# Last lecture (9)

- Aurora
- Magnetospheric dynamics
- Cosmic radiation

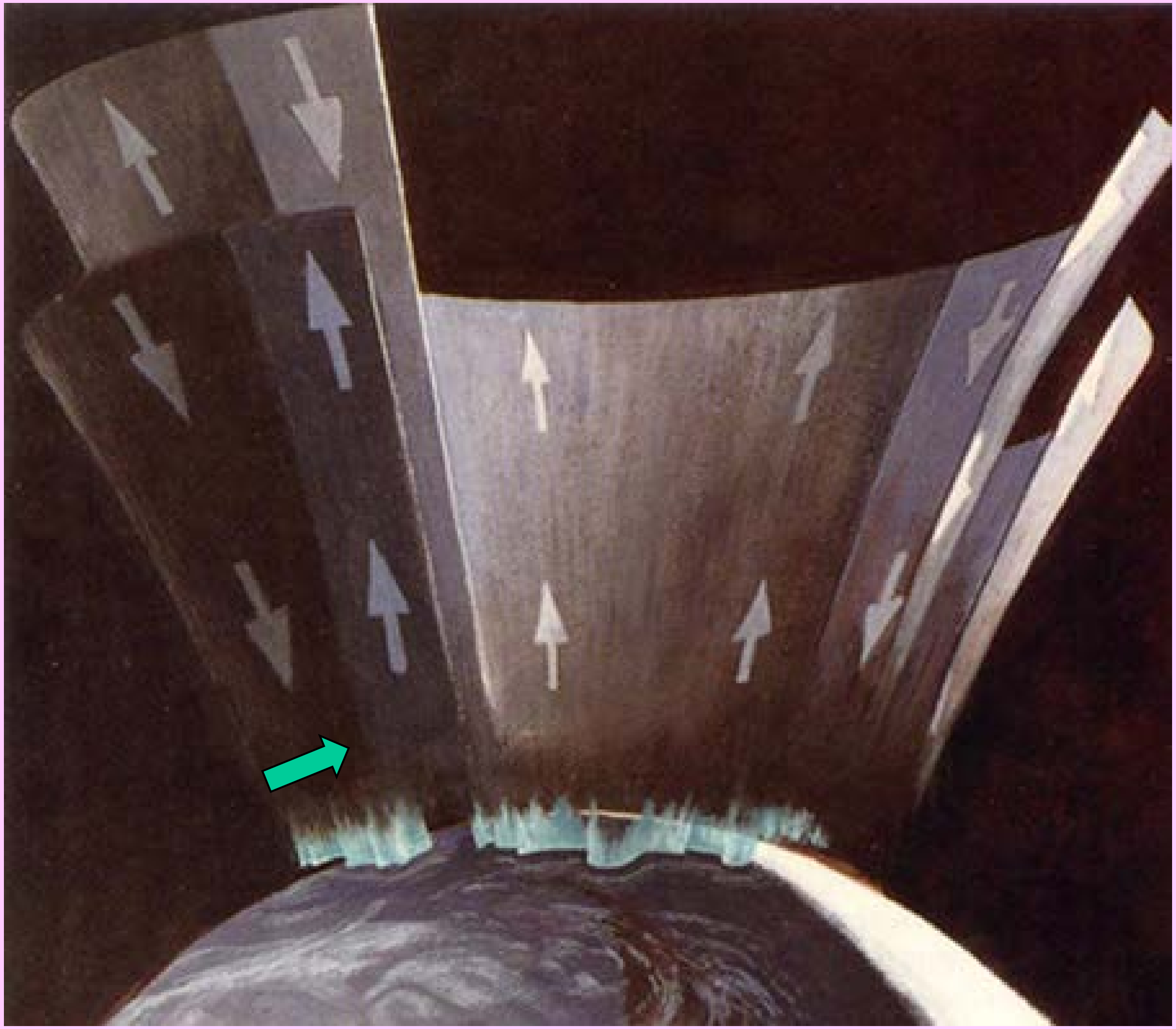
# Today’s lecture (10)

- Cosmic radiation
- Interstellar plasma
- Swedish space science research

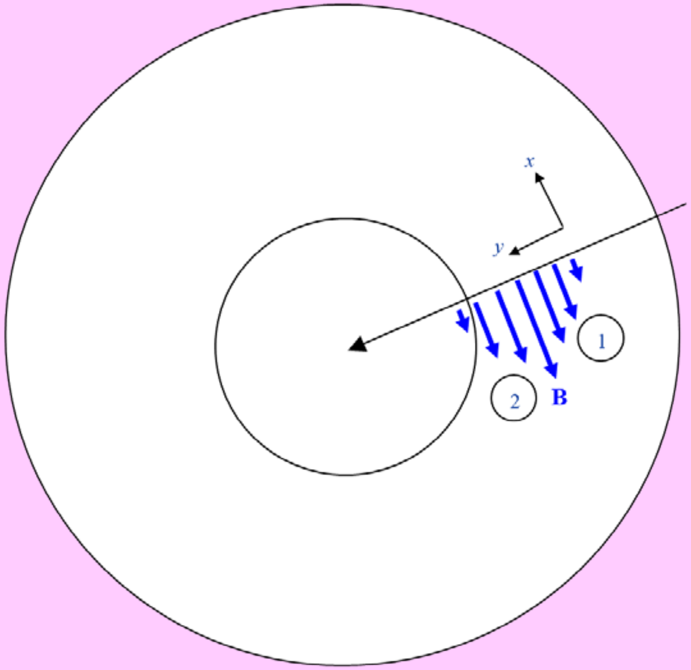
# Today

| 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 examination | 26/10 | 8-13 | F2 | | |
| | | | | | |

# Birkeland currents in the auroral oval



# Mini-groupwork 5



## Current sheet 1:

$$\frac{\partial B_x}{\partial y} < 0 \quad \Rightarrow \quad j_z > 0$$

$$\frac{\Delta B_x}{\Delta y} \approx -\frac{15\ \text{mm}}{22\ \text{mm}} \cdot 1000 \cdot 10^{-9} = -6.8 \cdot 10^{-7}\ \text{T}$$

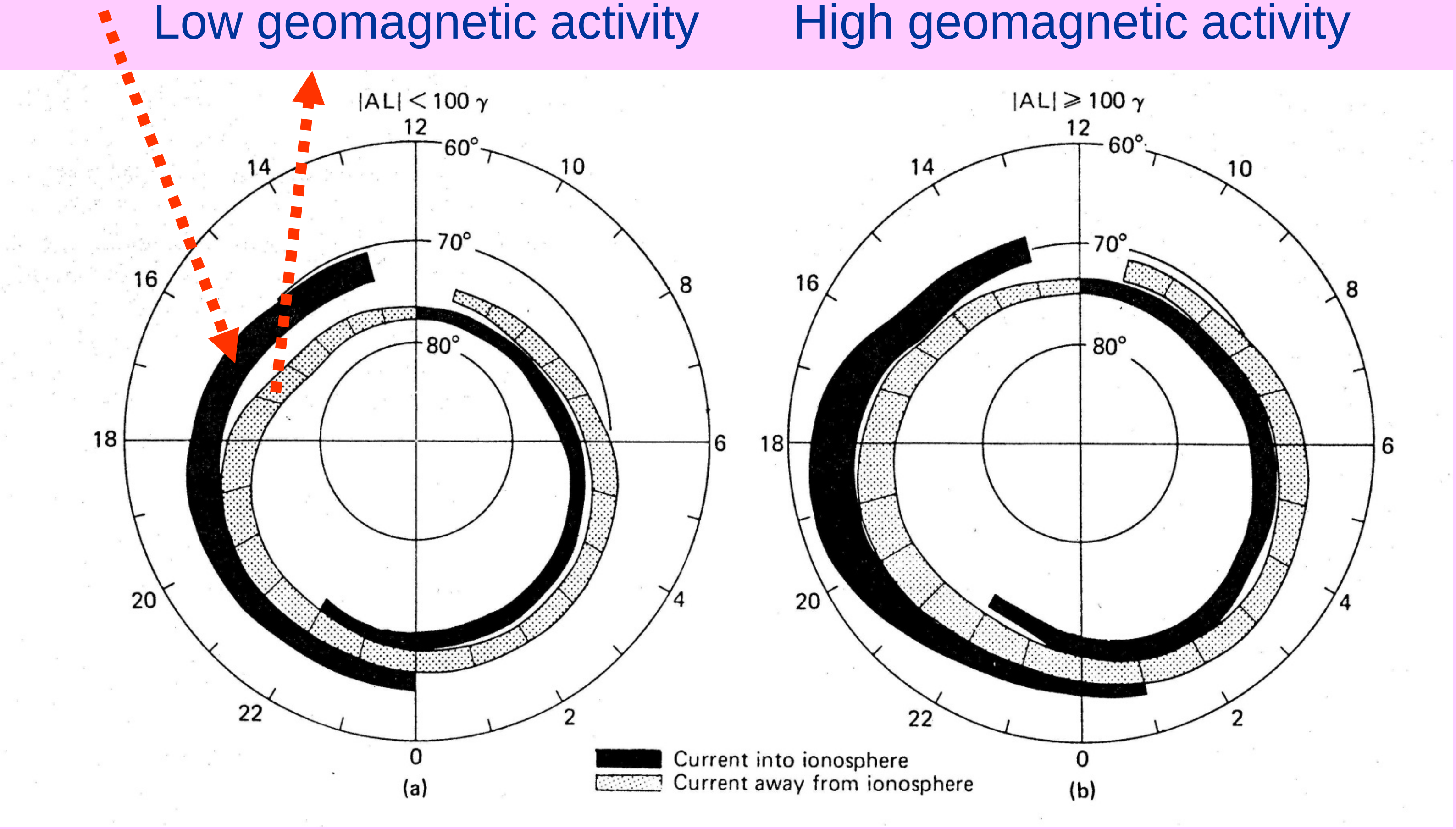
$$\Delta y \approx \frac{10\ \text{mm}}{10\ \text{mm}} \cdot \frac{2^\circ}{360^\circ} 2\pi\left(R_E + 800\right) = 250 \cdot 10^3\ \text{m}$$

$$j_z \approx -\frac{1}{\mu_0}\frac{\Delta B_x}{\Delta y} = 2.2 \cdot 10^{-6}\ \text{Am}^{-2}$$

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

# Birkeland currents in the auroral oval

Low geomagnetic activity High geomagnetic activity



# 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
- global oscillations of the magnetosphere

**First lecture Tuesday November 4, 10.15 at Teknikringen 29, seminar room, second floor.**
**(MEET AT  ENTRANCE!)**

# 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

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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.)

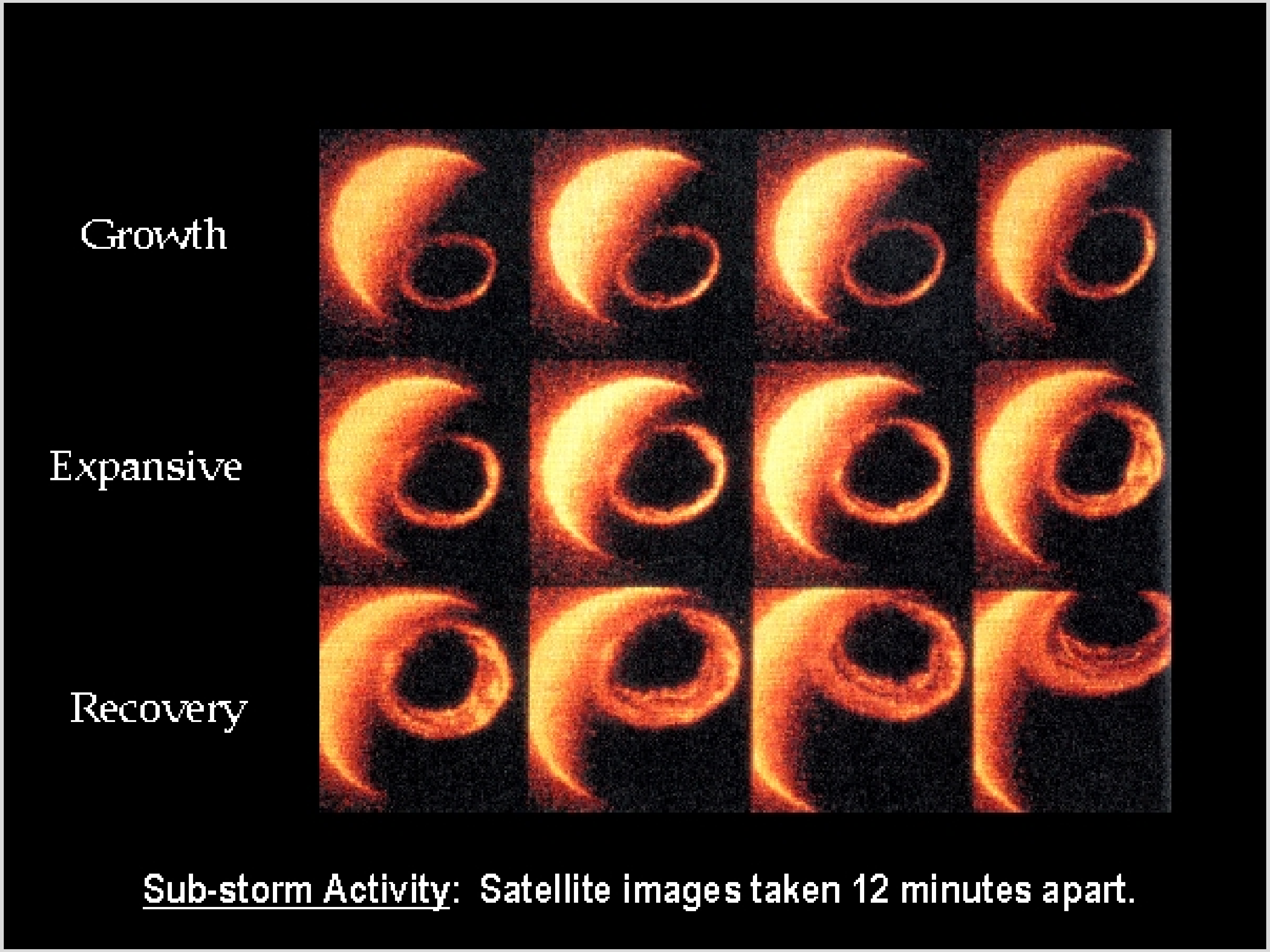
Approx. 5 different problems (which may contain sub-problems).

# About the exam

Motivate your answers!

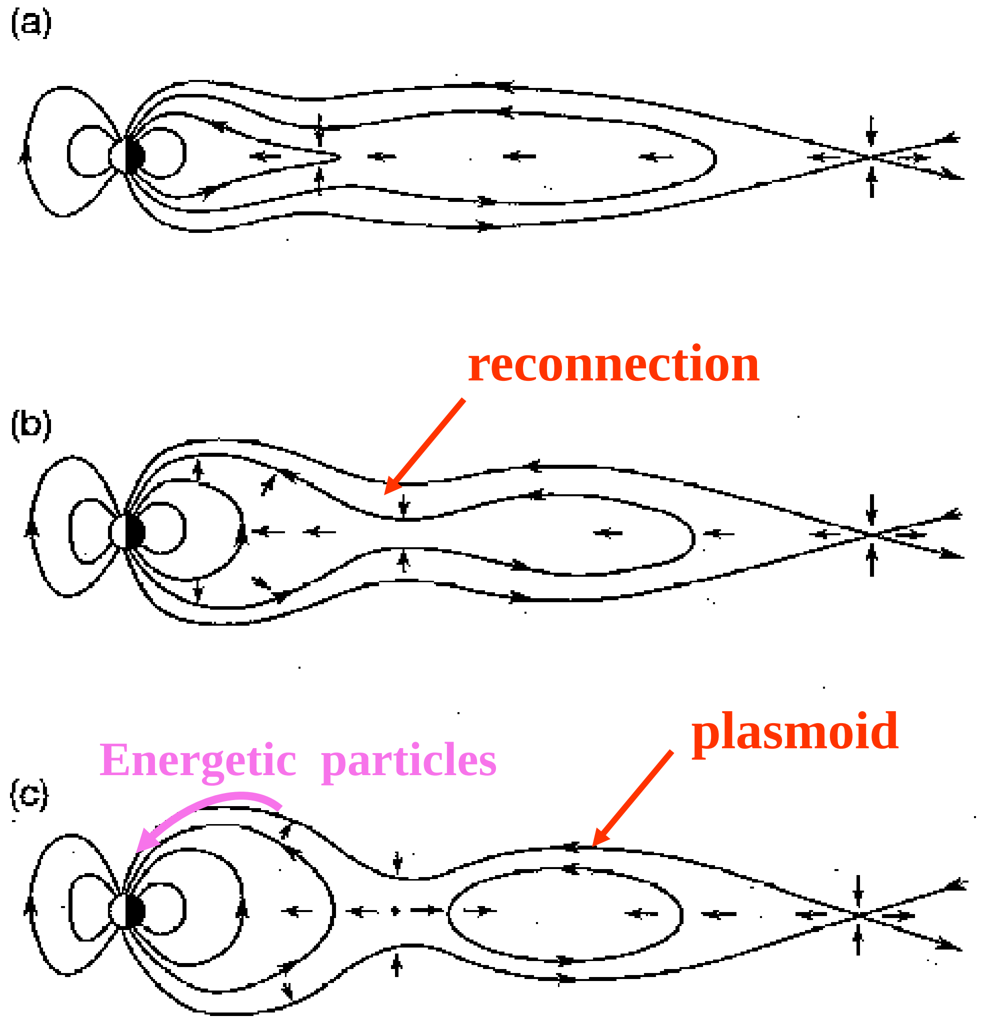
Be careful with units and numerical calculations!

# Aurora during substorm



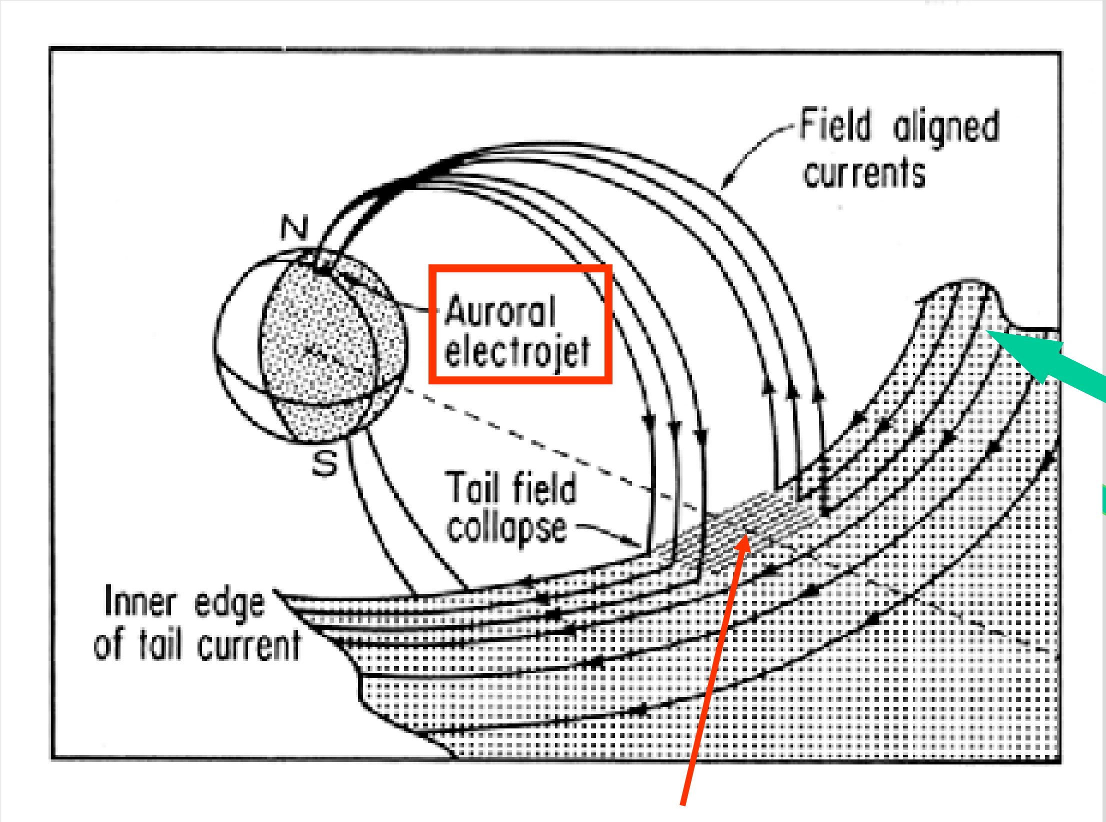
Sub-storm Activity: Satellite images taken 12 minutes apart.

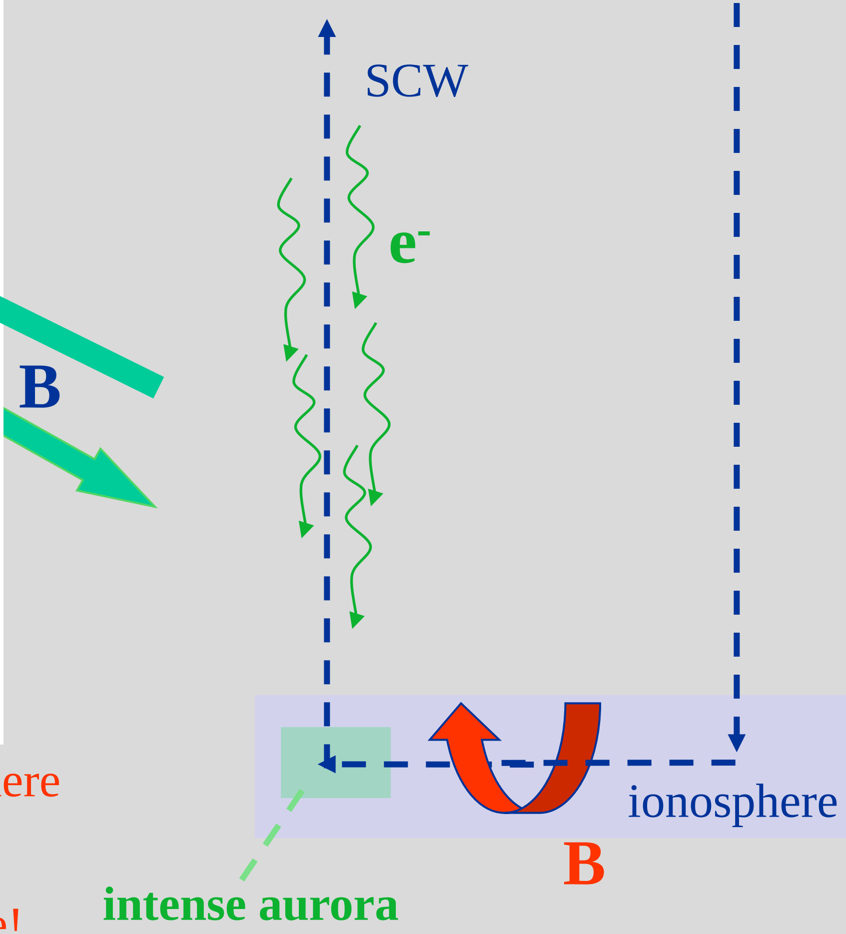
# Substorms - magnetosphere



- **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)



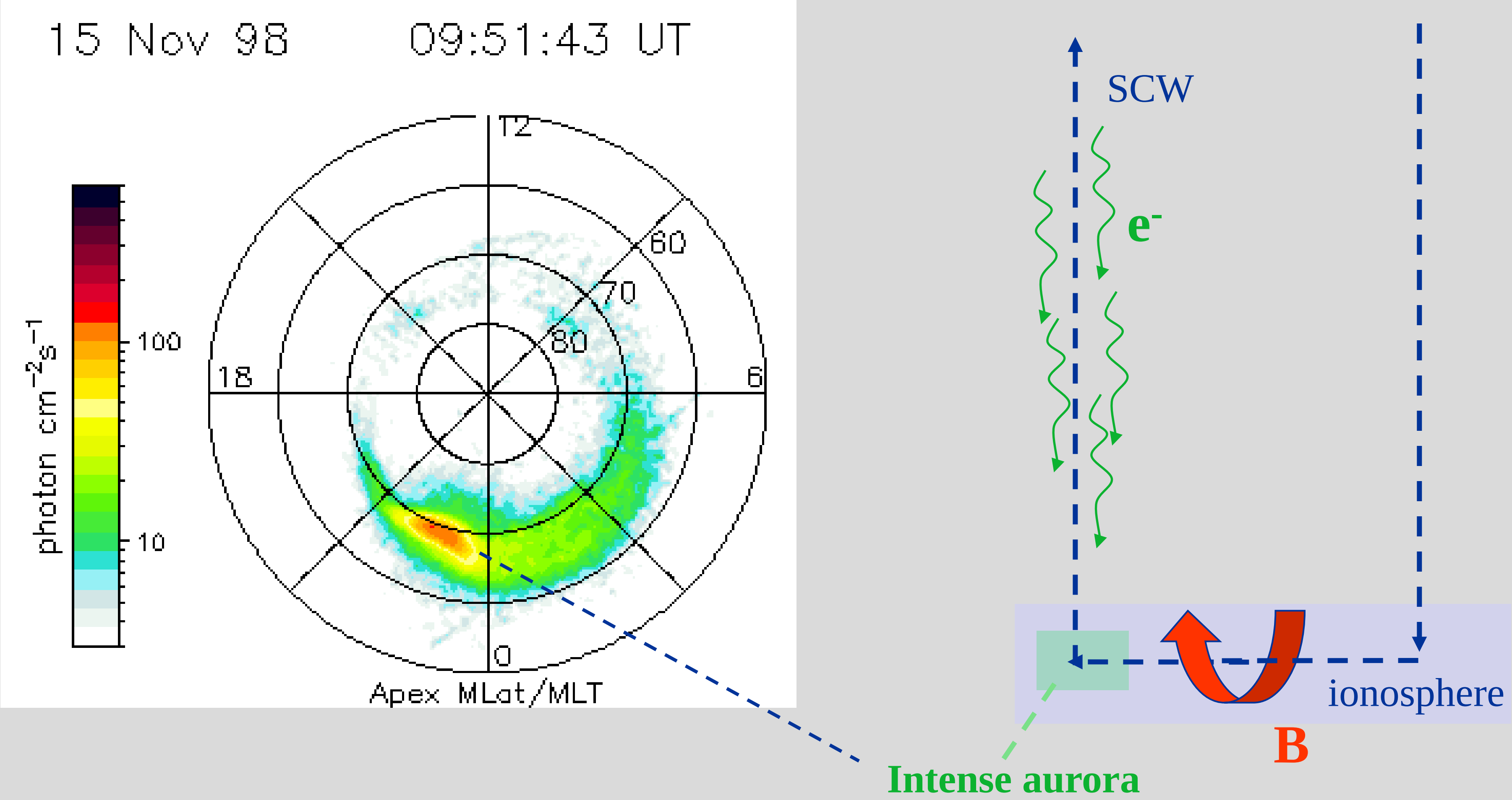


Due to reconnection processes the resistivity increases here

⇒

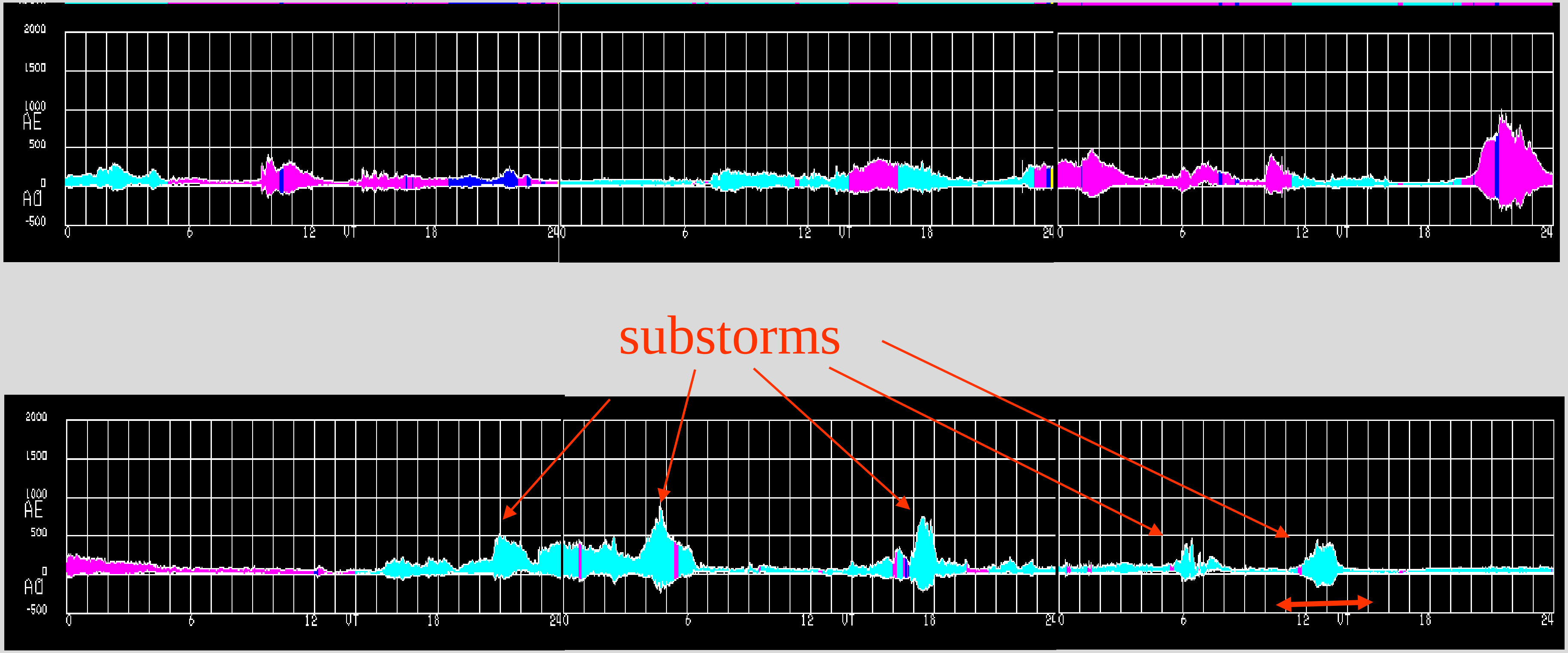
Current takes another direction – through the ionosphere!

# Substorm Current Wedge (SCW)



# Auroral Electrojet (AE) index

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

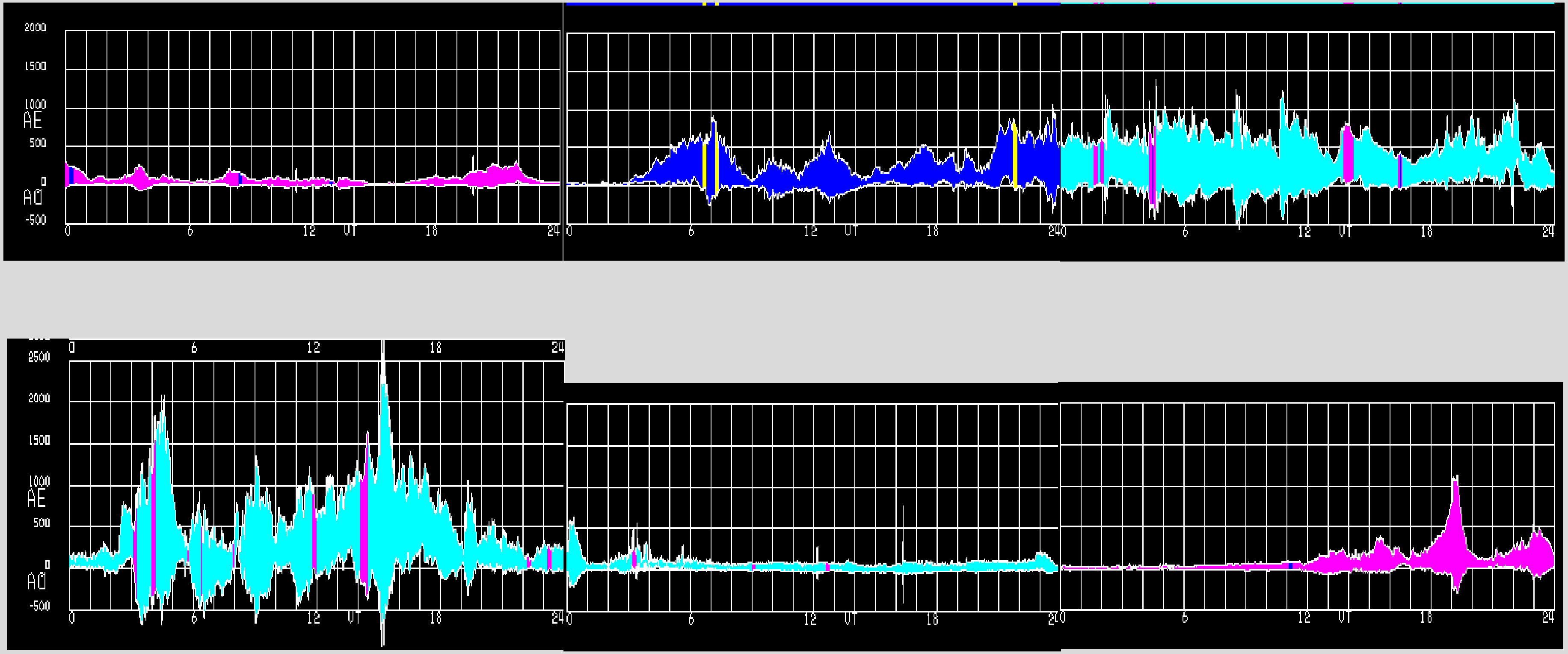


substorms

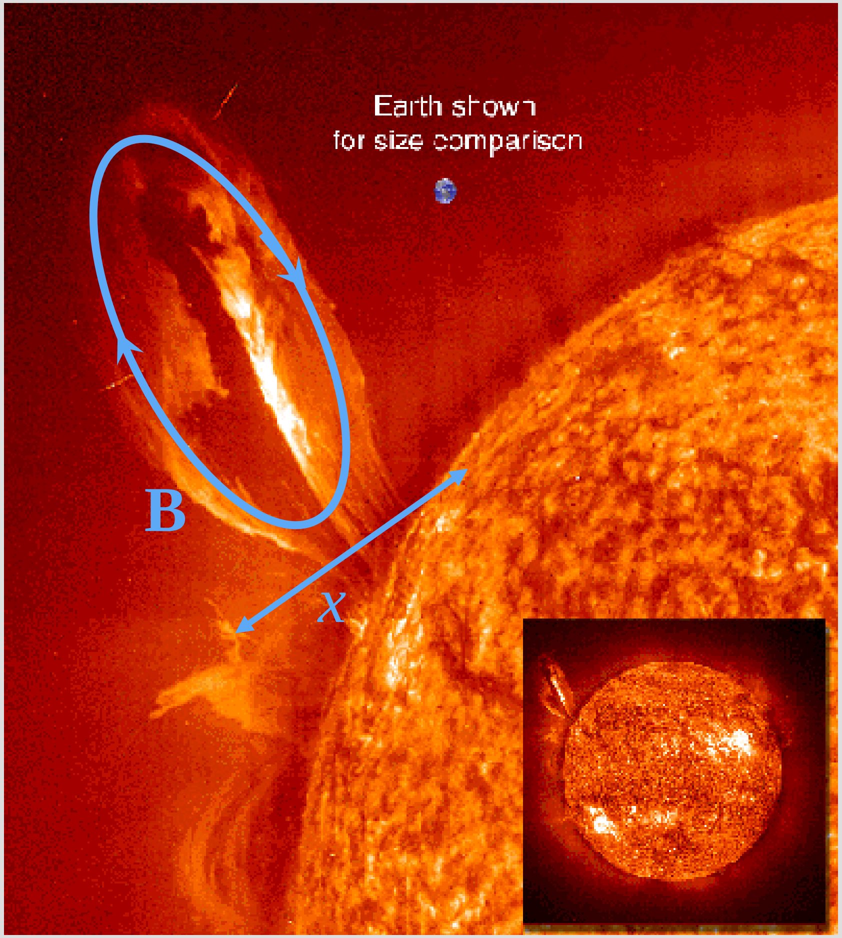
~1 – 3 h

# Geomagnetic storms

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

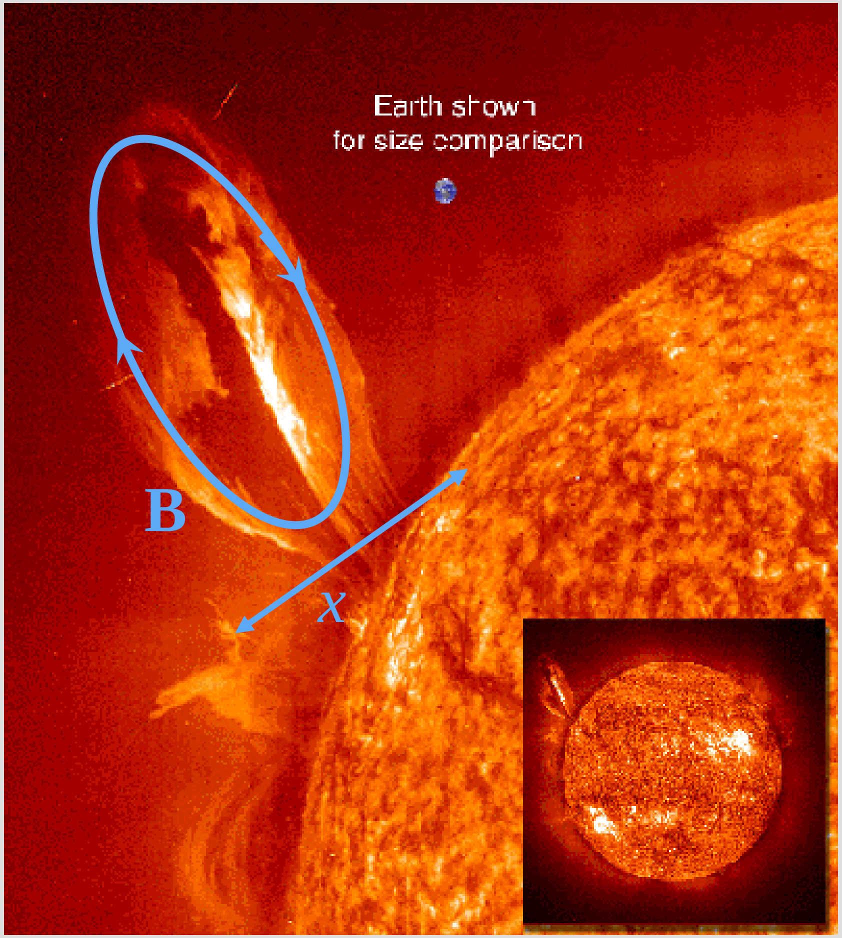


# Geomagnetic storms and coronal mass ejections



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

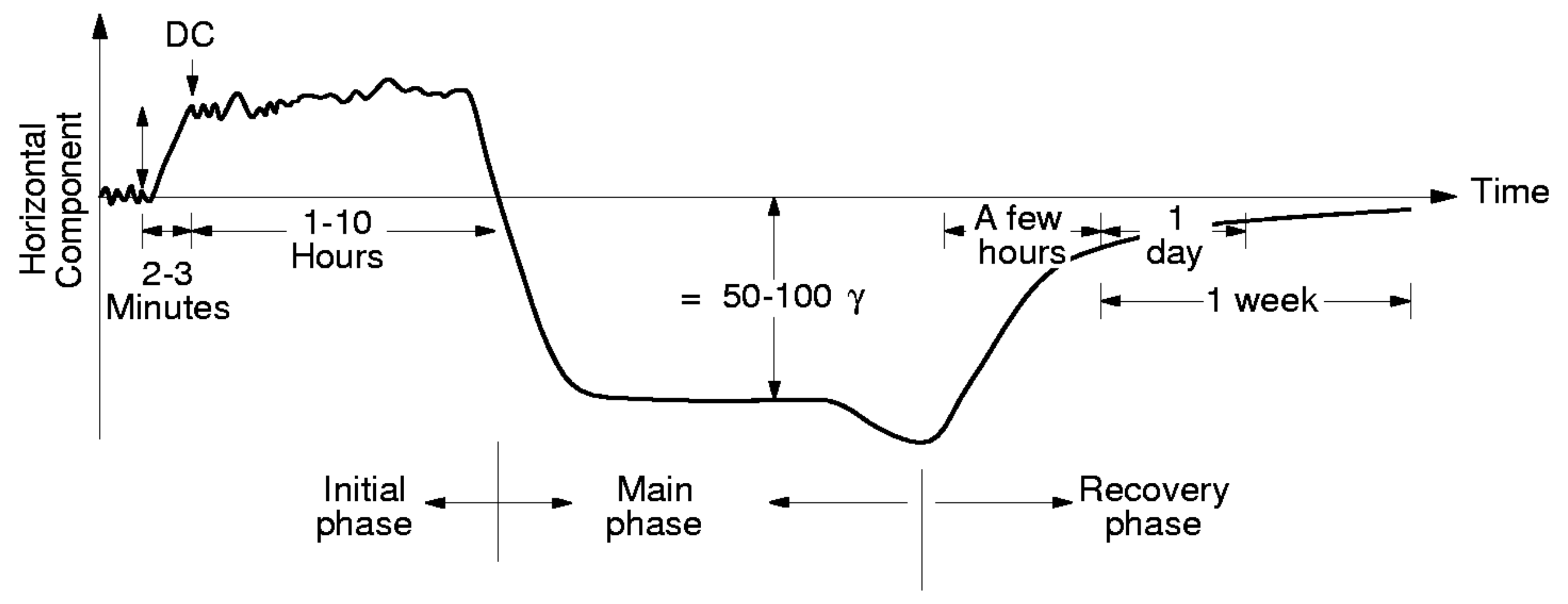
# Geomagnetic storms and coronal mass ejections



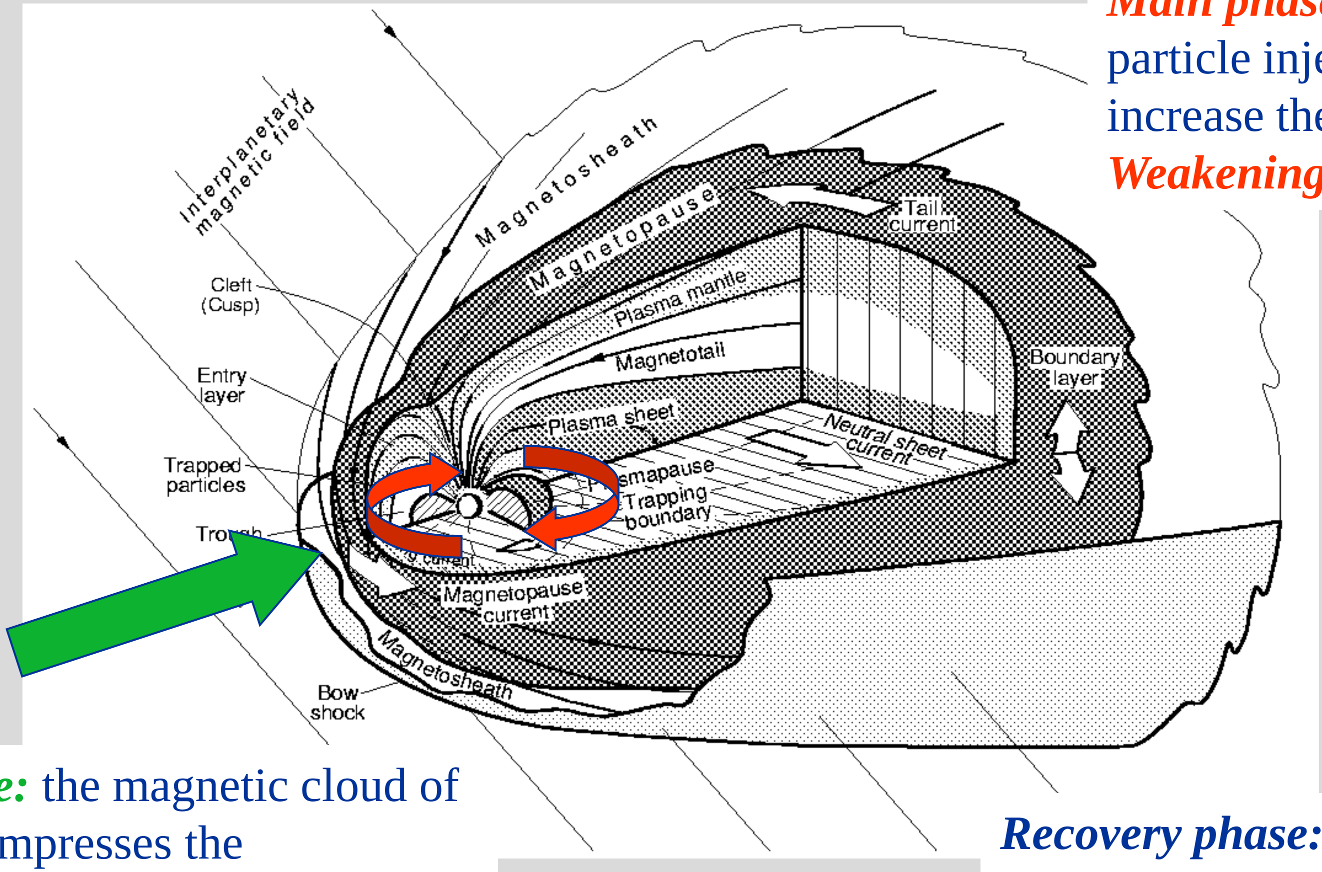
- Large geomagnetic storms are often associated with coronal mass ejections (CMEs)
- Because of their magnetic structure, they will give long periods with a constant IMF
- A typical time for a CME to pass Earth becomes $T = x/v \sim 100\ \mathrm{R_{sun}}/1000\ \mathrm{kms^{-1}} \sim 20$ h

# Geomagnetic storms - phases

*Magnetogram*



# Geomagnetic storms - phases

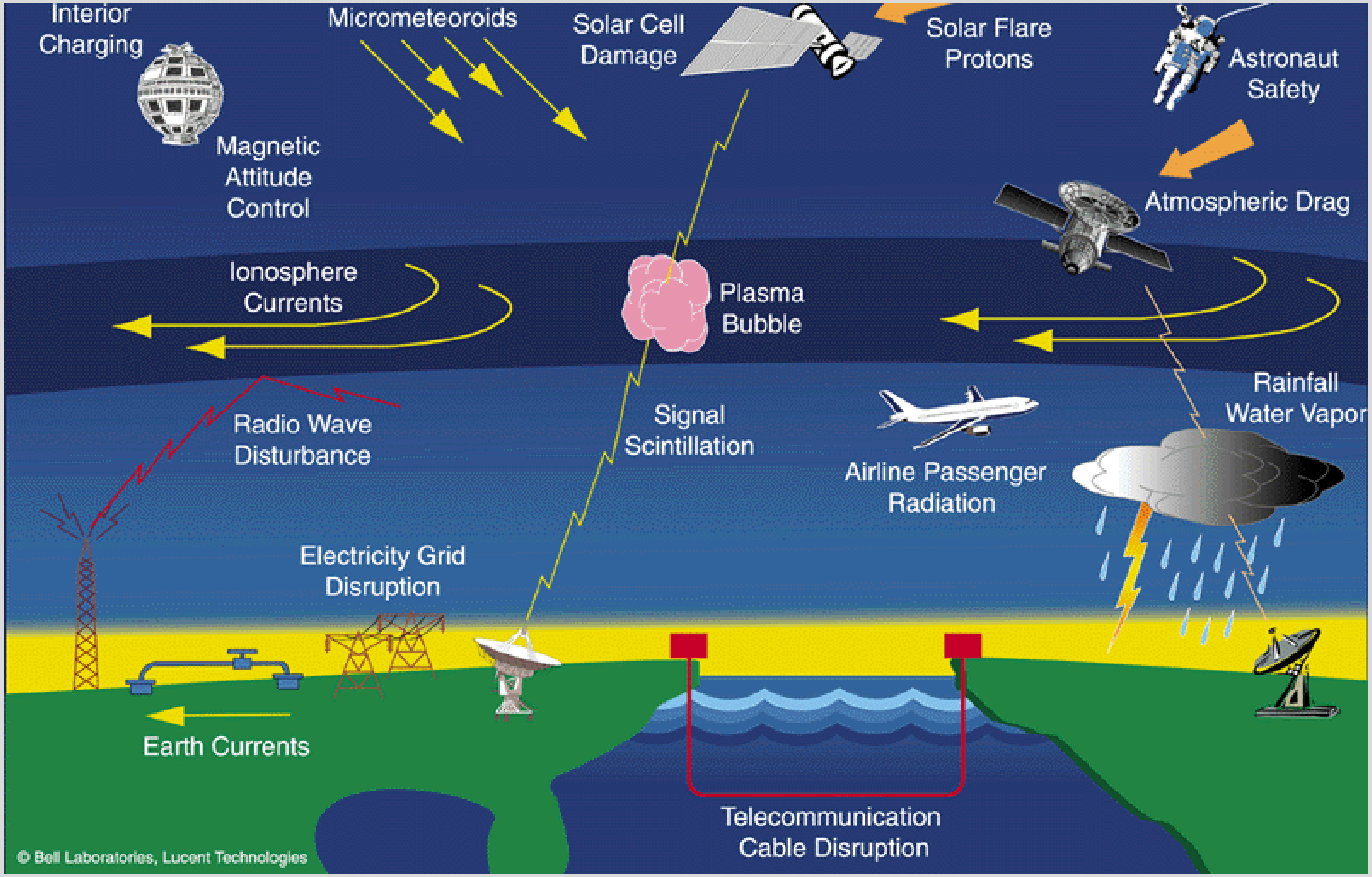


***Main phase:*** Several particle injections increase the ring current.
***Weakening of B***

***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



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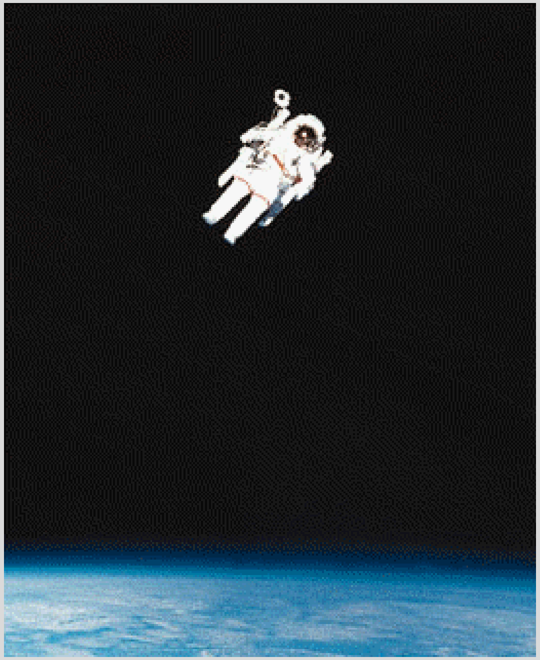
"conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health."

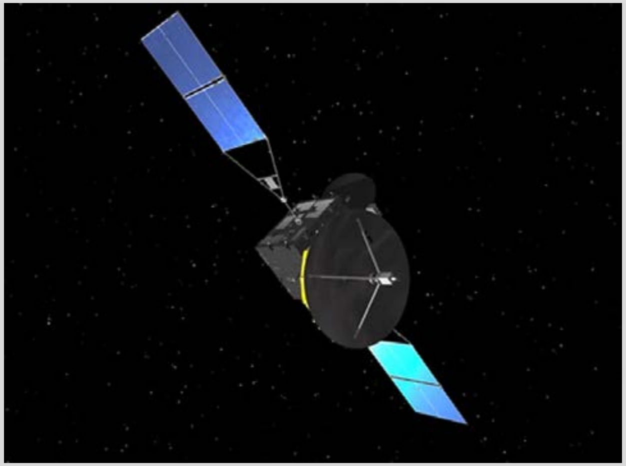
*US National Space Weather Programme*

# 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?

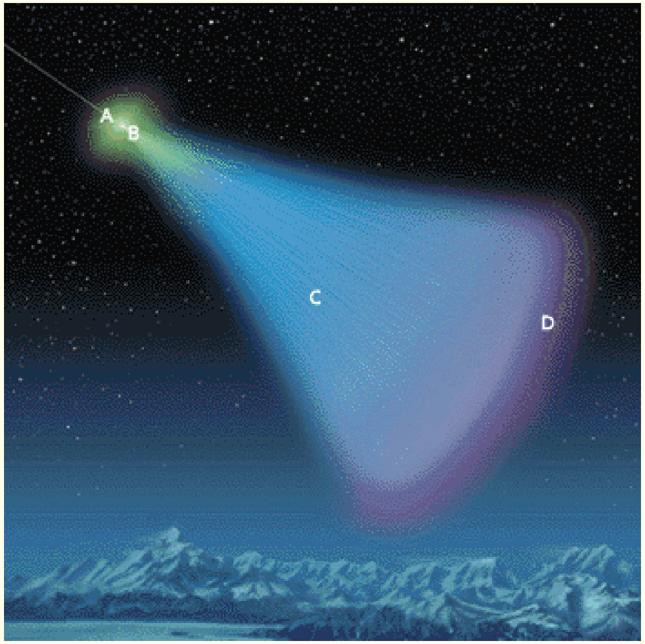
# Cosmic rays (= cosmic radiation)

*Primary cosmic radiation*

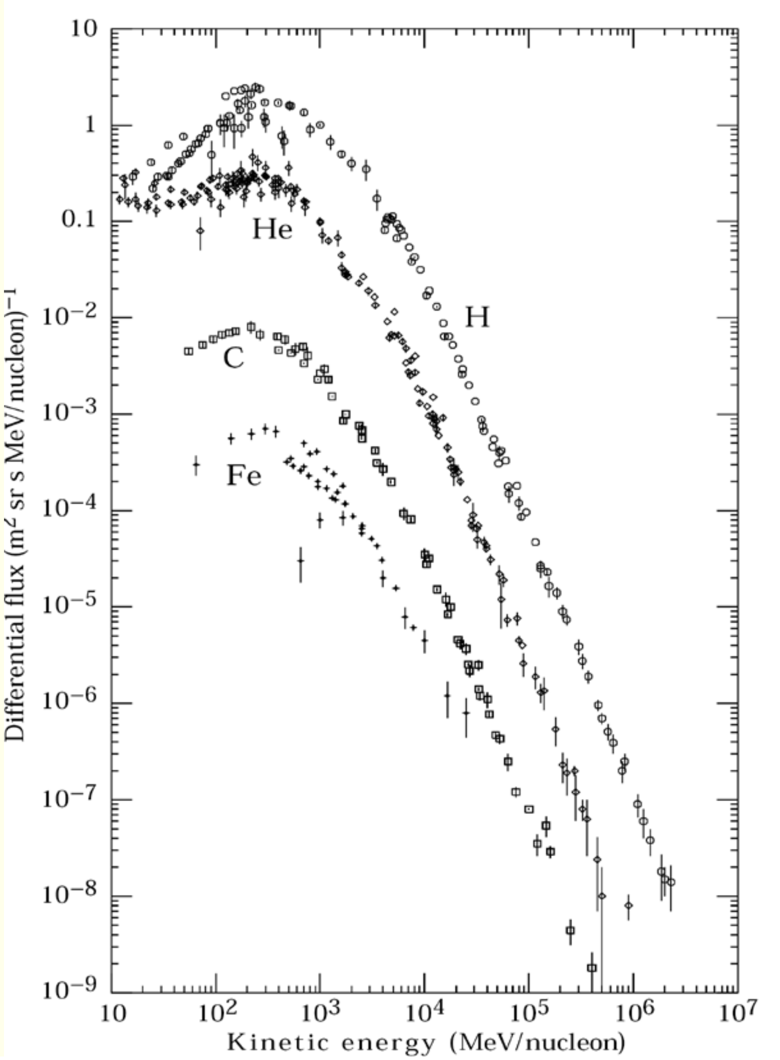
Extremely energetic particles (>$10^8$ eV)

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

*Secondary cosmic radiation*



# Composition and spectrum of galactic cosmic radiation

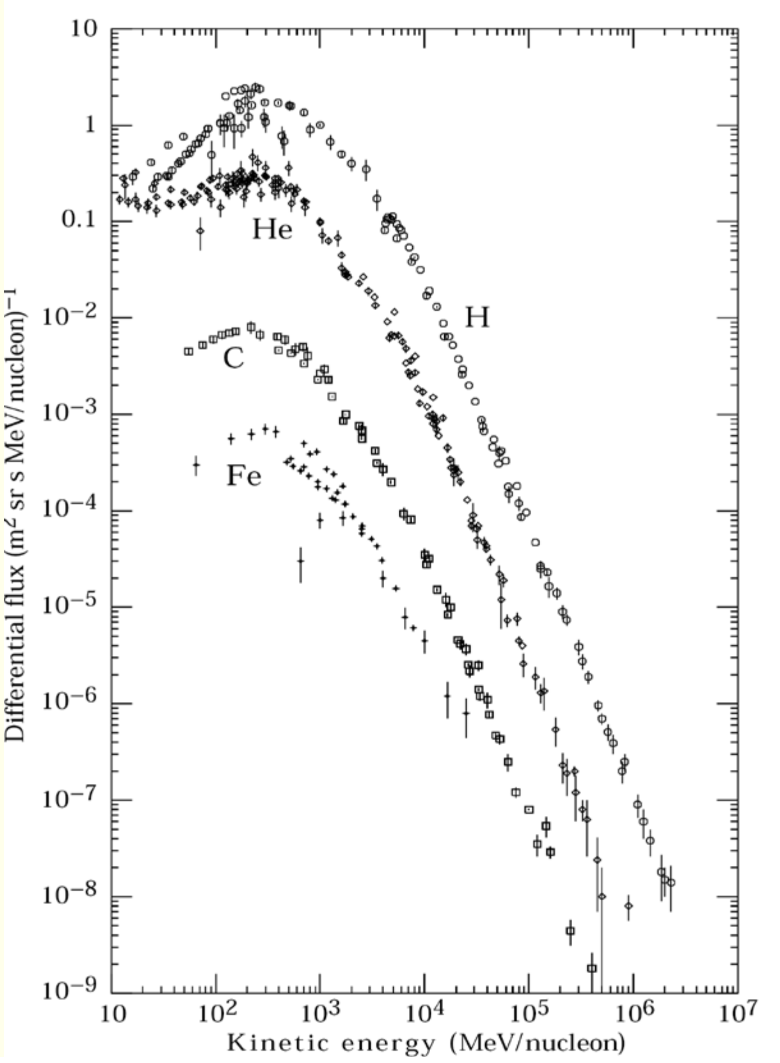


*Simpson, 1983.*

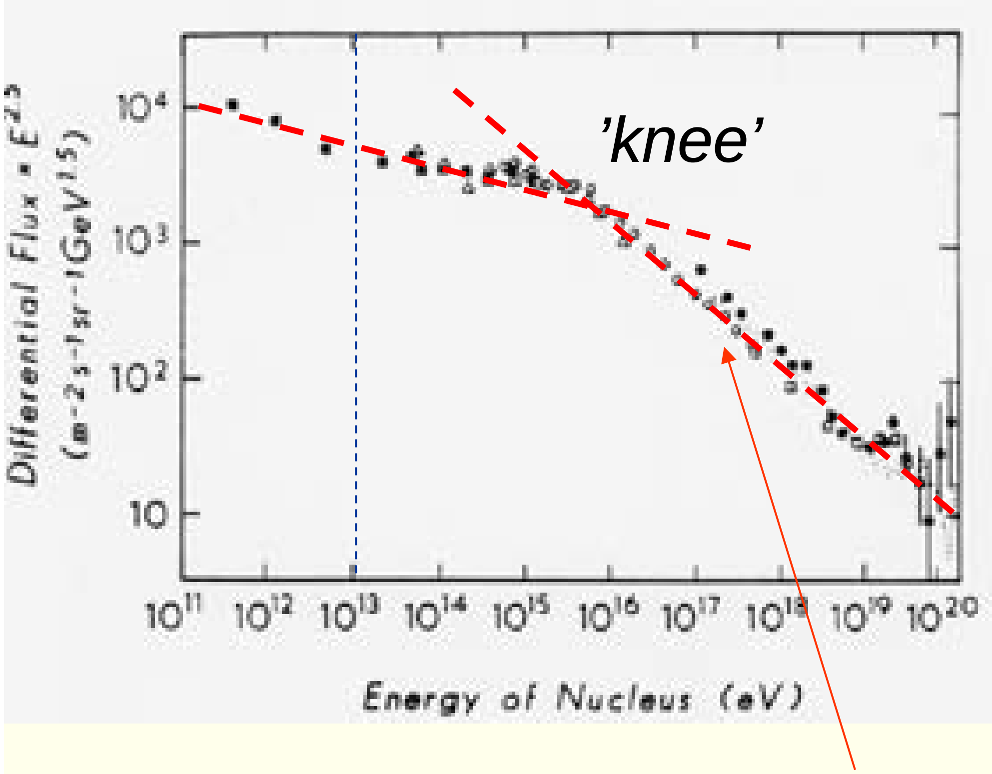
| | |
|---|---|
| 83 % | protons |
| 13 % | alpha particles |
| 3 % | electrons |
| 1 % | other nuclei |

All cosmic ray particles are fully ionized

# Spectrum of galactic cosmic radiation

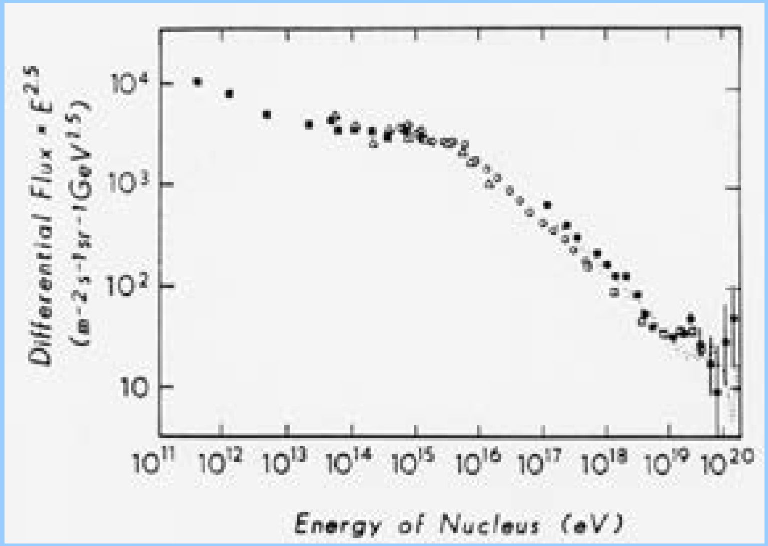


*Simpson, 1983.*



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 = $10^{20}\cdot1.6\cdot10^{-19}$ J = 16 J

A mosquito weighs about 5 mg. 10 km/h ≈ 2.8 m/s ⇒

$$\frac{mv^2}{2}=\frac{5\cdot10^{-6}\cdot(10/3.6)^2}{2}$$
$$=2\cdot10^{-5}\ \mathrm{J}$$

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

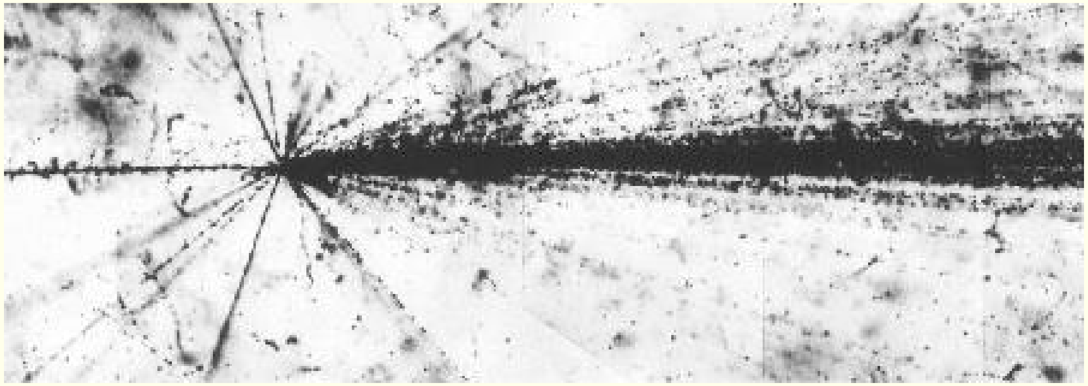
Tennis ball moving at 100 km/h

# 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

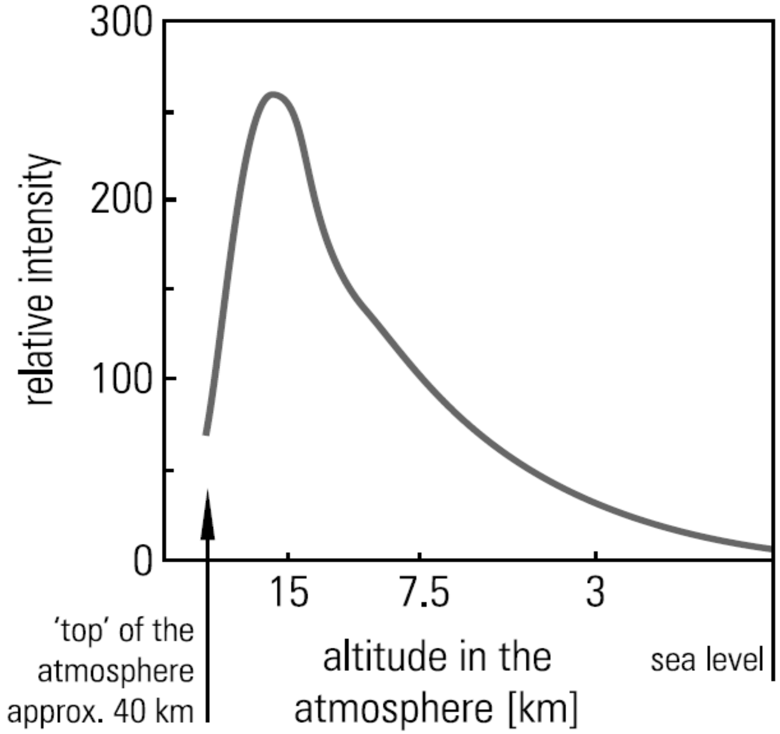
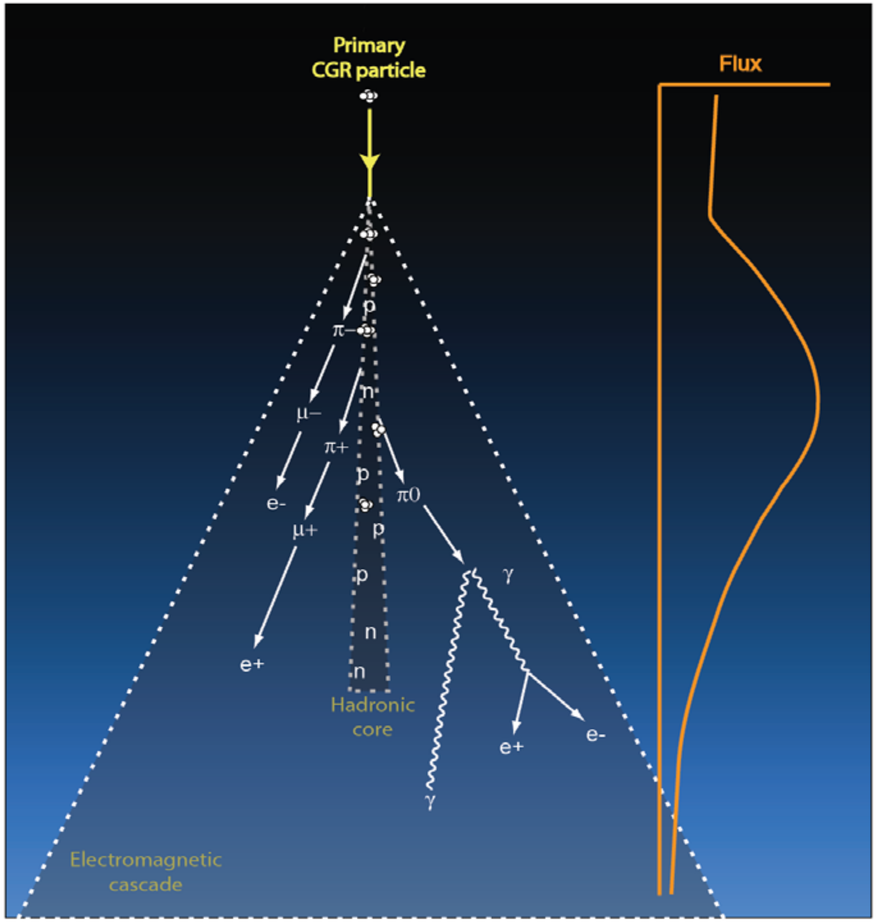
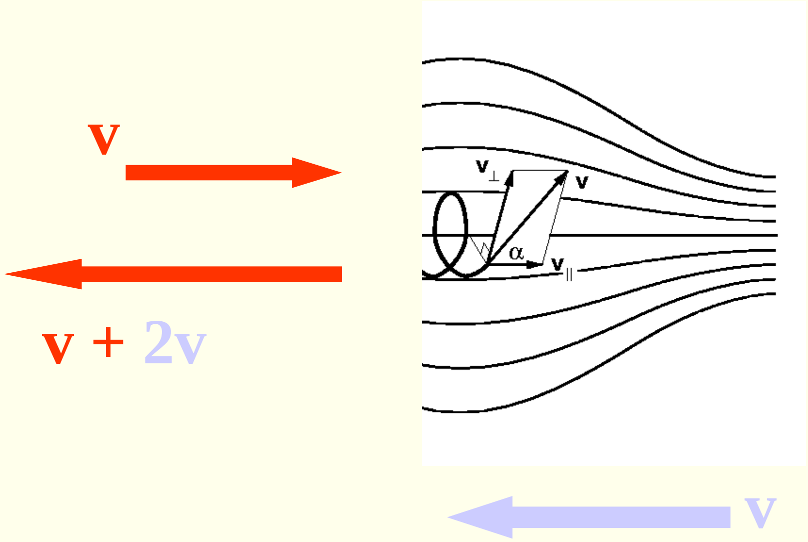


**Fig. 1.12**
Intensity profile of cosmic particles in the atmosphere

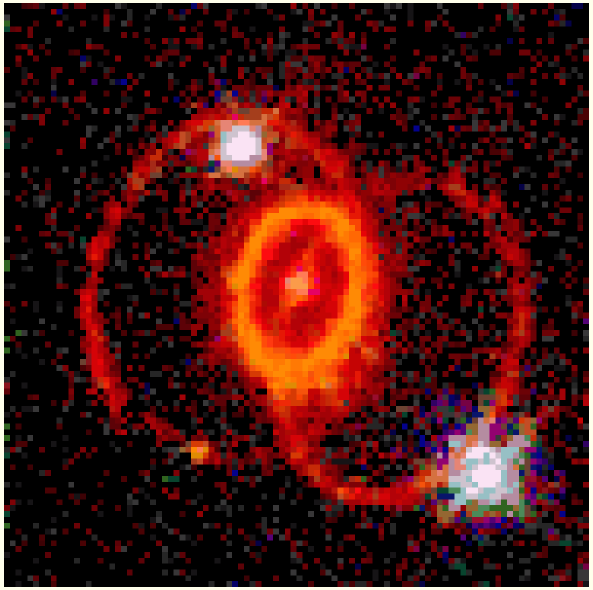


# Origin of galactic cosmic radiation

Two main theories

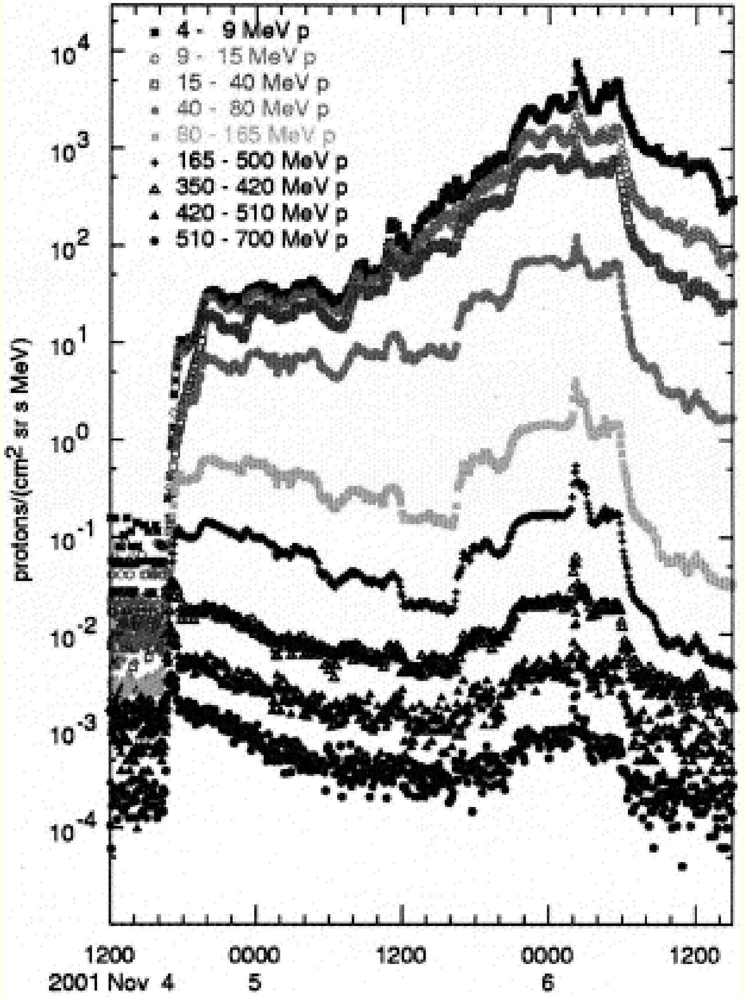


Fermi acceleration
by two magnetic
mirrors in motion



Shock waves from
supernova explosion

# Solar Energetic Particles (SEP)



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

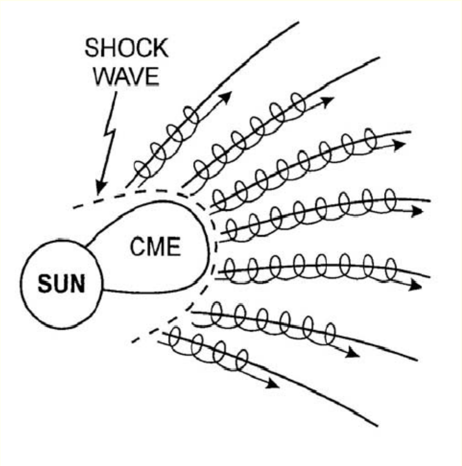


Figure 22: Time profiles of the strong SEP proton flux event of November 4, The peak at the time of shock passage is clearly defined early on November 6, even at proton energies as high as 510 – 700 MeV. From Reames (2004).

# Neutron albedo

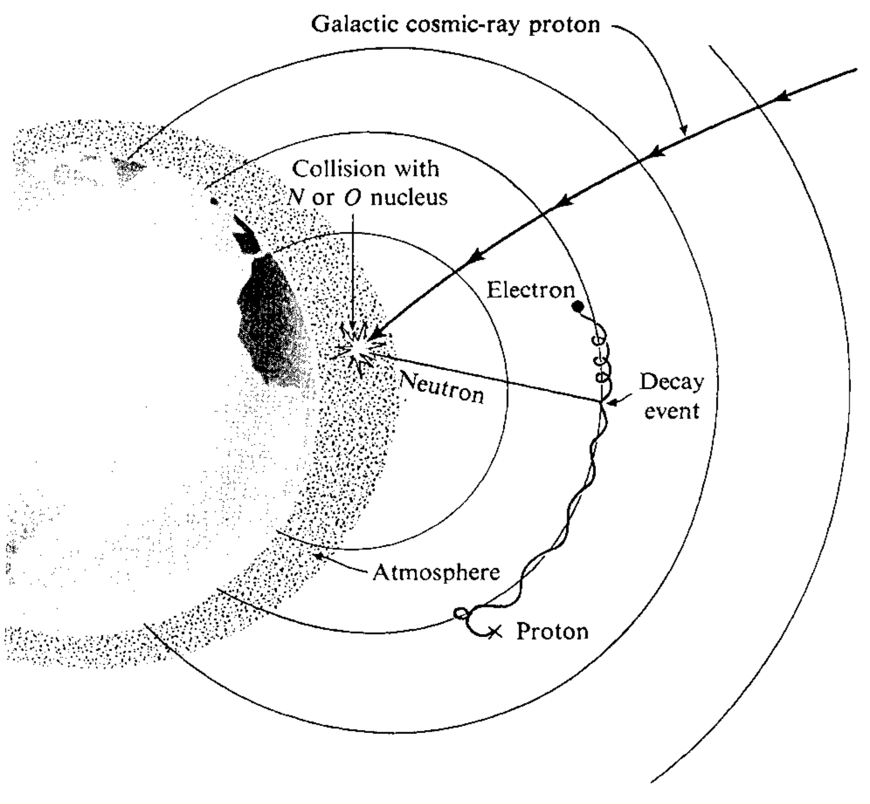


**Figure 8. An illustration of the CRAND process for populating the inner radiation belts [Hess, 1968].**

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

$$E = mc^2$$

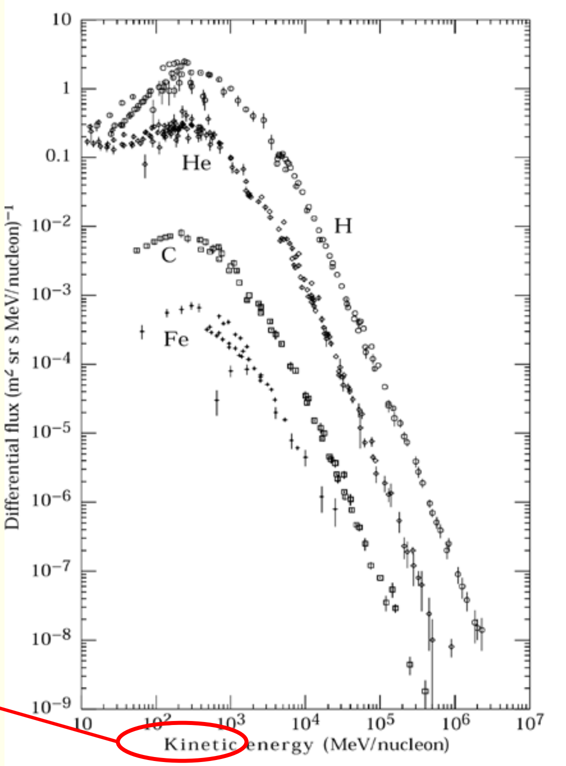
## Kinetic energy

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

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

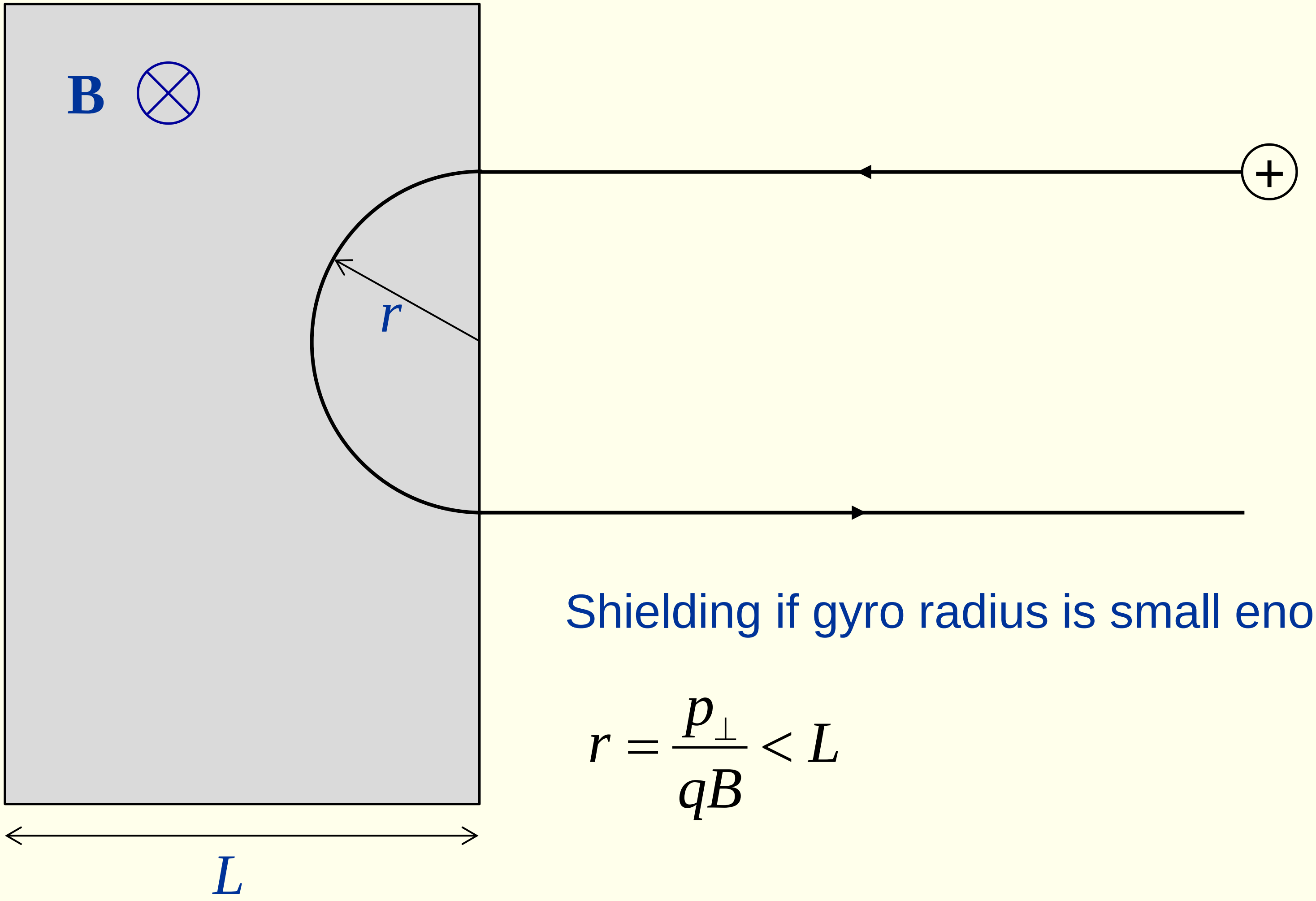
Non-relativistic
gyro radius

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

Relativistic
gyro radius

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

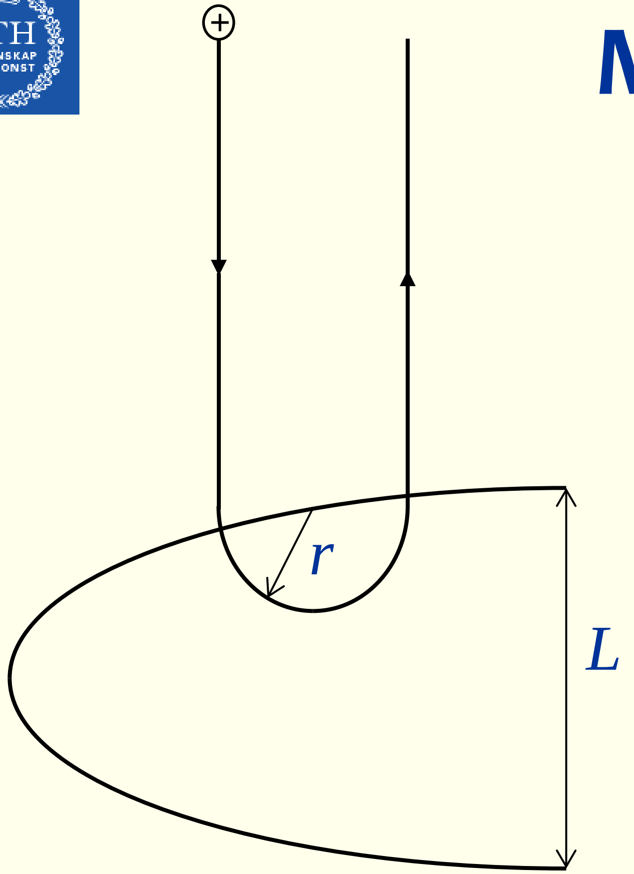
# Magnetic shielding



Shielding if gyro radius is small enough

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

# Magnetic shielding of magnetosphere



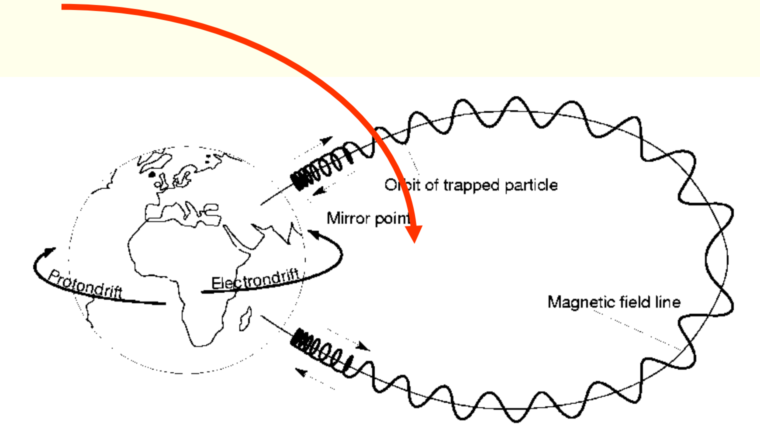
Shielding if

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

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

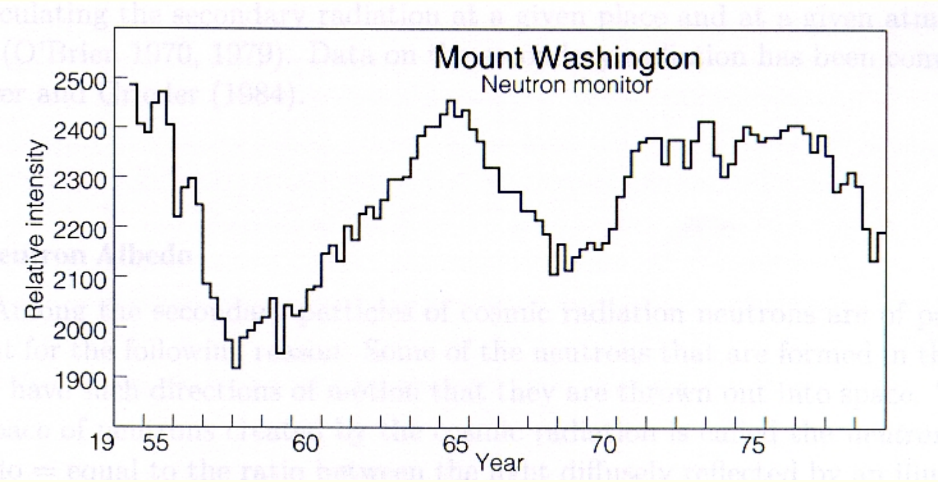
# Effect of magnetic field

- 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.



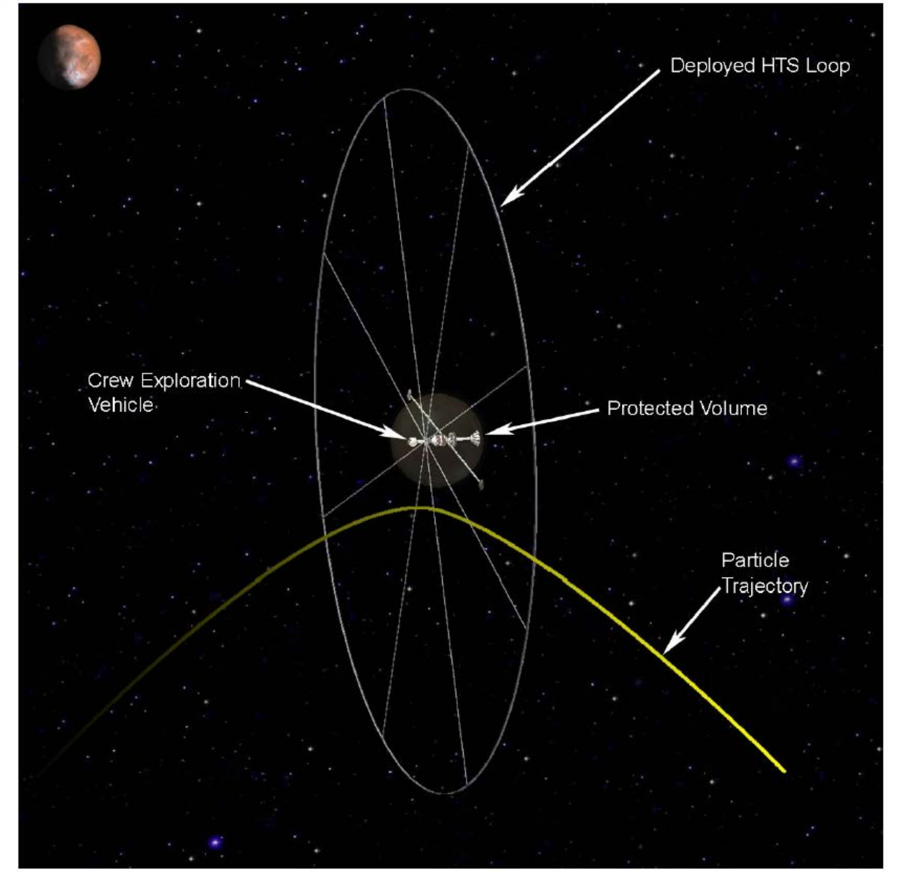
- Gyro radius is r = p/(eZB). Define rigidity:

$$P = pc/(eZ)$$



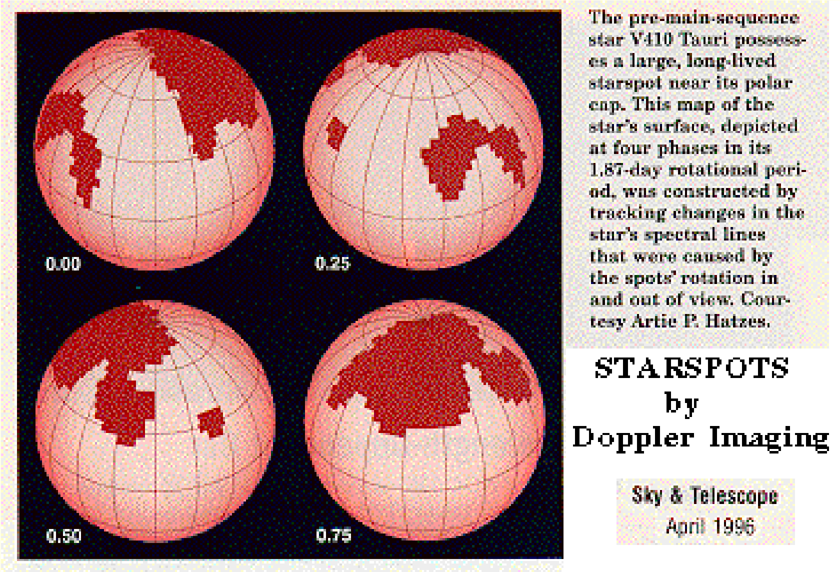
- Temporal variations:
  - –27 days (IMF, solar rotation)
  - –11 years (IMF, solar cycle)

# Artificial magnetic shielding of spacecraft



# Plasma outside of the solar system

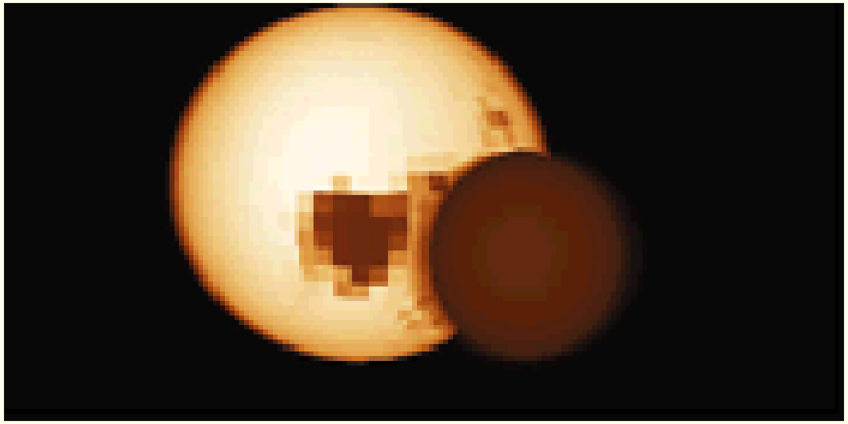
# Starspots



The pre-main-sequence star V410 Tauri possesses a large, long-lived starspot near its polar cap. This map of the star's surface, depicted at four phases in its 1.87-day rotational period, was constructed by tracking changes in the star's spectral lines that were caused by the spots' rotation in and out of view. Courtesy Artie P. Hatzes.

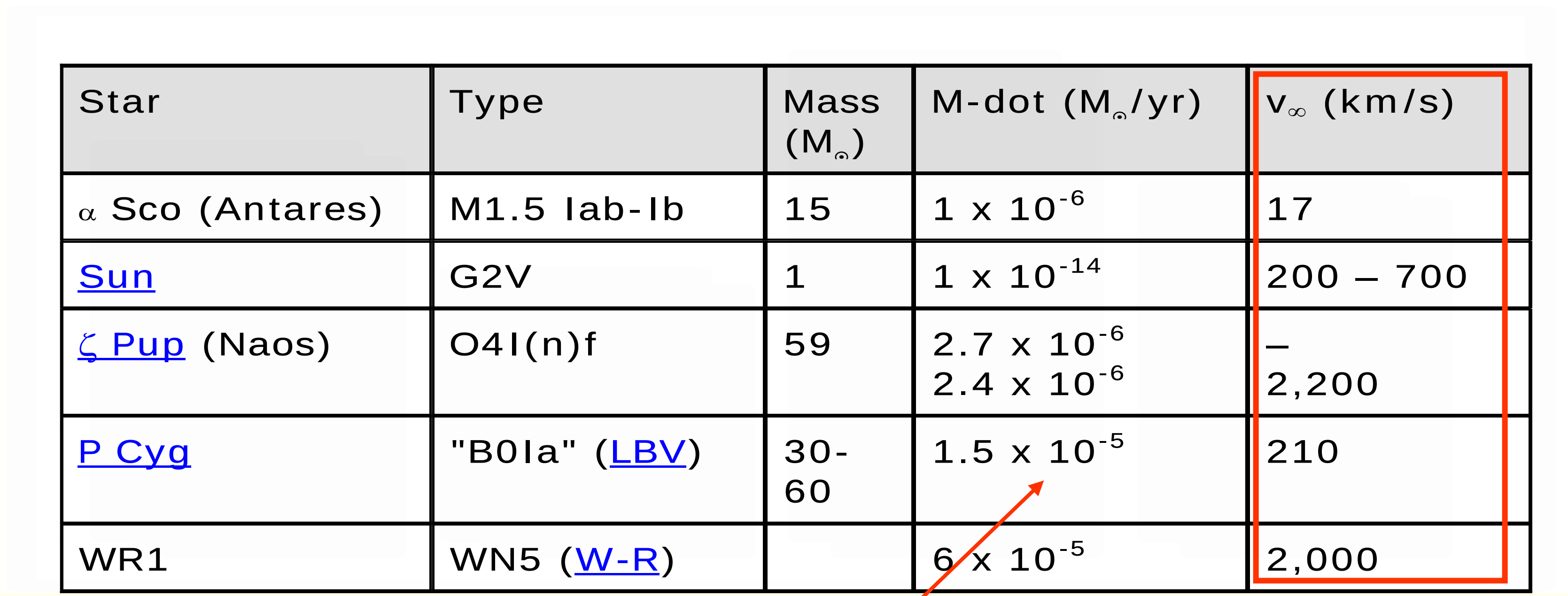
STARSPOTS
by
Doppler Imaging

Sky & Telescope
April 1996



Eclipse mapping, XY Ursae Majoris

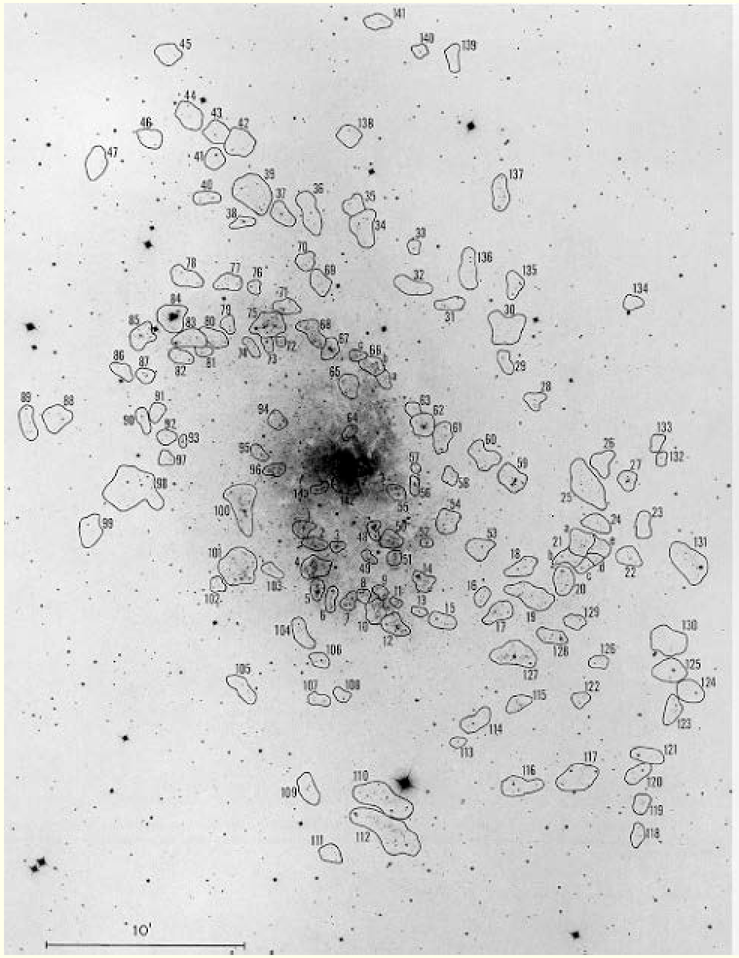
# Stellar winds



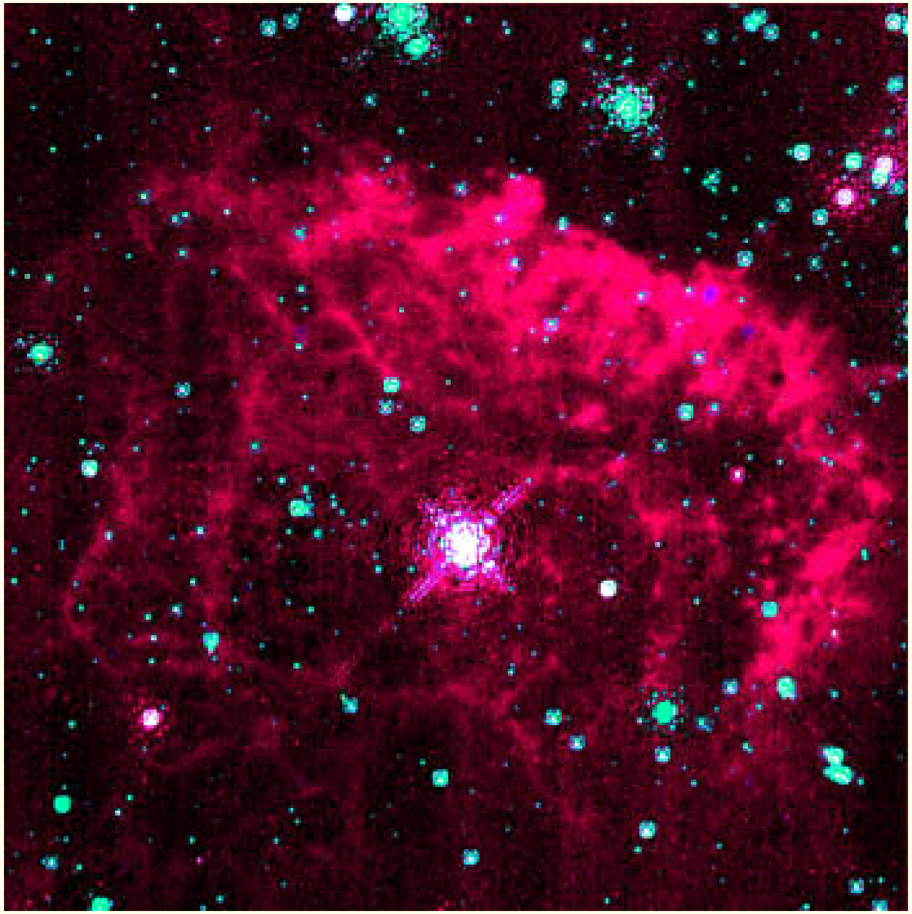
| Star | Type | Mass ($M_\odot$) | M-dot ($M_\odot$/yr) | $v_\infty$ (km/s) |
|---|---|---|---|---|
| $\alpha$ Sco (Antares) | M1.5 Iab-Ib | 15 | 1 x $10^{-6}$ | 17 |
| Sun | G2V | 1 | 1 x $10^{-14}$ | 200 – 700 |
| $\zeta$ Pup (Naos) | O4I(n)f | 59 | 2.7 x $10^{-6}$<br>2.4 x $10^{-6}$ | –<br>2,200 |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

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

# Stellar winds



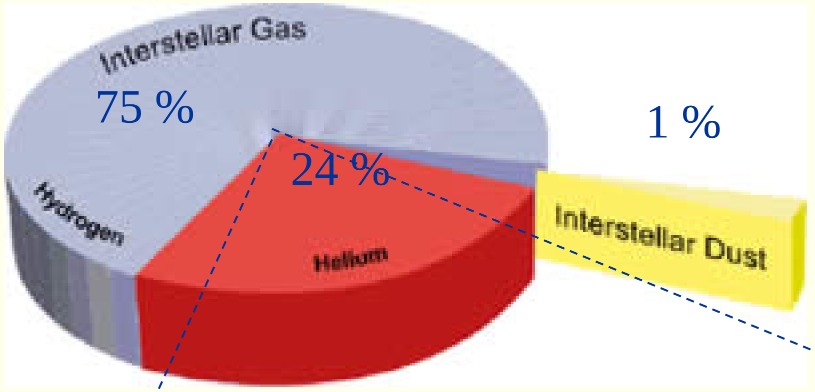
Doppler measurements of stellar winds



Pistol nebula – probably created by massive outflow of stellar plasma

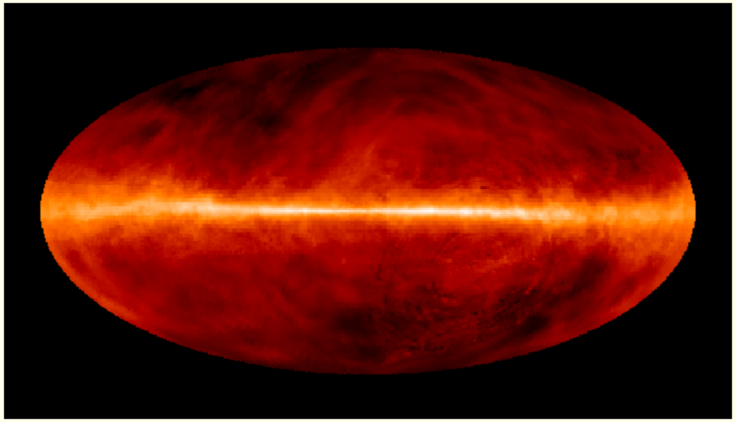
# Interstellar plasma

## Interstellar matter (10 % of Milky Way mass)



*Horsehead nebula*

## HI regions (neutral hydrogen)

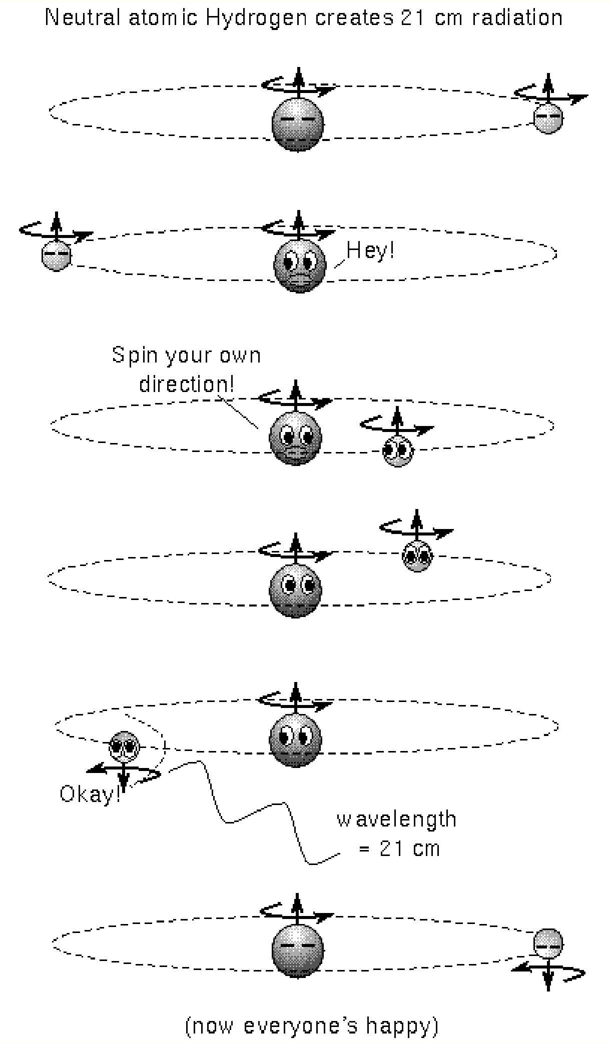


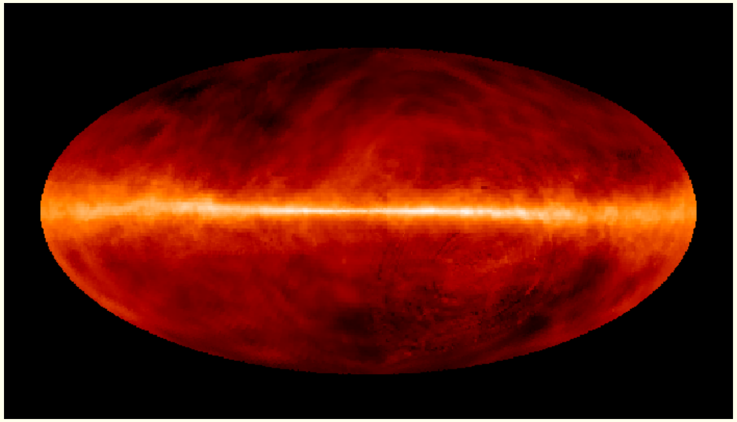
## HII regions
(emission nebulae)

*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*

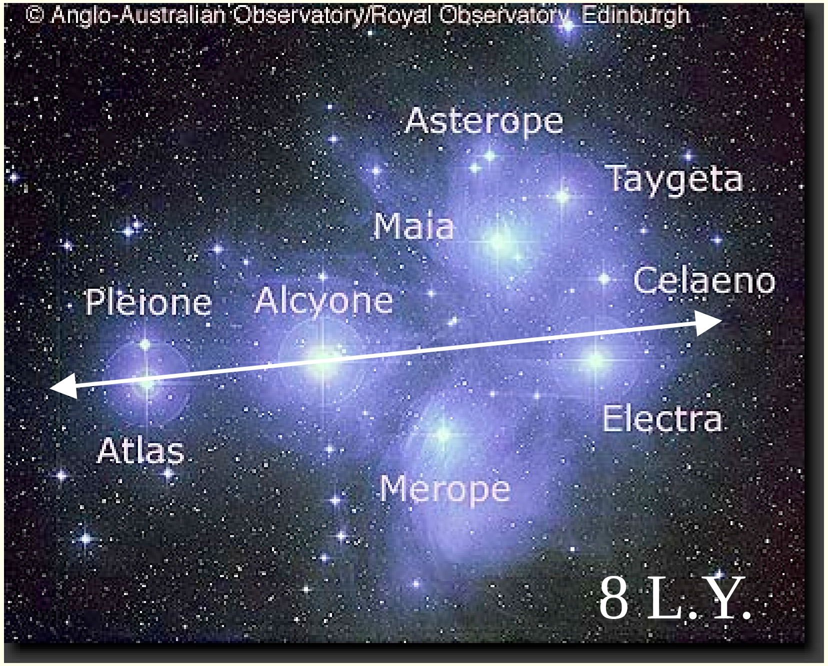




*Distribution of interstellar HI gas in the Northern sky, observed at the 21 cm radio spectral line.*

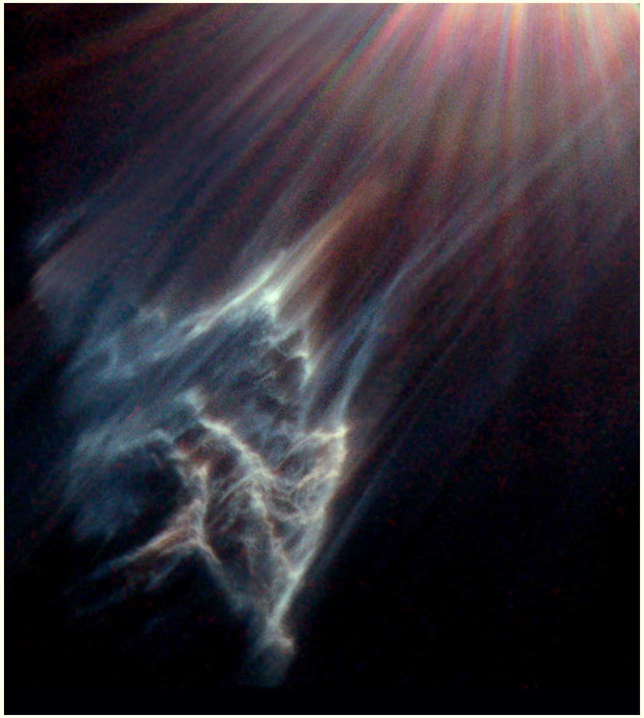
# H1 regions are reservoirs of material for star formation

Stars are formed by gravitational collaps of interstellar clouds



*Pleiades cluster*

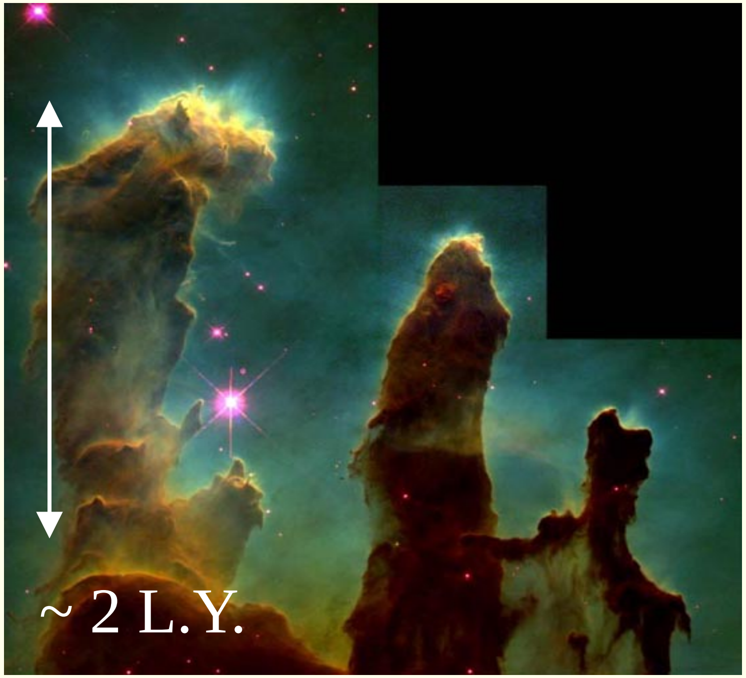
***Closeup of region close to Merope***



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.



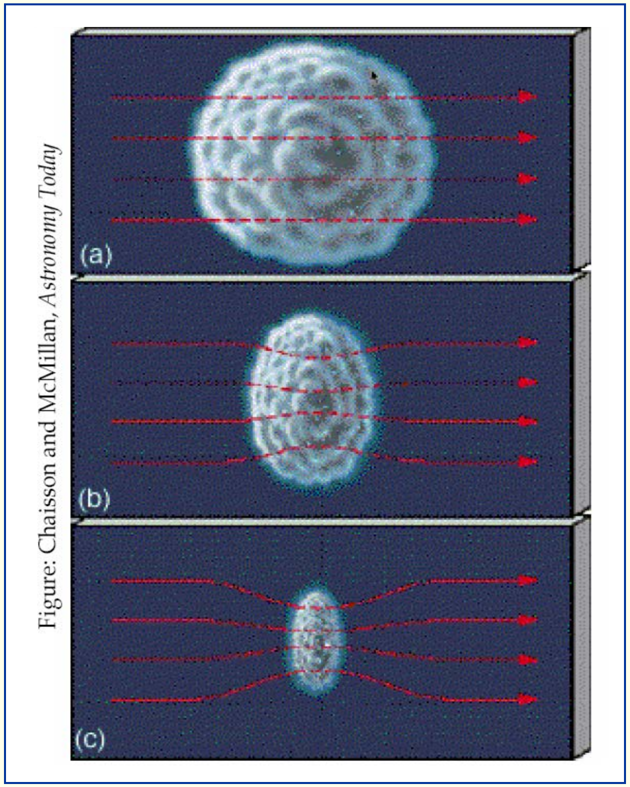
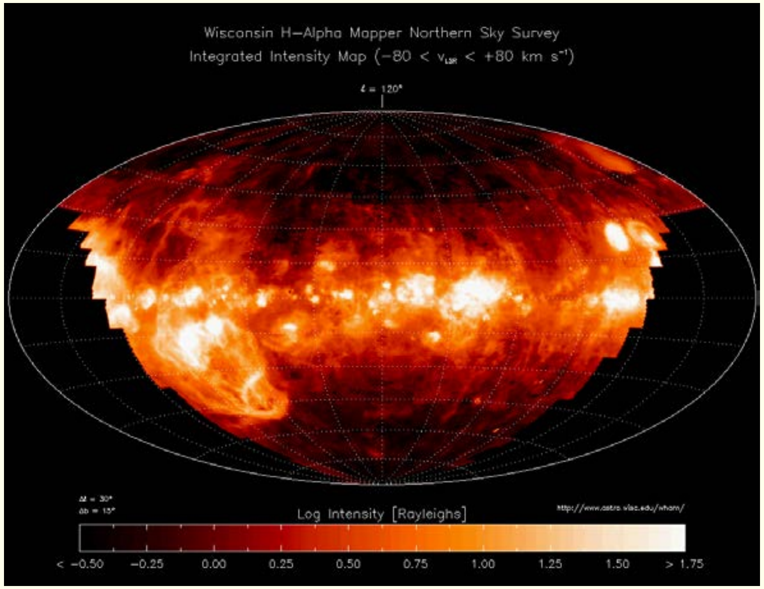


Figure: Chaisson and McMillan, *Astronomy Today*

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.

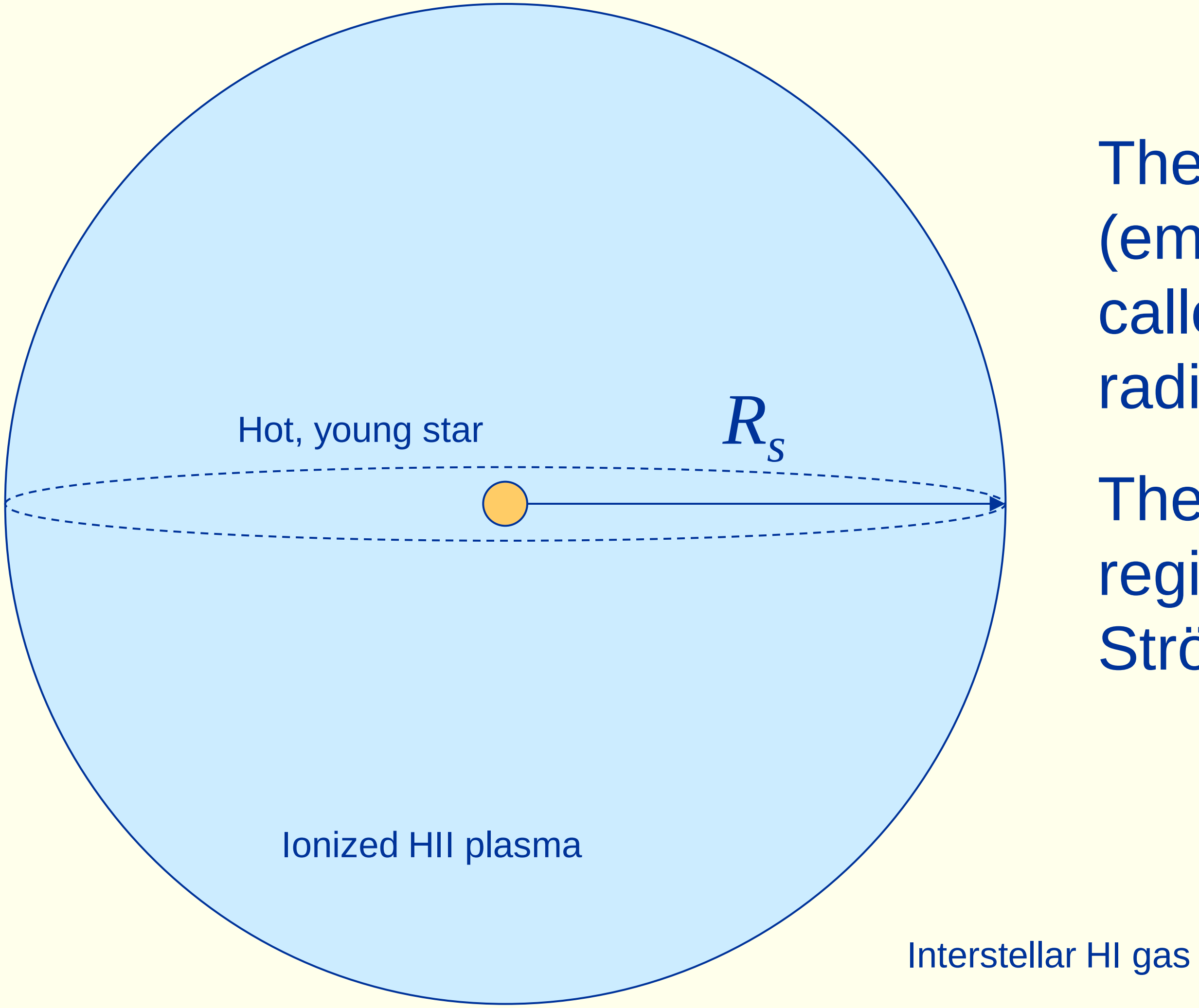
# Interstellar plasma – HII regions

- *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*

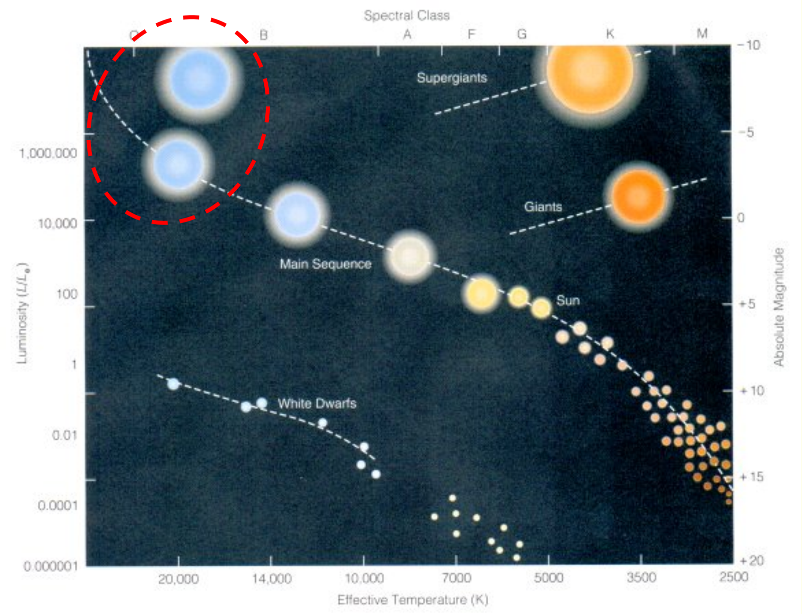
# Strömgren sphere



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

The modelled, spherical region is called a Strömgren sphere.

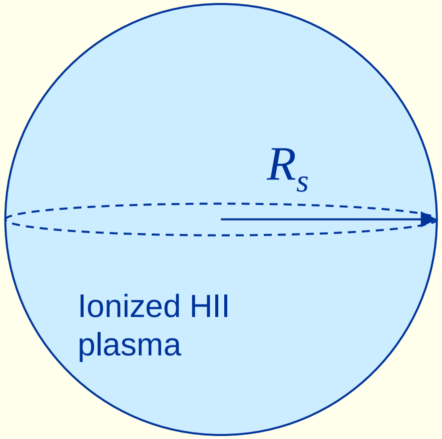
# Strömgren sphere



*Herzsprung-Russel diagram*

- A hot star (> 30 000 K) emits significant numbers of photons with energy > 13.6 eV (ionization energy for HI) $\leftrightarrow \lambda < 912$ 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



Interstellar HI plasma

- 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

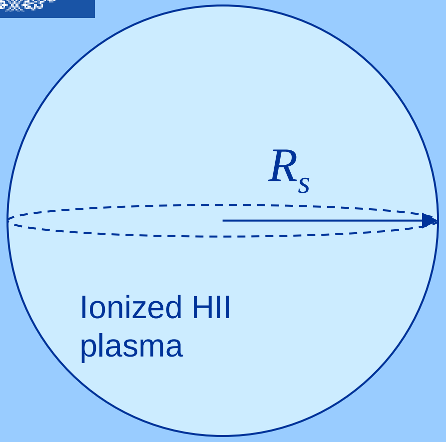
$$N_{UV} = rV = \alpha_H n_H^2 \frac{4\pi R_s^3}{3} \quad \Rightarrow$$

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

*Hotter star*

*Denser gas*

# 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 ~ $10^{49}$ s$^{-1}$. For a typical HII density of $n_H = 35$ cm$^{-3}$, what is the Strömgren radius in light years?

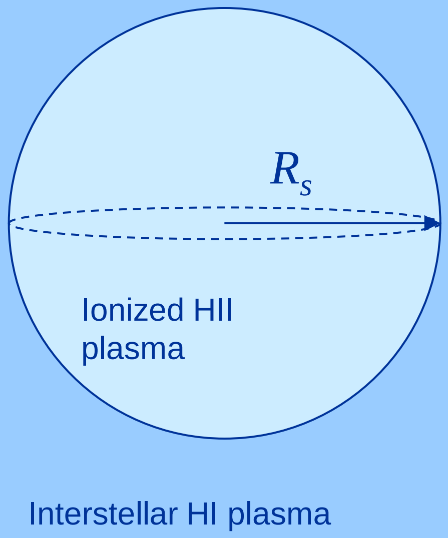
Interstellar HI plasma

$\alpha_H \approx 3\times10^{-13}$ 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 ~ $10^{49}$ $s^{-1}$. For a typical HI density of $n_H = 35$ $cm^{-3}$, we get

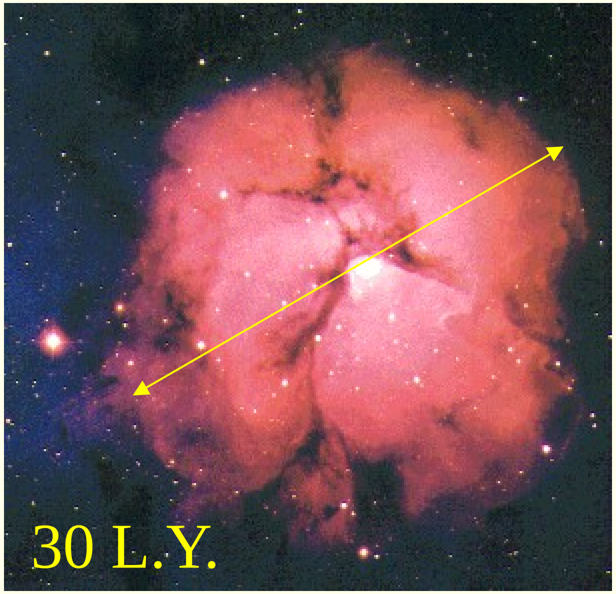
$\alpha_H \approx 3\times10^{-13}$ $cm^3s^{-1}$

Red

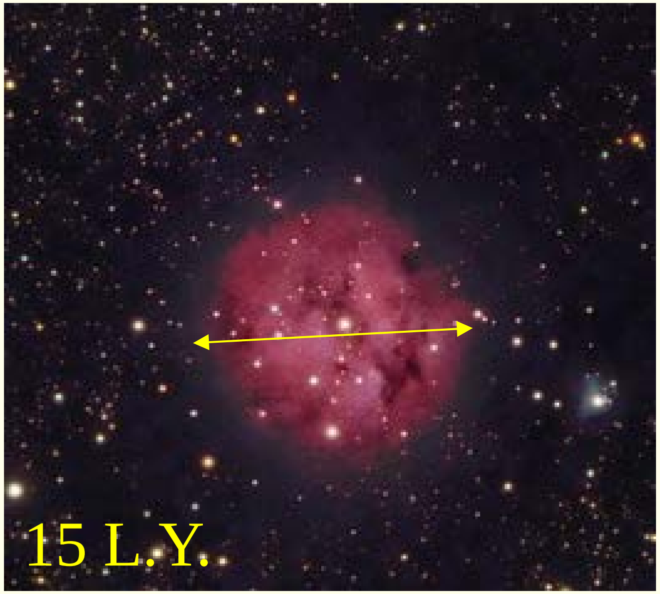
$$R_s = \left(\frac{3N_{UV}}{4\pi\alpha_H n_H^2}\right)^{1/3} = \left(\frac{3\cdot10^{49}}{4\pi\cdot3\cdot10^{-19}\cdot\left(3.5\cdot10^{7}\right)^{2}}\right)^{1/3} =$$

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

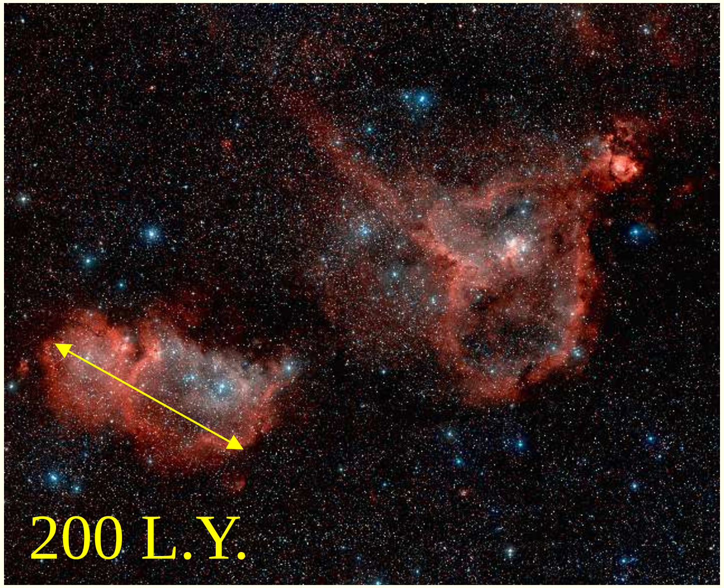
# Emission nebulae



*Triffid nebula (Messier 20)*



*IC5146*

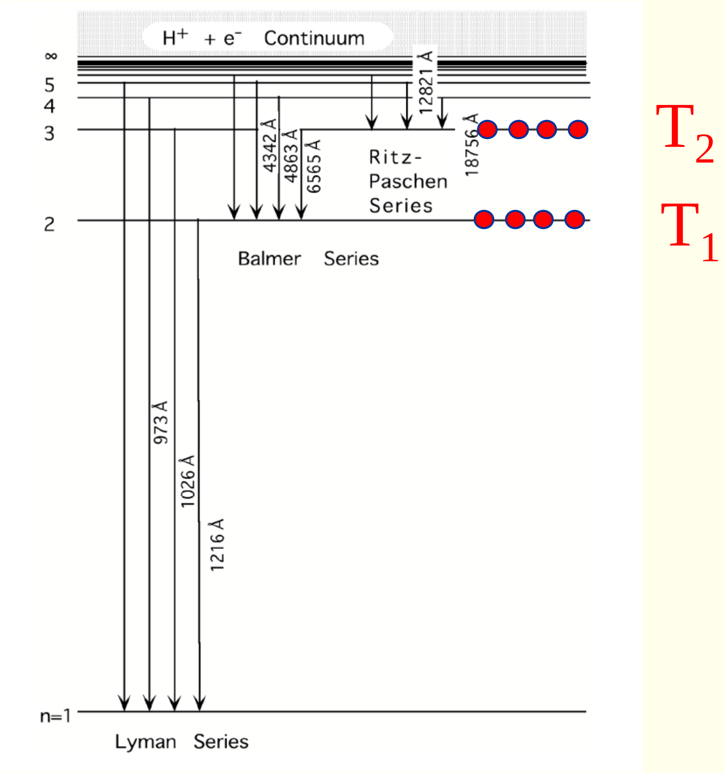


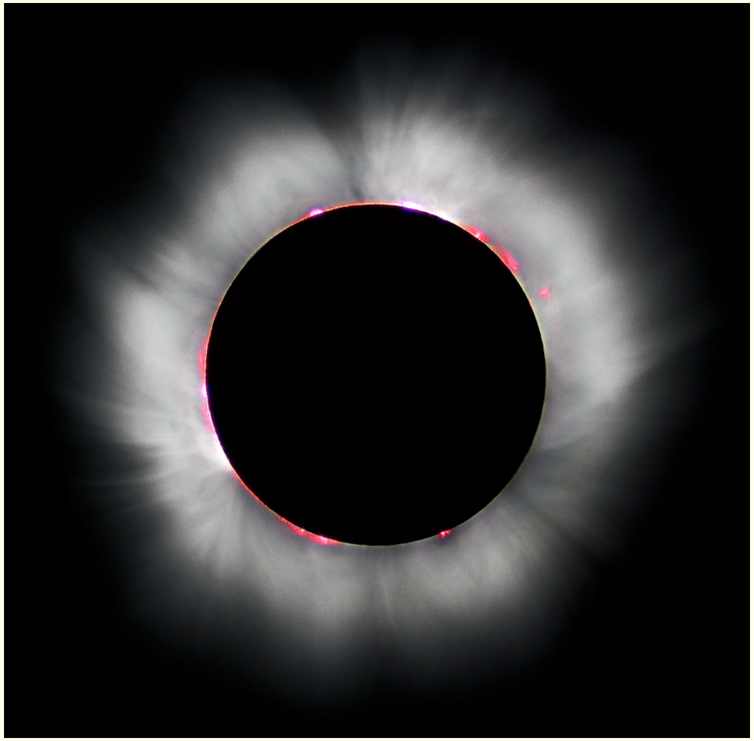
*Heart and Soul nebuale (IC1805, IC1848)*

- 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

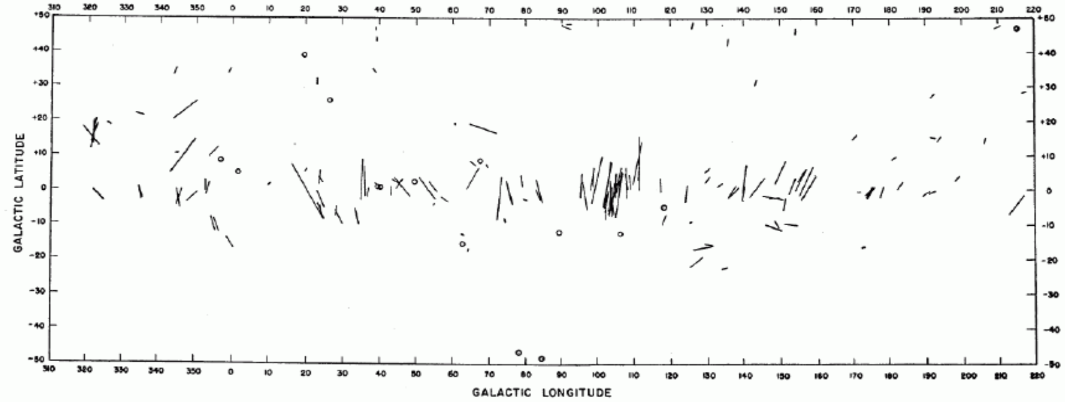


Figure 1. Vector diagram showing polarization of individual stars.

Hall & Mikesell, 1949, AJ, 54, 187

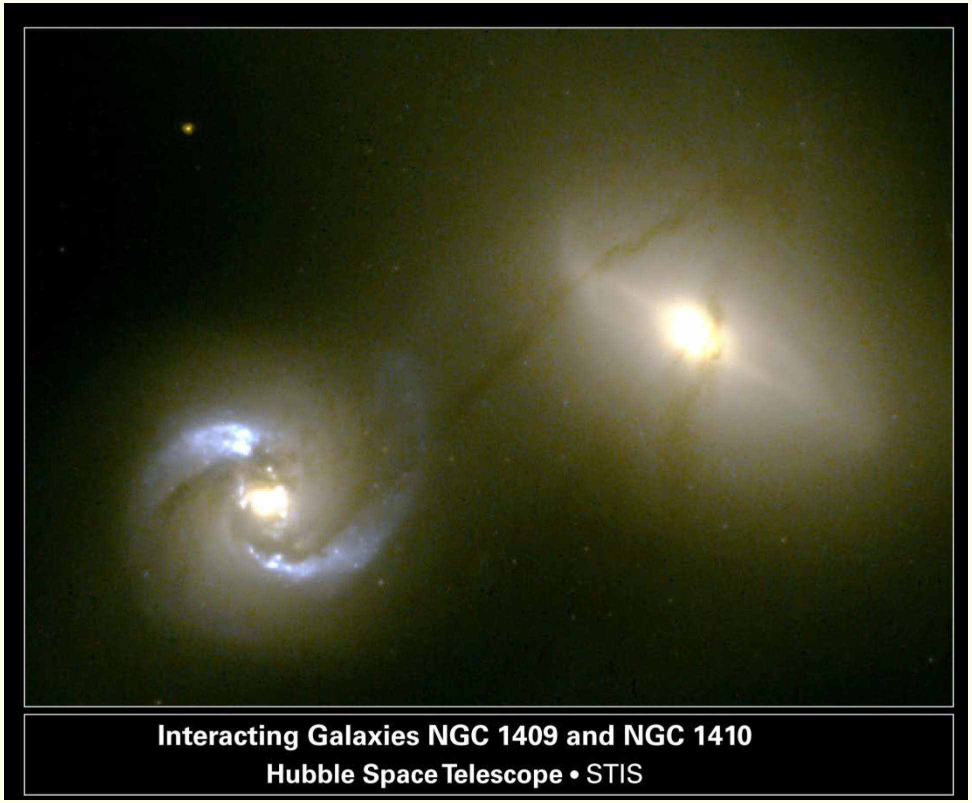
J

HI regions: ~ 0.1 nT

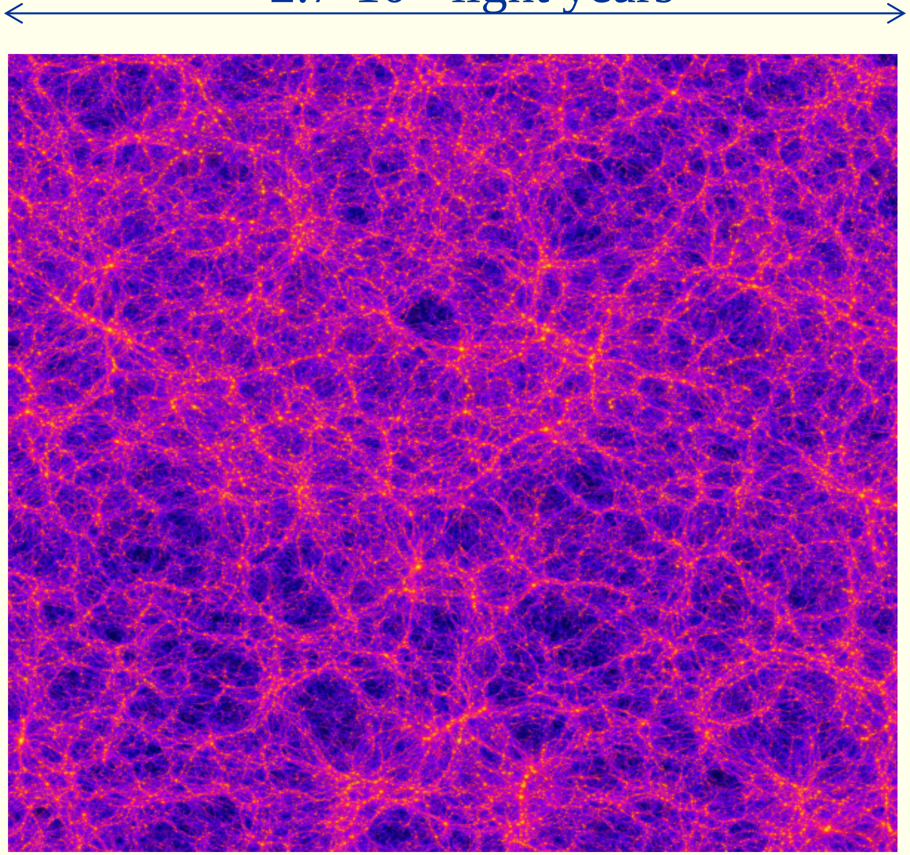
HII regions: ~1 nT

*Magnetic field important also in the interstellar medium!*

# Intergalactic matter



2.7´$10^9$ light years



Computer simulation of intergalactic mass distribution

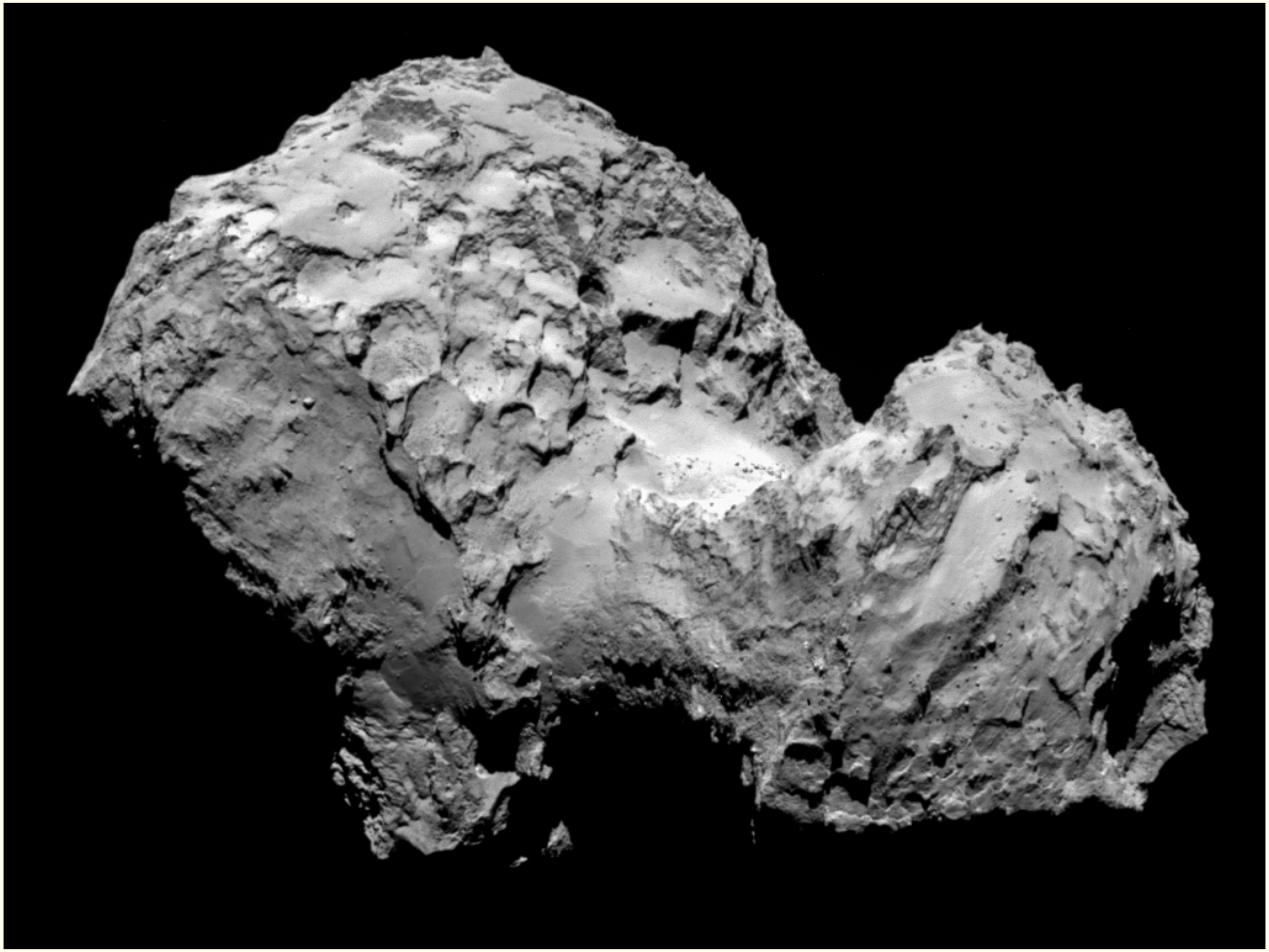
# Intergalactic plasma

- 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: $B \sim 10^{-2}$ nT

# Space research today
# and
# Space research in Sweden

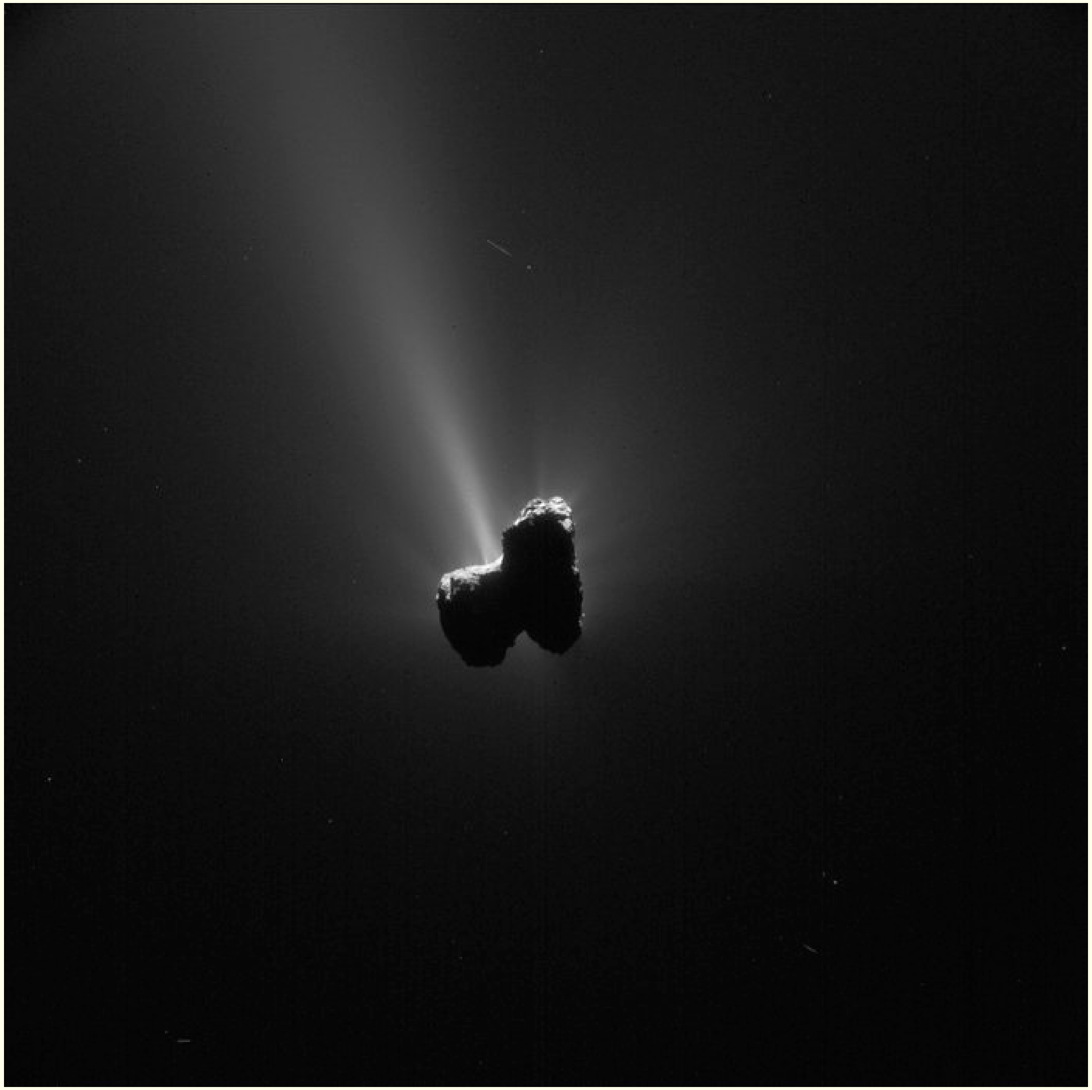
# The Rosetta mission to comet 67P/Churiumov-Gerasimenko

# The Rosetta mission to comet 67P



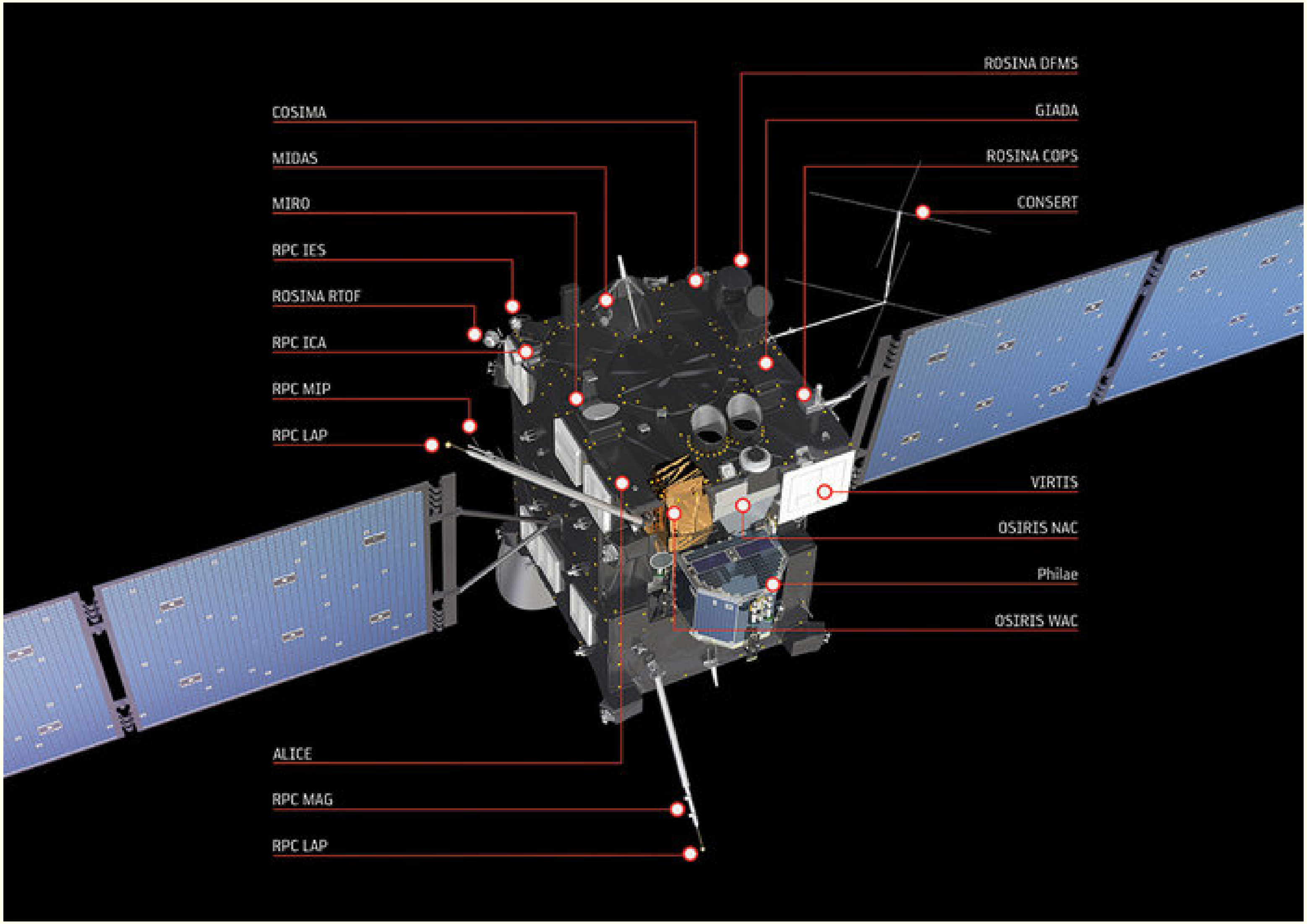
*3 August 2014*

# The Rosetta mission to comet 67P

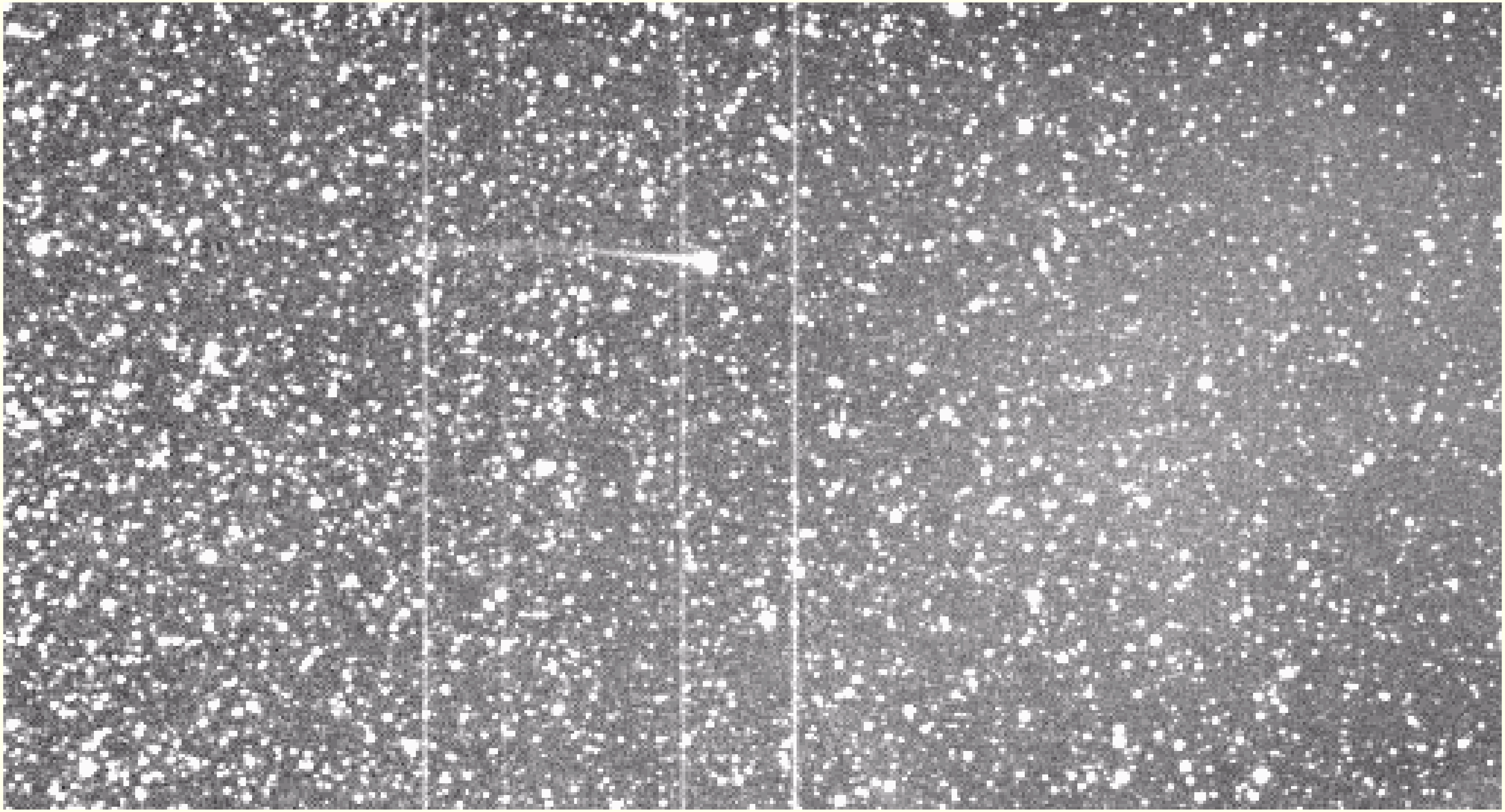


*11 September 2015*

# The Rosetta mission to comet 67P

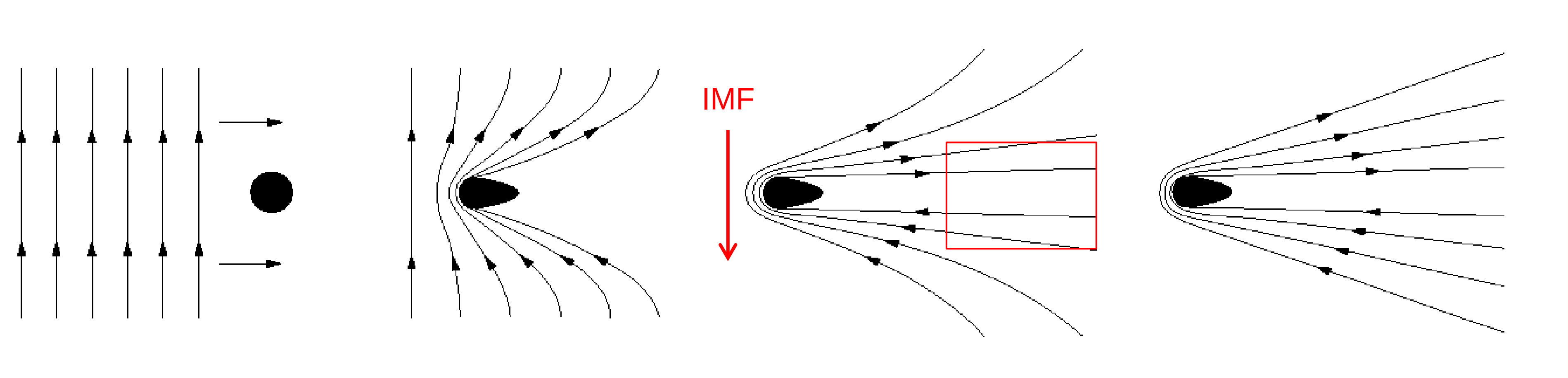


# Tail reconnection events?



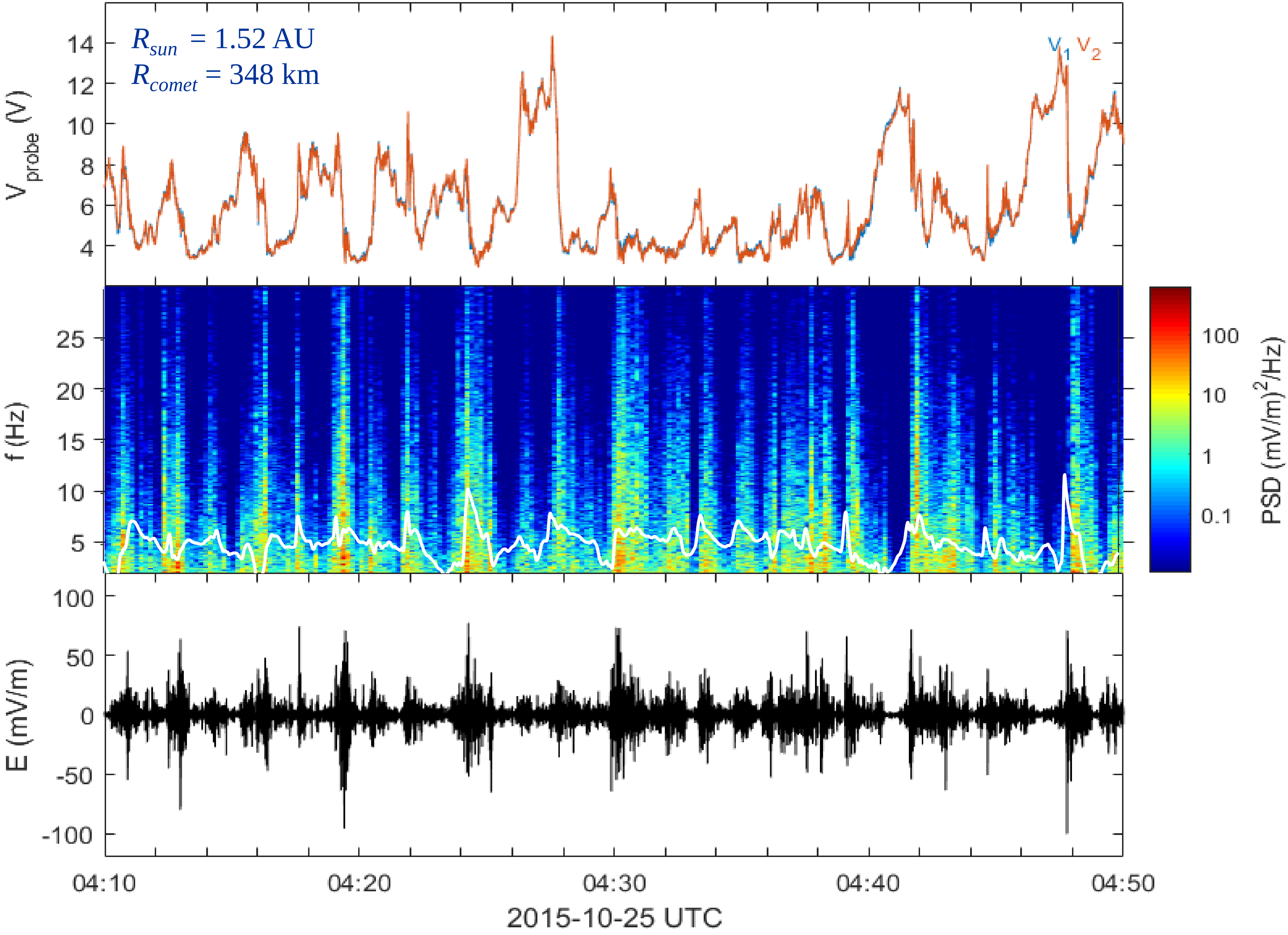
Comet Encke, STEREO-A

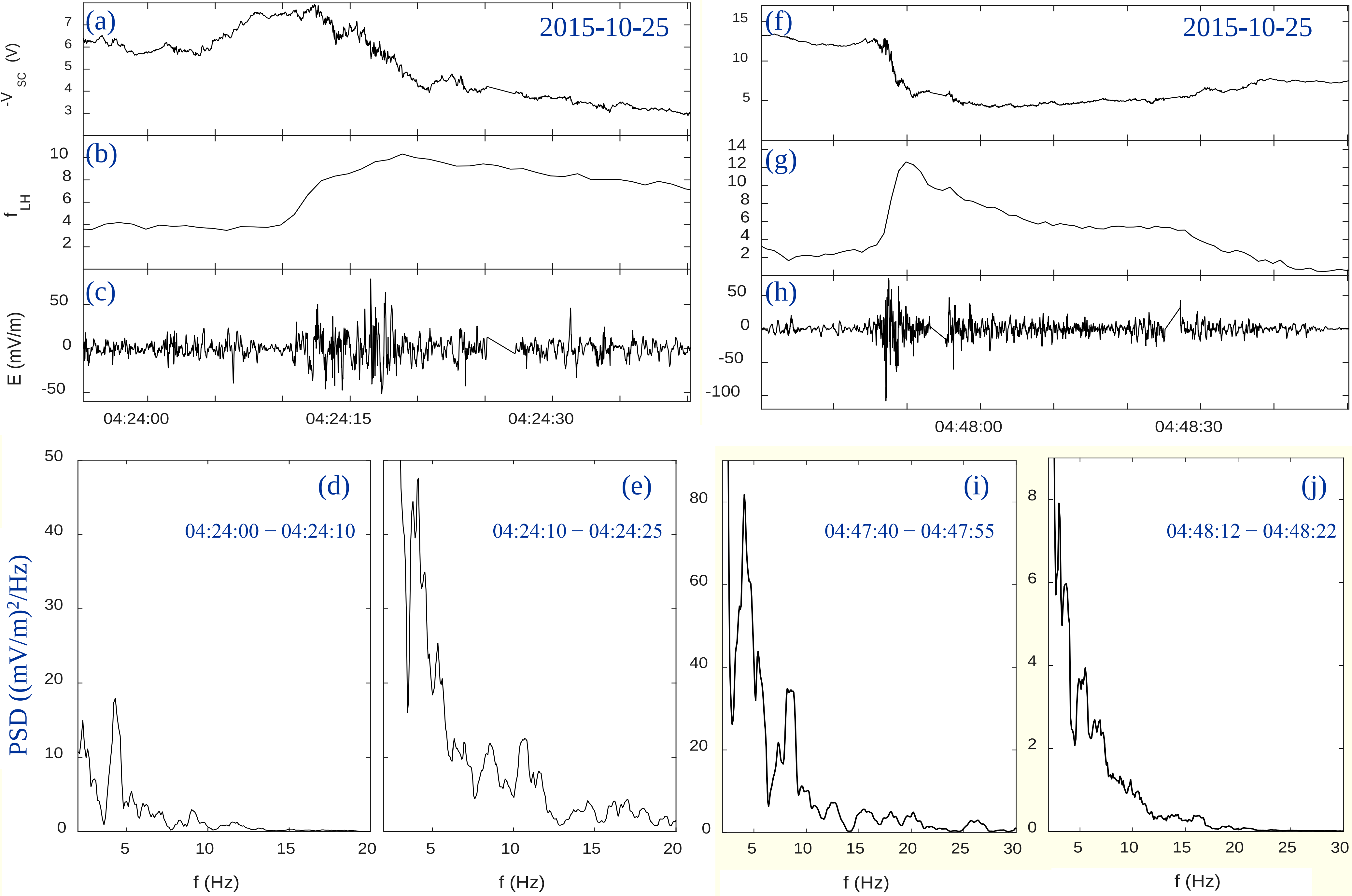
# Comets, induced magnetotail



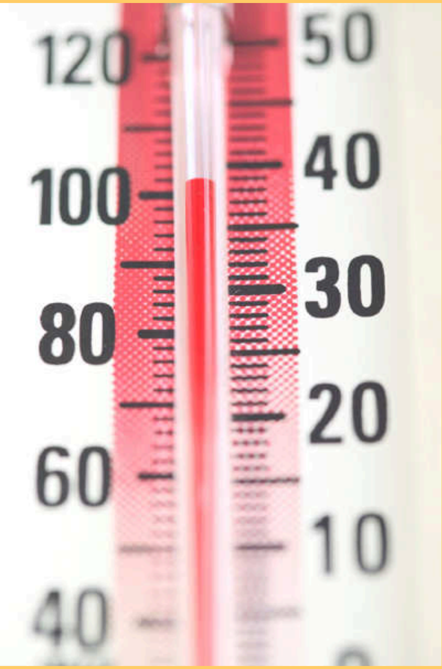
Where does reconnection take place?

# Electric field measurements from Rosetta

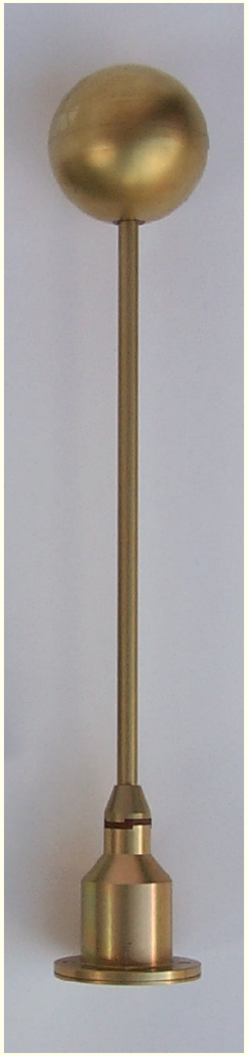

$R_{sun}$ = 1.52 AU
$R_{comet}$ = 348 km
$V_1$ $V_2$
$V_{probe}$ (V)
14
12
10
8
6
4
f (Hz)
25
20
15
10
5
PSD $(mV/m)^2/Hz$
100
10
1
0.1
E (mV/m)
100
50
0
-50
-100
04:10
04:20
04:30
04:40
04:50
2015-10-25 UTC


(a)
2015-10-25
-V_SC (V)
7
6
5
4
3
(b)
f_LH
10
8
6
4
2
(c)
E (mV/m)
50
0
-50
04:24:00
04:24:15
04:24:30
(f)
2015-10-25
15
10
5
(g)
14
12
10
8
6
4
2
(h)
50
0
-50
-100
04:48:00
04:48:30
PSD ((mV/m)²/Hz)
(d)
04:24:00 − 04:24:10
50
40
30
20
10
0
5
10
15
20
f (Hz)
(e)
04:24:10 − 04:24:25
5
10
15
20
f (Hz)
(i)
04:47:40 − 04:47:55
80
60
40
20
0
5
10
15
20
25
30
f (Hz)
(j)
04:48:12 − 04:48:22
8
6
4
2
0
5
10
15
20
25
30
f (Hz)

# How can we measure temperatures and densities in space?



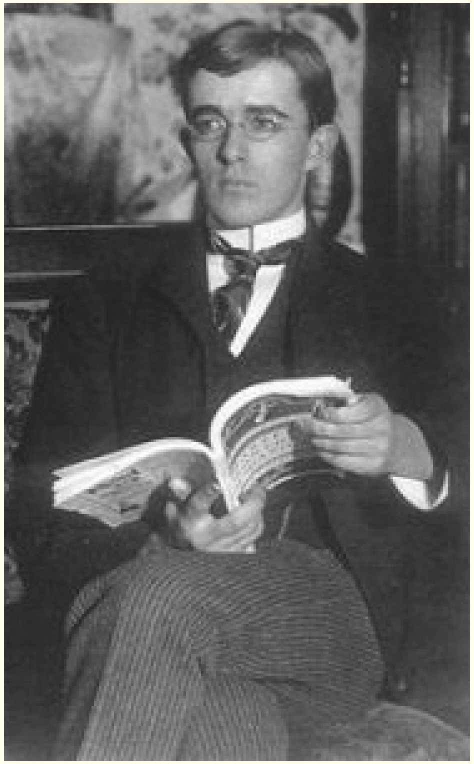
# Langmuir probe



Langmuir probe from the Rosetta spacecraft

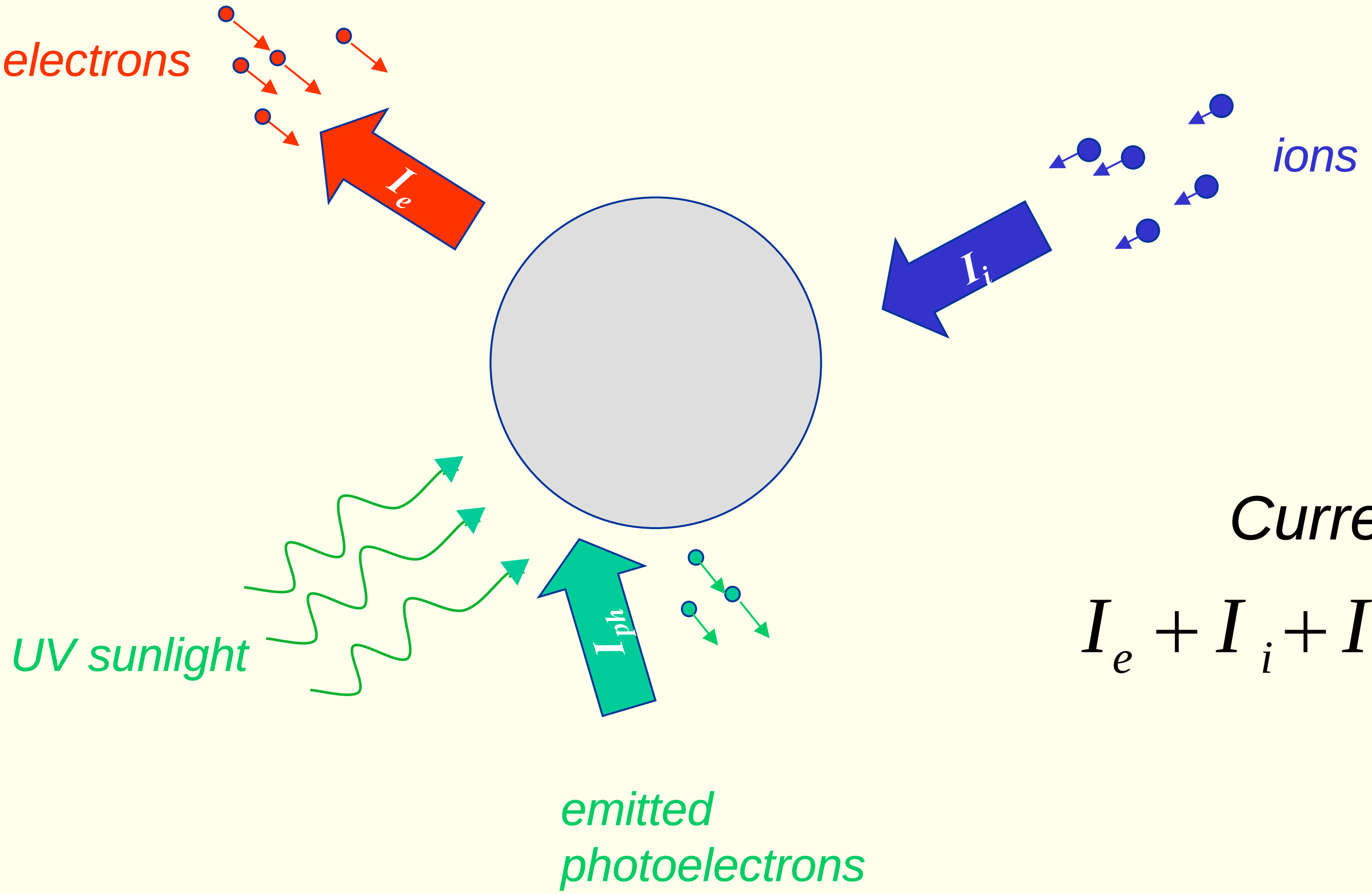
Rosetta spacecraft, launched 2004. Now placed in orbit around the comet 67/P Churyumov-Gerasimenko.

# Irving Langmuir



- 1881-1957
- American chemist and physicist
- Nobel prize in 1932 in chemistry
- Worked with gas discharges in vacuum tubes

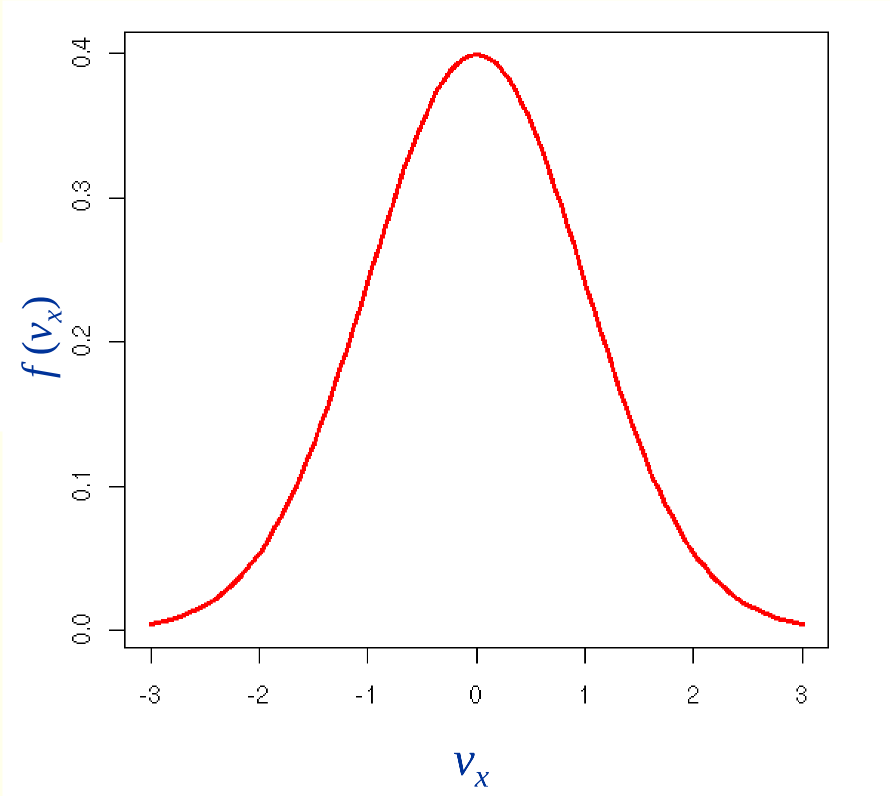
# Electrical potential of metal sphere in a plasma



*Current balance:*

$$I_e + I_i + I_{ph} \approx I_e + I_{ph} = 0$$

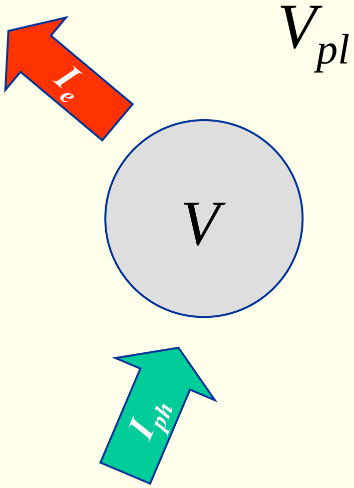
# Maxwellian distribution of velocities in a gas



$$f\left(v_x\right) = Ce^{\frac{-mv_x^2}{2k_B T}}$$

$$C = n\sqrt{\frac{m}{2\pi k_B T}}$$

# Floating potential



$I$ positive into the probe

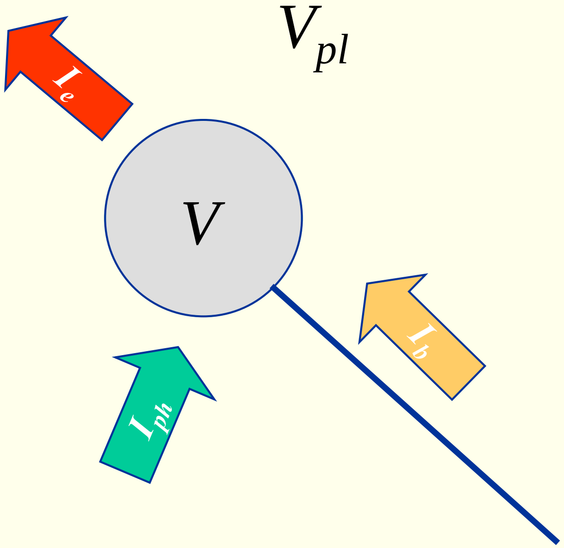
$$I_e + I_{ph} = 0$$

$$I_e = -An_e e\sqrt{\frac{k_BT}{2\pi m_e}} \cdot e^{\frac{e(V - V_{pl})}{k_BT}} = -I_{ph}$$

$$\Rightarrow$$

$$V - V_{pl} = \frac{k_BT}{e}\ln\left(\frac{I_{ph}}{An_e e}\sqrt{\frac{2\pi m_e}{k_BT}}\right)$$

# Electrical potential of metal sphere in a plasma with bias current



$I$ positive into the probe

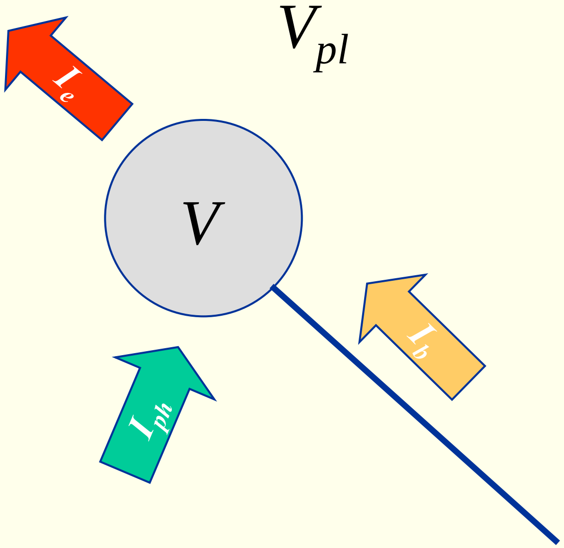
$$I_e + I_{ph} + I_b = 0$$

$$I_e = -An_e e\sqrt{\frac{k_B T_e}{2\pi m_e}} \cdot e^{\frac{e(V-V_{pl})}{k_B T_e}} = -I_{ph} - I_b$$

$$\Rightarrow$$

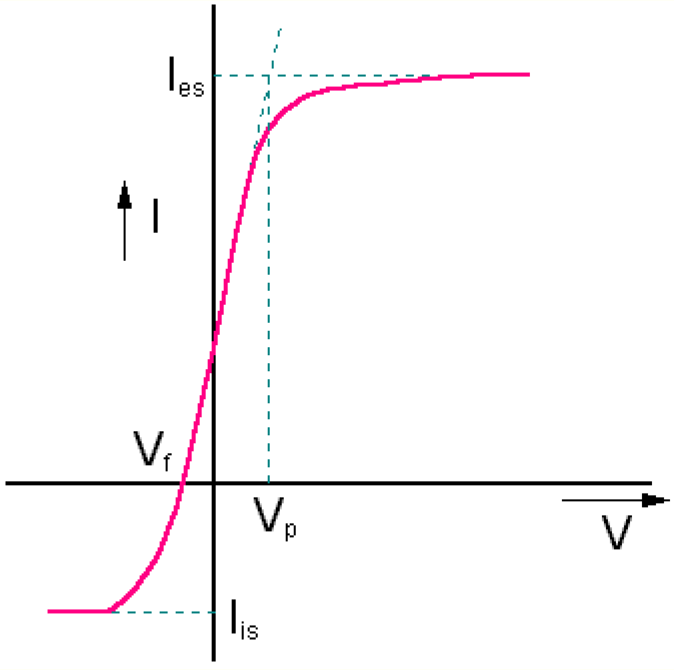
$$V - V_{pl} = \frac{k_B T_e}{e} \ln\left(\frac{I_{ph} + I_b}{An_e e}\sqrt{\frac{2\pi m_e}{k_B T_e}}\right)$$

# Langmuir probe

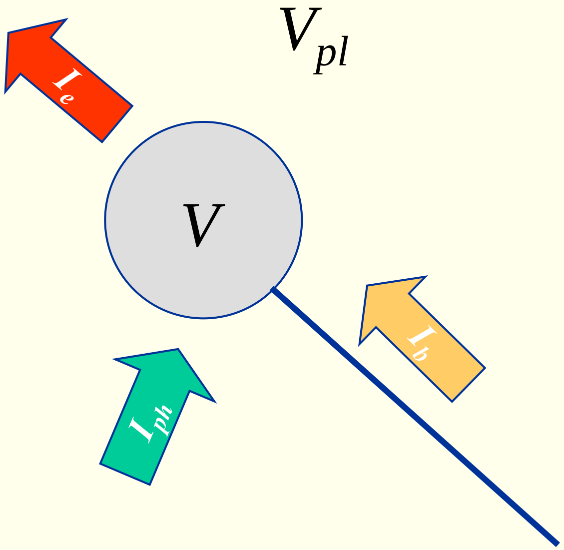


*I* positive into the probe

$$V - V_{pl} = \frac{k_B T_e}{e} \ln\left( \frac{I_{ph} + I_b}{A n_e e} \sqrt{\frac{2\pi m_e}{k_B T_e}} \right)$$



# Langmuir probe



$I$ positive into the probe

$$I_b - I_{ph} = An_e e\sqrt{\frac{k_B T_e}{2\pi m_e}} \cdot e^{\frac{e(V-V_{pl})}{k_B T_e}}$$

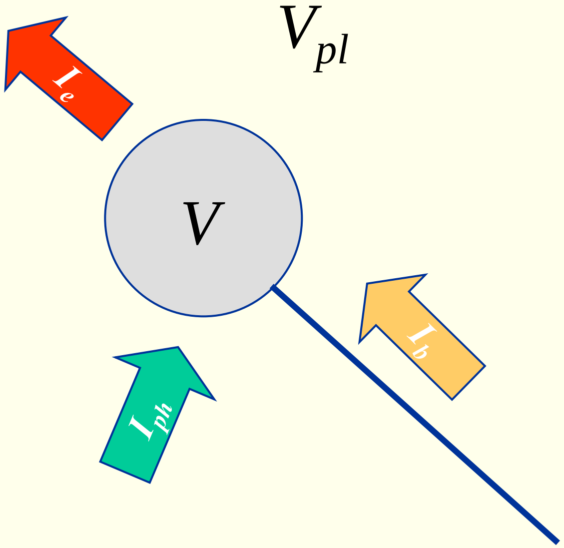
$$\Rightarrow$$

$$\ln\left(I_b - I_{ph}\right) = \ln\left( An_e e\sqrt{\frac{k_B T_e}{2\pi m_e}} \cdot e^{\frac{e(V-V_{pl})}{k_B T_e}} \right)$$

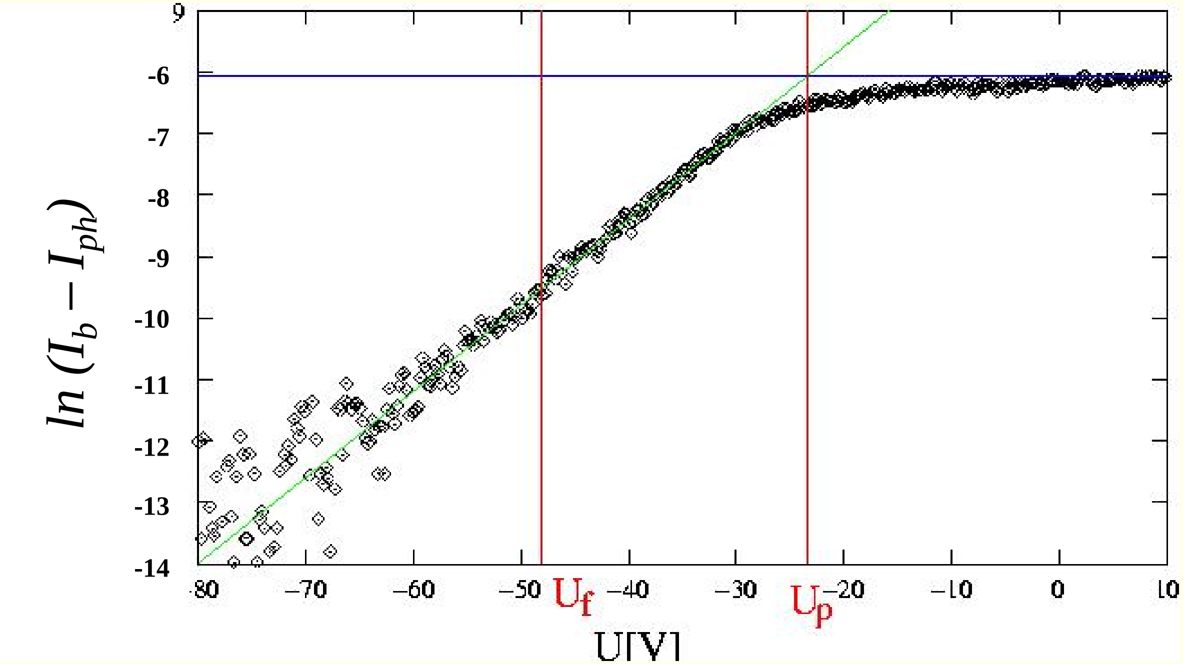
$$= \ln\left( An_e e\sqrt{\frac{k_B T_e}{2\pi m_e}} \right) + \ln\left( e^{\frac{e(V-V_{pl})}{k_B T_e}} \right) = C + \frac{e(V - V_{pl})}{k_B T_e}$$

# Langmuir probe

$$\ln\left(I_b - I_{ph}\right) = C + \frac{e(V - V_{pl})}{k_B T_e}$$



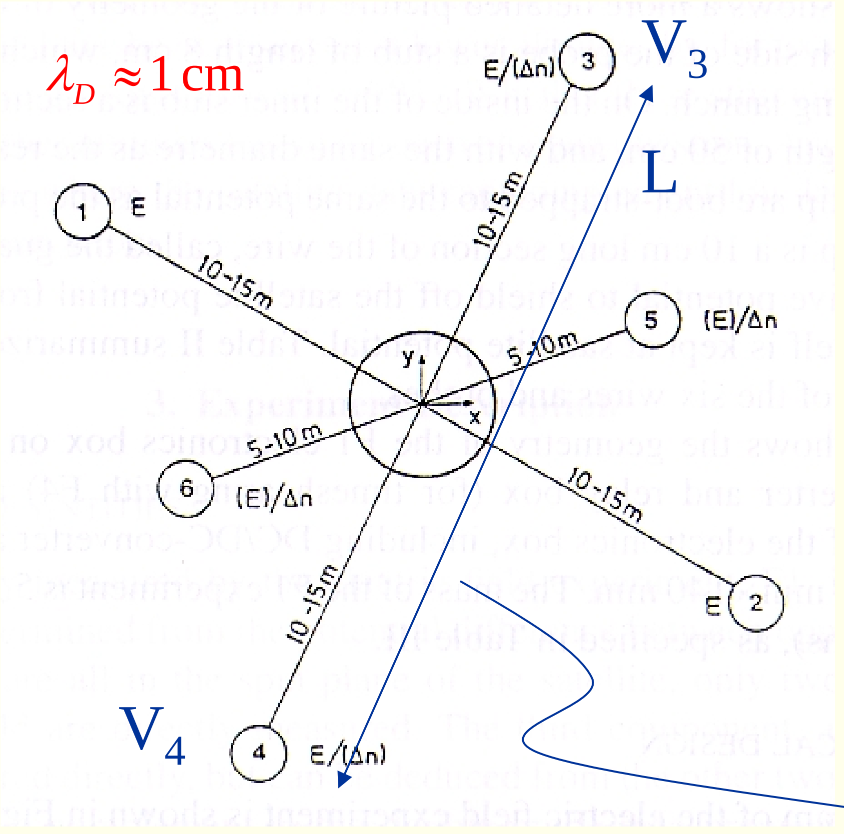
*I* positive into the probe



*The slope gives you* $\frac{k_B T_e}{e}$ *which is temperature in eV*

# Measurement of E-field in space plasmas

$\lambda_D \approx 1\,\mathrm{cm}$



$$A n_e e \sqrt{\frac{k_B T}{2\pi m_e}} \cdot e^{\frac{eV}{k_B T}} + I_{ph} = 0$$

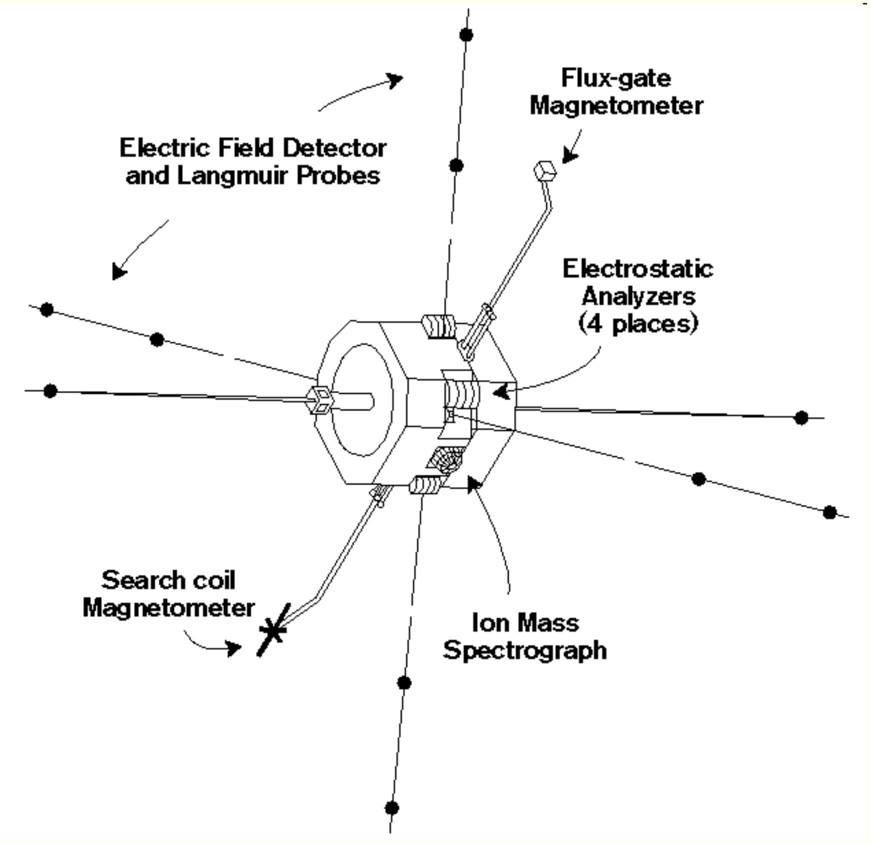
Potential between plasma and probe

Since the potential between the plasma and each probe is constant if the probes are identical, the E-field can be measured by taking the potential difference between the probes and divide by the probe separation length.

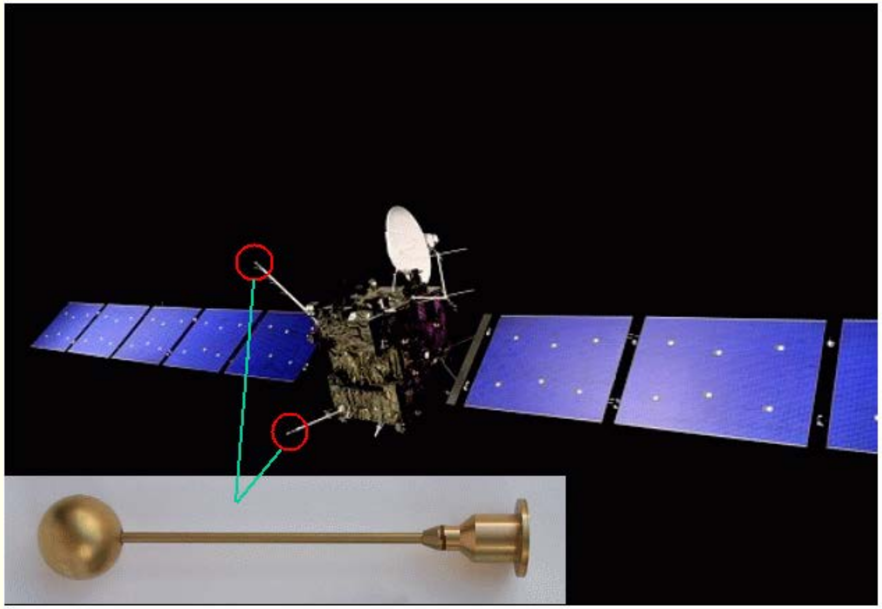
$V_3 = (V_{probe,3}-V_{plasma})$

$(V_{probe\ 4}-V_{probe\ 3})/L = (V_4+V_{plasma\ 4}-V_3-V_{plasma\ 3})/L = (V_{plasma\ 4}-V_{plasma\ 3})/L = E$

# Langmuir probe and electric field probes on a spaceraft



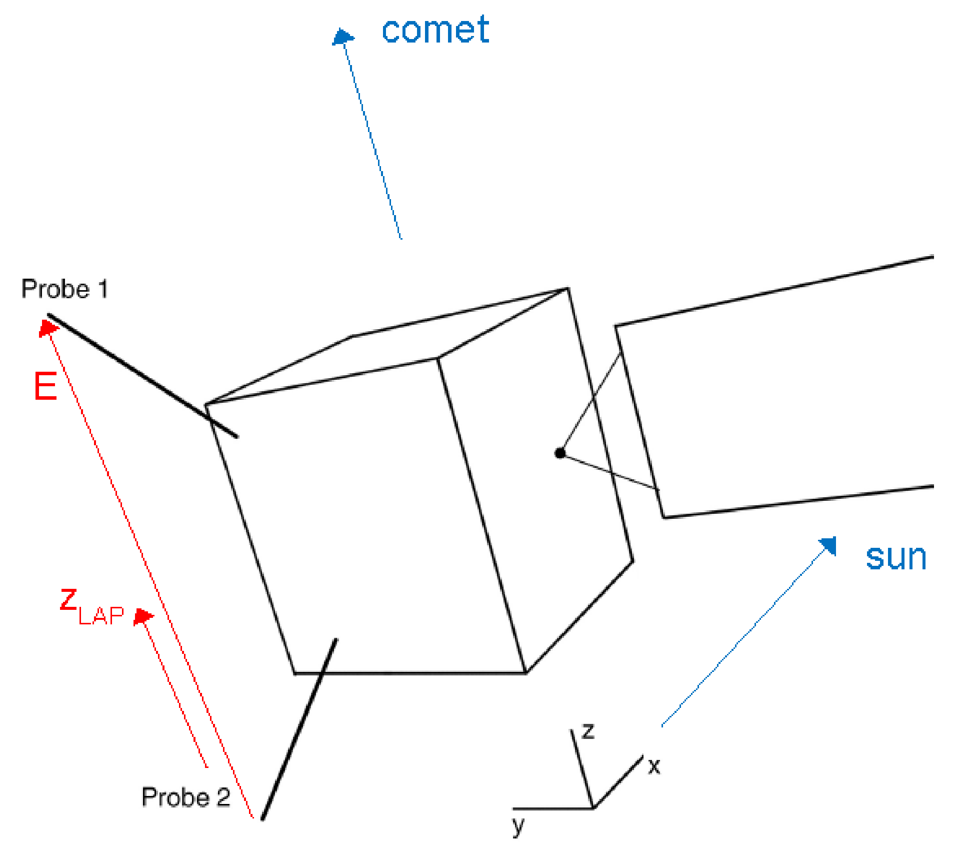
FAST

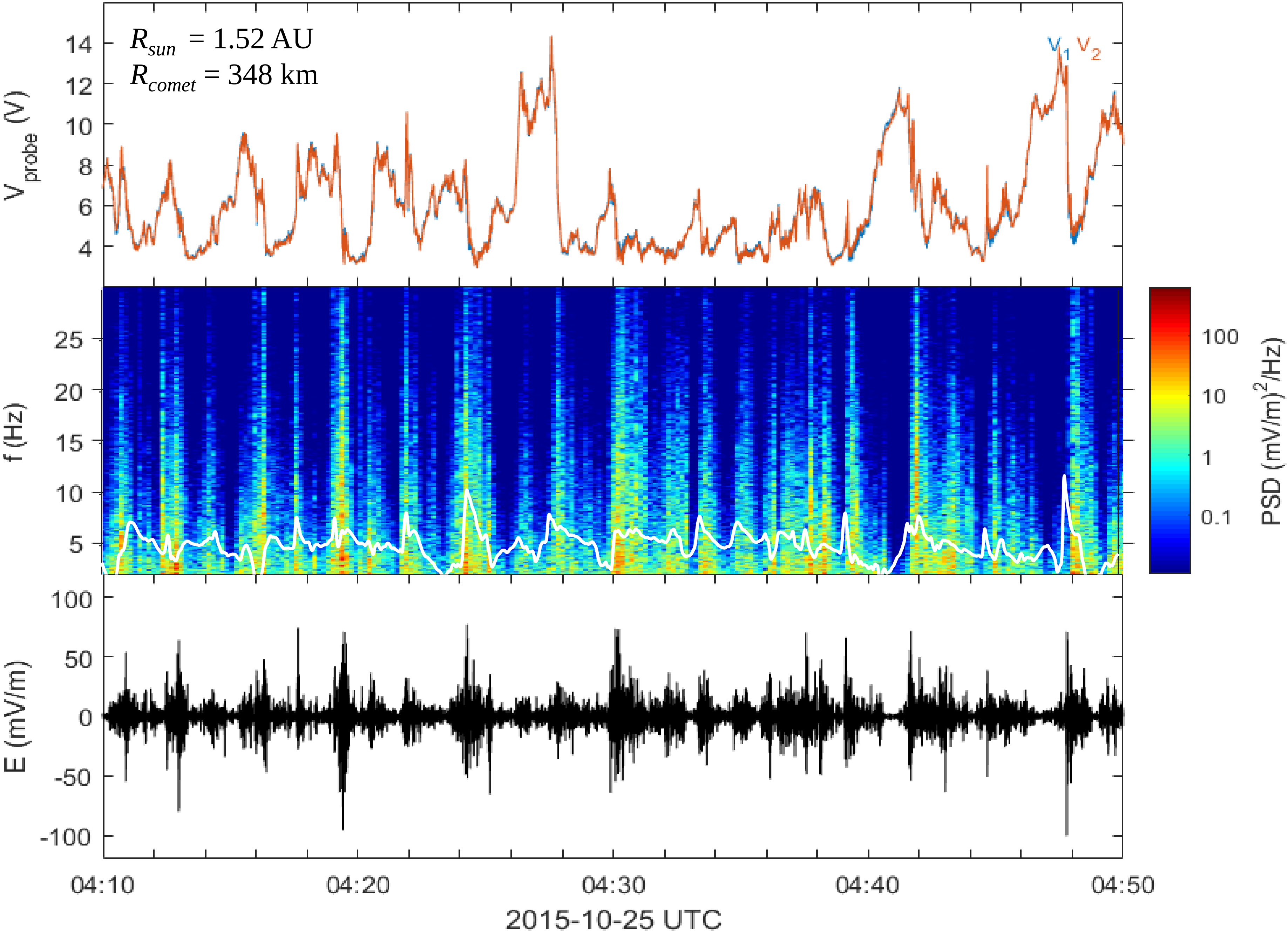


Rosetta

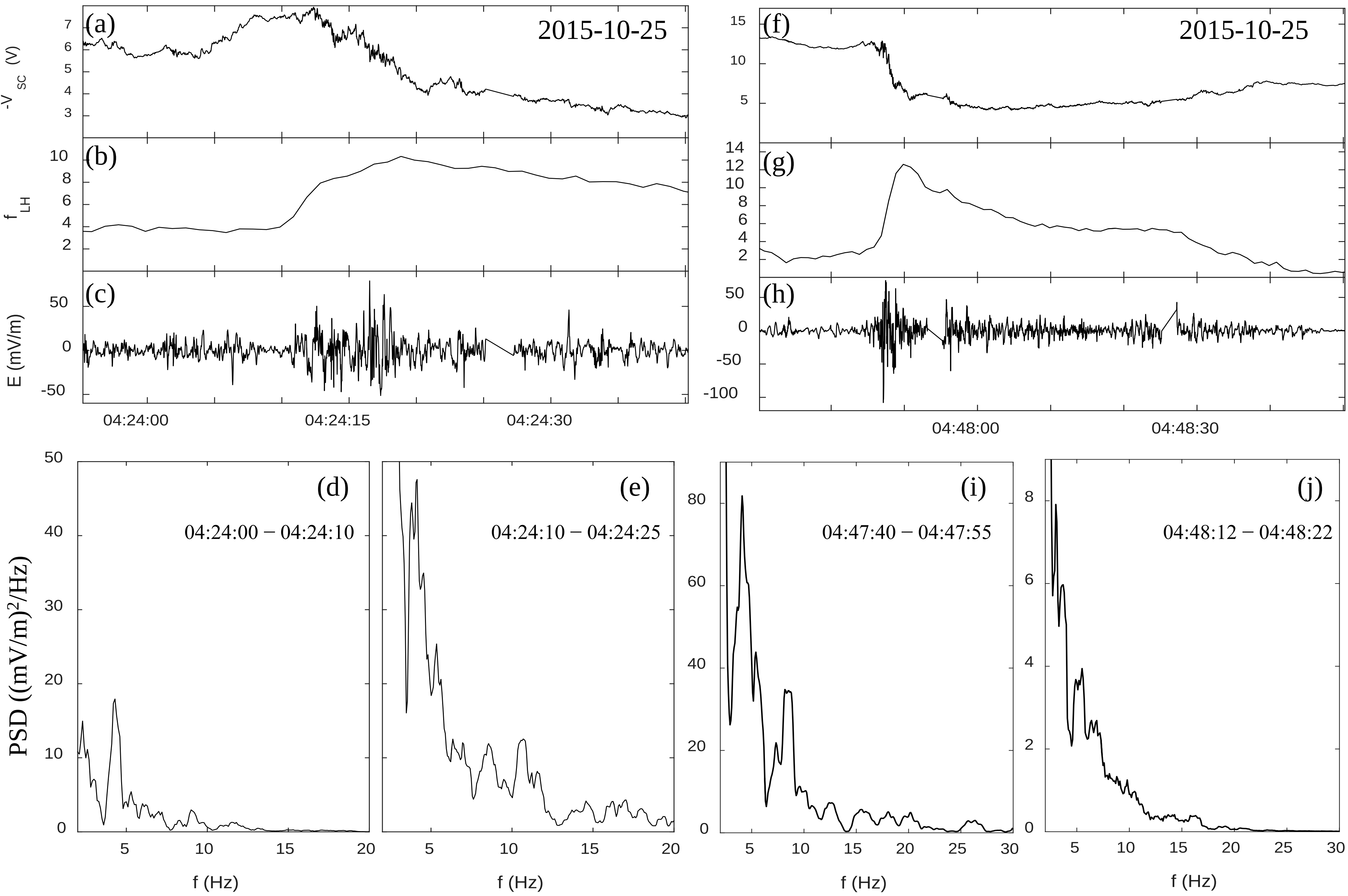
# Electric field measurements from Rosetta

# Electric field measurements from Rosetta





$R_{sun}$ = 1.52 AU
$R_{comet}$ = 348 km
$V_1$ $V_2$
$V_{probe}$ (V)
14
12
10
8
6
4
f (Hz)
25
20
15
10
5
PSD $(mV/m)^2$/Hz)
100
10
1
0.1
E (mV/m)
100
50
0
-50
-100
04:10
04:20
04:30
04:40
04:50
2015-10-25 UTC


(a)
2015-10-25
$-V_{SC}$ (V)
7
6
5
4
3
(b)
$f_{LH}$
10
8
6
4
2
(c)
E (mV/m)
50
0
-50
04:24:00
04:24:15
04:24:30
(f)
2015-10-25
15
10
5
(g)
14
12
10
8
6
4
2
(h)
50
0
-50
-100
04:48:00
04:48:30
(d)
04:24:00 − 04:24:10
(e)
04:24:10 − 04:24:25
(i)
04:47:40 − 04:47:55
(j)
04:48:12 − 04:48:22
PSD ((mV/m)$^2$/Hz)
50
40
30
20
10
0
80
60
40
20
0
8
6
4
2
0
5
10
15
20
25
30
f (Hz)

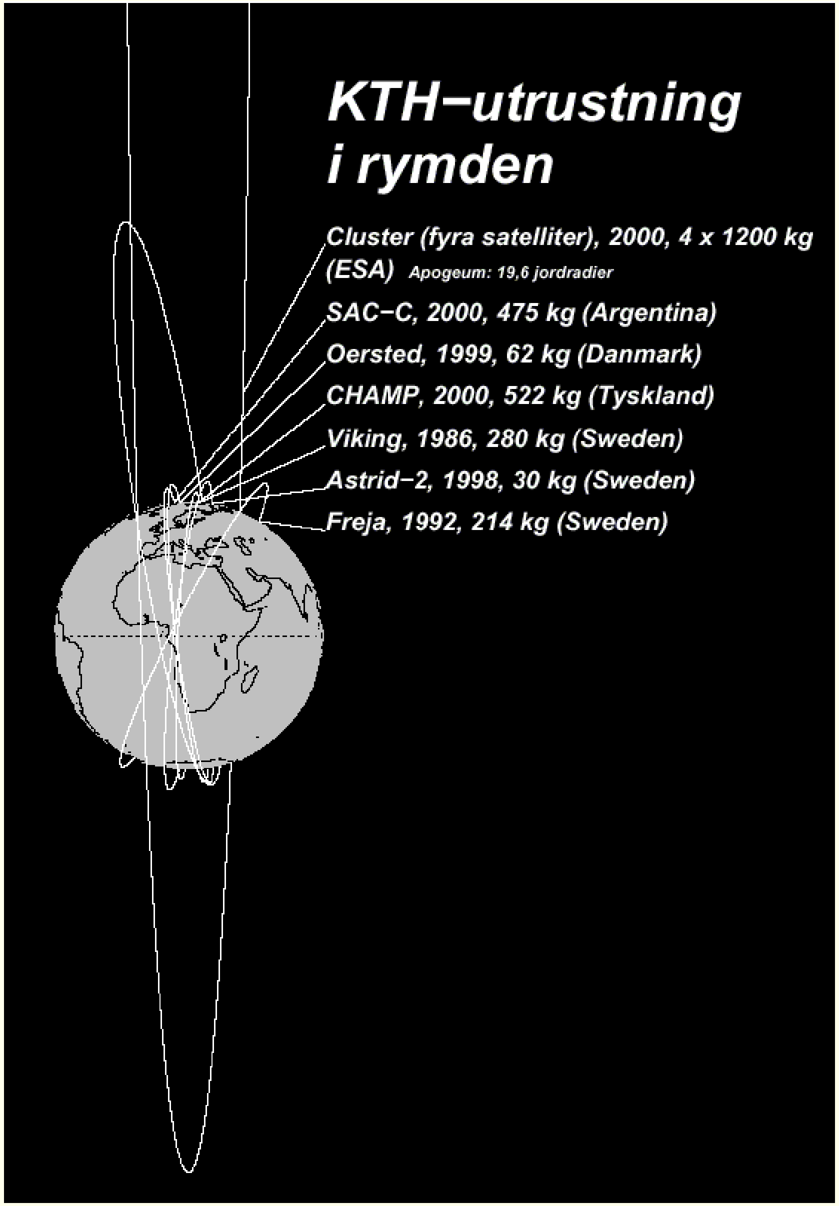
# Swedish research satellites

# *Newly launched*

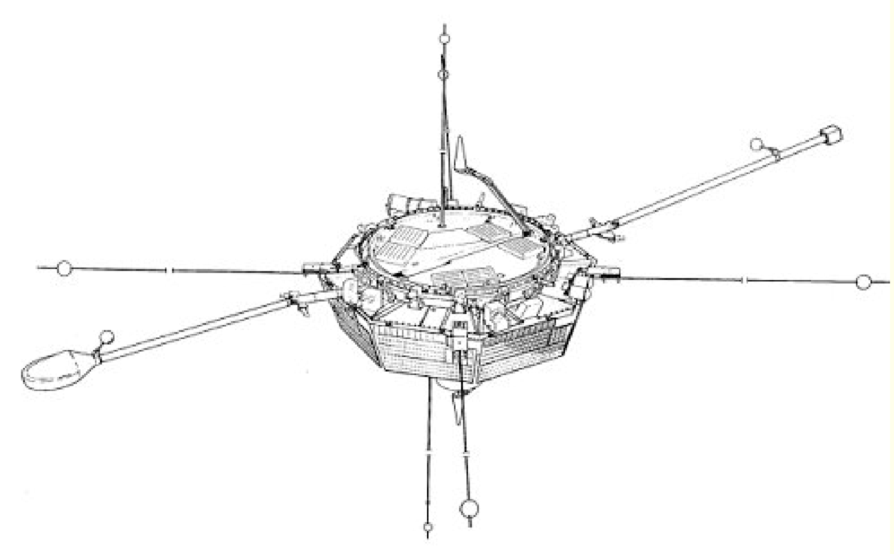
## **MMS –**
## ***Magnetospheric Multiscale***

- NASA mission
- Launch 2015
- Apogee 12-31 $R_E$
- KTH have provide an electric field instrument – a part of the FIELDS instrument suite

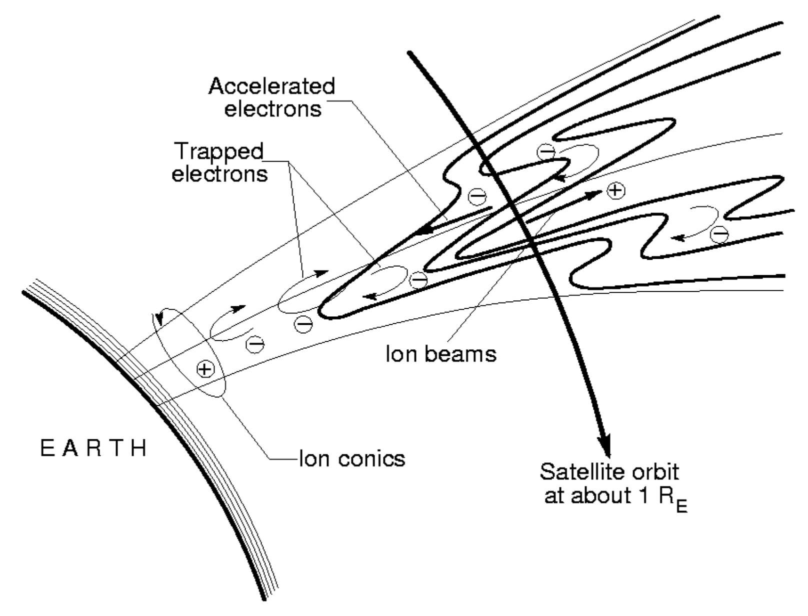
# KTH equipment in space



# Viking



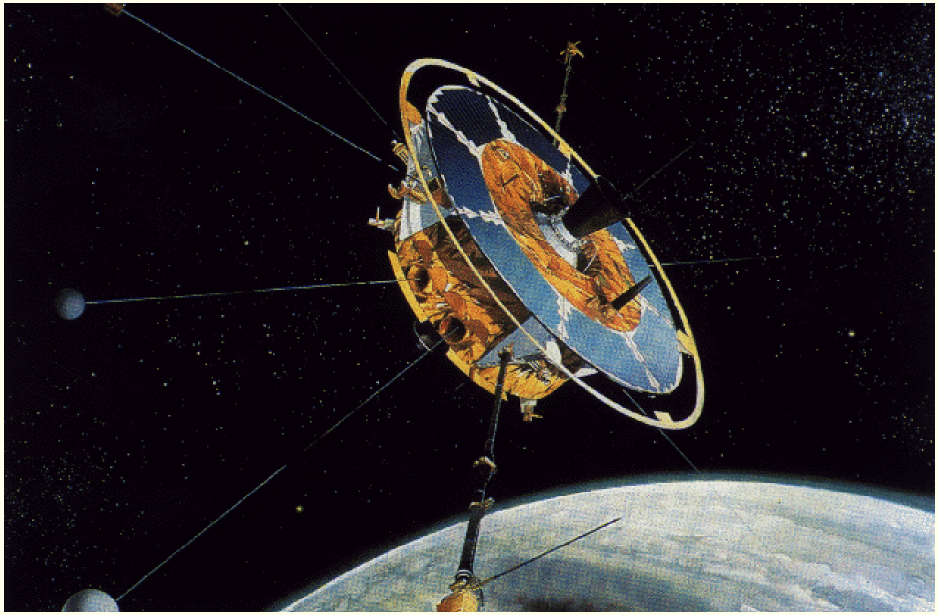
Auroral acceleration region

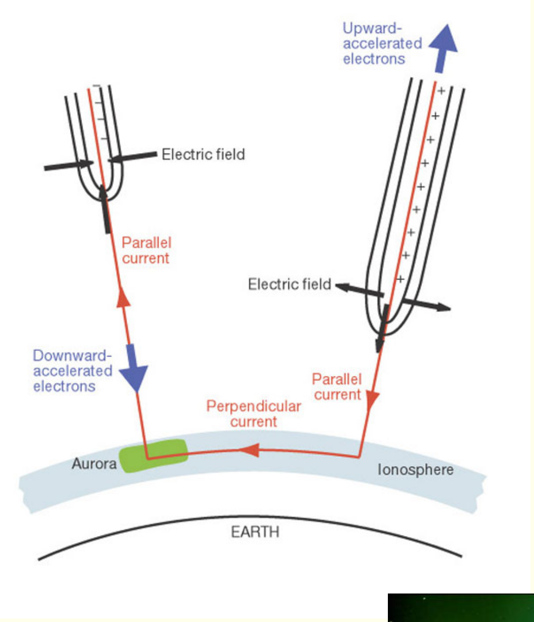


- Launch: 1986
- Apogee: 13500 km
- Perigee: 800km

# Freja

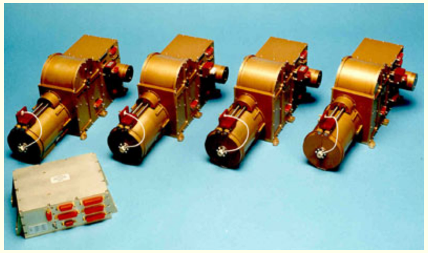
## The mirror image of the aurora – the black aurora





- Launched 1992
- Apogee: 1800 km
- Perigee: 600km

# Freja instrumentation

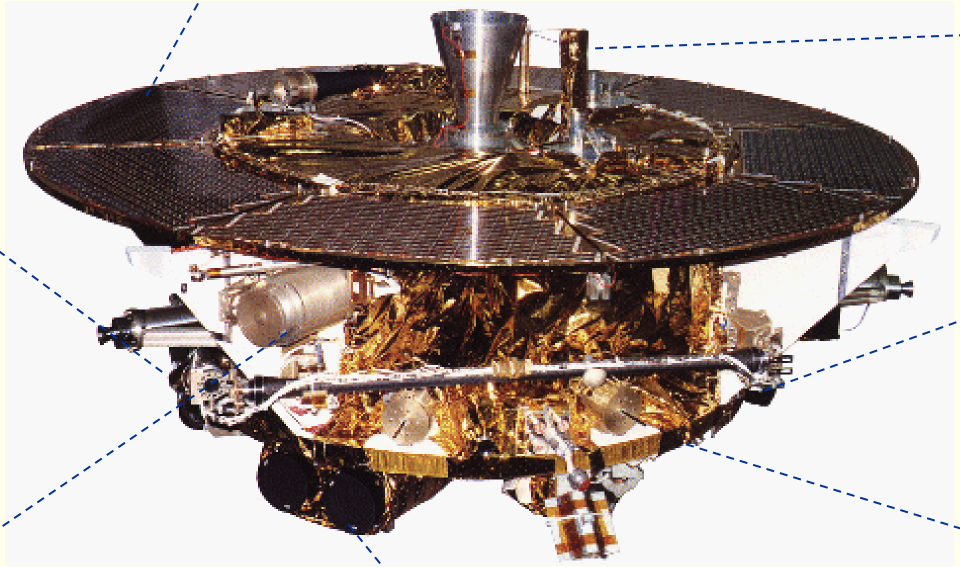


E-field instrument

Solar panel

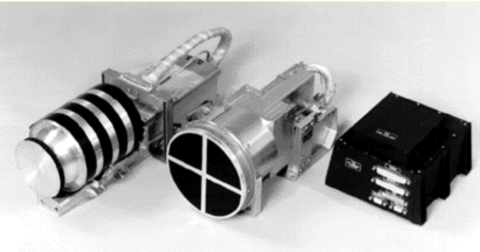
Rocket engine

Antenna

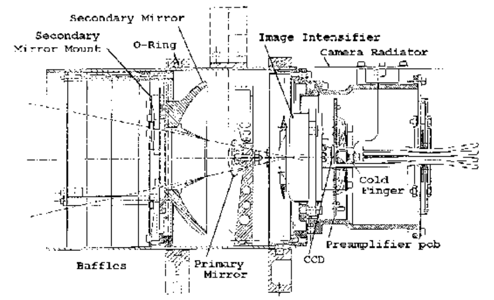


Magnetometer

Langmuir probe
($n_e$ measurement)

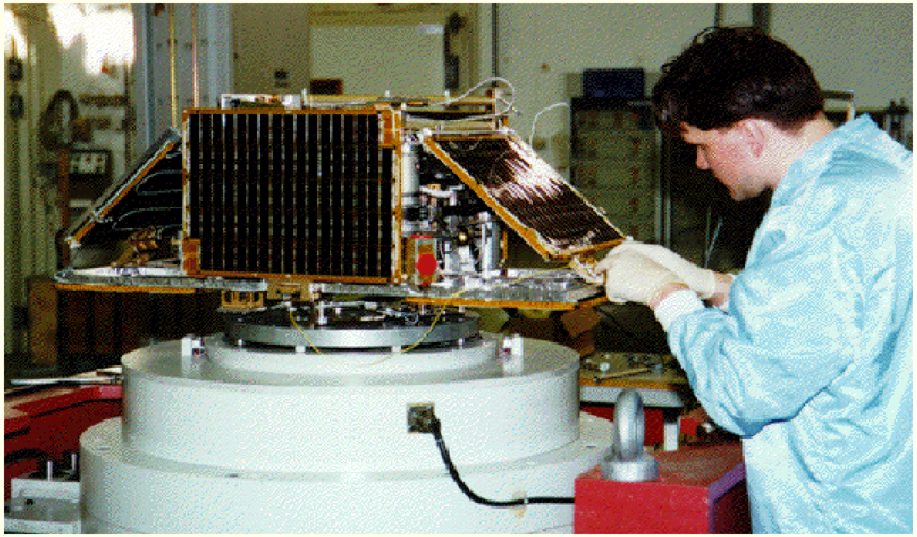


Particle instrument

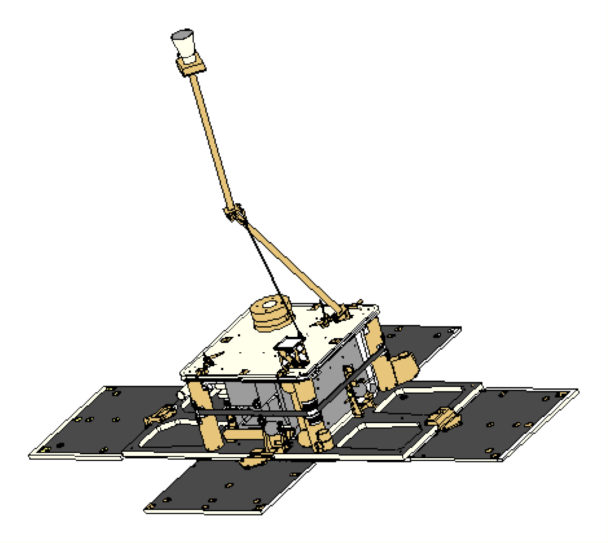


UV camera

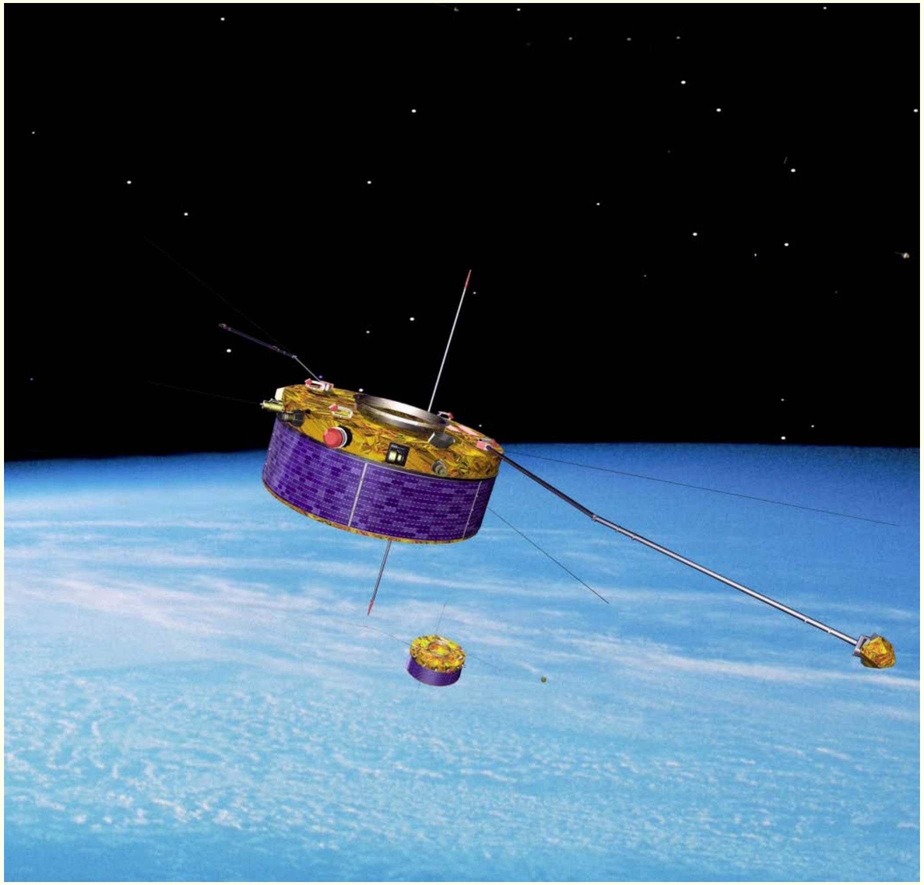
# Micro satellite Astrid II



Minituriazation of the payload gave a very cheap mission



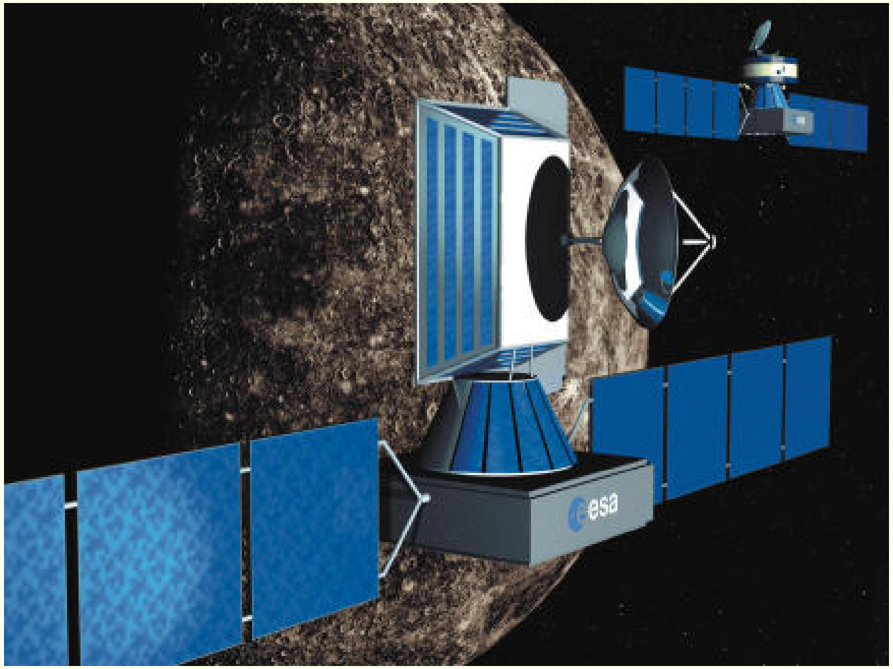
- Launched 1998
- Apogee: 1000 km
- Perigee: 1000 km



# Cluster

- Launched 2000
- Apogee: 20 $R_E$
- Perigee: 4 $R_E$
- Separations:
  200-10000 km

# *Future mission*

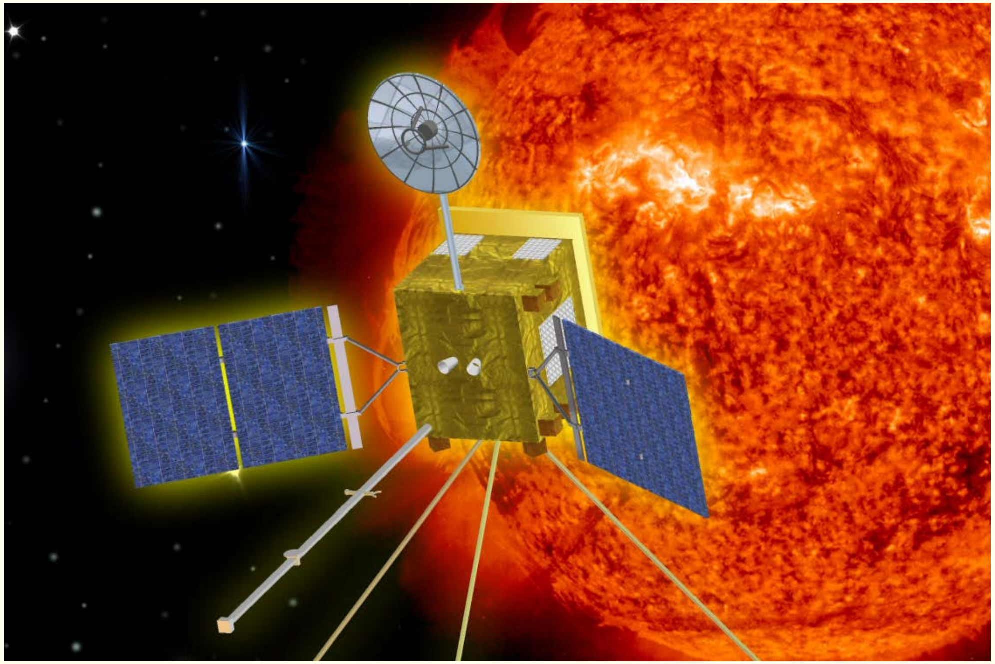


## **Bepi-Colombo**

- ESA-JAXA mission
- Launch 2013
- Arrival at Mercury: 2019
- KTH involved in MEFISTO, an electric field instrument

# *Future mission*

# Solar orbiter



- ESA mission
- Apohelion 0.28 AU (inside Mercury's orbit)
- KTH part of electric field instrument in RPW (radio and plasma waves)
- Final go-ahead 2011-10-05!
- Launch 2017-2018