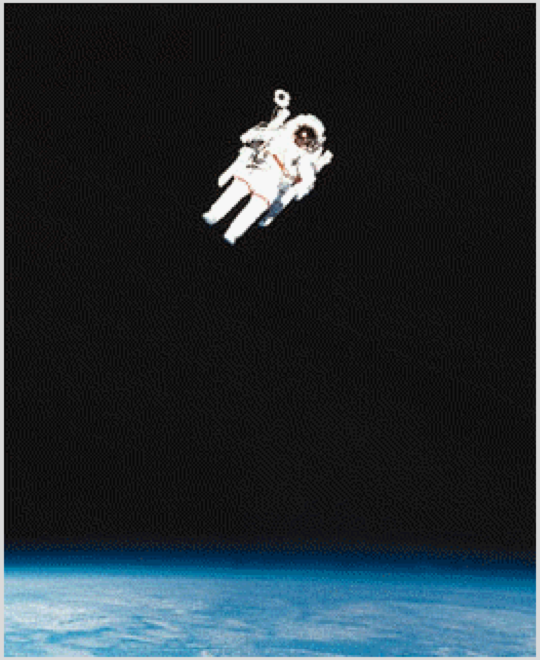


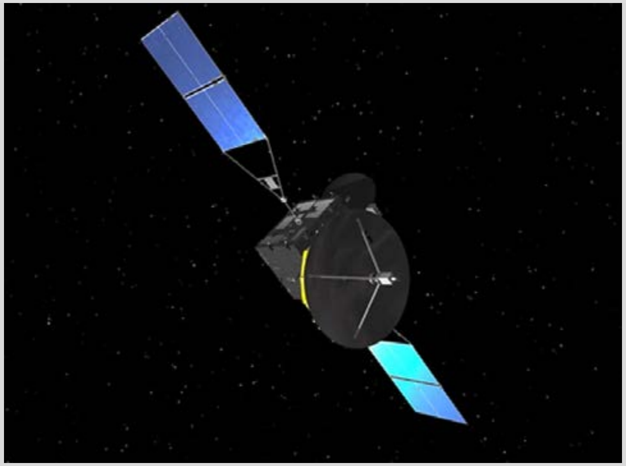
Induced currents is pipelines increase corrosion.

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.

What is cosmic radiation?

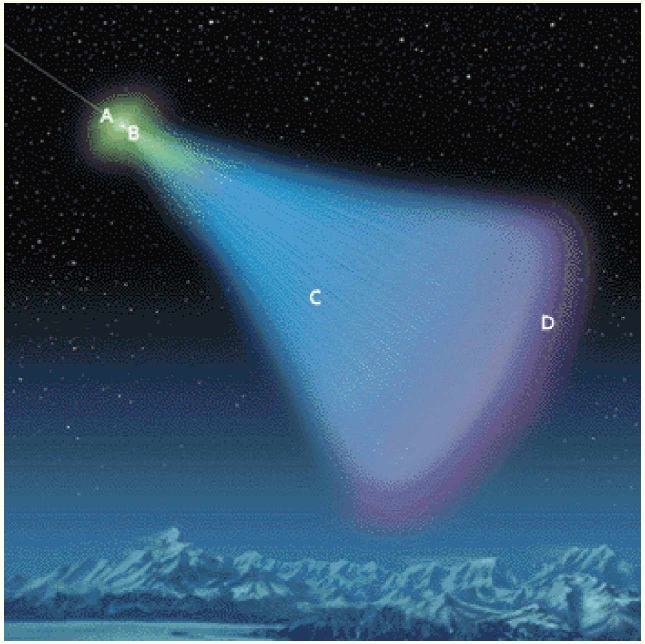
Cosmic rays (= cosmic radiation)

Primary cosmic radiation

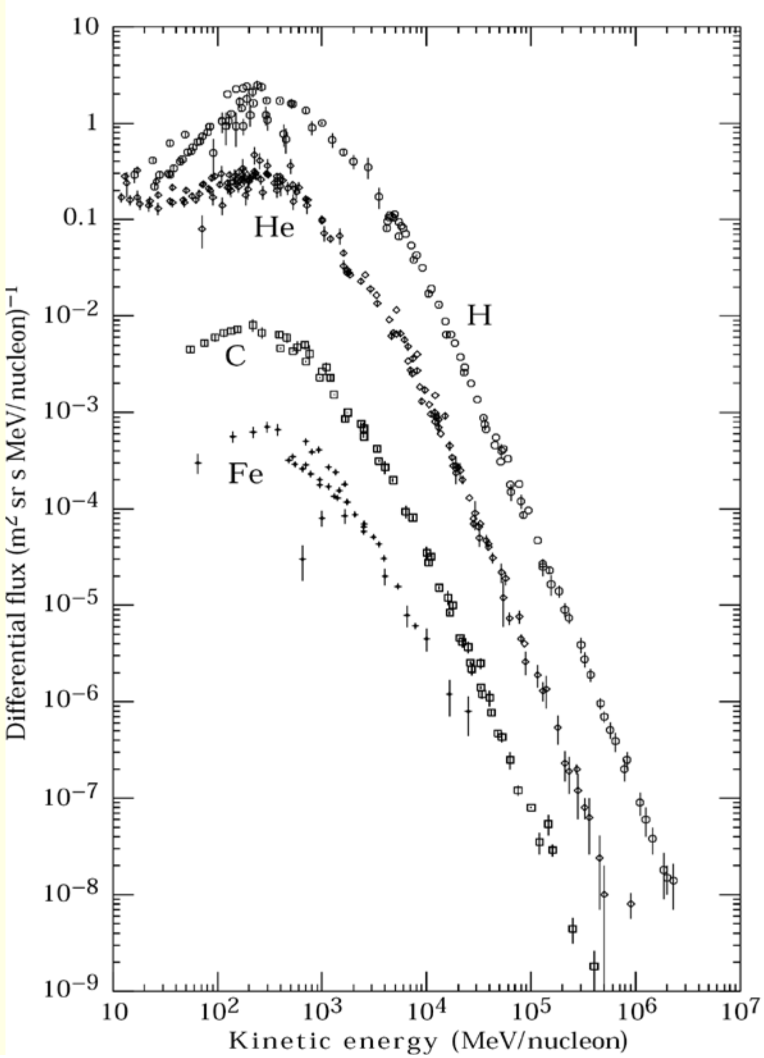
Extremely energetic particles ($>10^8$ eV)

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

Secondary cosmic radiation



Composition and spectrum of galactic cosmic radiation

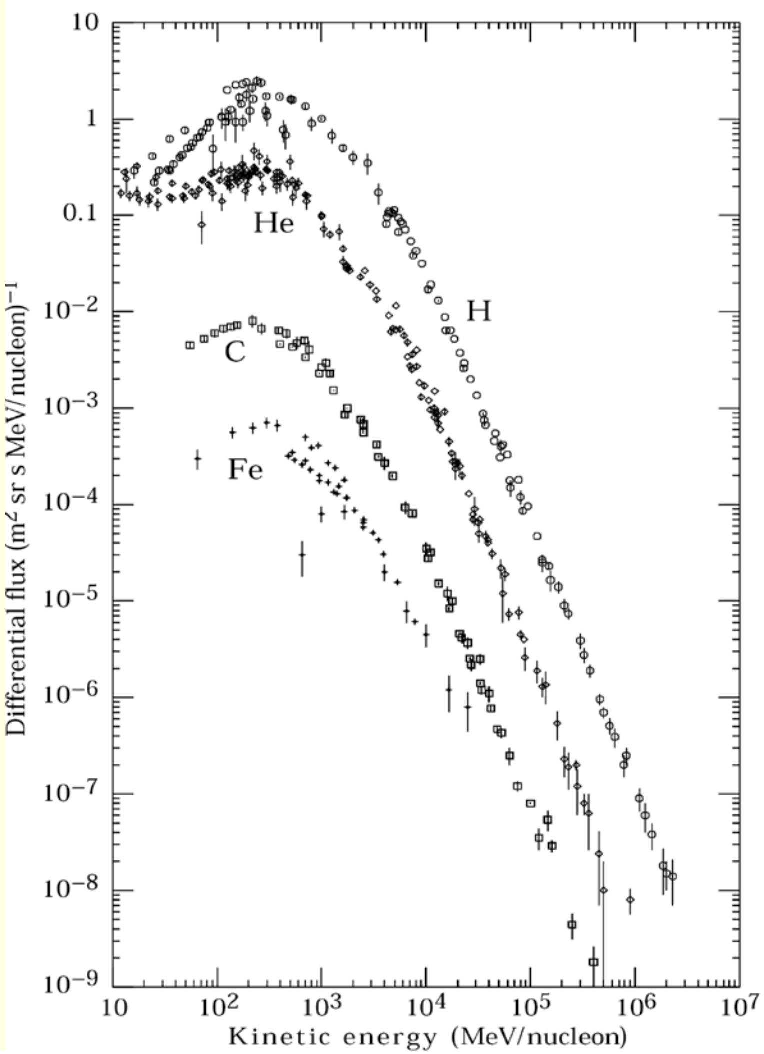


Simpson, 1983.

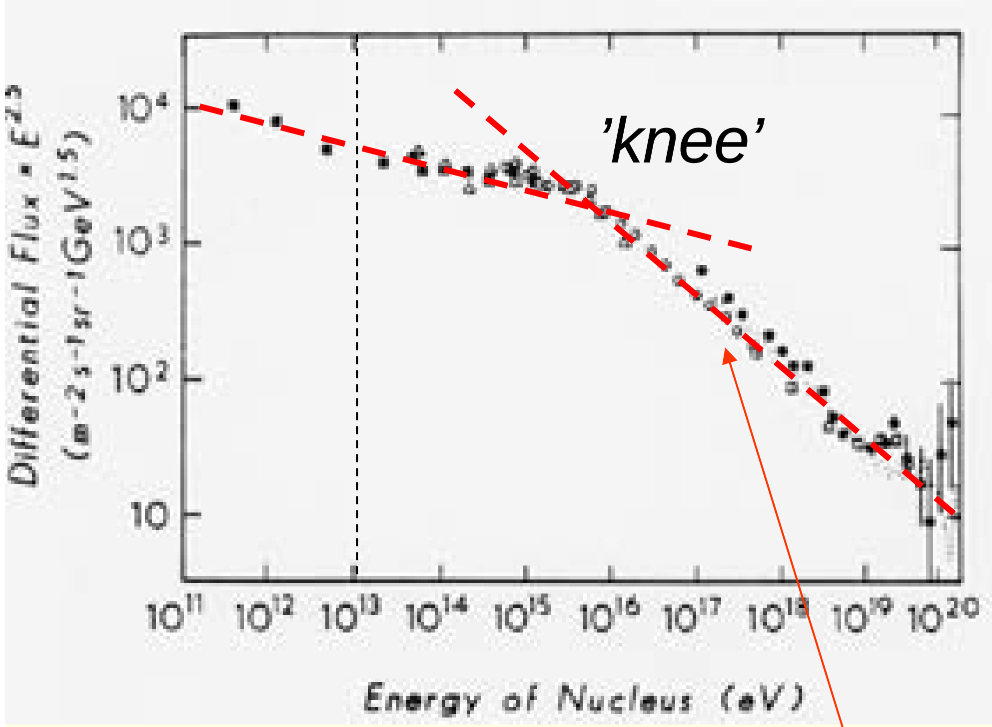
83 % protons
13 % alpha particles
3 % electrons
1 % other nuclei

All cosmic ray particles are fully ionized

Spectrum of galactic cosmic radiation

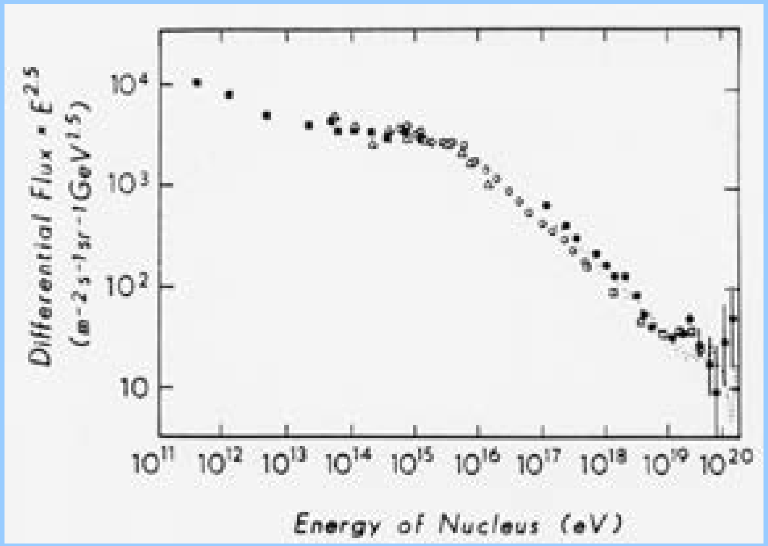


Simpson, 1983.



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 ⇒

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

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

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

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

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

Yellow

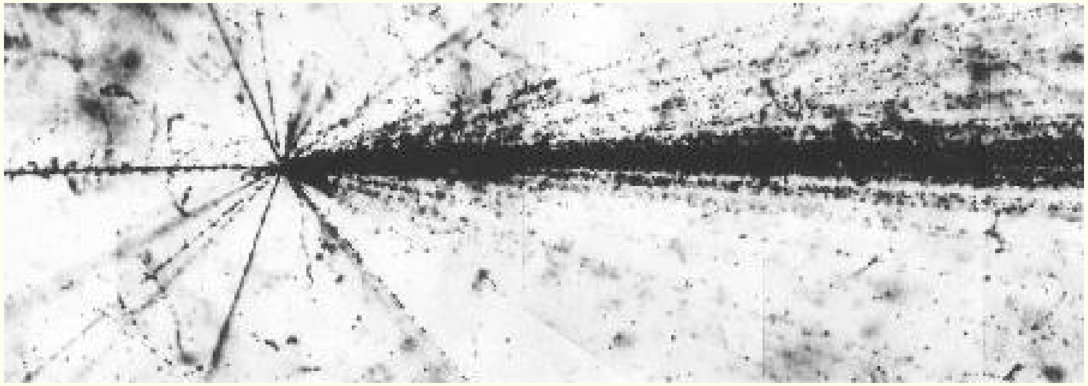
Tennis ball moving at 100 km/h

Cosmic radiation

Primary cosmic radiation

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

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



Secondary cosmic radiation

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

Pfotzer maximum

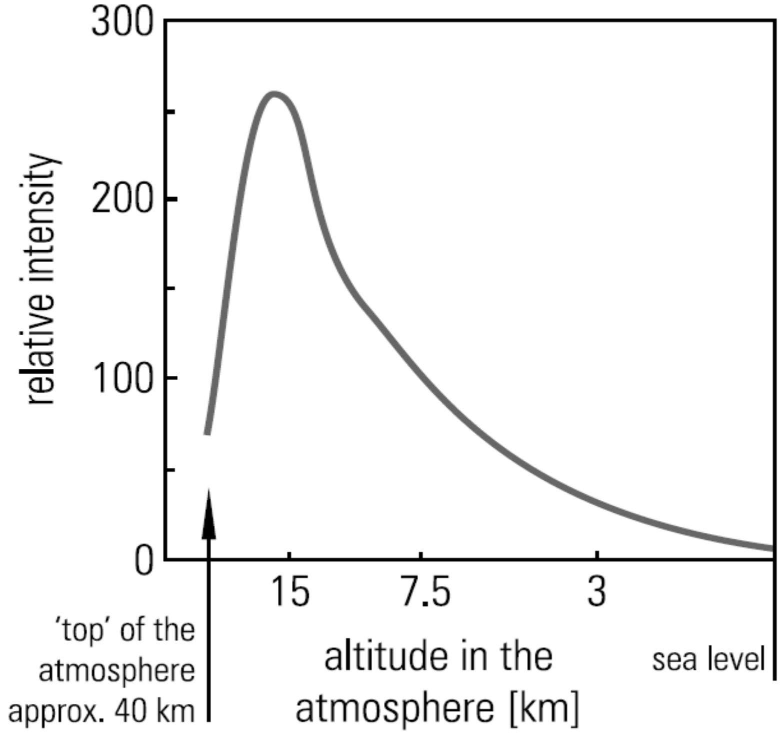
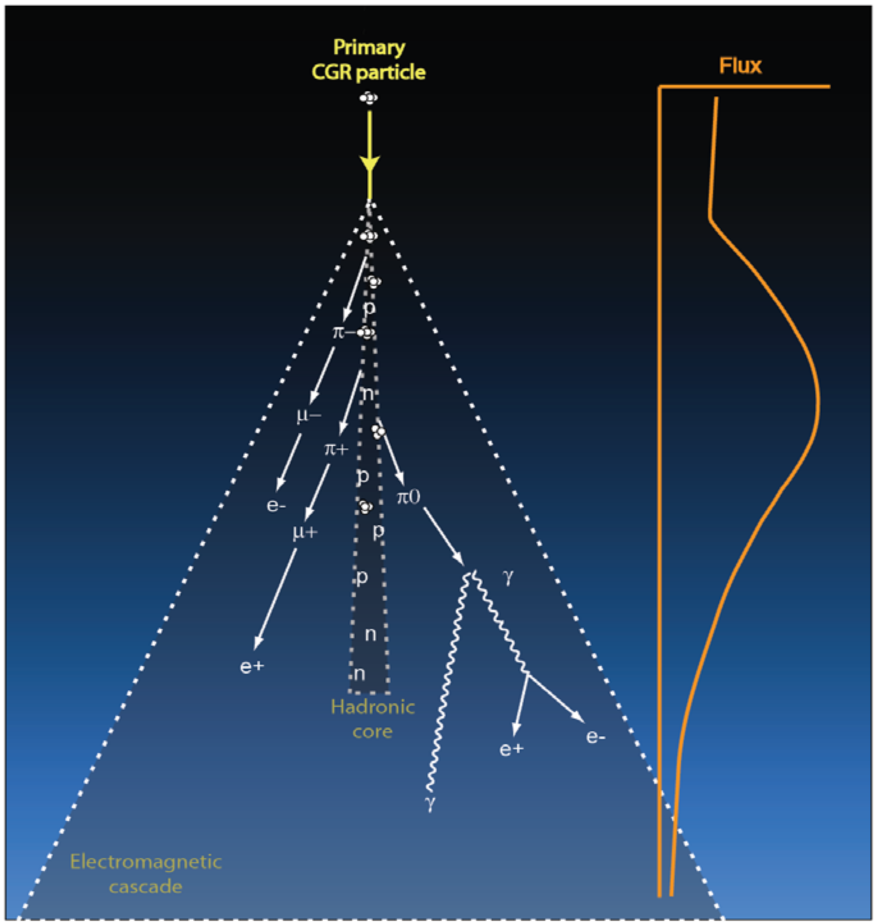
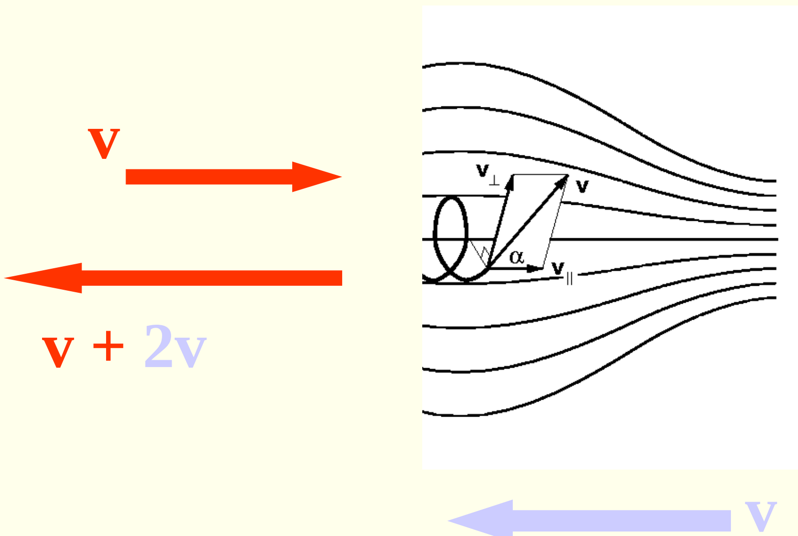


Fig. 1.12
Intensity profile of cosmic particles in the atmosphere

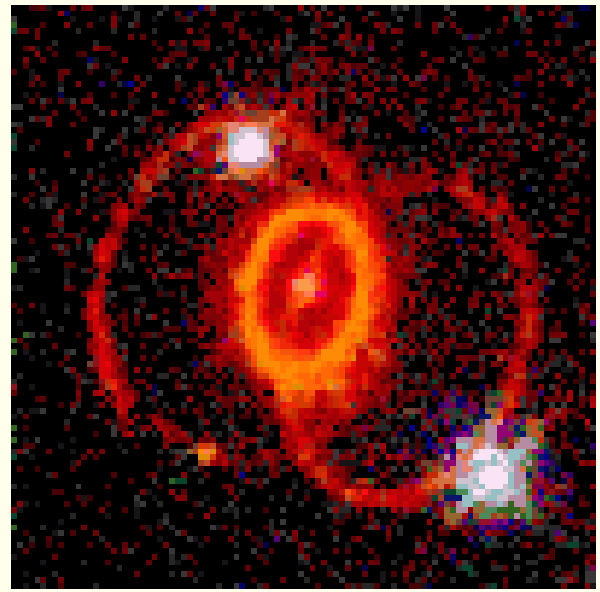


Origin of galactic cosmic radiation

Two main theories

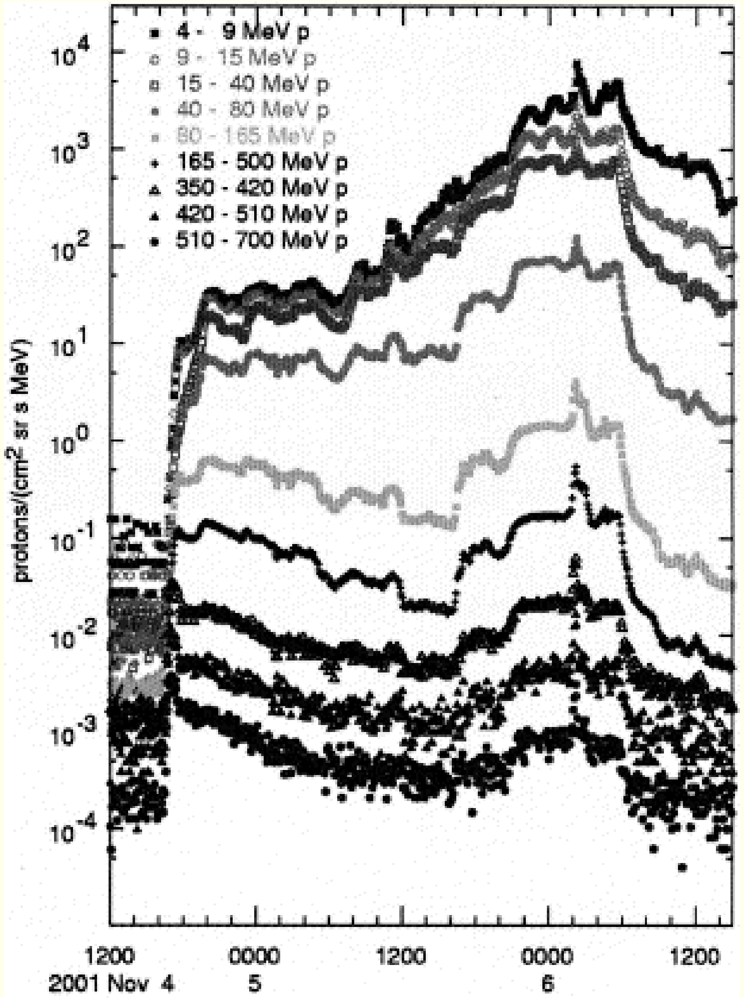


Fermi acceleration by two magnetic mirrors in motion



Shock waves from supernova explosion

Solar Energetic Particles (SEP)



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

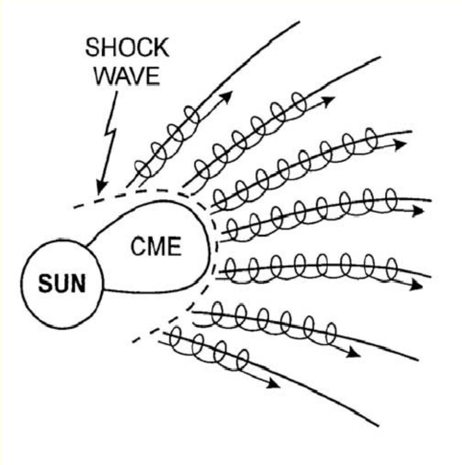


Figure 22: Time profiles of the strong SEP proton flux event of November 4, The peak at the time of shock passage is clearly defined early on November 6, even at proton energies as high as 510 – 700 MeV. From Reames (2004).

Neutron albedo

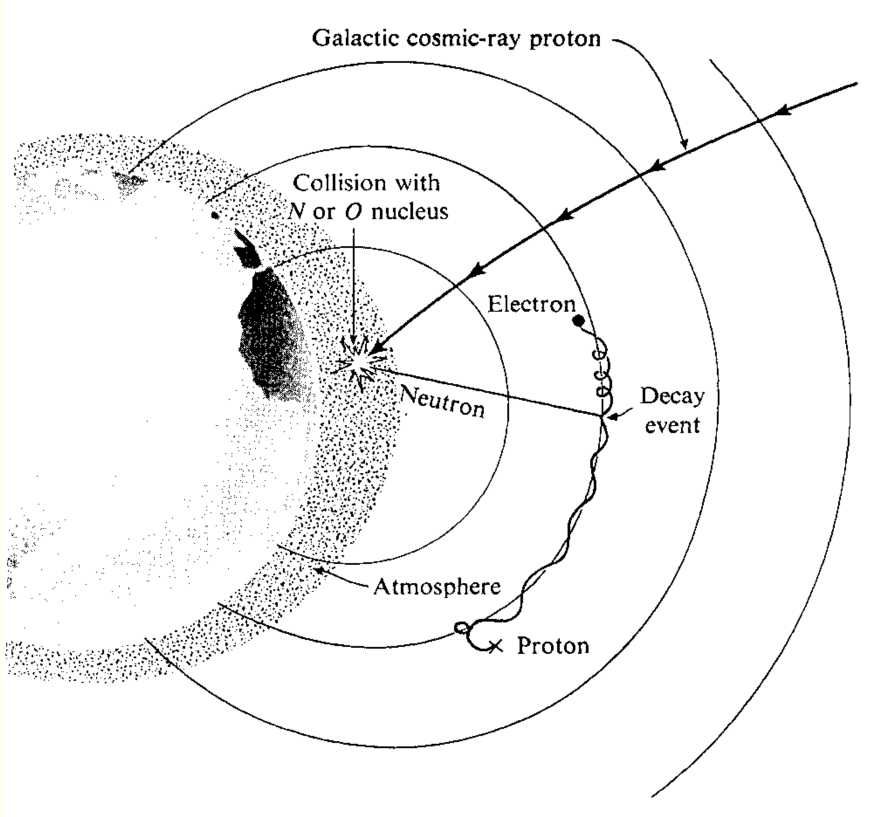


Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].

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

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

Relativistic dynamics

Relativistic momentum

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

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

Relativistic energy

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

Relation between energy and momentum

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

Relativistic dynamics

Rest energy

$$E = mc^2$$

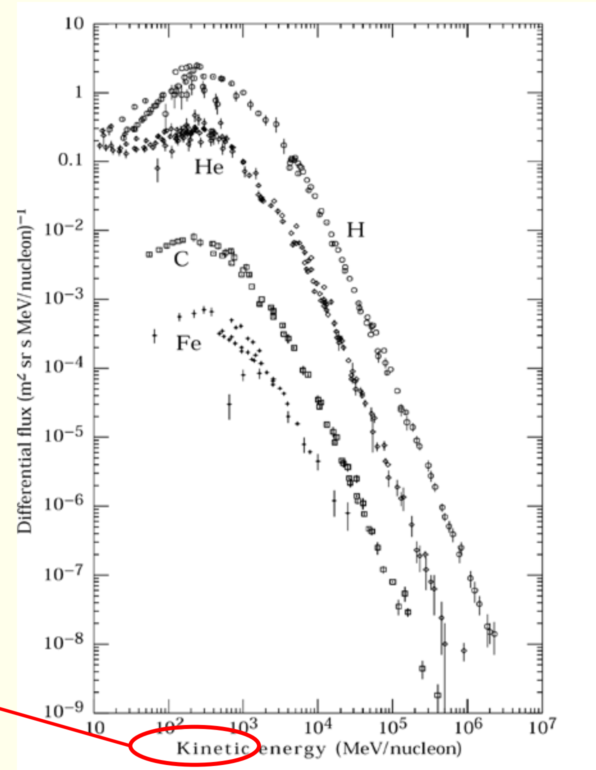
Kinetic energy

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

Rest energy of electron : 512 keV ~ 0.5 MeV

Rest energy of proton: 939 MeV ~ 1 GeV

!!!



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

Relativistic gyro radius

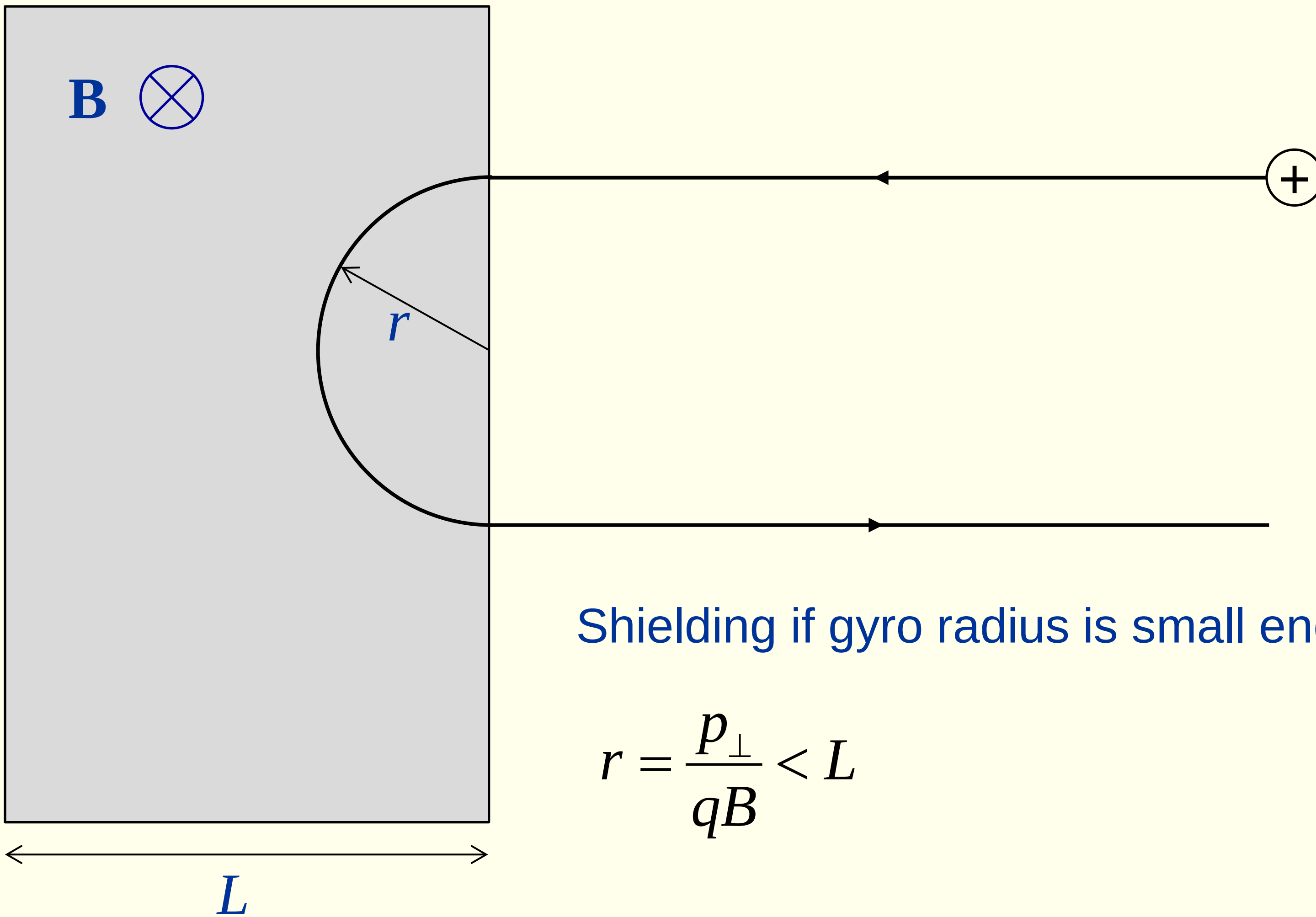
Non-relativistic gyro radius

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

Relativistic gyro radius

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

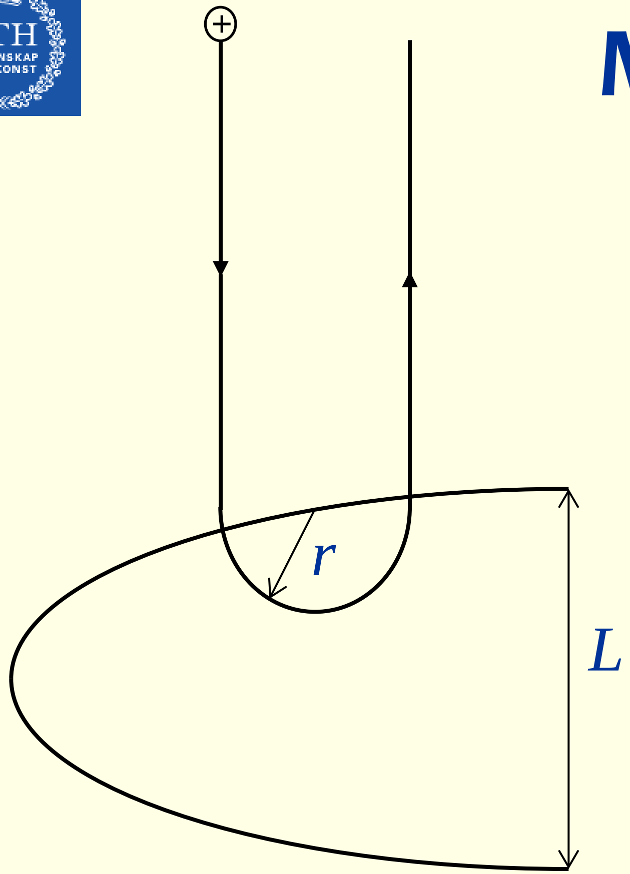
Magnetic shielding



Shielding if gyro radius is small enough

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

Magnetic shielding of magnetosphere



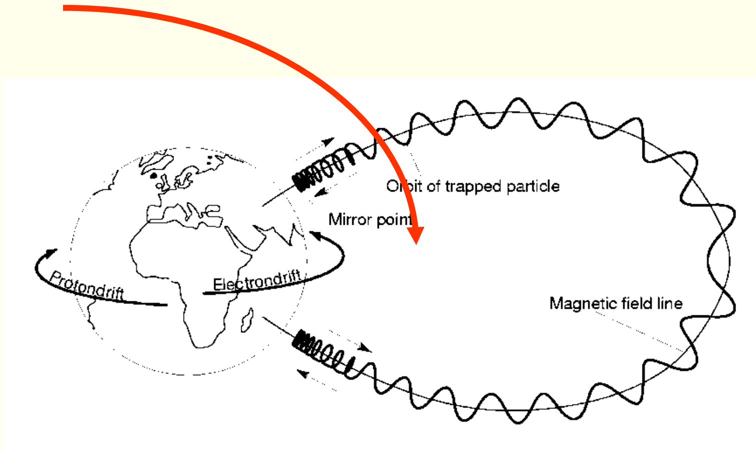
Shielding if

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

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

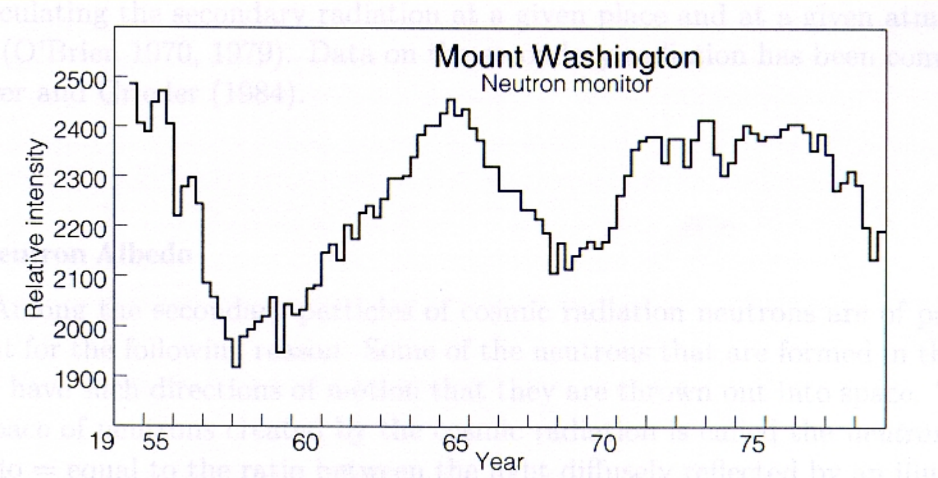
Effect of magnetic field

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



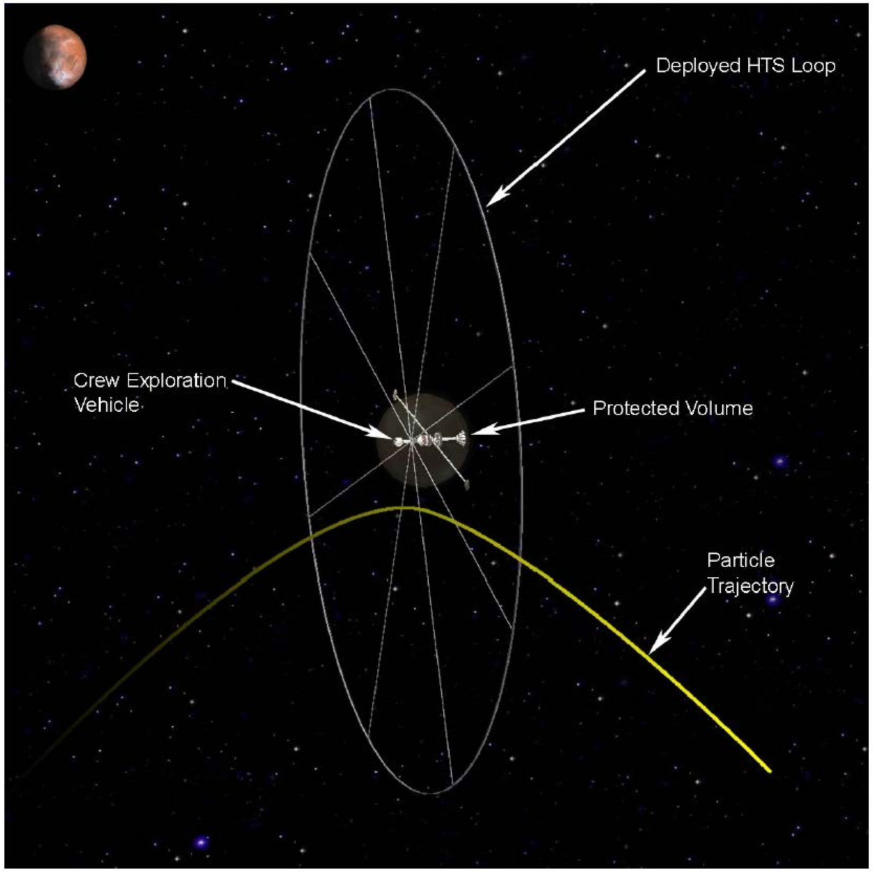
- Gyro radius is r = p/(eZB). Define rigidity:

$$P = pc/(eZ)$$



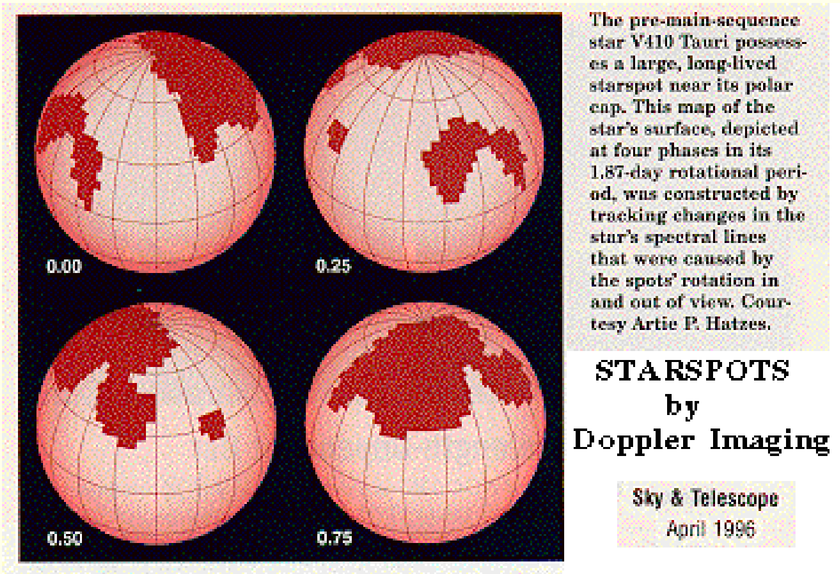
- Temporal variations:
  - –27 days (IMF, solar rotation)
  - –11 years (IMF, solar cycle)

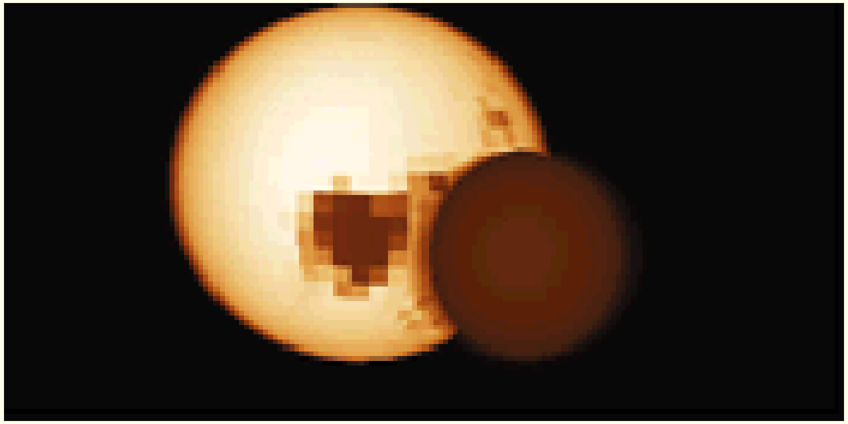
Artificial magnetic shielding of spacecraft



Plasma outside of the solar system

Starspots





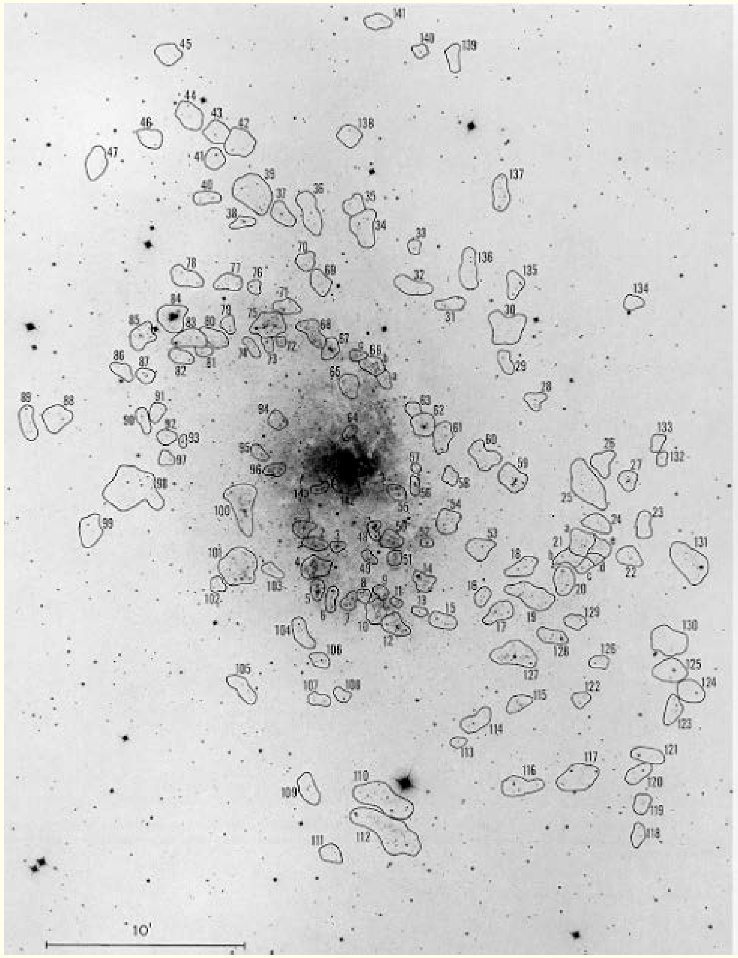
Eclipse mapping, XY Ursae Majoris

Stellar winds

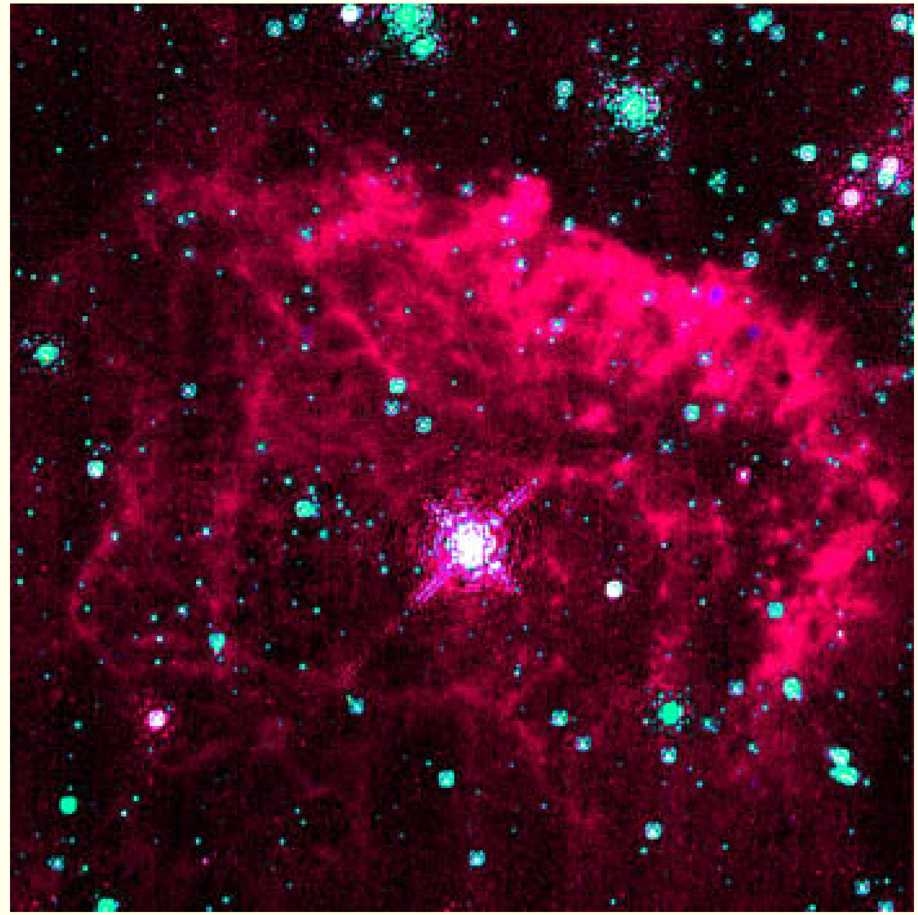
Star	Type	Mass ($M_\odot$)	M-dot ($M_\odot$/yr)	v_∞ (km/s)
α Sco (Antares)	M1.5 Iab-Ib	15	1×10^{-6}	17
Sun	G2V	1	1×10^{-14}	200 – 700
ζ Pup (Naos)	O4I(n)f	59	2.7×10^{-6} 2.4×10^{-6}	– 2,200
P Cyg	"B0Ia" (LBV)	30-60	1.5×10^{-5}	210
WR1	WN5 (W-R)		6×10^{-5}	2,000

~20 % of the mass during the star's life time

Stellar winds



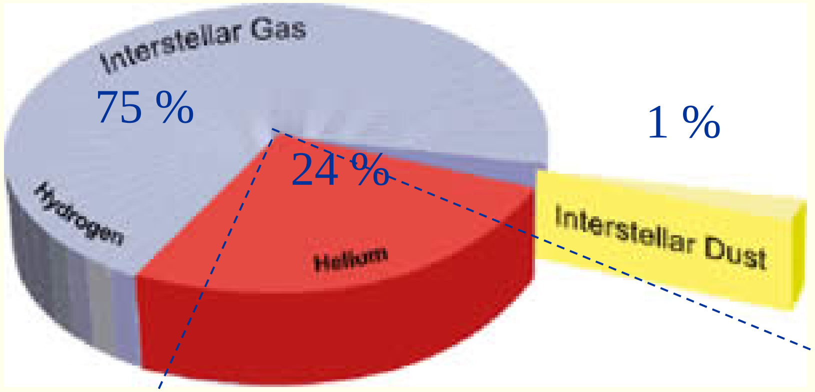
Doppler measurements of stellar winds



Pistol nebula – probably created by massive outflow of stellar plasma

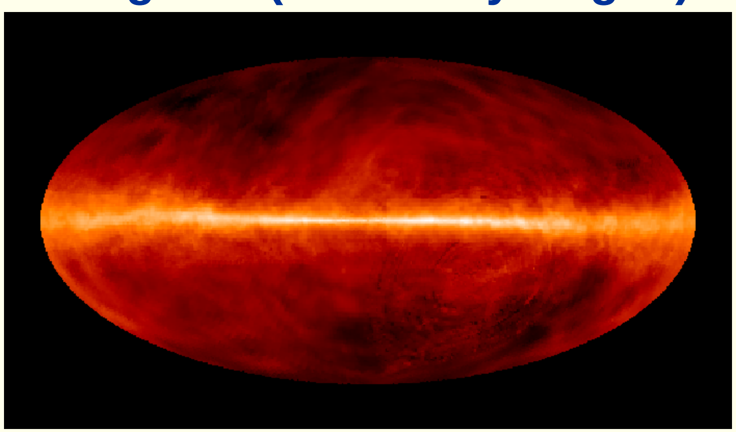
Interstellar plasma

Interstellar matter (10 % of Milky Way mass)



Horsehead nebula

HI regions (neutral hydrogen)

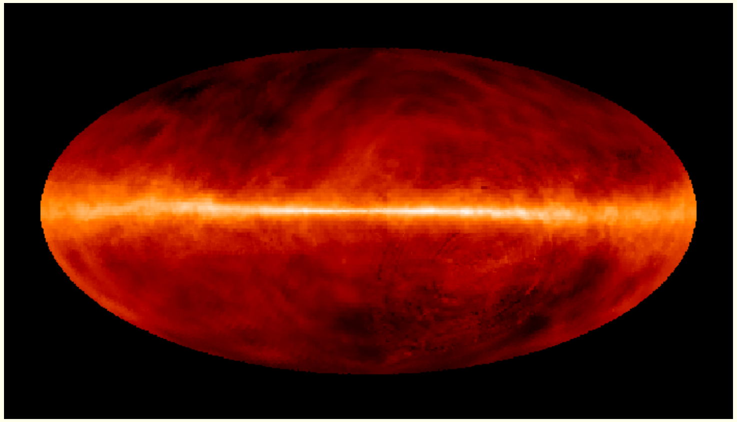


HII regions (emission nebulae)

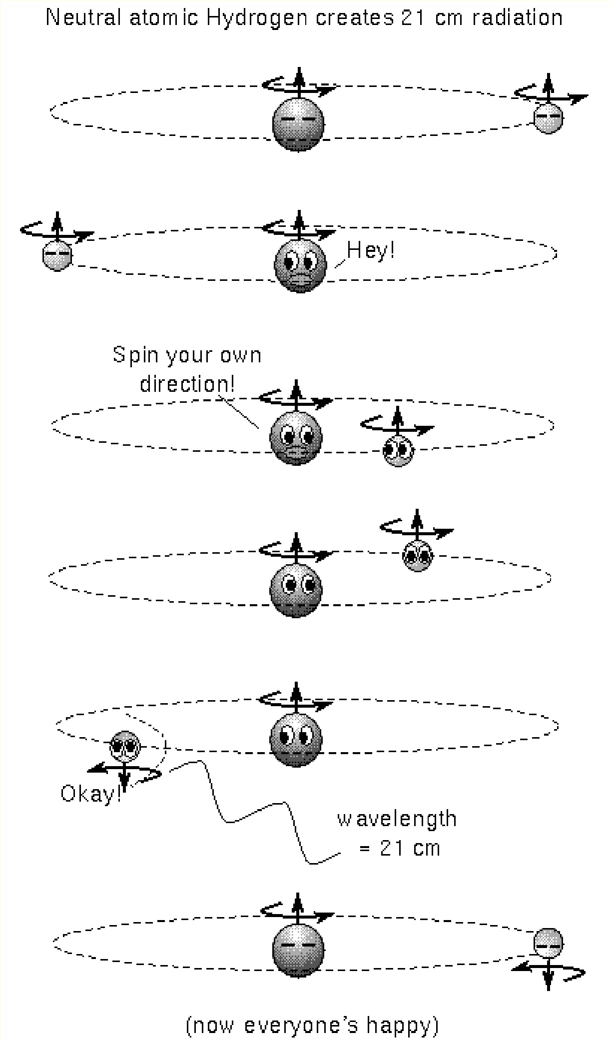
Triffid nebula

H1 regions

- *Not reached by UV radiation from stars*
- *Either diffuse or concentrated as* **interstellar clouds**
- *Mostly contains unionized hydrogen, but also some ionized Ca*
- *Density of diffuse part is 0.1 - 50 cm^{-3}*
- *Ionization degree ~ 0.01 %*
- *T ~ 50 -100 K*
- *B ~ 0.1 nT*

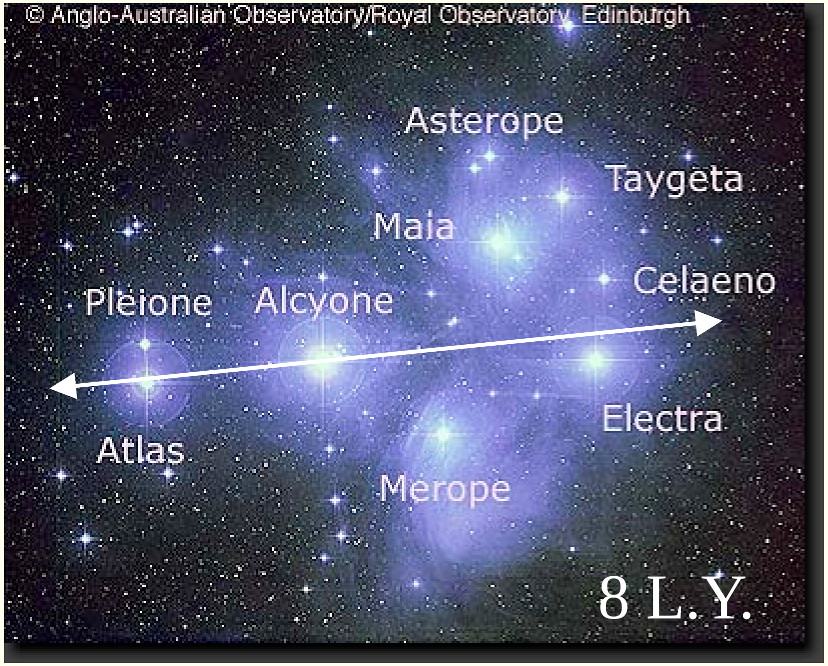


Distribution of interstellar HI gas in the Northern sky, observed at the 21 cm radio spectral line.



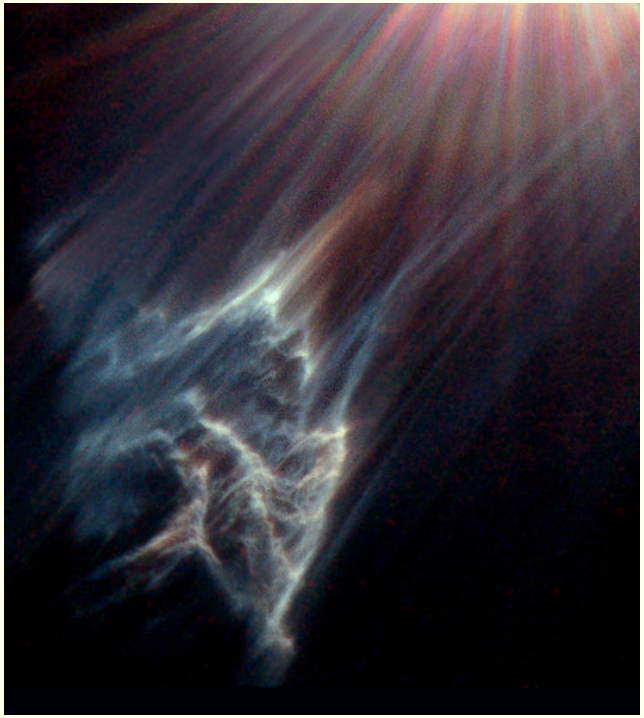
H1 regions are reservoirs of material for star formation

Stars are formed by gravitational collaps of interstellar clouds



Pleiades cluster

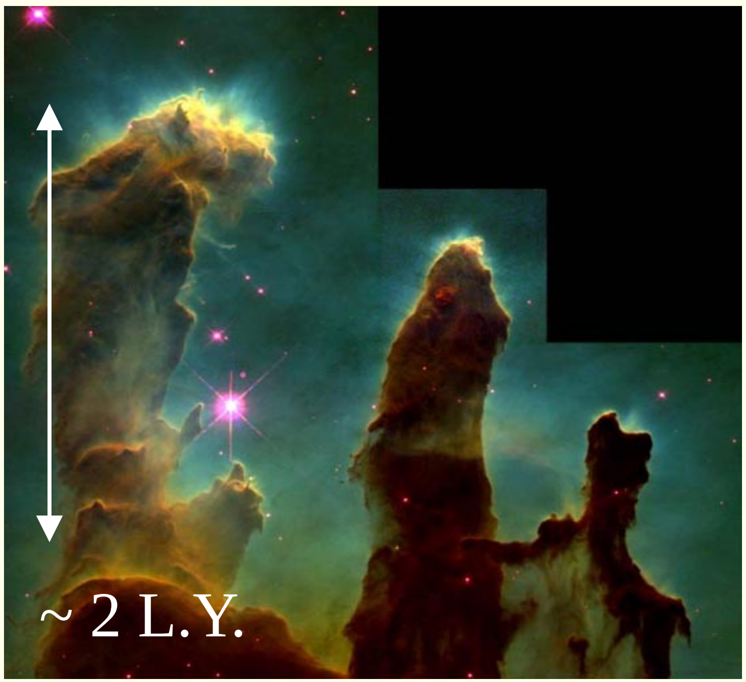
Closeup of region close to Merope

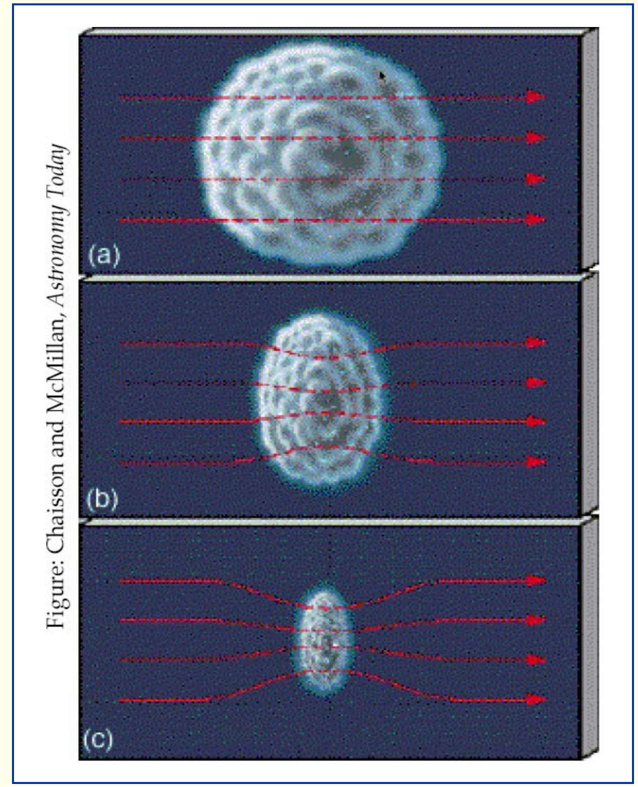


The emissions are caused by reflection by the dust particle component of the clouds.

H1 regions are reservoirs of material for star formation

The interstellar medium is turbulent, and localized density enhancements (clouds) are often created. These may contain molecular Hydrogen and dust.

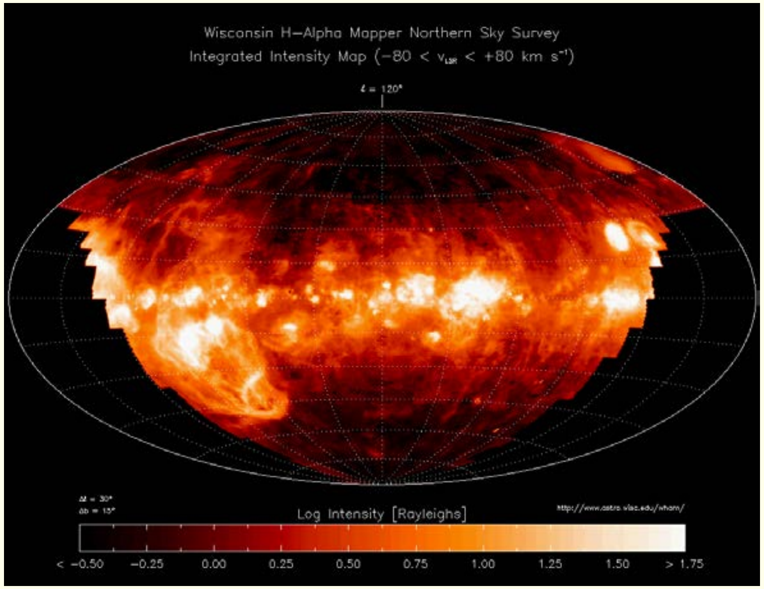




The small ionized part of the cloud can collapse more easily along B than across it, because of the gyro motion, creating a pancake form. Centrifugal forces may also be important.

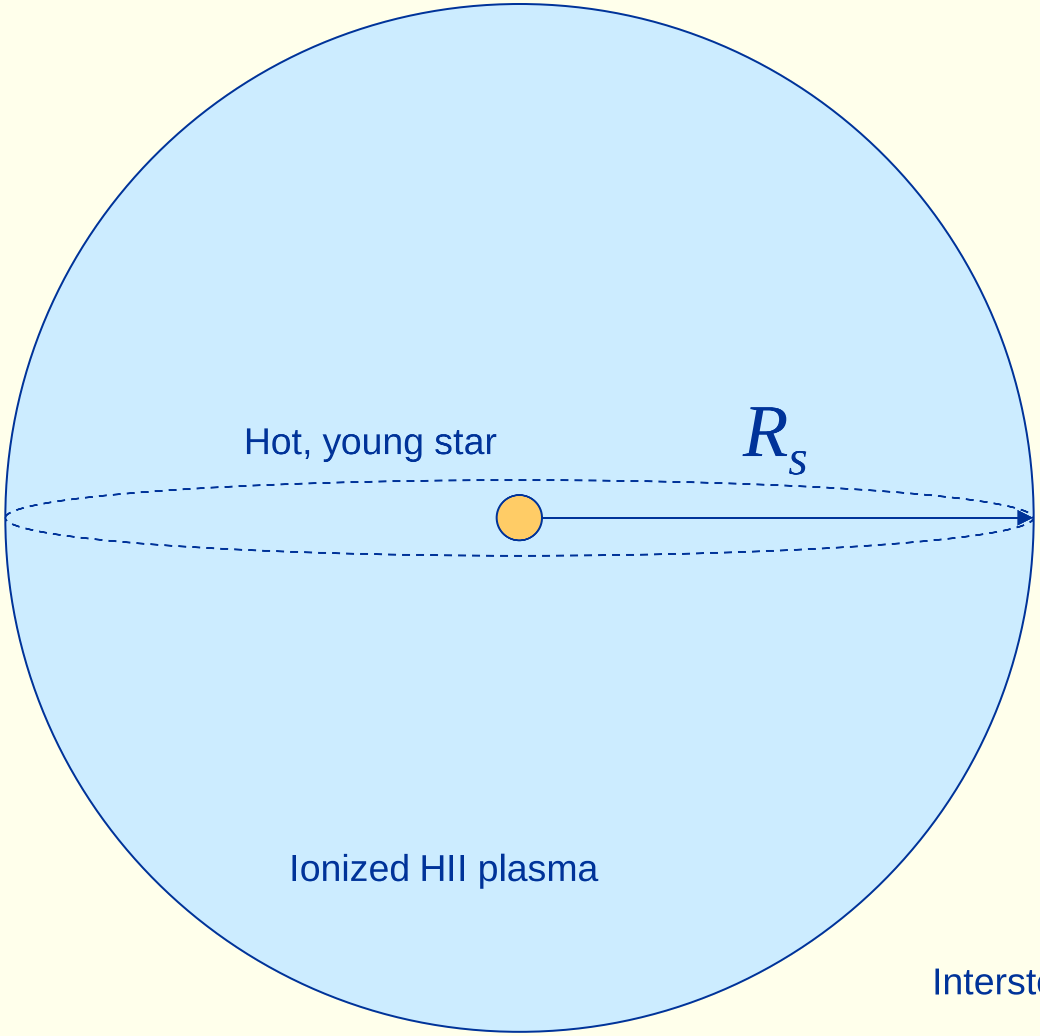
Interstellar plasma – HII regions

- *Reached by UV radiation by young hot stars.*
- *Mostly contains ionized hydrogen*
- *Approx. same density as HI regions.*
- *Ionization degree ~100 %*
- *T ~ 10 000 K*
- *B ~ 1 nT*



Distribution of interstellar HII gas in the Northern sky

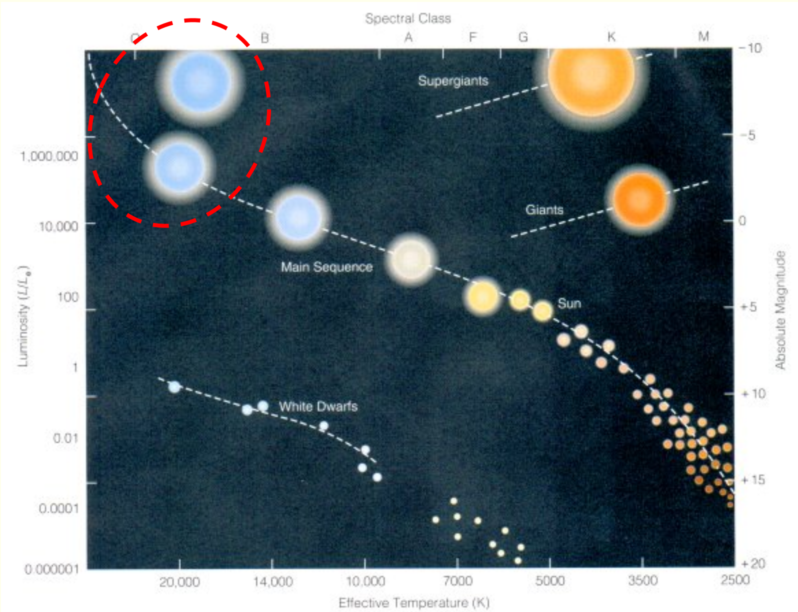
Strömgren sphere



The size of the HII region (emission nebula) is called the Strömgren radius, R_s.

The modelled, spherical region is called a Strömgren sphere.

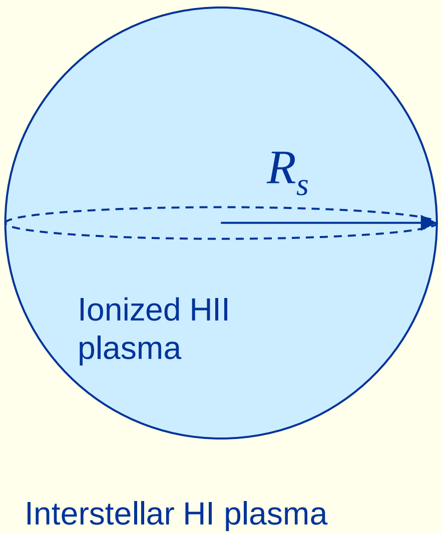
Strömgren sphere



Herzsprung-Russel diagram

- A hot star (> 30 000 K) emits significant numbers of photons with energy > 13.6 eV (ionization energy for HI) $\leftrightarrow$ λ < 912 Å = EUV radiation
- The star emits N_{UV} photons/s
- Interstellar plasma originally contains n_0 HI atoms
- The absorption cross section of HI is very high, so EUV radiation is quickly absorbed and we can assume 100 % ionization ratio.

Strömgren radius



- The recombination rate inside the Strömgren radius is

$$r = \alpha_H n_e n_p = \alpha_H n_e^2 = \alpha_H n_H^2$$

- In equilibrium, we have

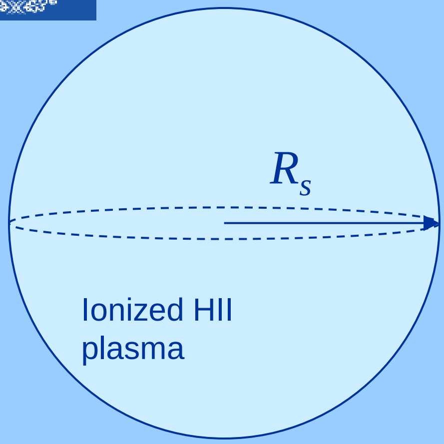
$$N_{UV} = rV = \alpha_H n_H^2 \frac{4\pi R_s^3}{3} \quad \Rightarrow$$

$$R_s = \left(\frac{3N_{UV}}{4\pi \alpha_H n_H^2} \right)^{1/3}$$

Hotter star (N_{UV})

Denser gas (n_H)

Strömgren radius



Interstellar HI plasma

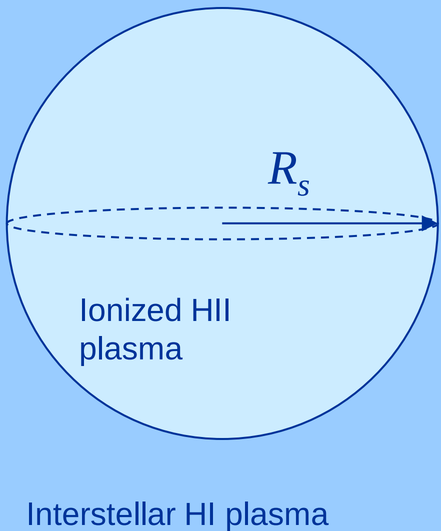
N_{UV} can be determined by considering black-body radiation properties of the star (Temperature and surface area). For a hot, young star it can be $\sim 10^{49}\ s^{-1}$. For a typical HII density of $n_H = 35\ cm^{-3}$, what is the Strömgren radius in light years?

$\alpha_H \approx 3\times 10^{-13}\ cm^3 s^{-1}$

$$R_s = \left(\frac{3N_{UV}}{4\pi \alpha_H n_H^2} \right)^{1/3}$$

Blue	0.2 L.Y.	Yellow	2000 L.Y.
Red	20 L.Y.	Green	2×10^5 L.Y.

Strömgren radius



N_{UV} can be determined by considering black-body radiation properties of the star (Temperature and surface area). For a hot, young star it can be $\sim 10^{49}\ s^{-1}$. For a typical HI density of $n_H = 35\ cm^{-3}$, we get

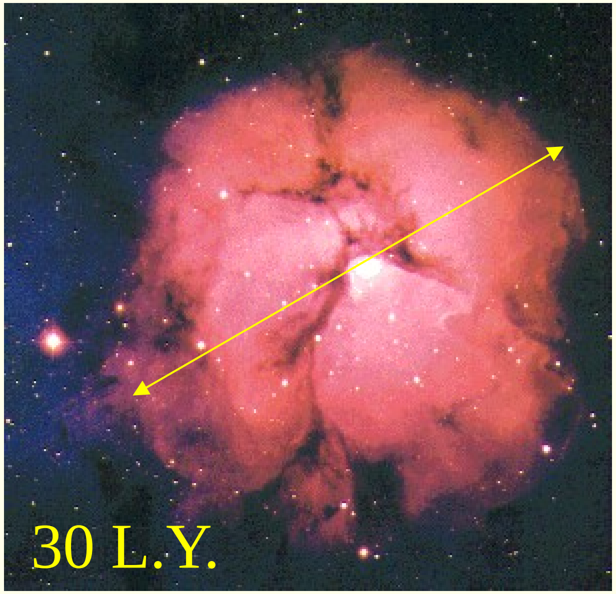
$\alpha_H \approx 3\times10^{-13}\ cm^3s^{-1}$

Red

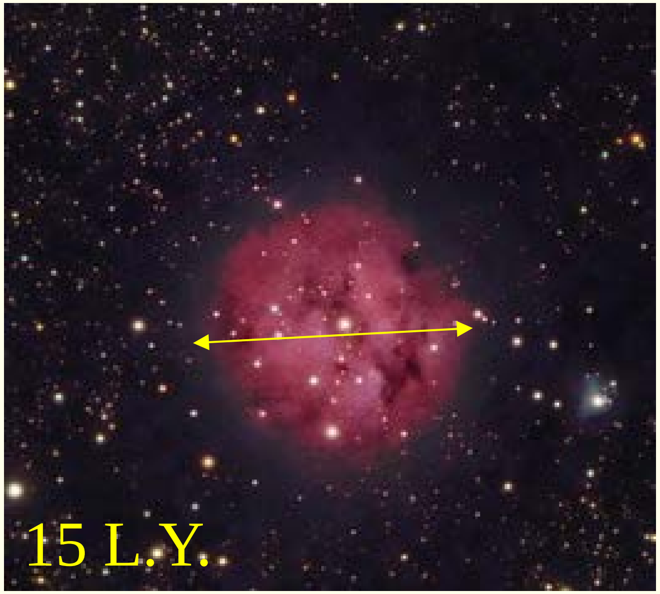
$$R_s = \left(\frac{3N_{UV}}{4\pi\alpha_H n_H^2}\right)^{1/3} = \left(\frac{3\cdot10^{49}}{4\pi\cdot3\cdot10^{-19}\cdot\left(3.5\cdot10^{7}\right)^2}\right)^{1/3} =$$

$$1.9\cdot10^{17}\,m = 20\ L.Y.$$

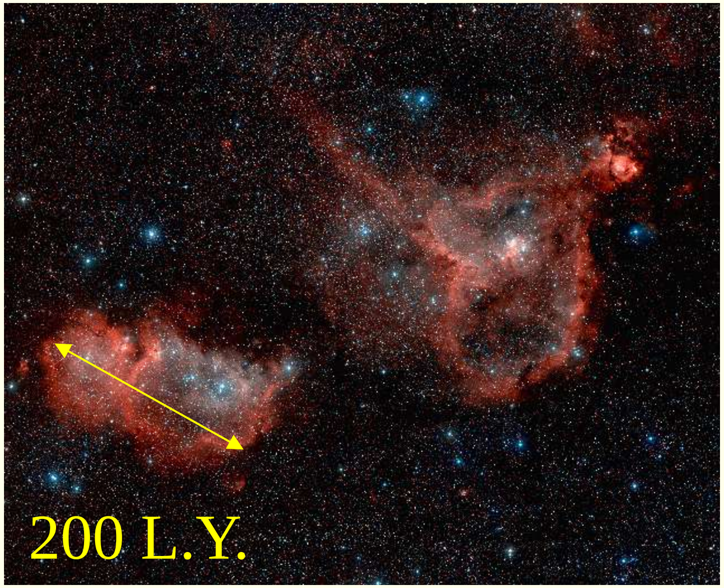
Emission nebulae



Triffid nebula (Messier 20)



IC5146

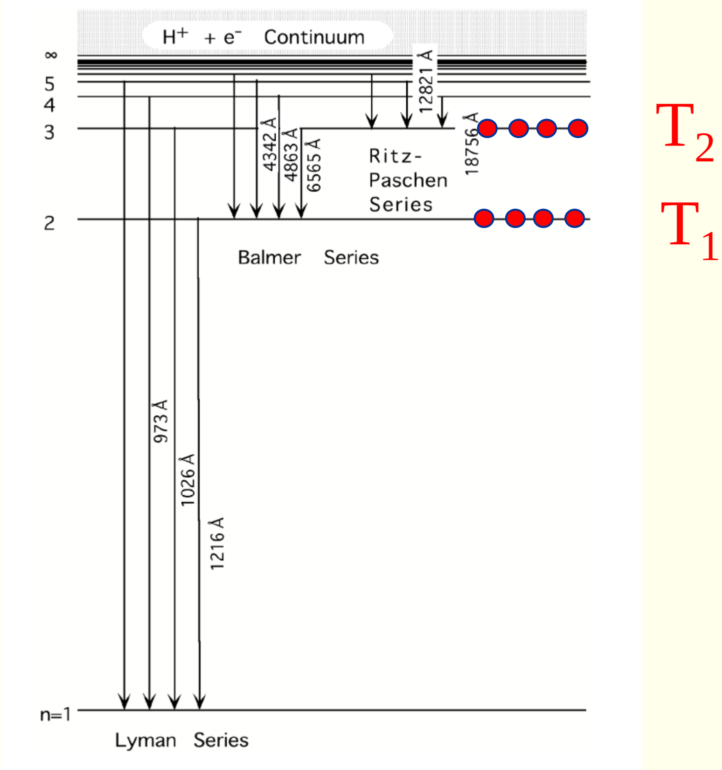


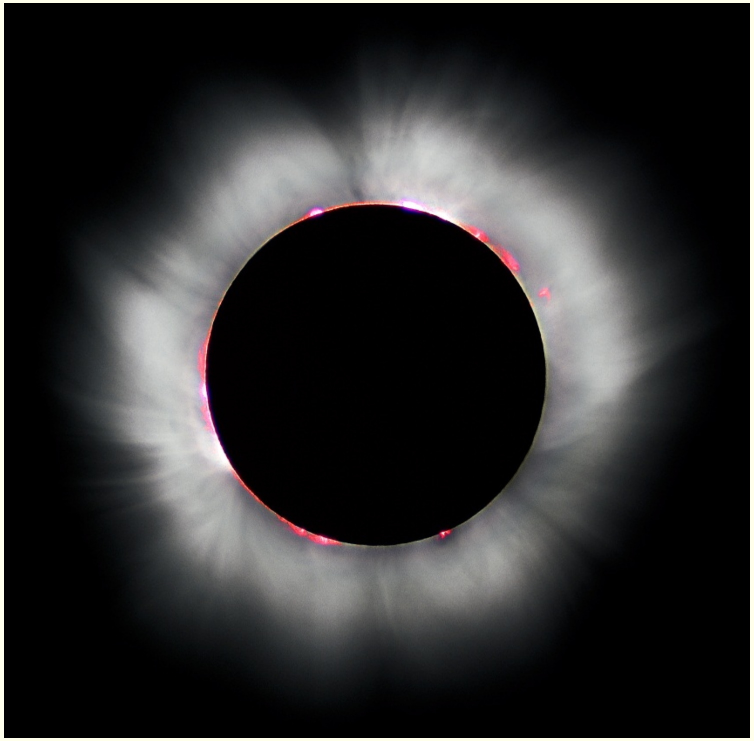
Heart and Soul nebuale (IC1805, IC1848)

- Emission nebulae often appear red, due to a prominent emission in the Balmer series
- May be non-spherical due to
  - *Gradients in the background medium*
  - *Multiple stars at the core*

Why is the chromosphere red?

Hydrogen spectrum





Interstellar magnetic field

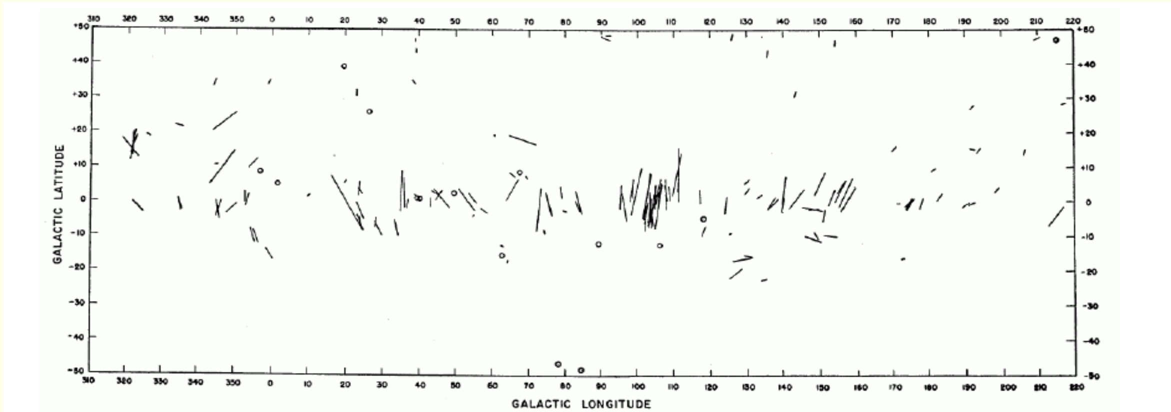


Figure 1. Vector diagram showing polarization of individual stars.

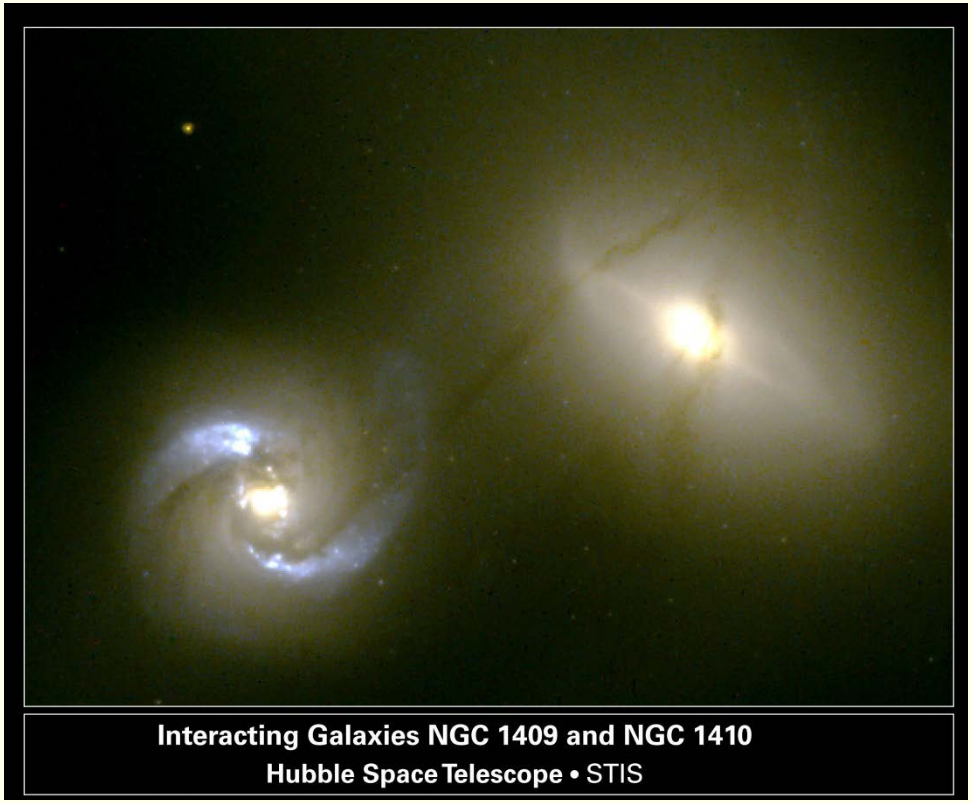
Hall & Mikesell, 1949, AJ, 54, 187

HI regions: ~ 0.1 nT

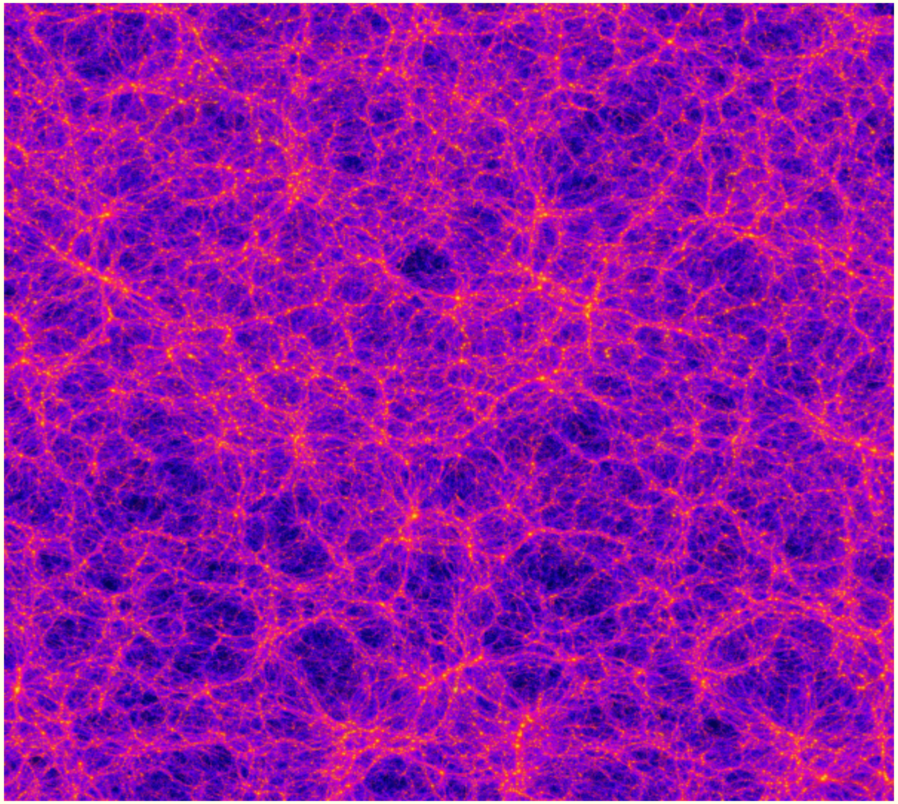
HII regions: ~1 nT

Magnetic field important also in the interstellar medium!

Intergalactic matter



2.7´10^9 light years



Computer simulation of intergalactic mass distribution

Intergalactic plasma

- Mostly made up of “bridges” between galaxies (~10^6 l.y.) (Radius of Milky Way is ~10^4 l.y.)

- Detected by radio telescope measurements of synchrotron radiation from energetic electrons.

- Typical densites are 10^{-4} cm^{-3}

- Typical magnetic field: B ~ 10^{-2} nT

Last Minute!

Last Minute!

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