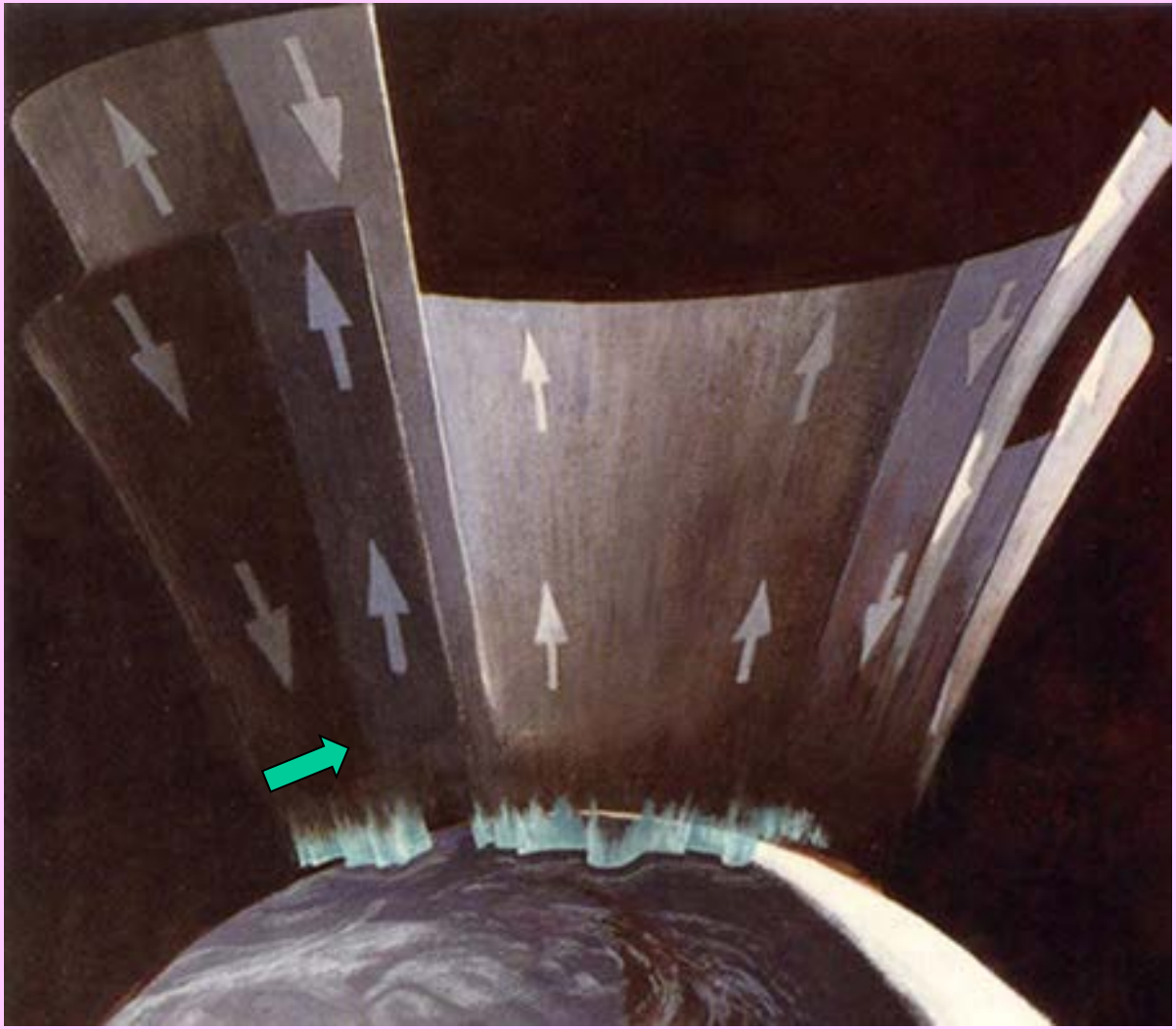
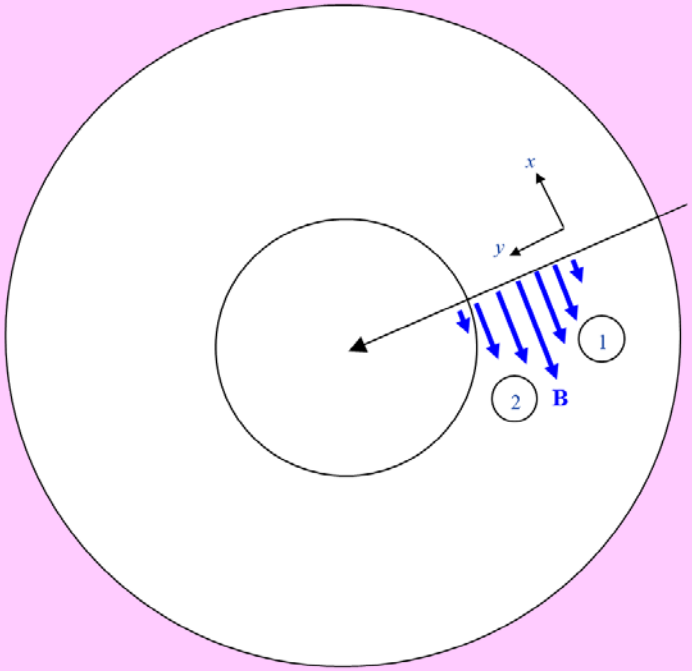
Birkeland currents in the auroral oval



Mini-groupwork 5



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

Current sheet 1:

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

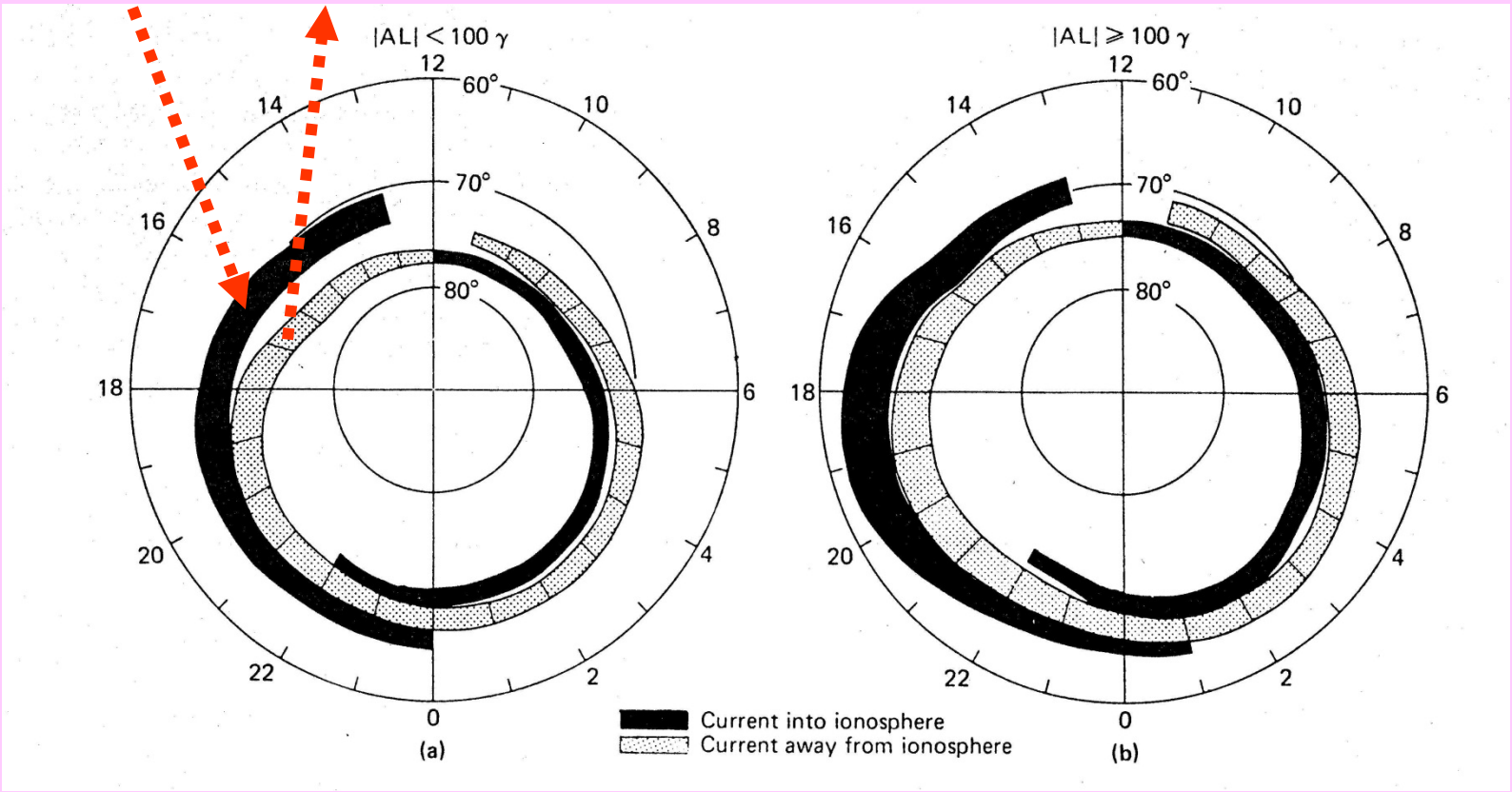
$$\frac{\Delta B_x}{\Delta y} \approx -\frac{15\ \text{mm}}{22\ \text{mm}} \cdot 1000 \cdot 10^{-9} = -6.8 \cdot 10^{-7}\ \text{T}$$

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

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

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
- 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)

Teknikringen 31

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)

Written examination, 28/10, 2014, 8-13, Q21, Q26
(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.)

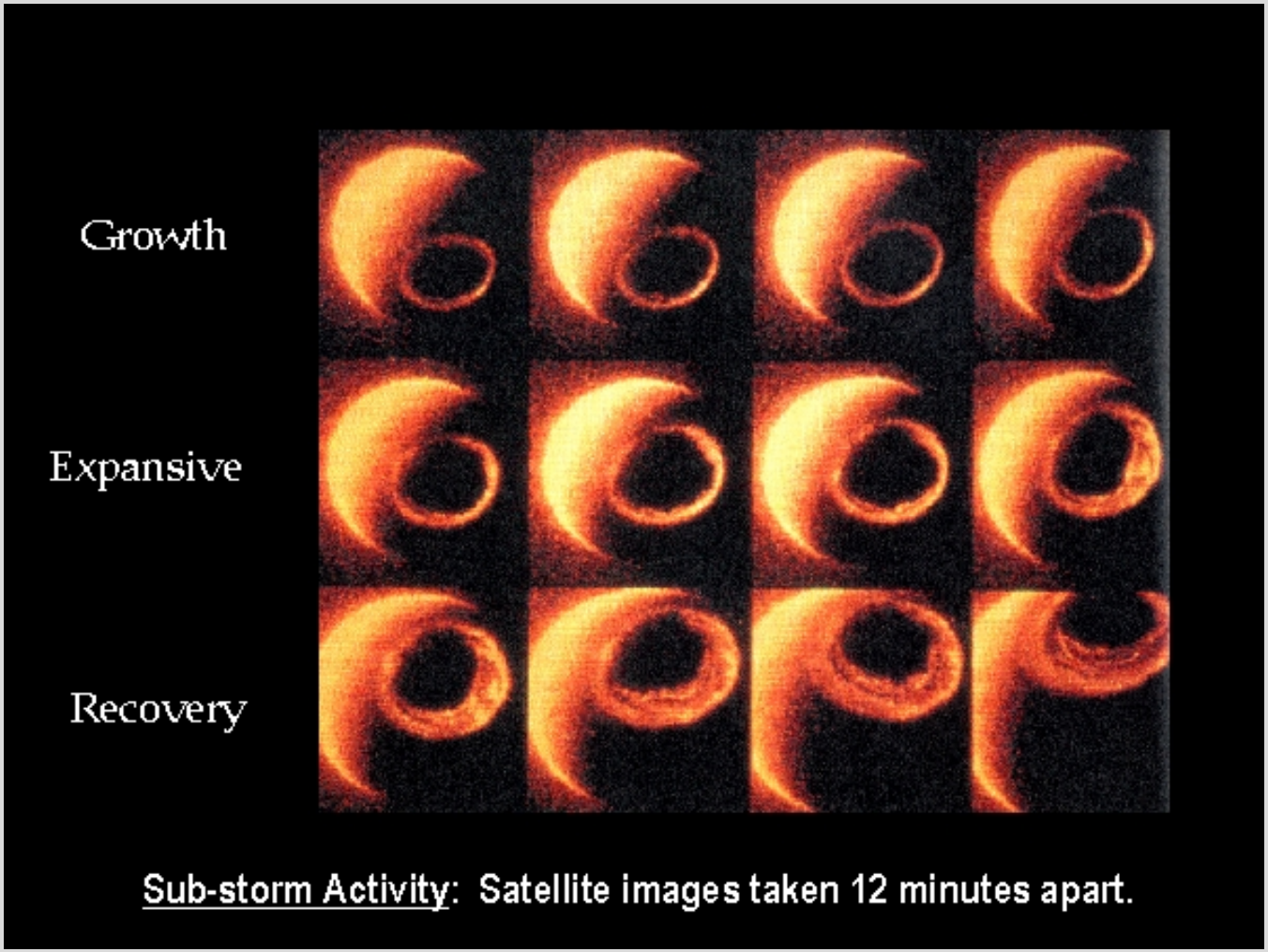
Approx. 5 different problems (which may contain sub-problems).

About the exam

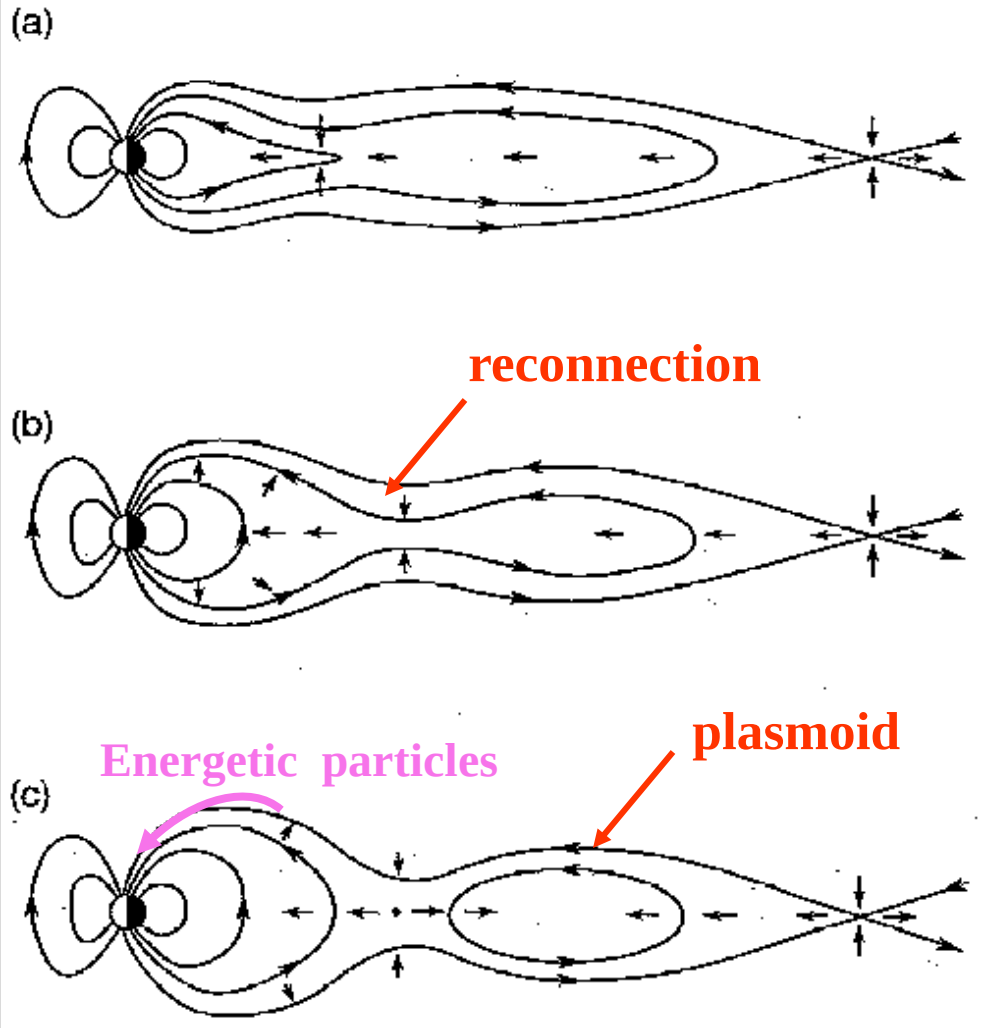
Motivate your answers!

Be careful with units and numerical calculations!

Aurora during substorm

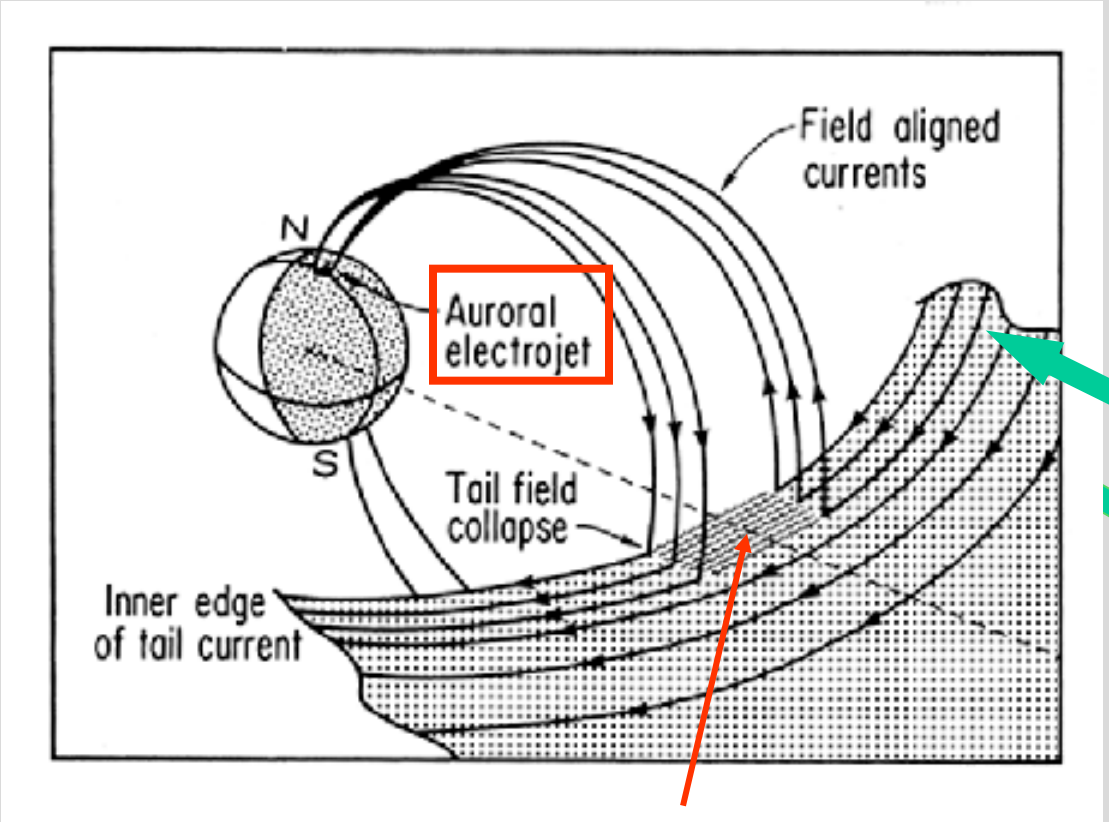


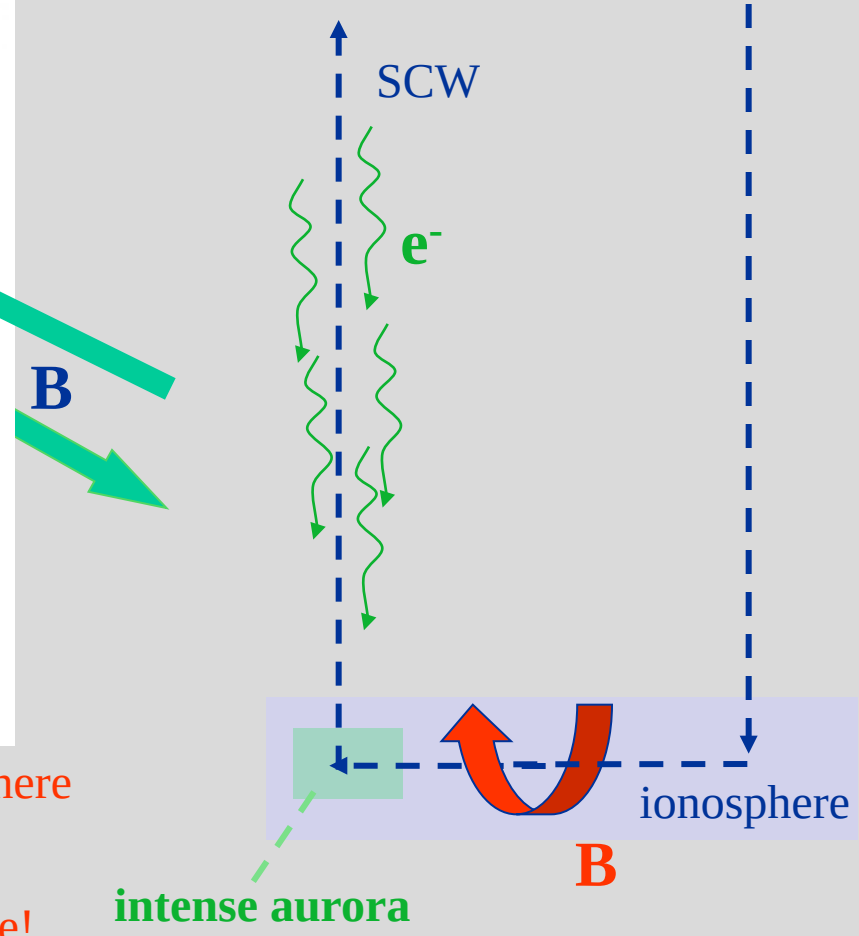
Substorms - magnetosphere



- **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)



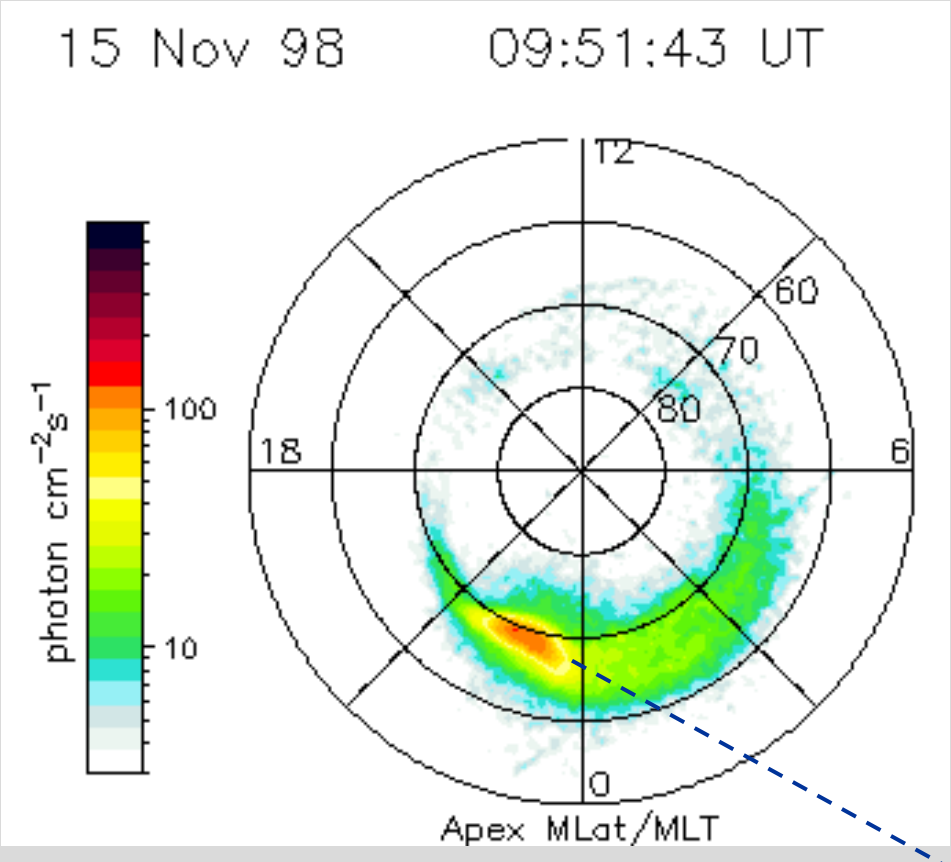


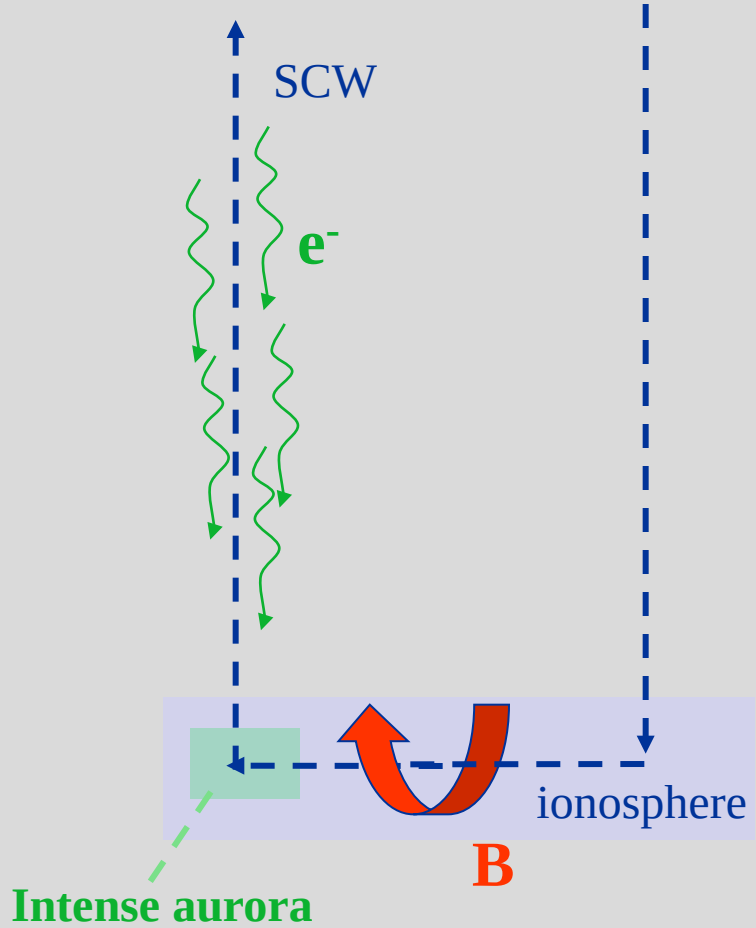
Due to reconnection processes the resistivity increases here

⇒

Current takes another direction – through the ionosphere!

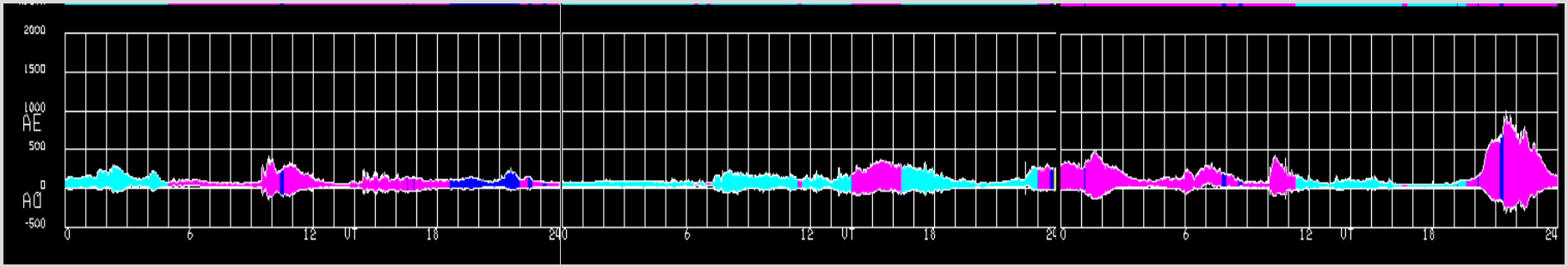
Substorm Current Wedge (SCW)

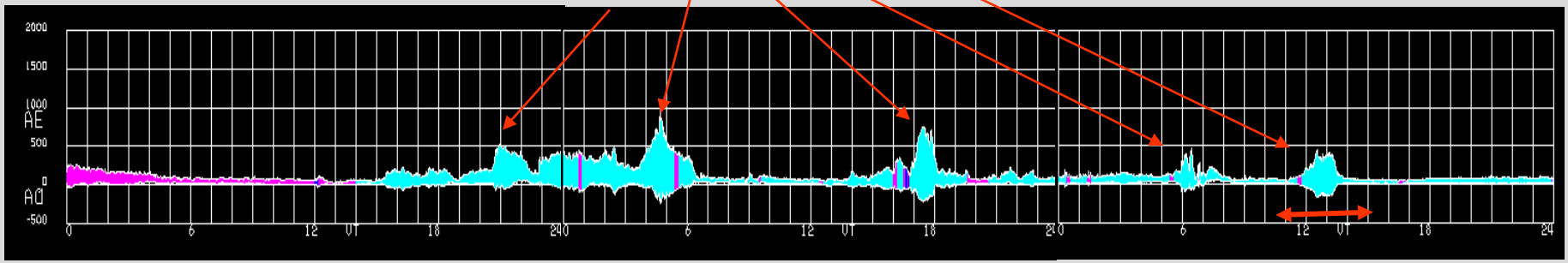




Auroral Electrojet (AE) index

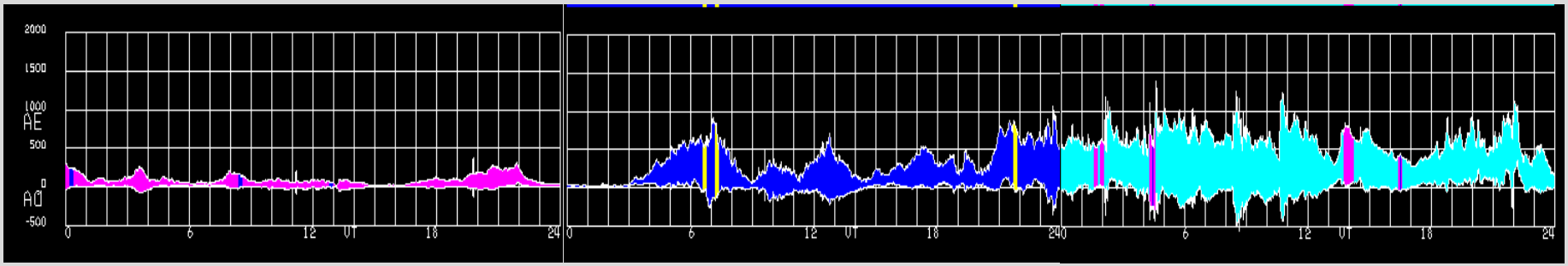
The AE index Measures the strength of the substorm current wedge (SCW), by using the information from several magnetic observatories.

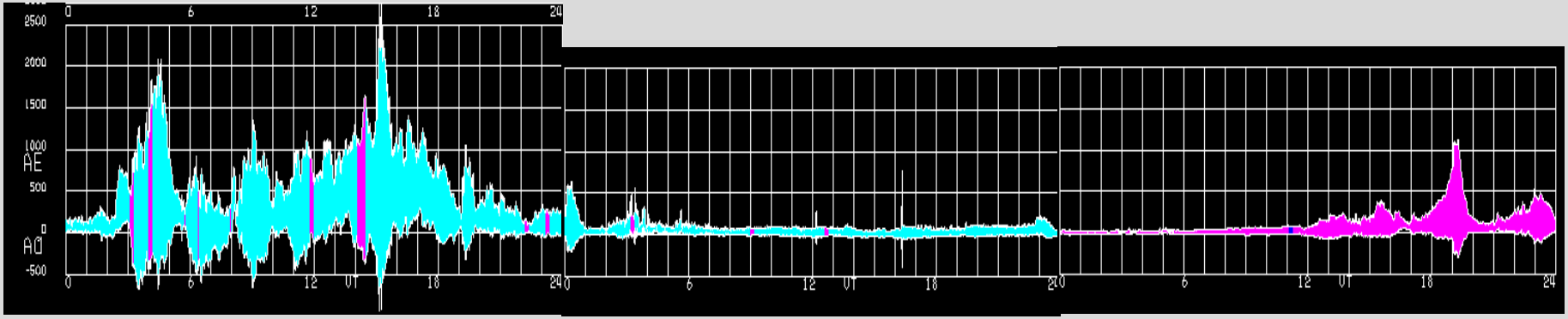




Geomagnetic storms

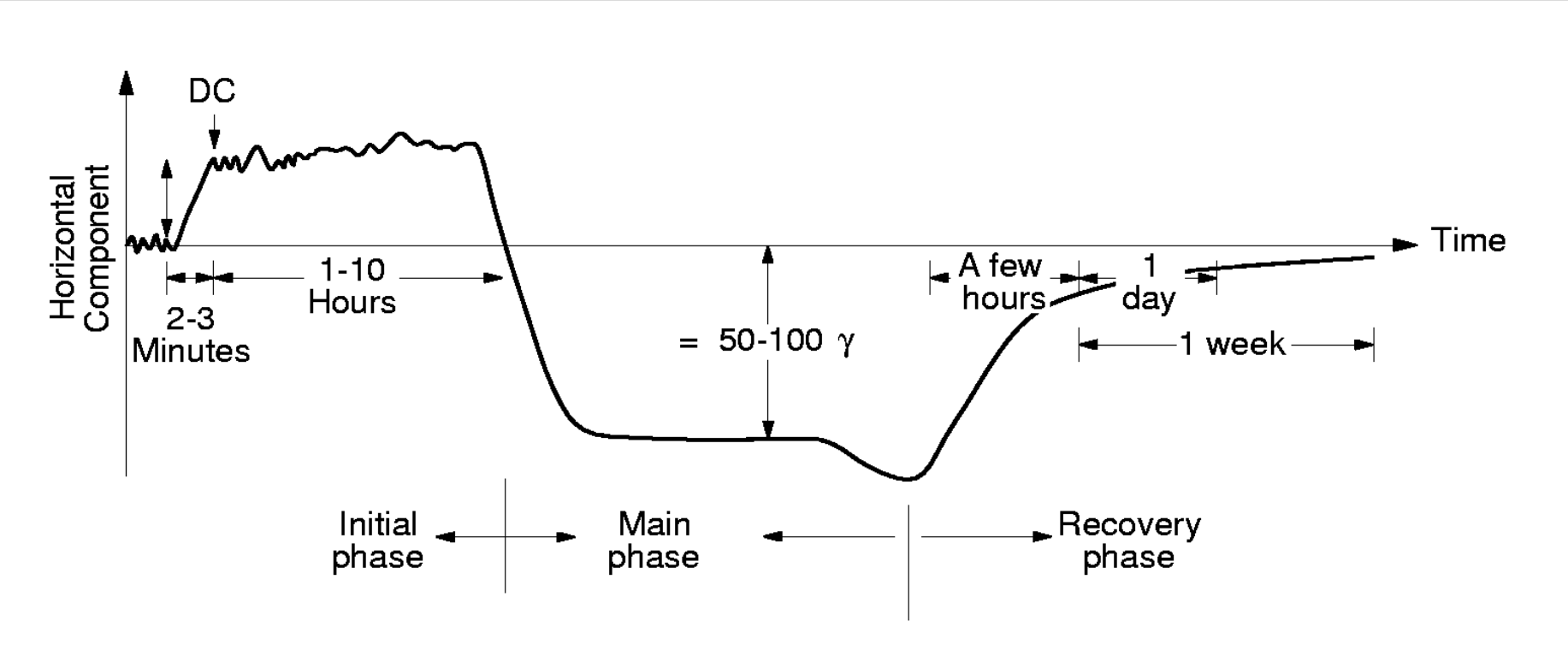
Geomagnetic storms are extended periods with southward interplanetary magnetic field (IMF) and a large energy input into the magnetosphere.





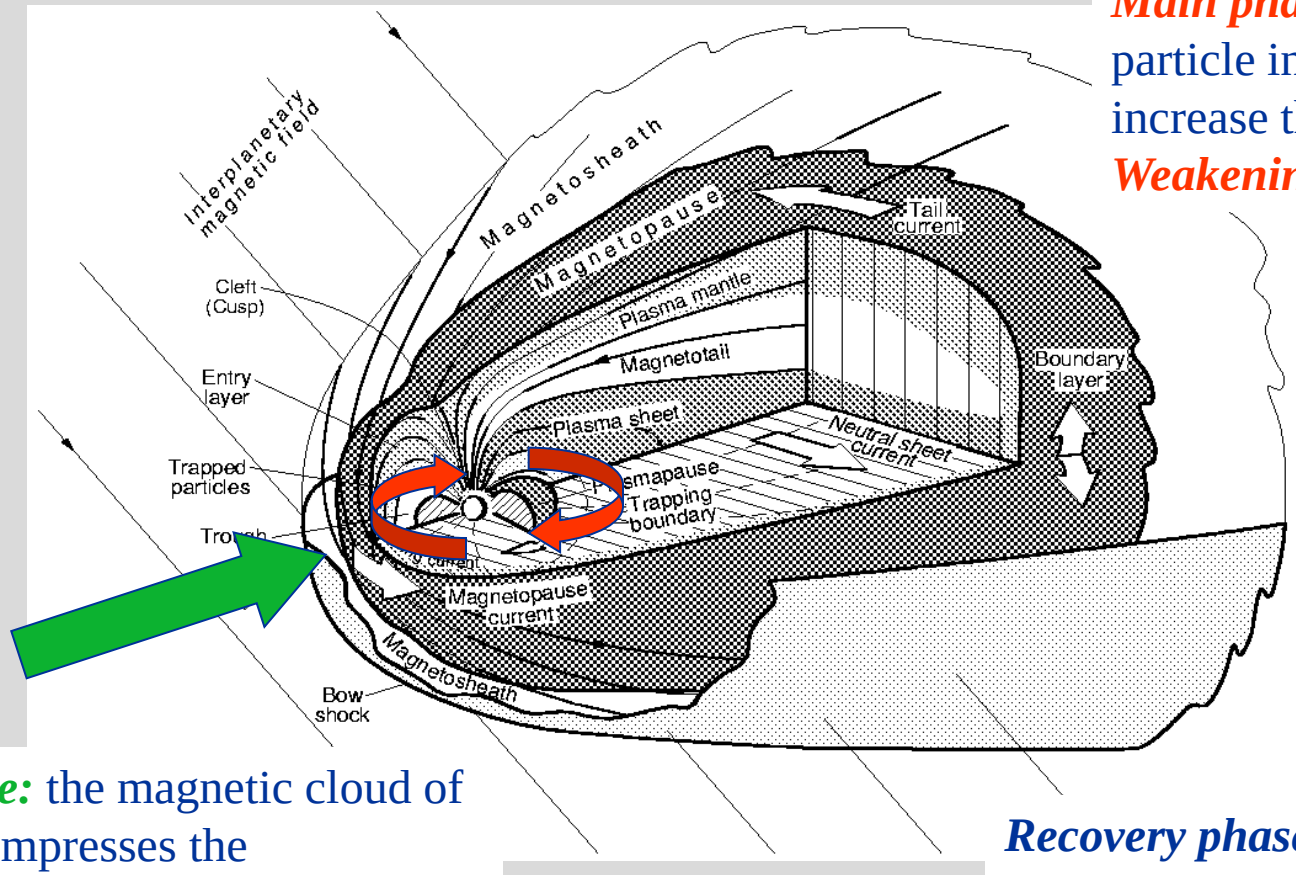
Geomagnetic storms - phases

Magnetogram



Geomagnetic storms - phases

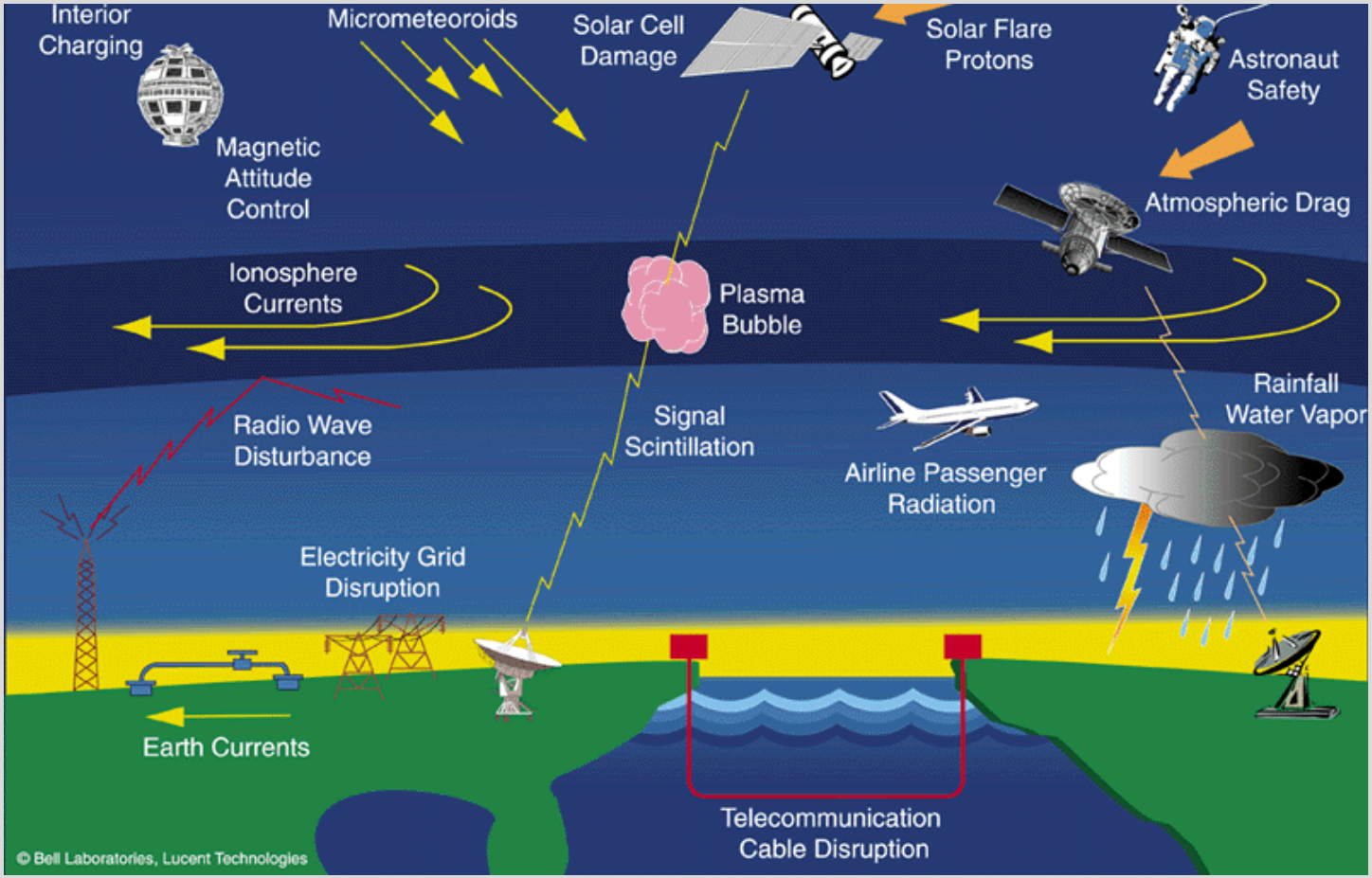
Main phase: Several particle injections increase the ring current.
Weakening of B



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

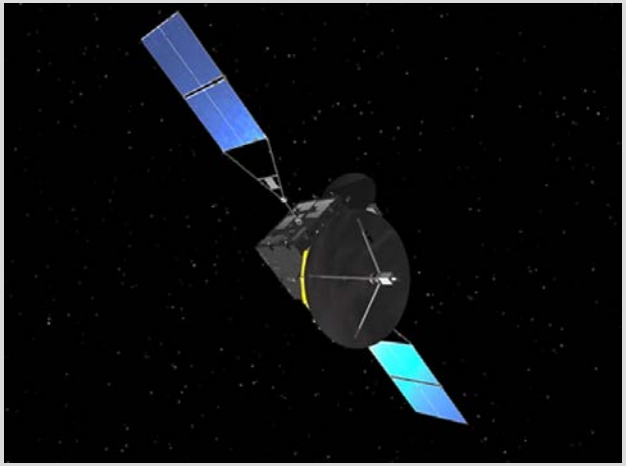


"conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health."

US National Space Weather Programme

Highly energetic particles

- Particles in the radiation belts.
- Particles from solar activity (solar flares, CME)
- Cosmic radiation



Disturb or damage electronics on satellites and aeoreplanes.

Danger to astronauts

Increase the rate of ionization in lower D region and thus increases absorption of radio waves.

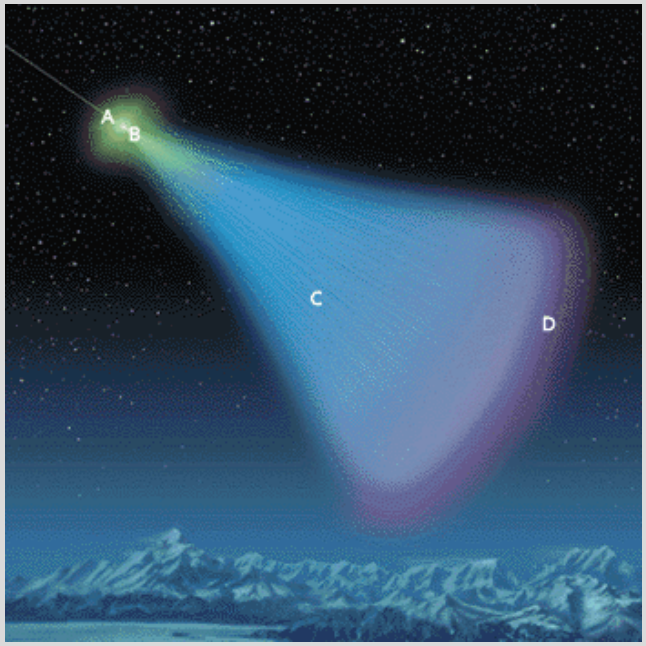
Cosmic rays (= cosmic radiation)

Primary cosmic radiation

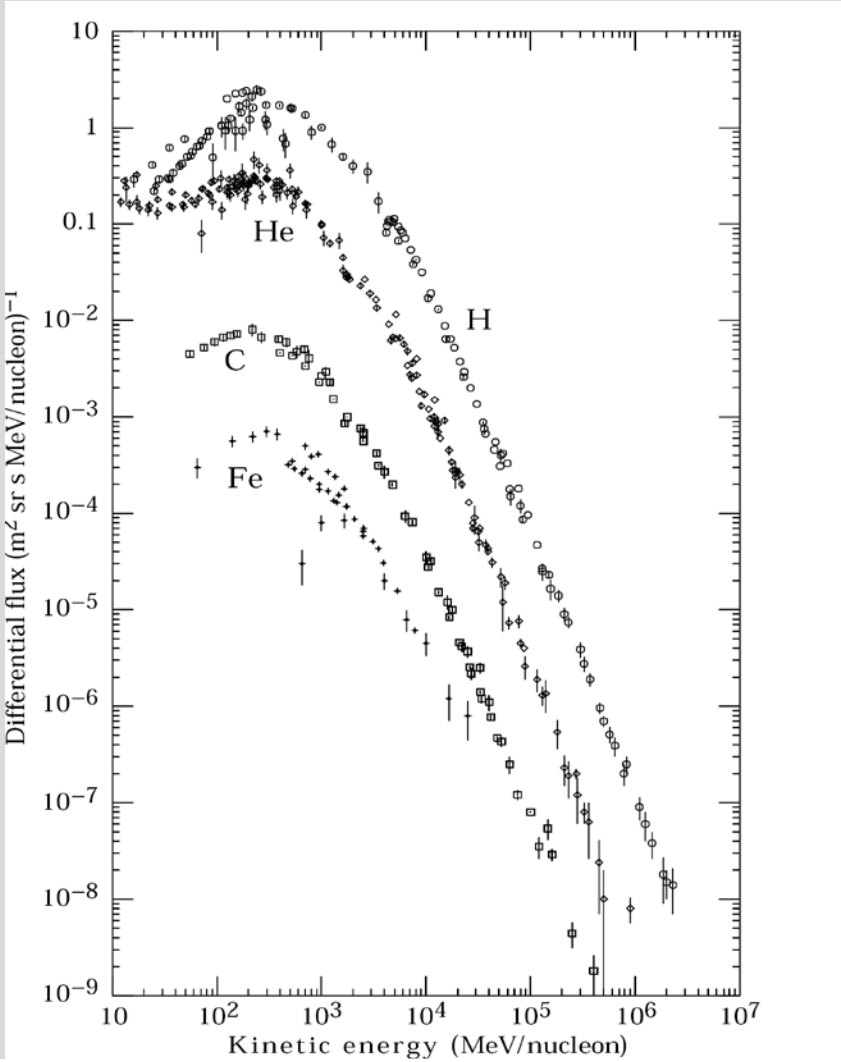
Extremely energetic particles (>10^8 eV)

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

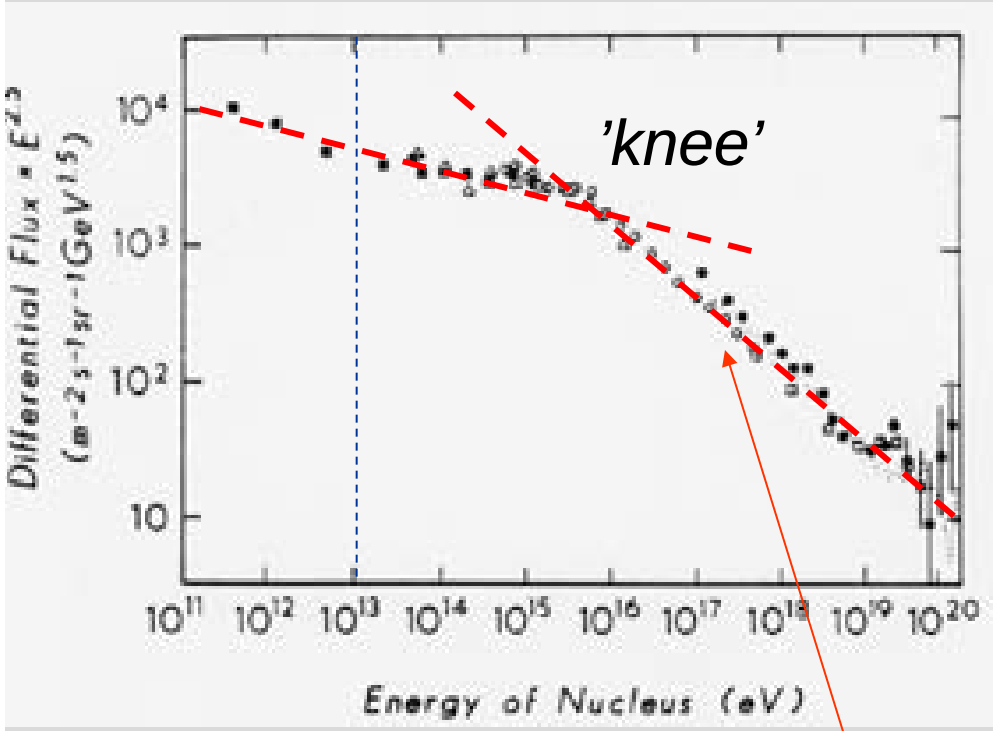
Secondary cosmic radiation



Spectrum of galactic cosmic radiation



Simpson, 1983.



Ultra-energetic cosmic radiation.
Origin unknown. Extragalactic???

Pfotzer maximum

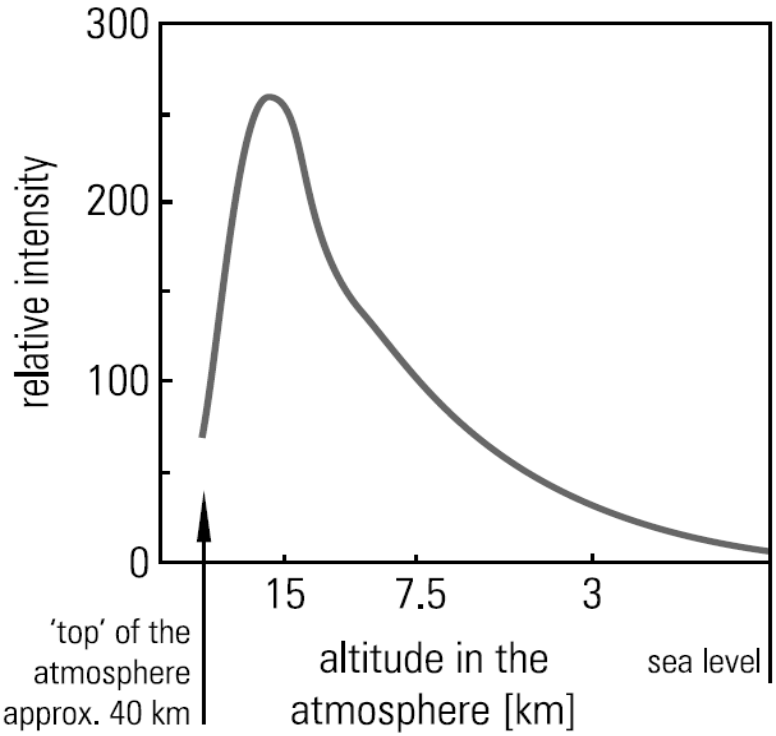
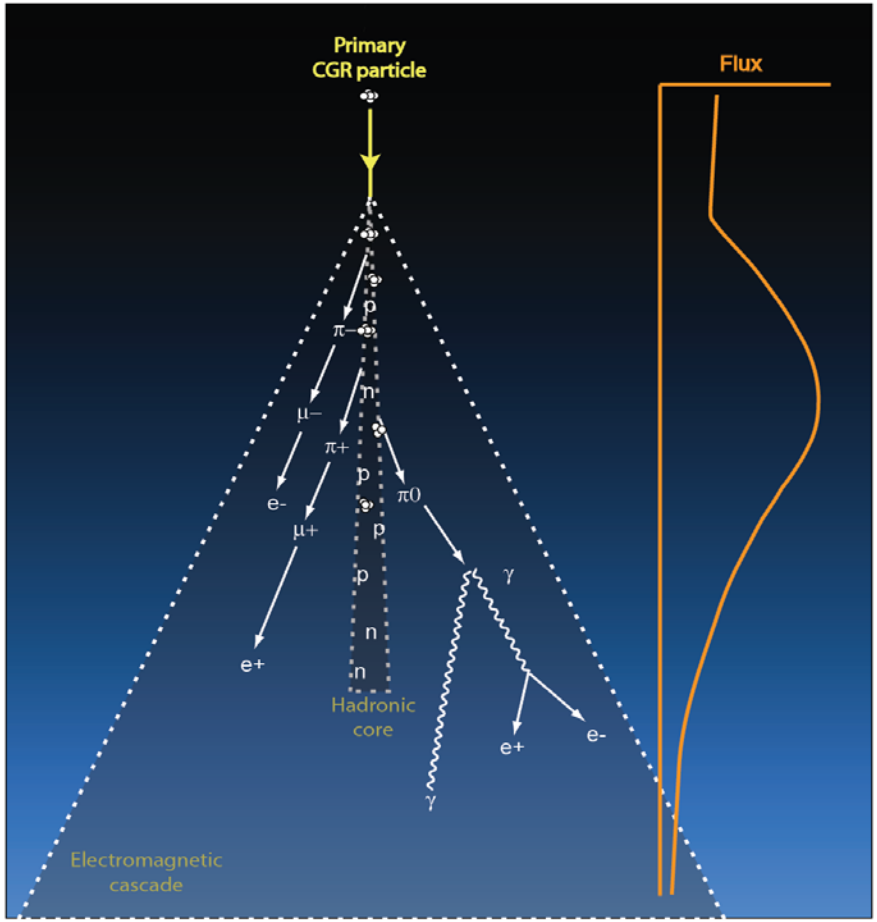


Fig. 1.12
Intensity profile of cosmic particles in the atmosphere



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

$$E = mc^2$$

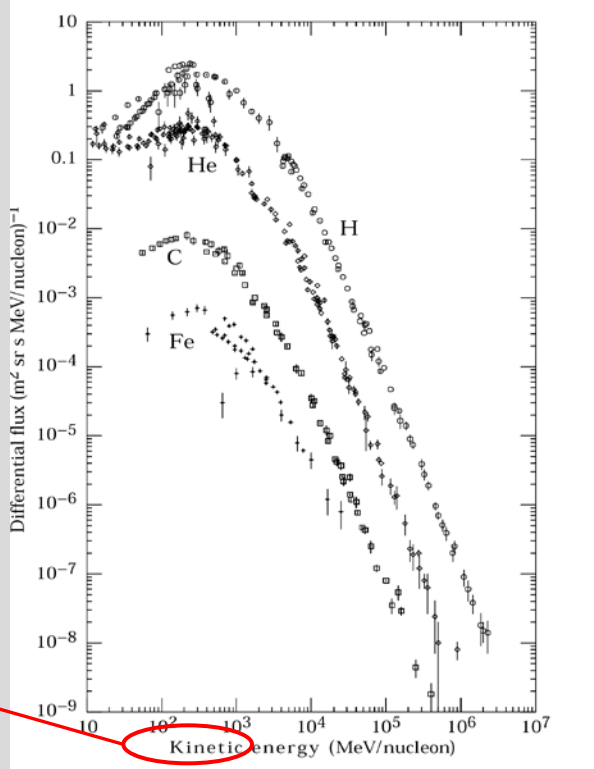
Kinetic energy

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

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

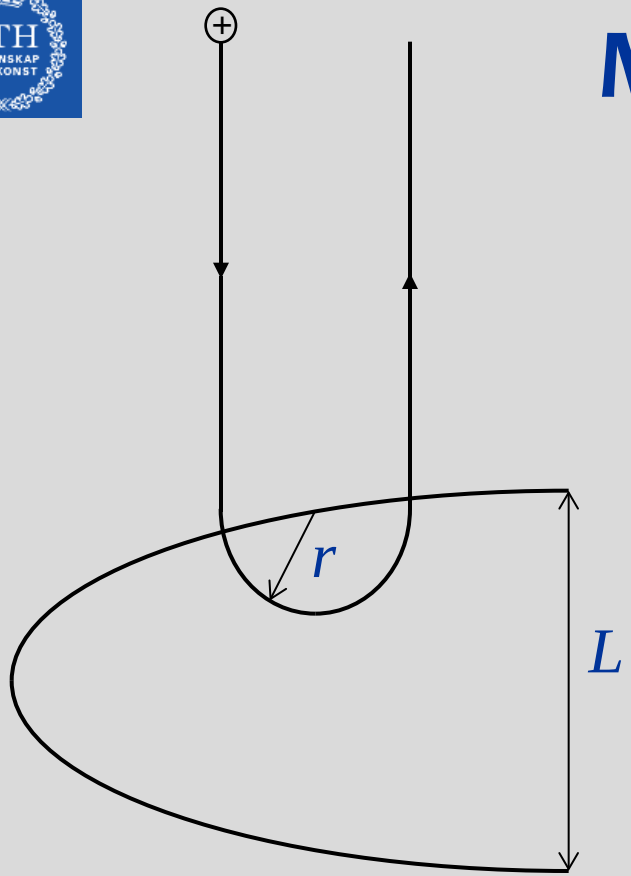
Non-relativistic gyro radius

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

Relativistic gyro radius

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

Magnetic shielding of magnetosphere



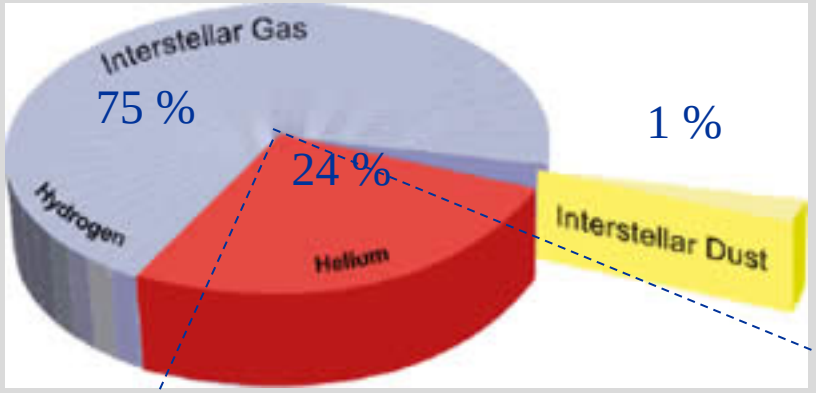
Shielding if

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

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

Interstellar plasma

Interstellar matter (10 % of Milky Way mass)

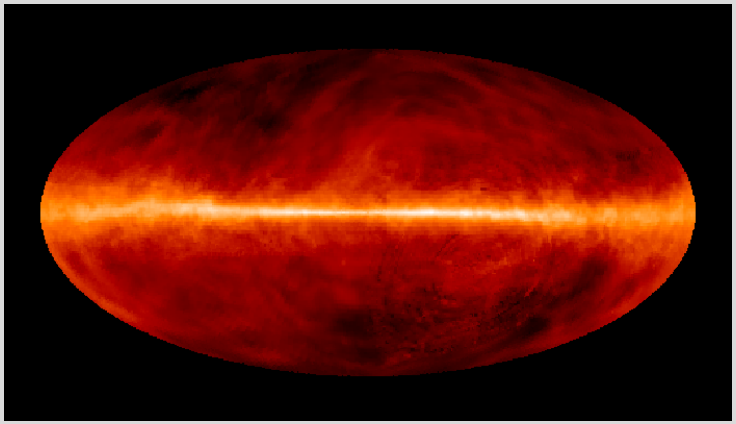


Horsehead nebula

HII regions (emission nebulae)

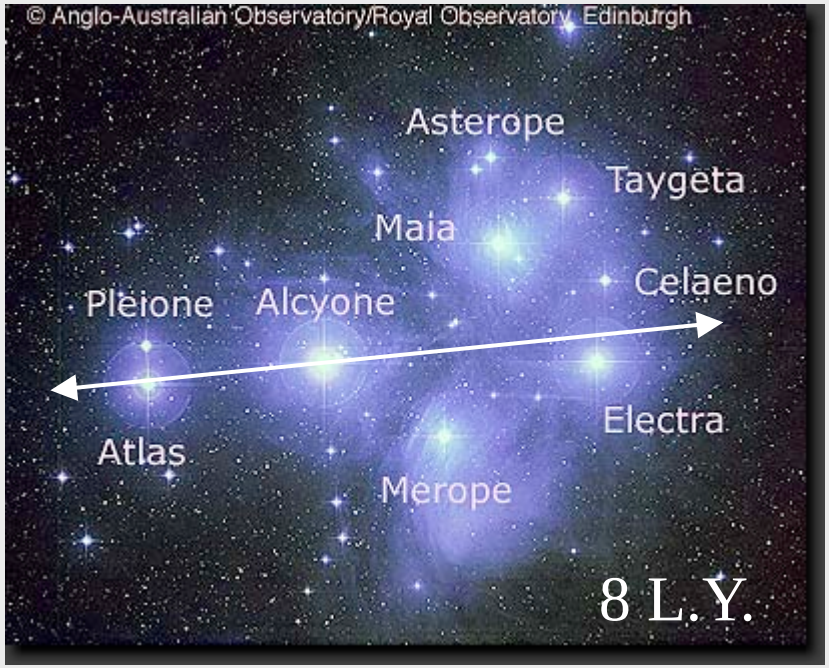
Triffid nebula

HI regions (neutral hydrogen)



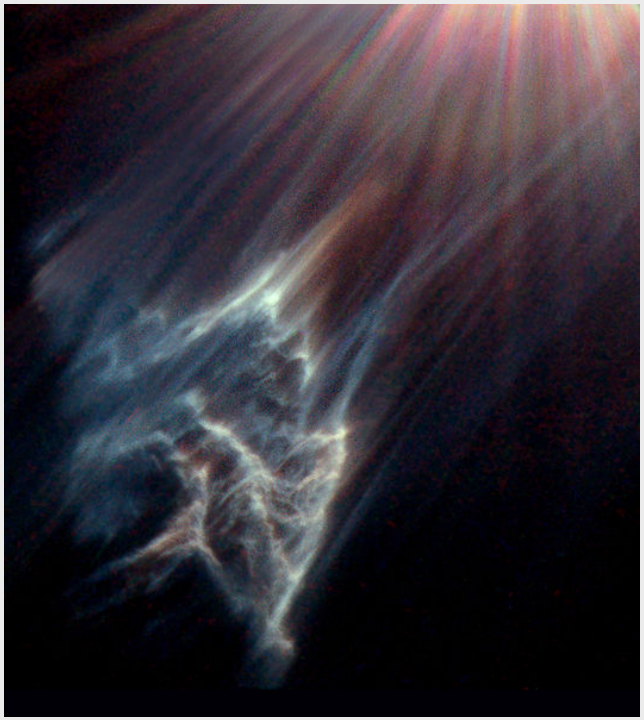
H1 regions are reservoirs of material for star formation

Stars are formed by gravitational collaps of interstellar clouds



Pleiades cluster

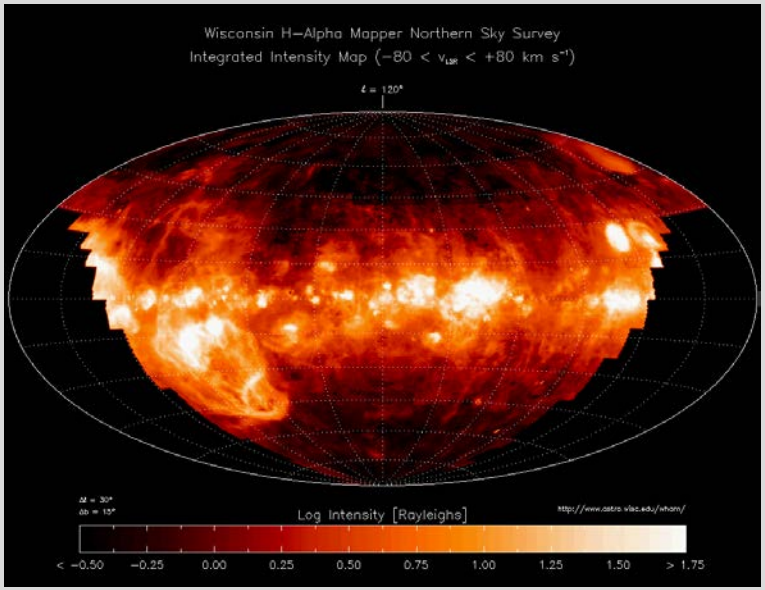
Closeup of region close to Merope



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

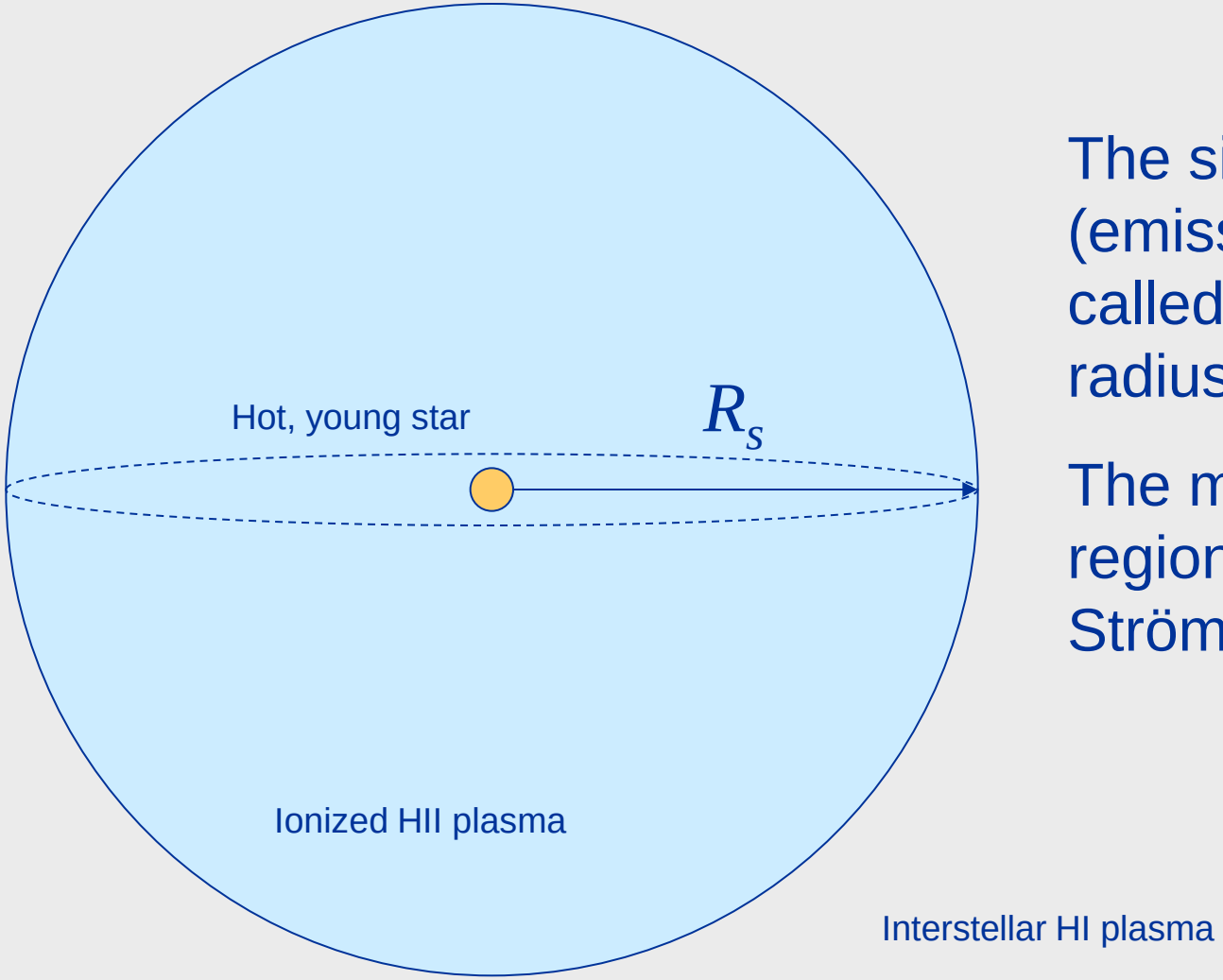
Interstellar plasma – HII regions

- *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

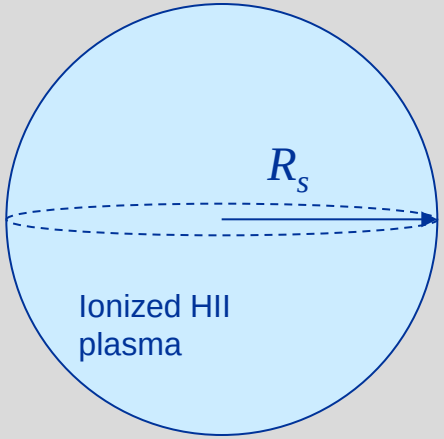
Strömgren sphere



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 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

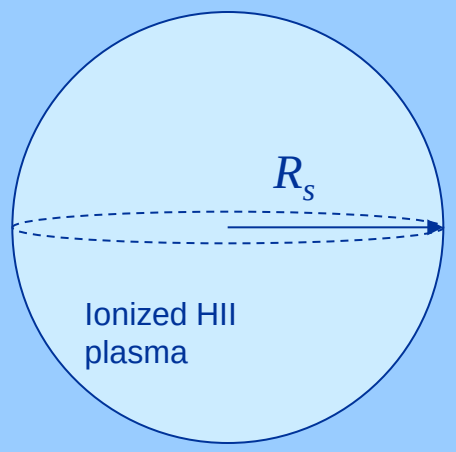
$$N_{UV} = rV = \alpha_H n_H^2 \frac{4\pi R_s^3}{3} \quad \Rightarrow$$

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

Hotter star

Denser gas

Strömgren radius



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

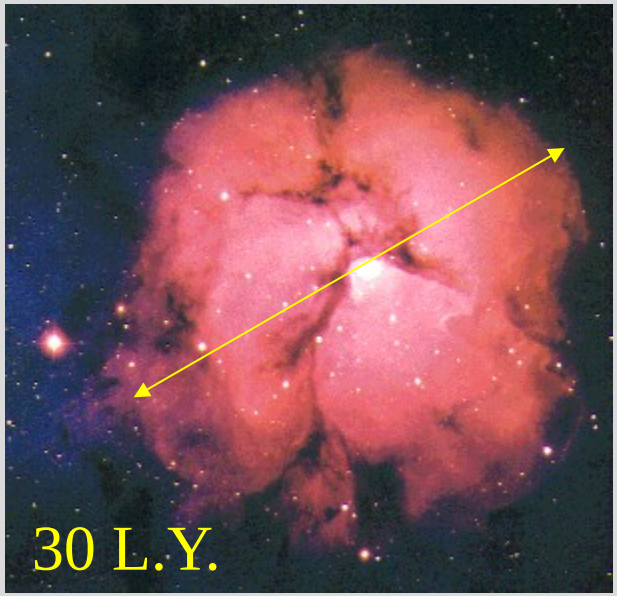
$\alpha_H \approx 3\times10^{-13}$ $cm^3 s^{-1}$

Red

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

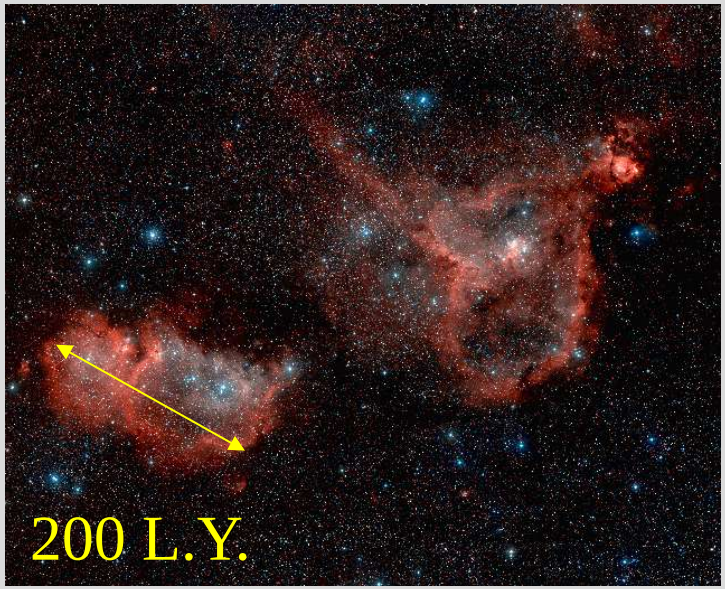
$$1.9\cdot10^{17}\,m = 20\ L.Y.$$

Emission nebulae



Triffid nebula (Messier 20)

IC5146

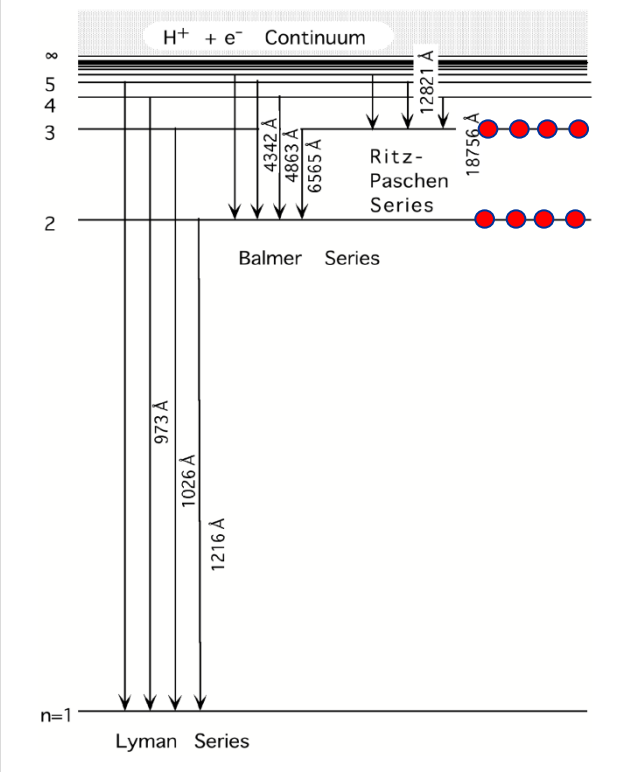


Heart and Soul nebuale (IC1805, IC1848)

- 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*

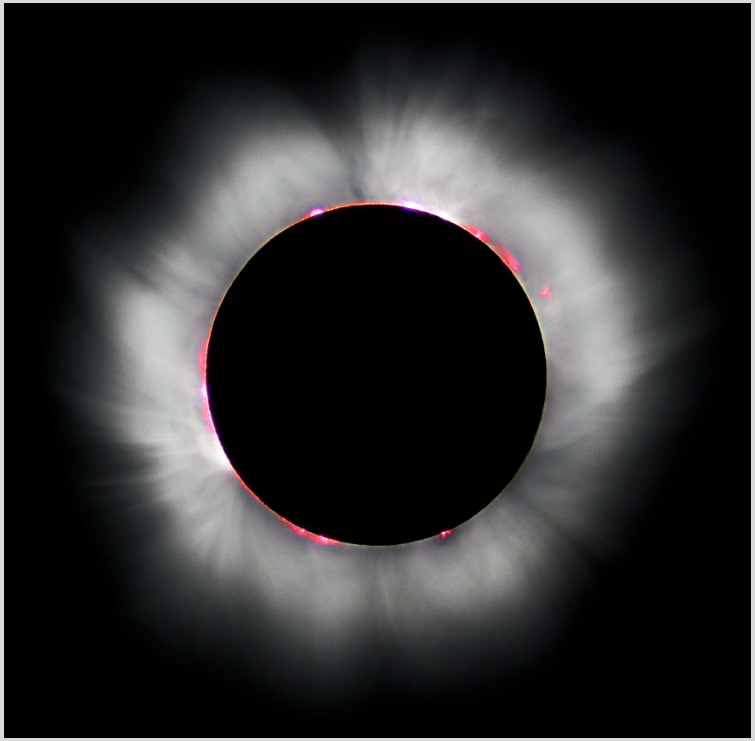
Why is the chromosphere red?

Hydrogen spectrum



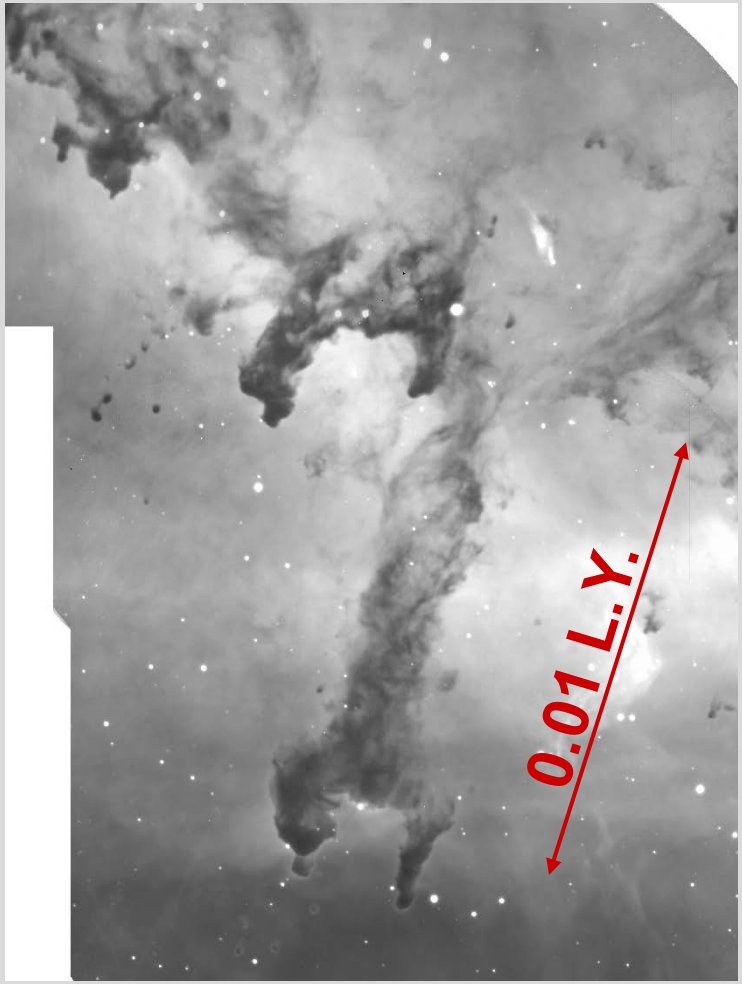
T_2

T_1



Hγ 434 nm Hβ 486 nm Hα 656 nm

Interstellar magnetic field



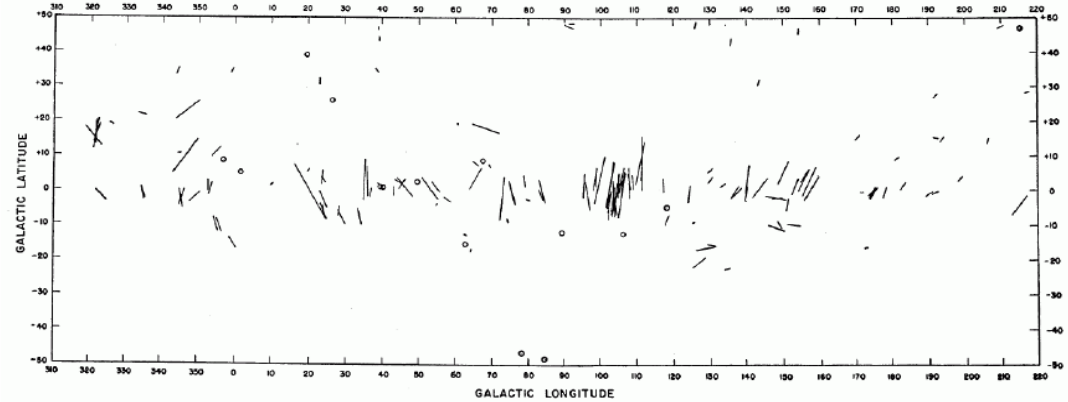


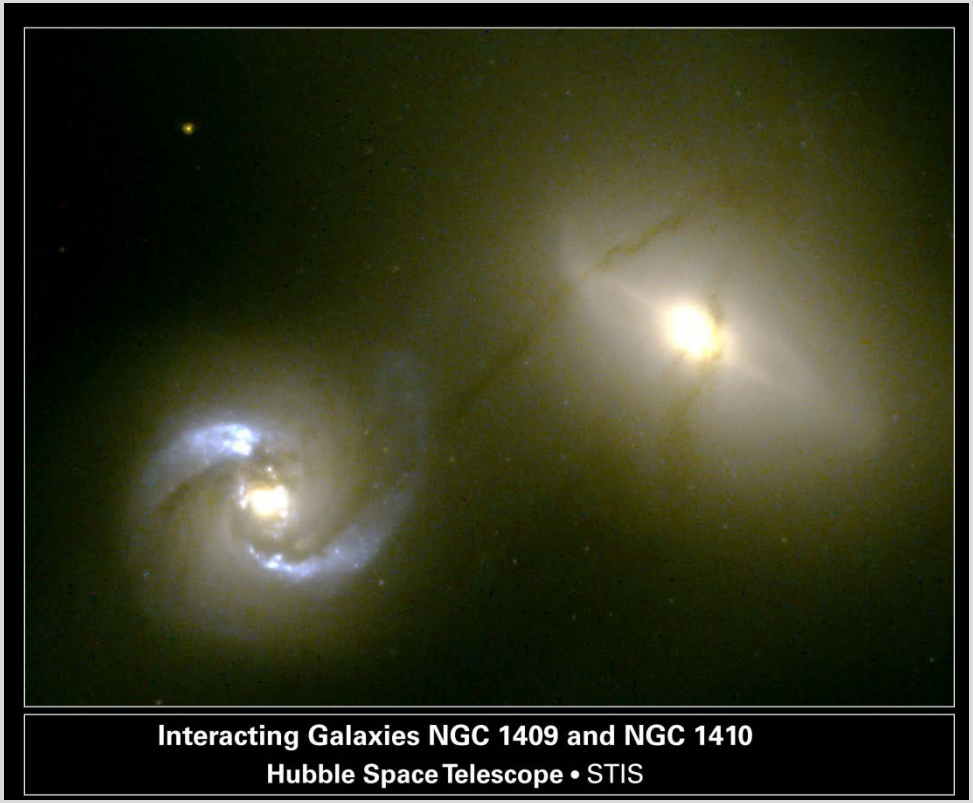
Figure 1. Vector diagram showing polarization of individual stars. Hall & Mikesell, 1949, AJ, 54, 187

HI regions: ~ 0.1 nT

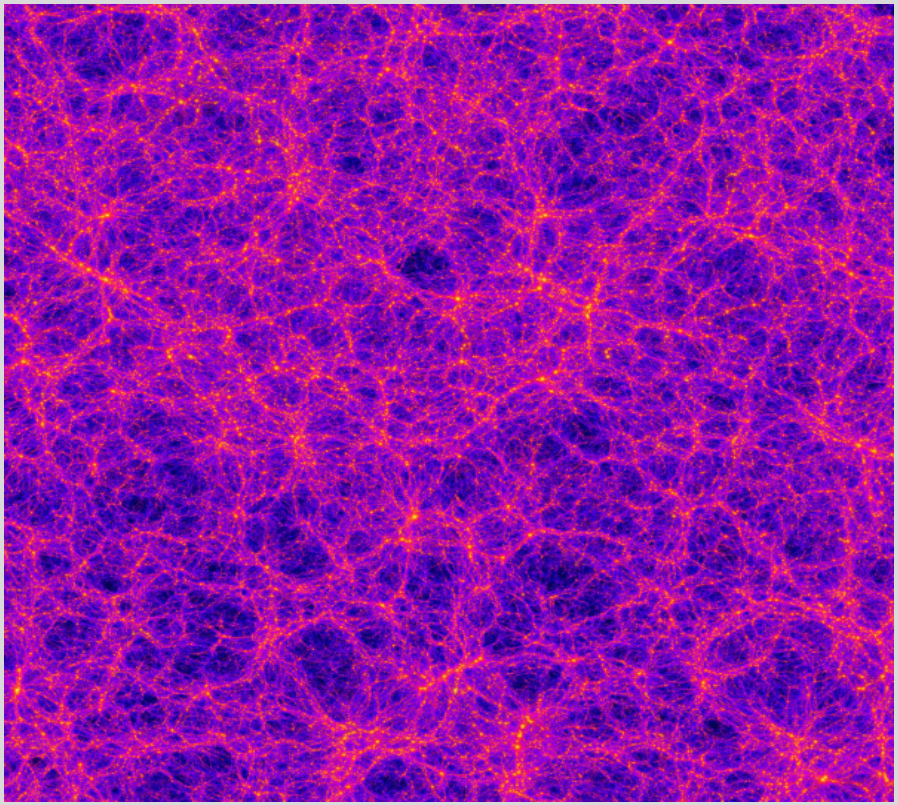
HII regions: ~1 nT

Magnetic field important also in the interstellar medium!

Intergalactic matter



$2.7 \acute{} 10^9$ light years



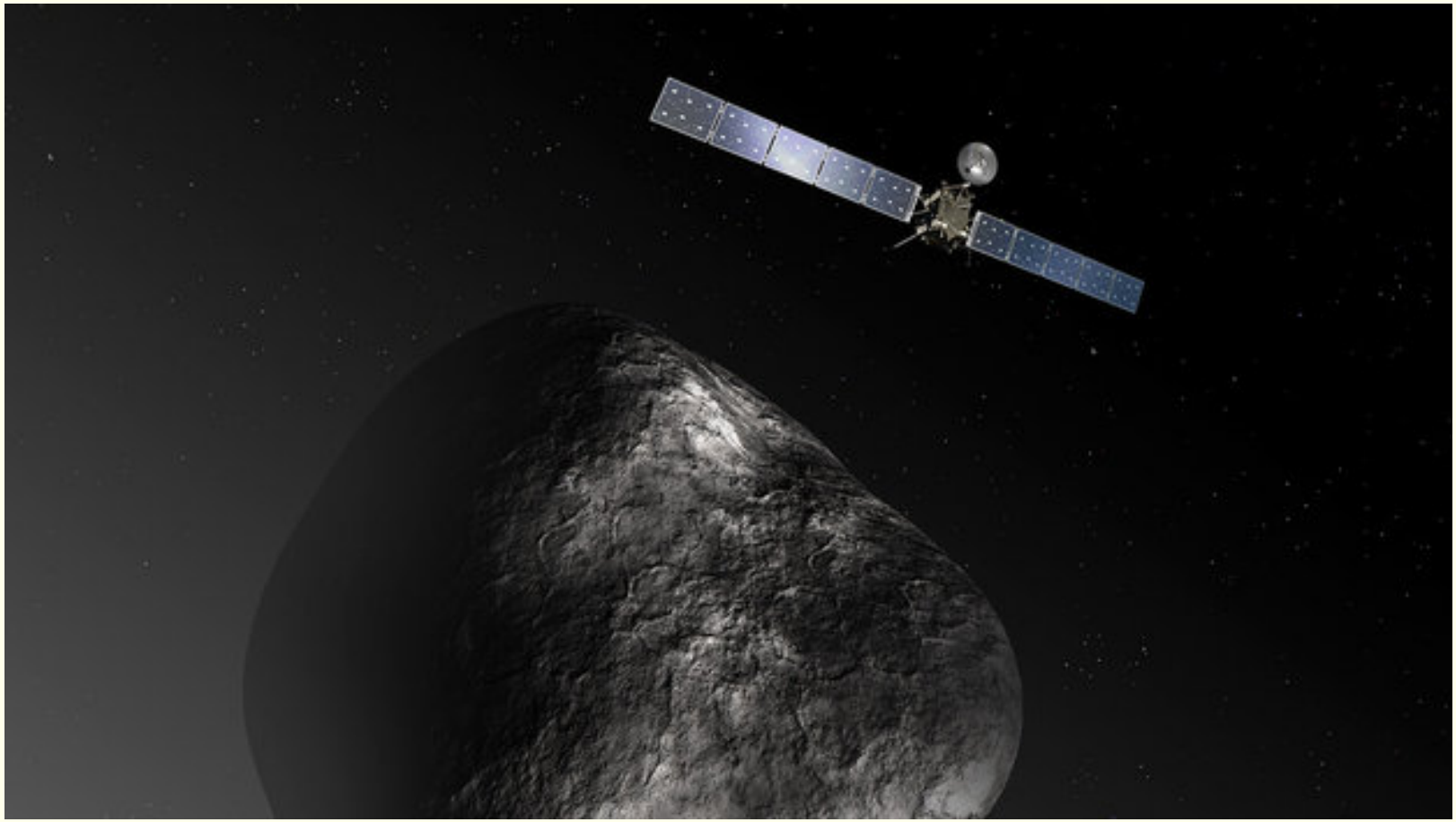
Computer simulation of intergalactic mass distribution

Intergalactic plasma

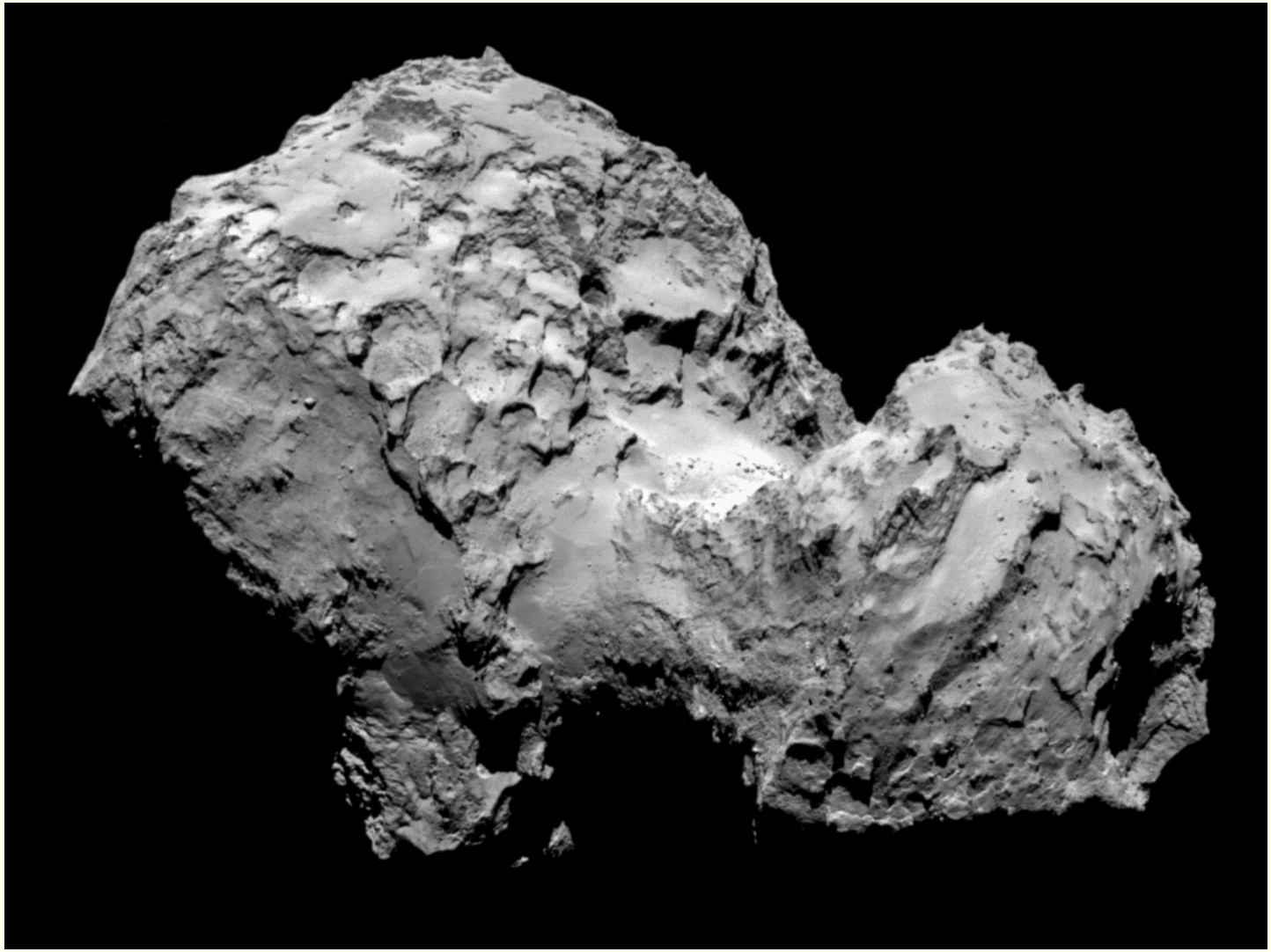
- Mostly made up of “bridges” between galaxies (~10^6 l.y.) (Radius of Milky Way is ~10^4 l.y.)
- Detected by radio telescope measurements of synchrotron radiation from energetic electrons.
- Typical densites are 10^{-4} cm^{-3}
- Typical magnetic field: B ~ 10^{-2} nT

Space research today
and
Space research in Sweden

The Rosetta mission to comet 67P/Churiumov-Gerasimenko

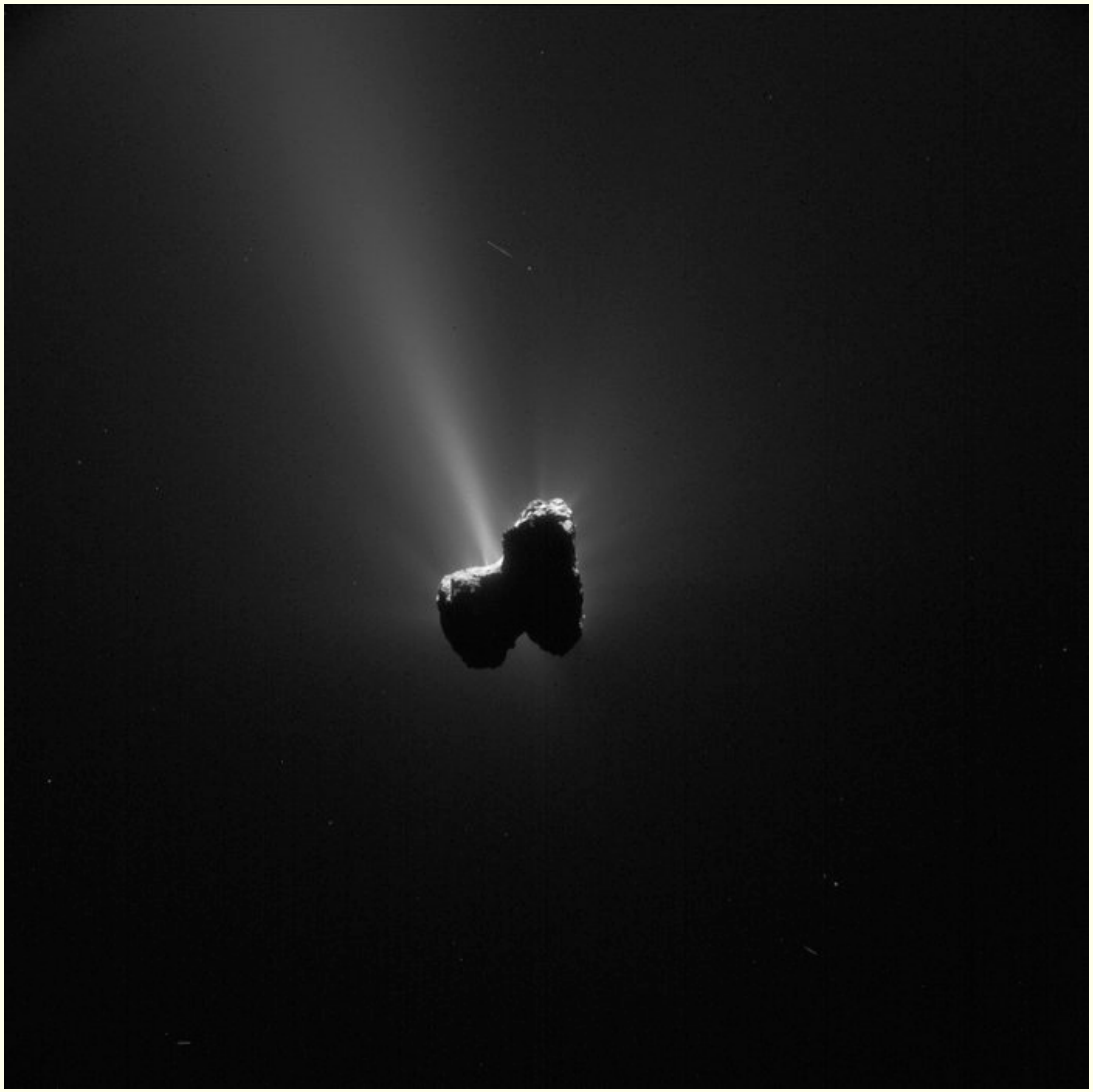


The Rosetta mission to comet 67P



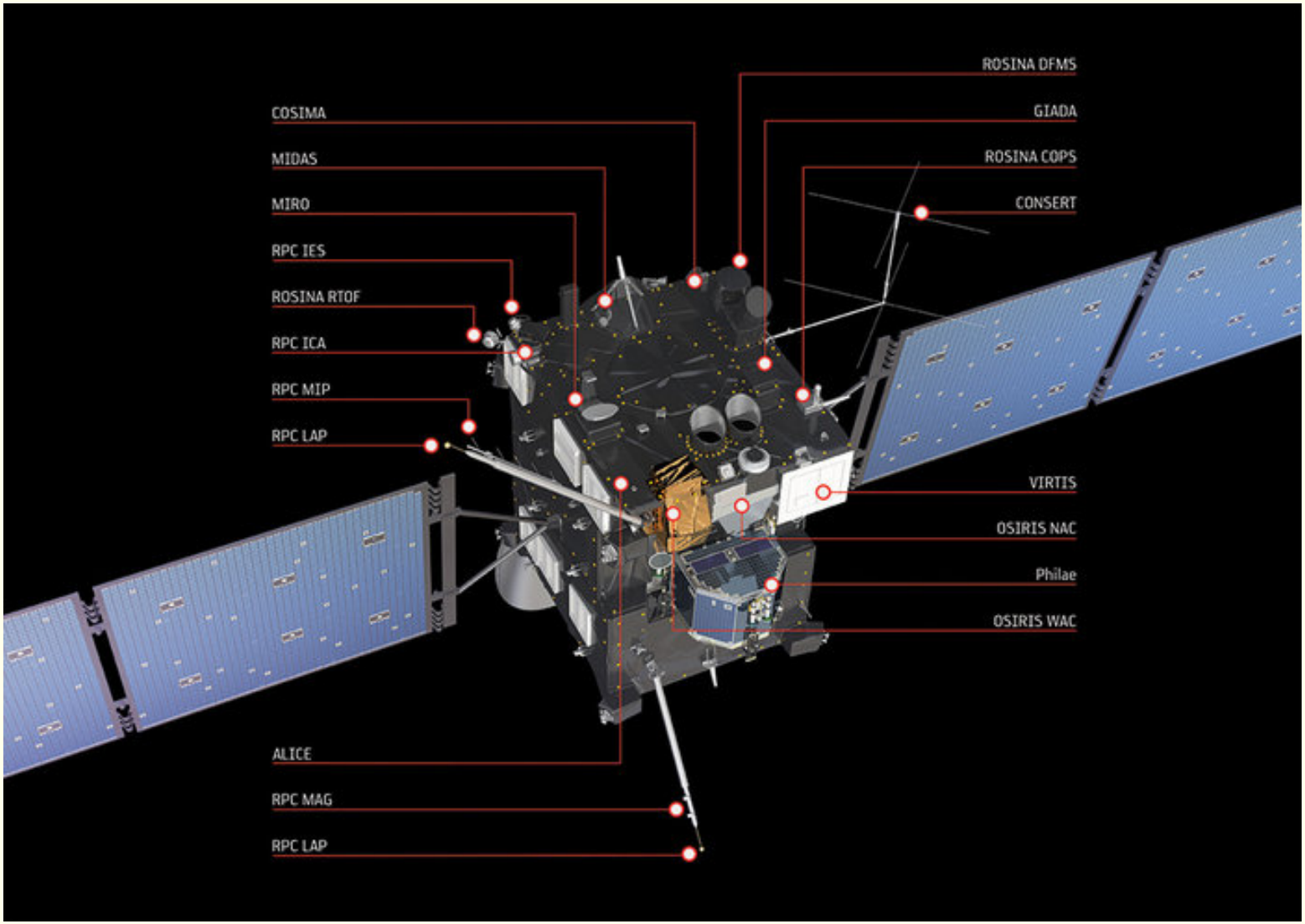
3 August 2014

The Rosetta mission to comet 67P

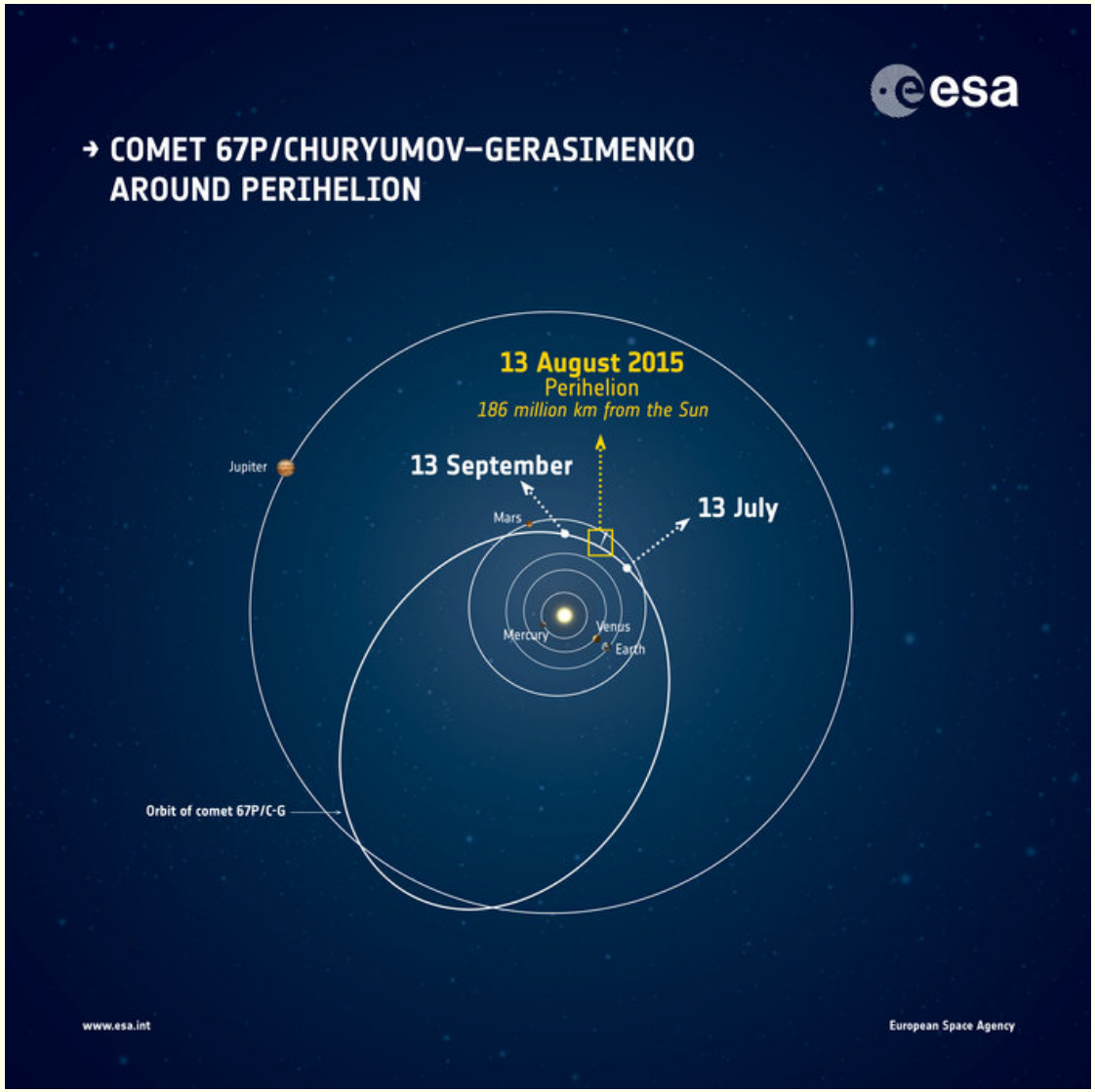


11 September 2015

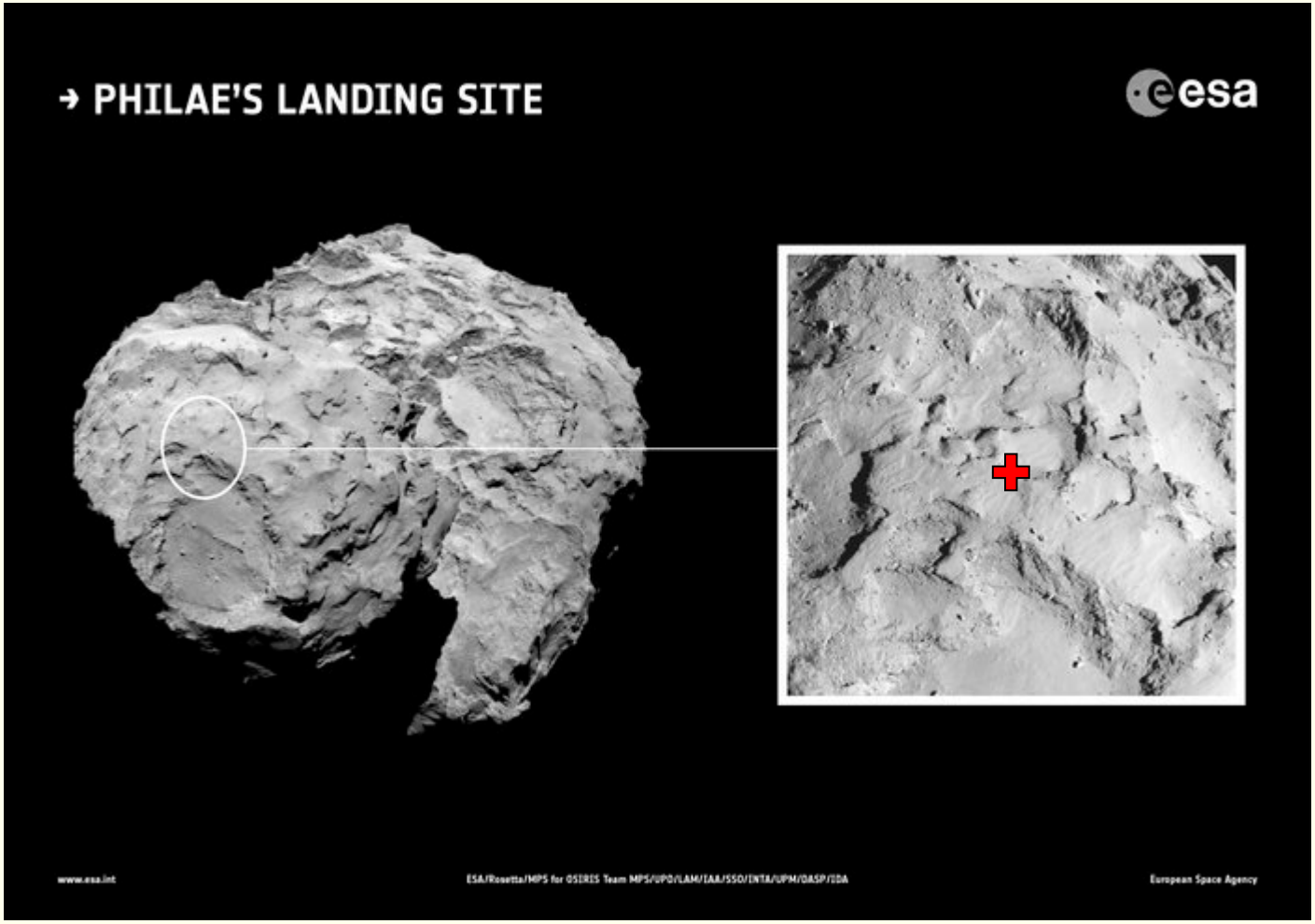
The Rosetta mission to comet 67P



Perihelion

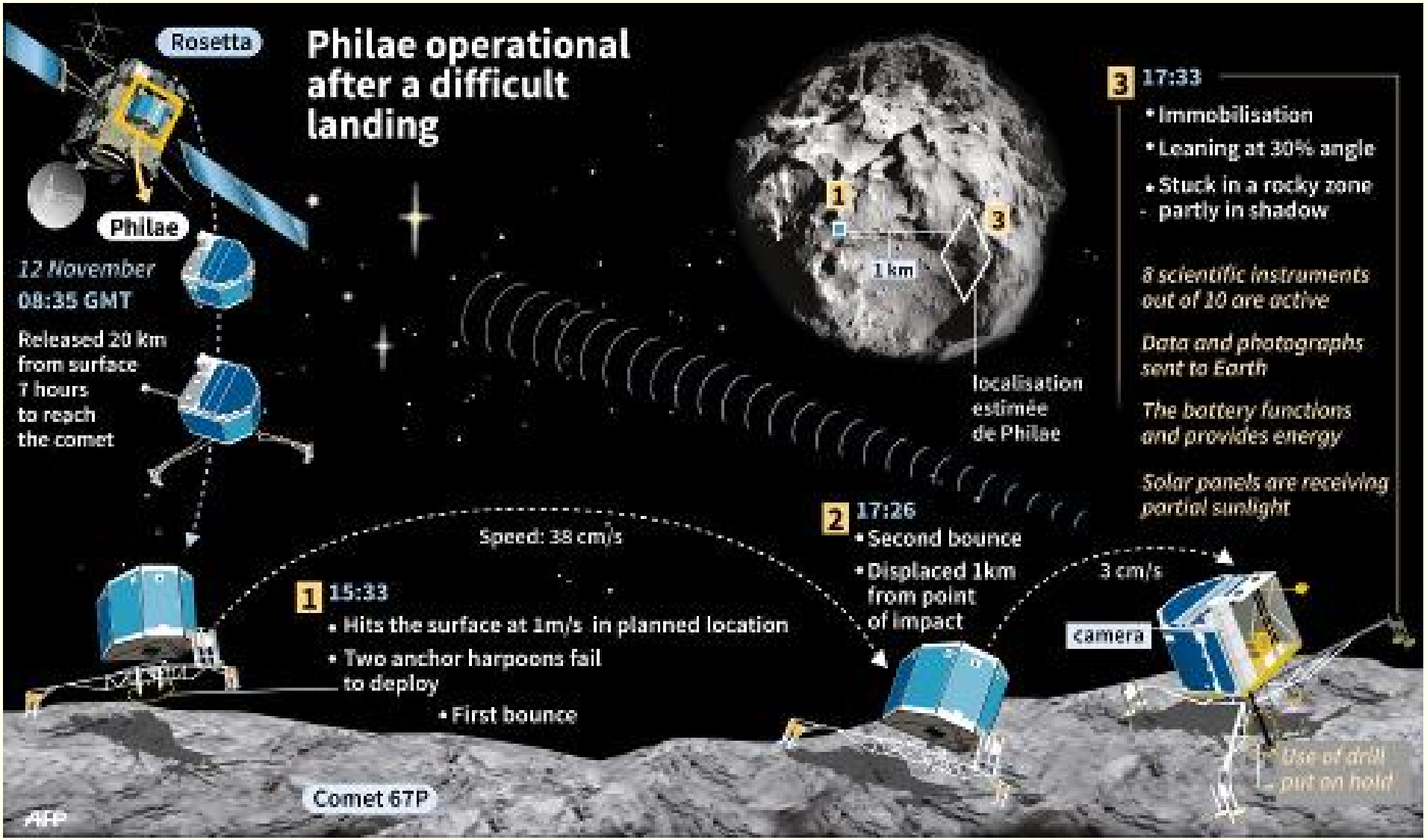

esa
→ COMET 67P/CHURYUMOV–GERASIMENKO
AROUND PERIHELION
13 August 2015
Perihelion
186 million km from the Sun
13 September
13 July
Jupiter
Mars
Mercury
Venus
Earth
Orbit of comet 67P/C-G
www.esa.int
European Space Agency

Landing site of Philae lander

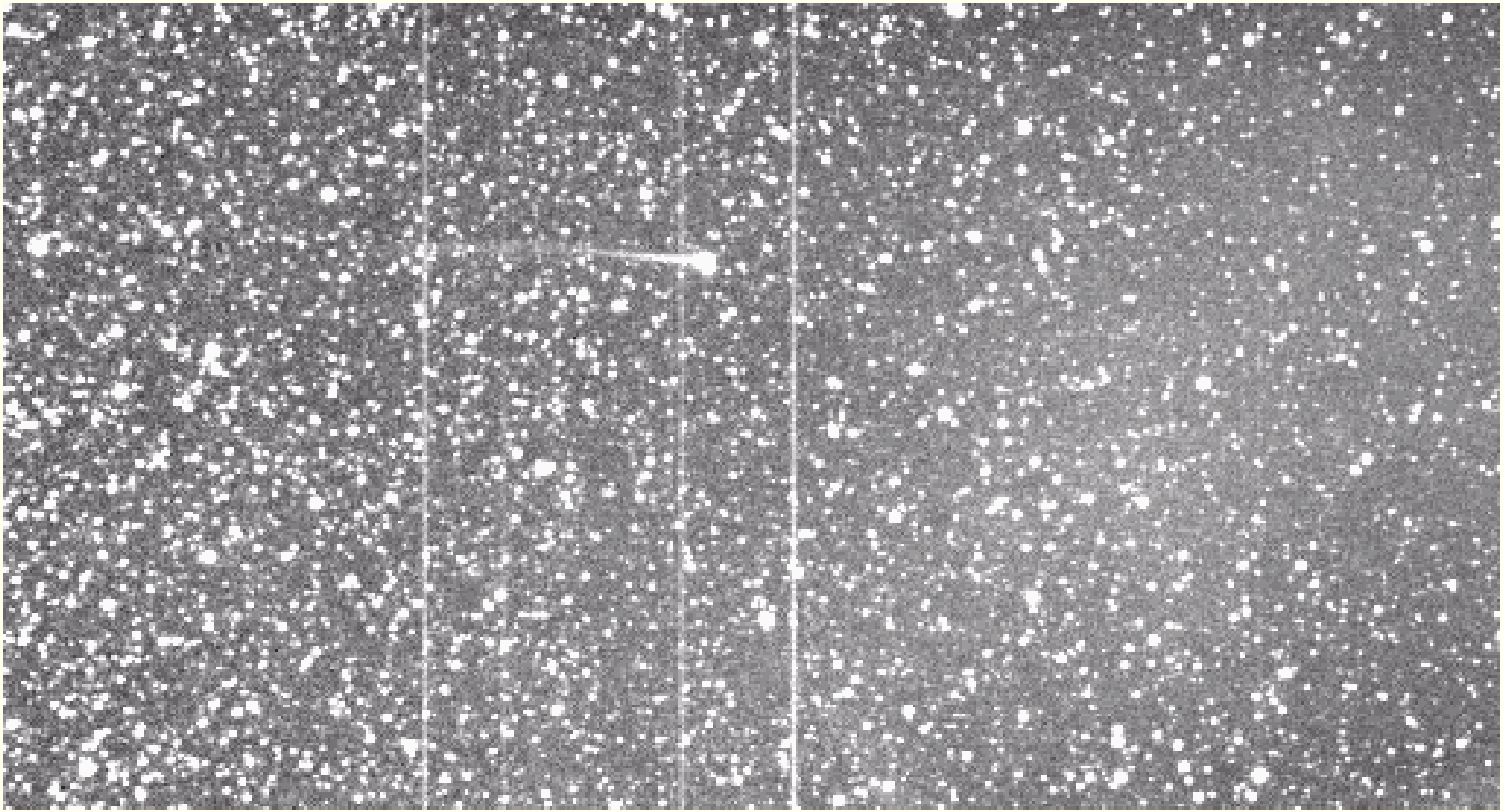


Landing Took place on November 12, 2014

Philae lander

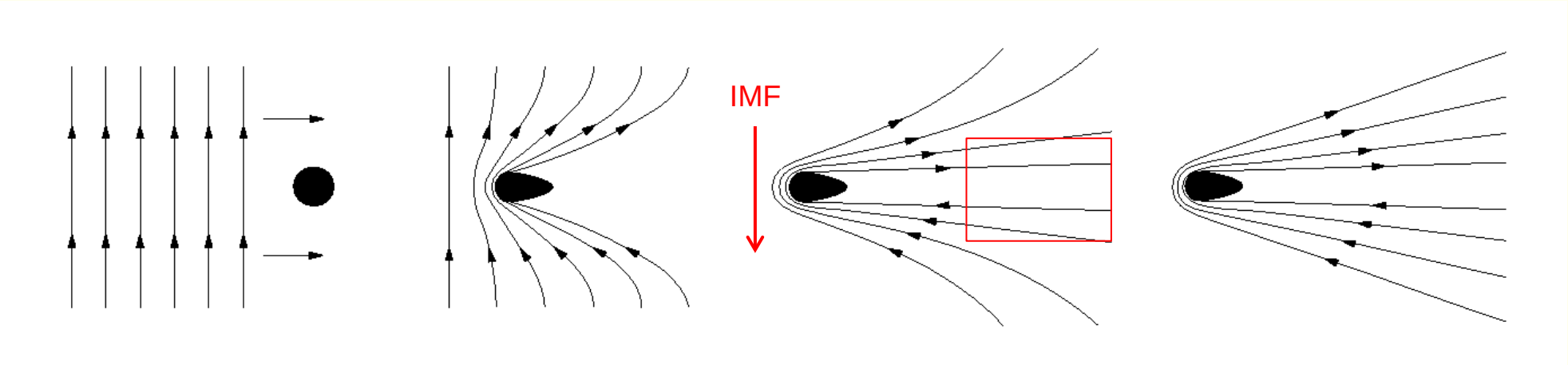

Philae operational after a difficult landing
Rosetta
Philae
12 November
08:35 GMT
Released 20 km from surface 7 hours to reach the comet
1 km
localisation estimée de Philae
3 17:33
• Immobilisation
• Leaning at 30% angle
• Stuck in a rocky zone - partly in shadow
8 scientific instruments out of 10 are active
Data and photographs sent to Earth
The battery functions and provides energy
Solar panels are receiving partial sunlight
Speed: 38 cm/s
2 17:26
• Second bounce
• Displaced 1km from point of impact
3 cm/s
1 15:33
• Hits the surface at 1m/s in planned location
• Two anchor harpoons fail to deploy
• First bounce
camera
Use of drill put on hold
Comet 67P
AFP

Tail reconnection events?



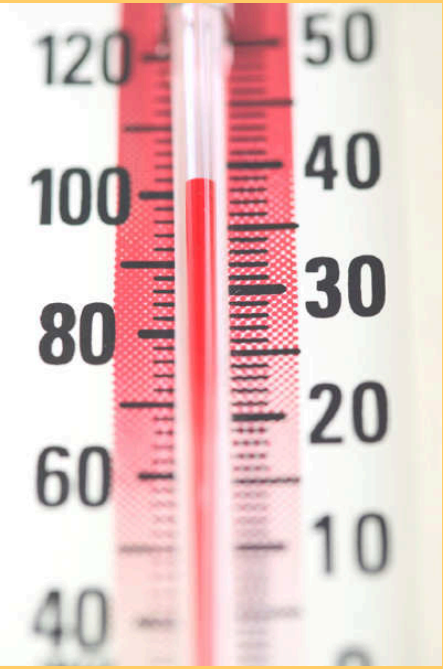
Comet Encke, STEREO-A

Comets, induced magnetotail

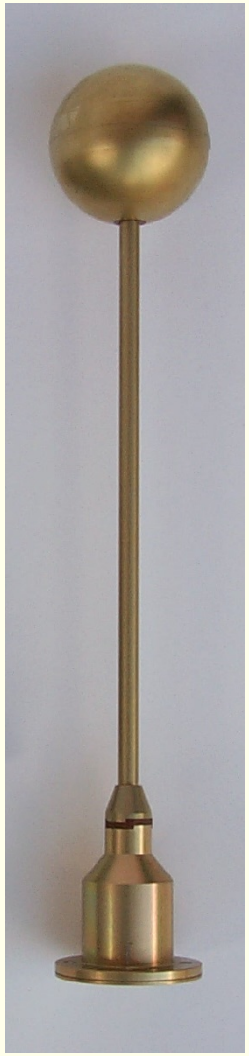


Where does reconnection take place?

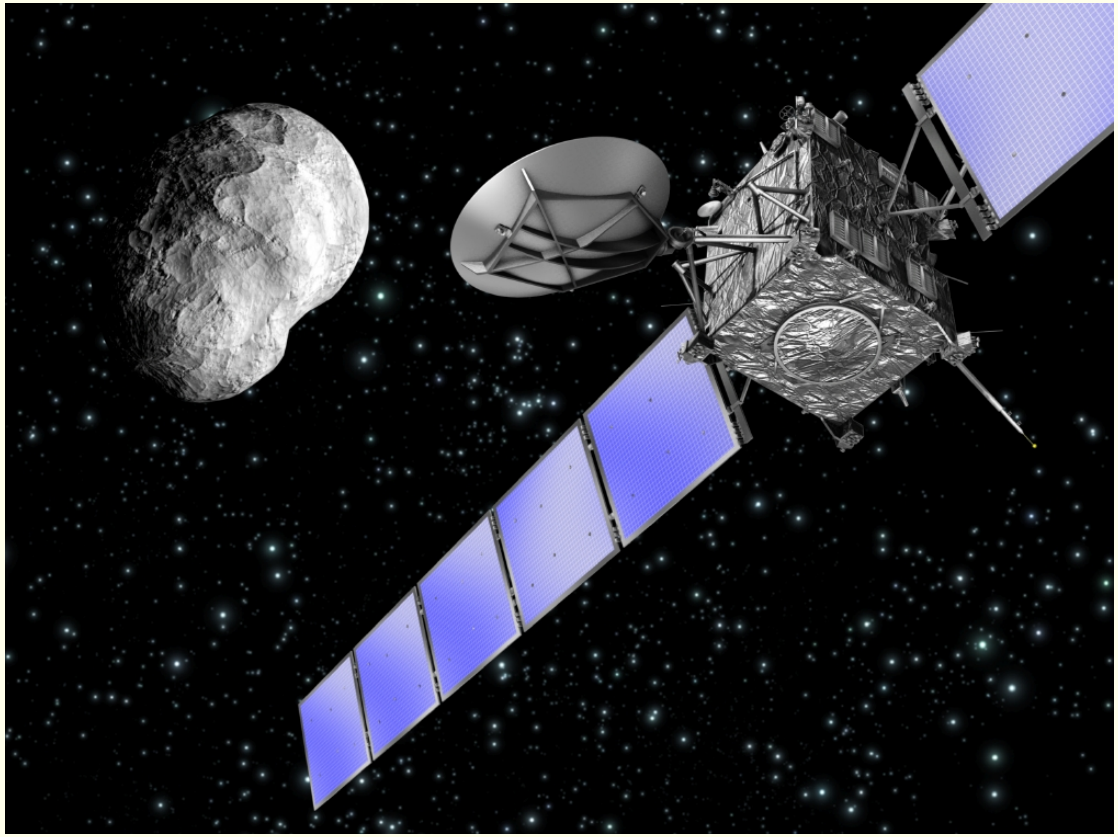
How can we measure temperatures and densities in space?



Langmuir probe

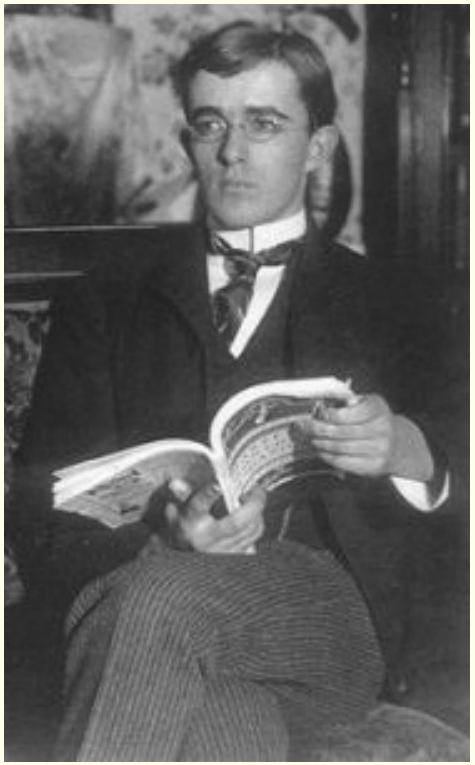


Langmuir probe from the Rosetta spacecraft



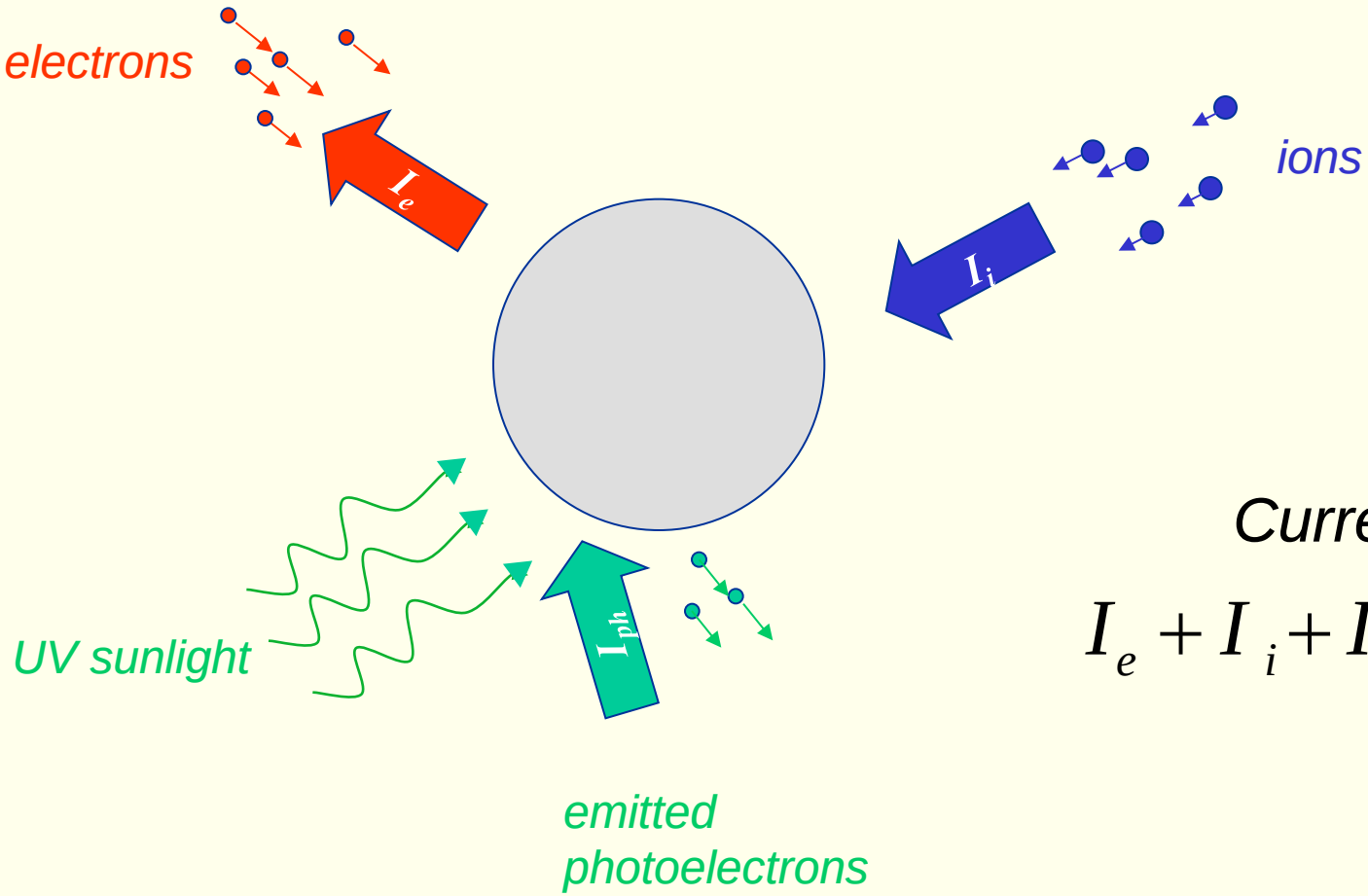
Rosetta spacecraft, launched 2004. Now placed in orbit around the comet 67/P Churyumov-Gerasimenko.

Irving Langmuir



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

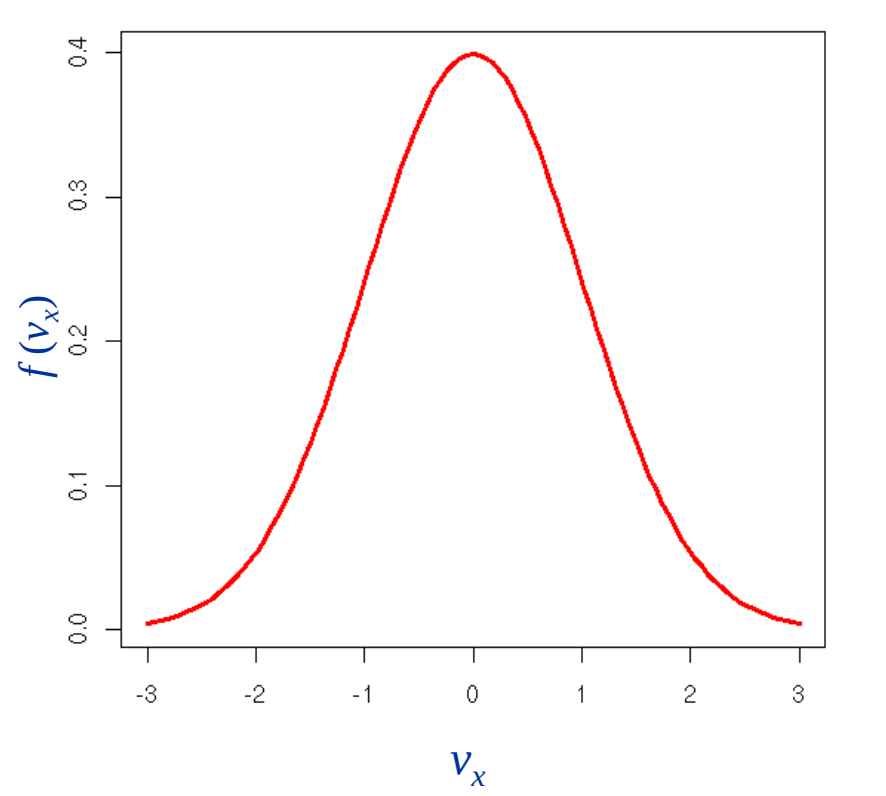
Electrical potential of metal sphere in a plasma



Current balance:

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

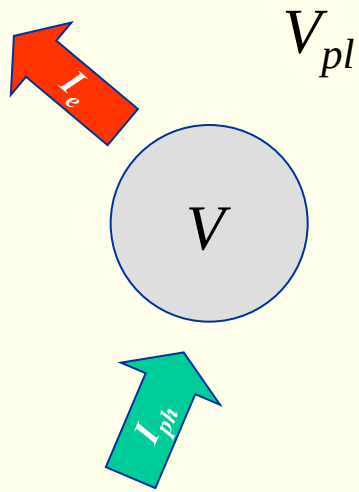
Maxwellian distribution of velocities in a gas



$$f(v_x) = Ce^{\frac{-mv_x^2}{2k_BT}}$$

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

Floating potential



I positive into the probe

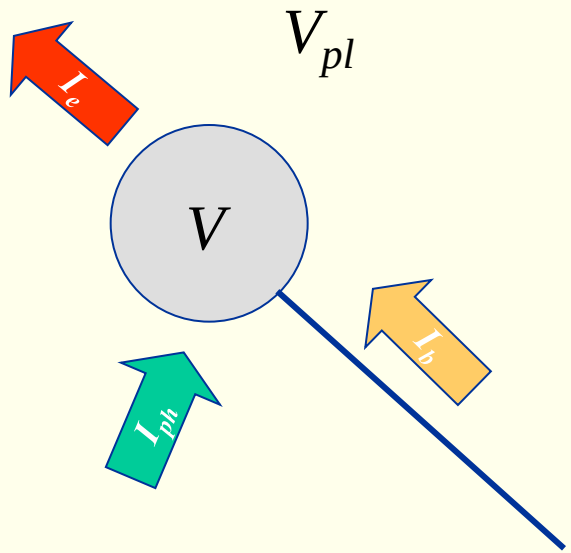
$$I_e + I_{ph} = 0$$

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

$$\Rightarrow$$

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

Electrical potential of metal sphere in a plasma with bias current



I positive into the probe

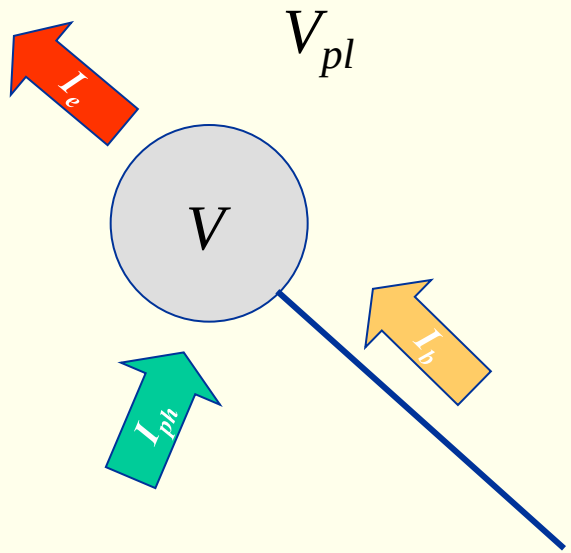
$$I_e + I_{ph} + I_b = 0$$

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

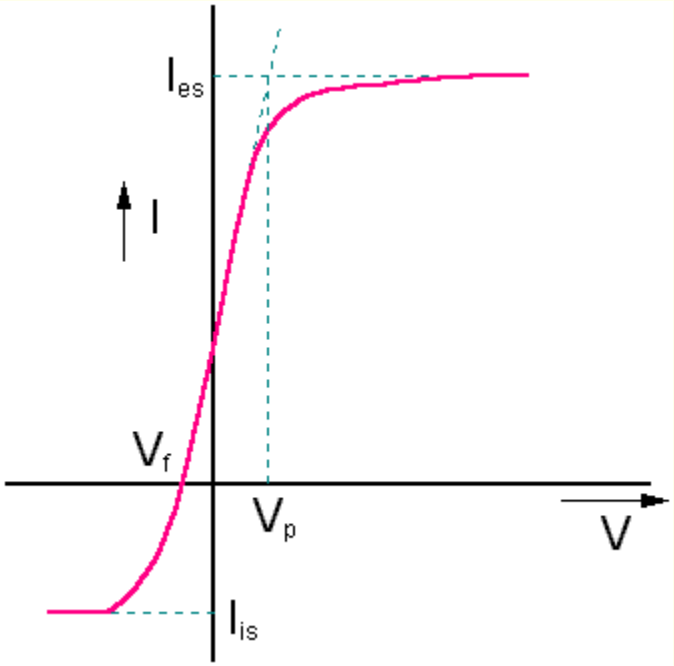
$$\Rightarrow$$

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

Langmuir probe

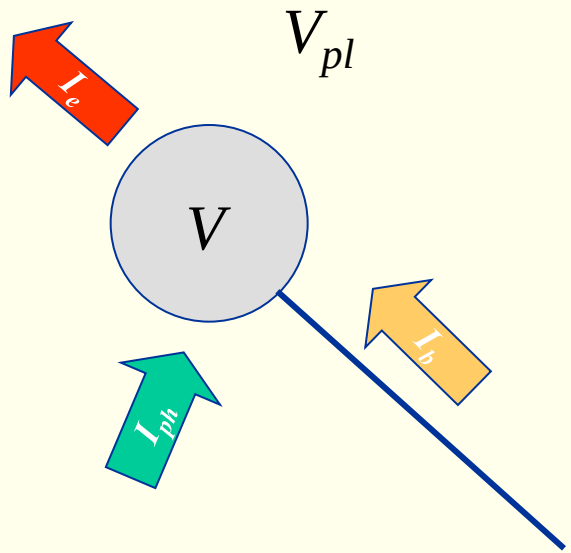


$$V - V_{pl} = \frac{k_B T_e}{e} \ln\left(\frac{I_{ph} + I_b}{A n_e e} \sqrt{\frac{2\pi m_e}{k_B T_e}} \right)$$



I positive into the probe

Langmuir probe



I positive into the probe

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

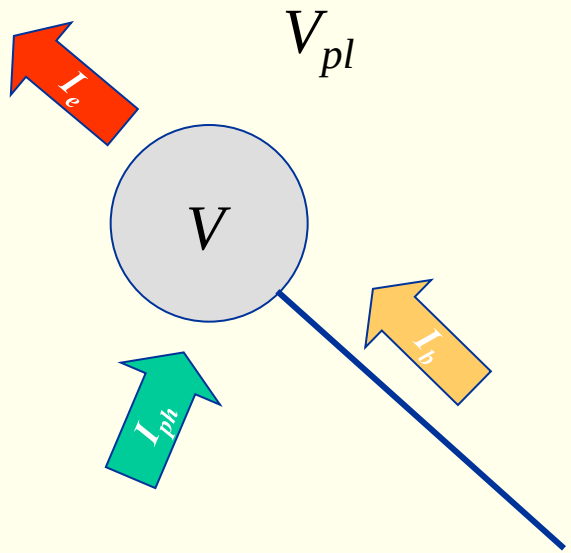
$$\Rightarrow$$

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

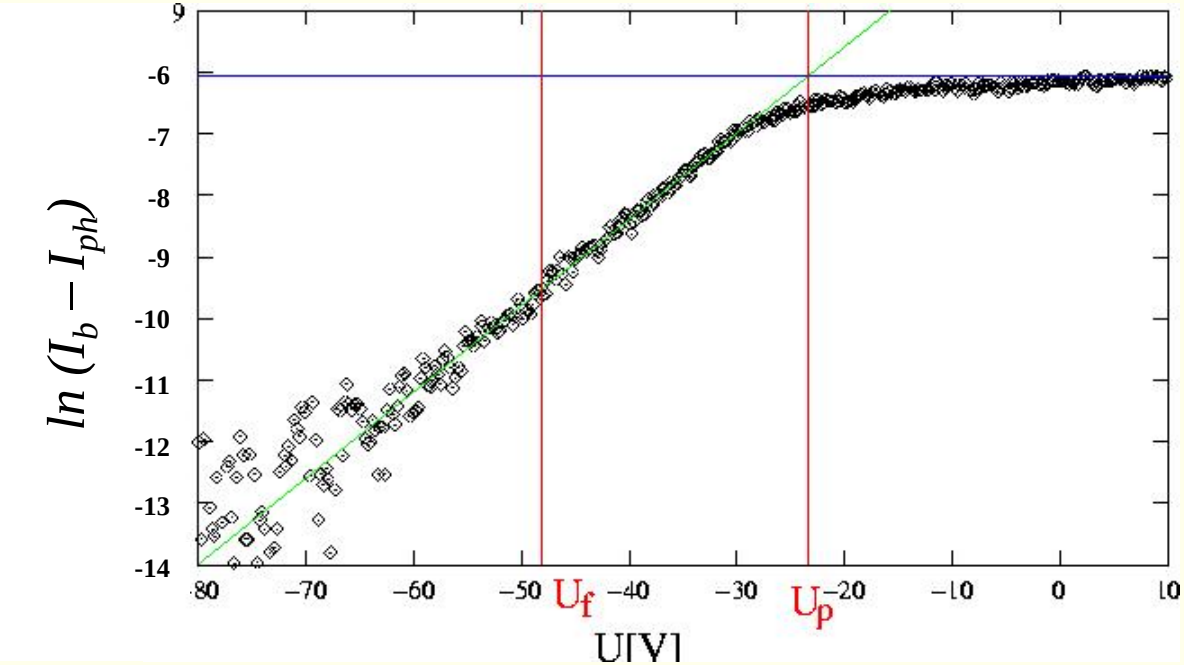
$$= \ln\left(An_e e\sqrt{\frac{k_B T_e}{2\pi m_e}}\right) + \ln\left(e^{\frac{e(V-V_{pl})}{k_B T_e}}\right) = C + \frac{e(V-V_{pl})}{k_B T_e}$$

Langmuir probe

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

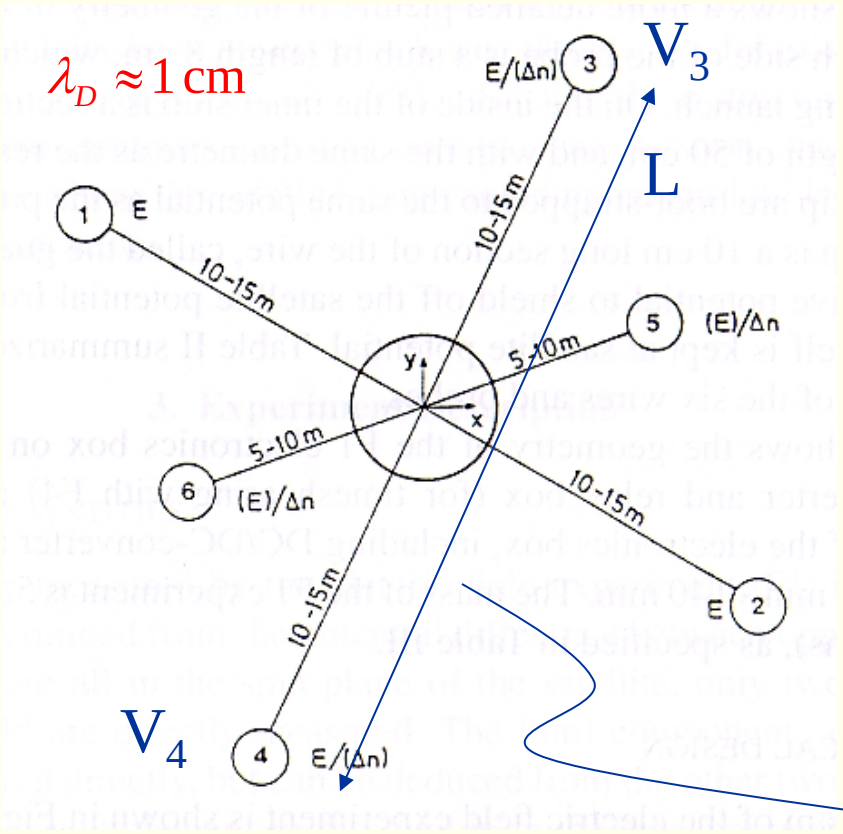


I positive into the probe



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

Measurement of E-field in space plasmas



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

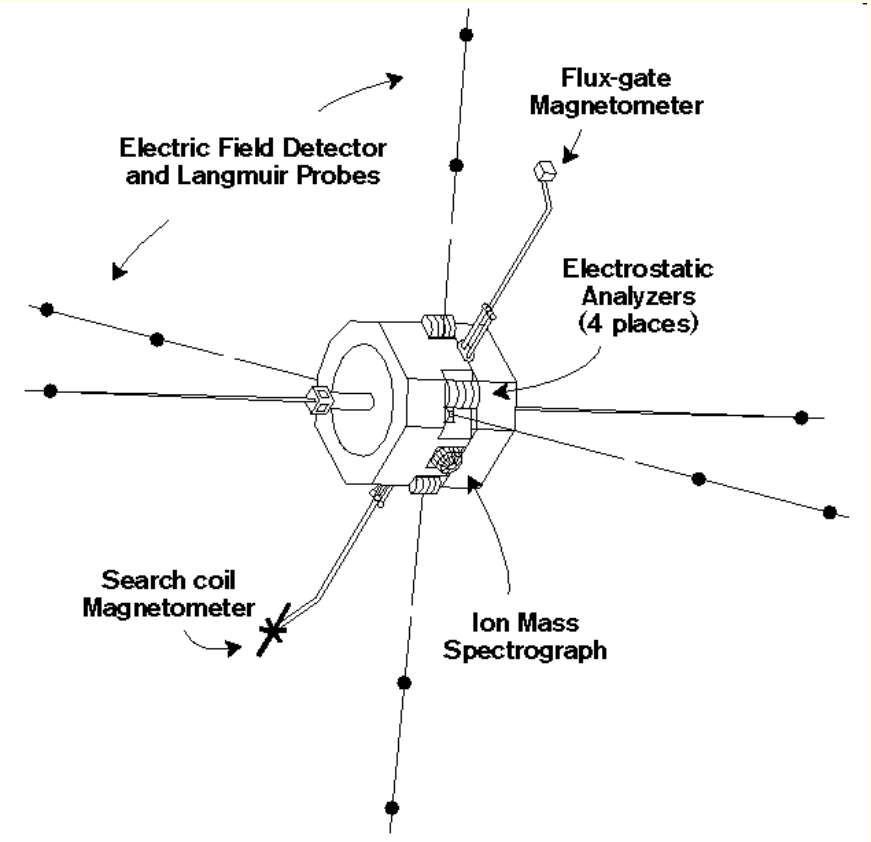
Potential between plasma and probe

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.

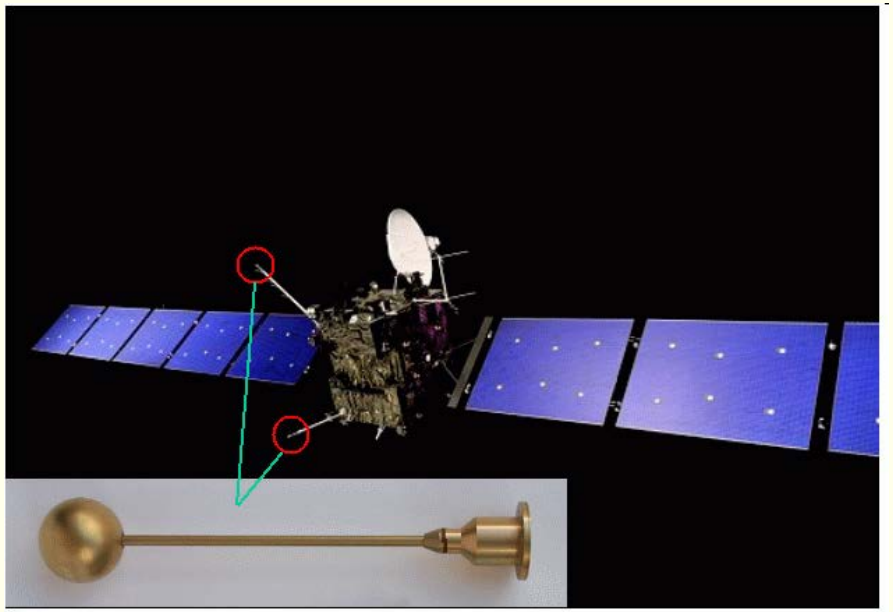
$$V_3 = (V_{probe,3} - V_{plasma})$$

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

Langmuir probe and electric field probes on a spaceraft



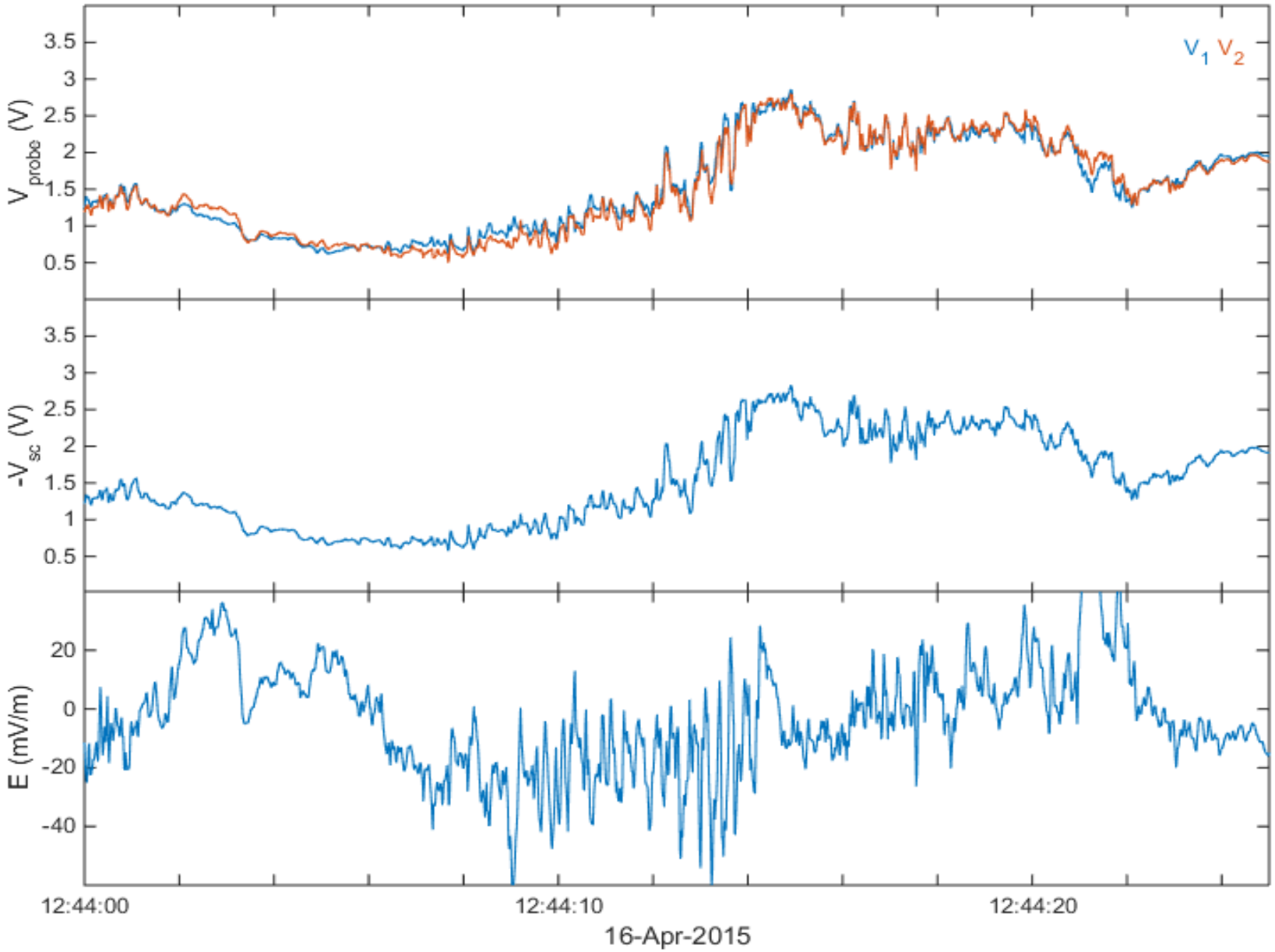
FAST

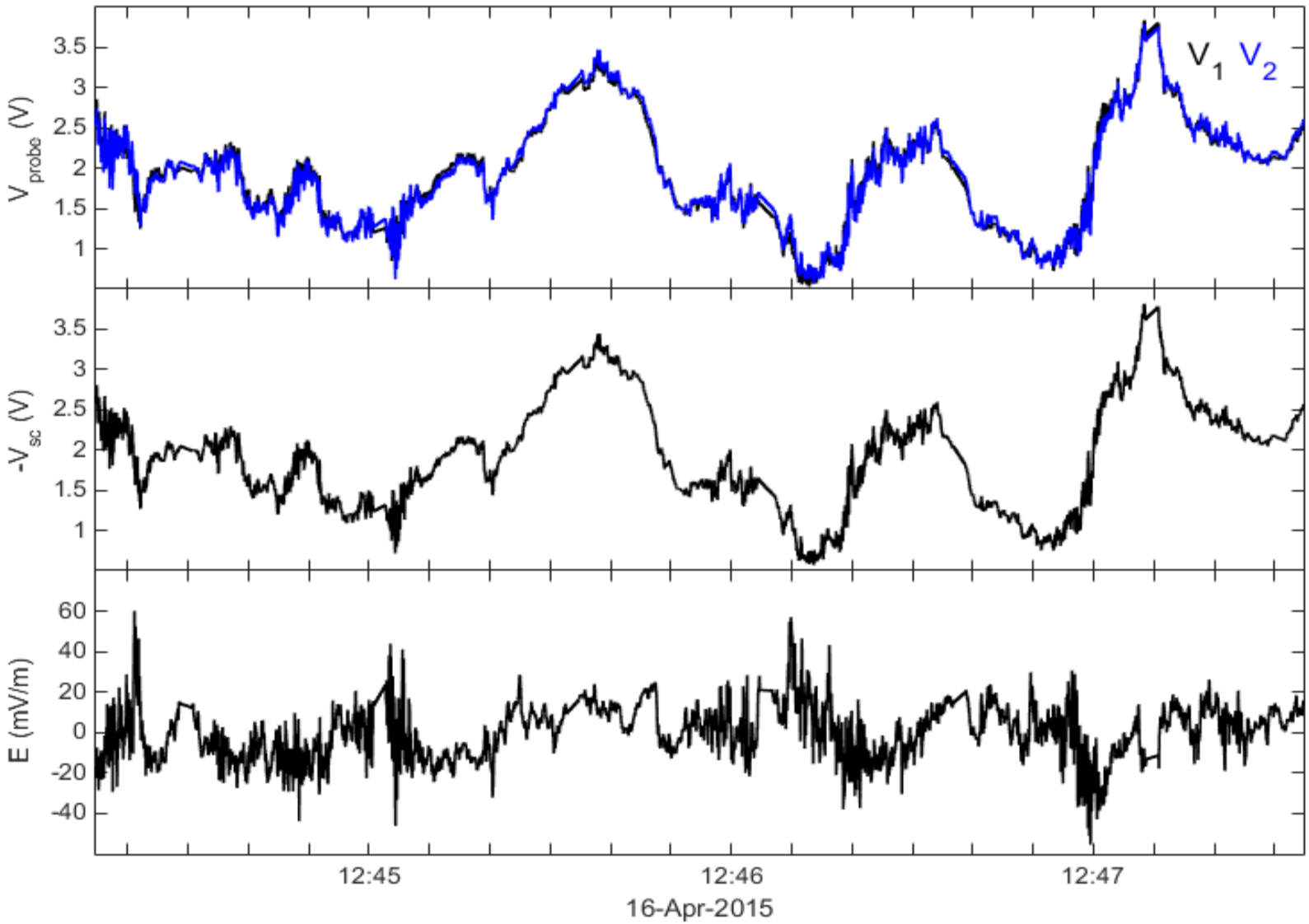


Rosetta

Electric field measurements from Rosetta

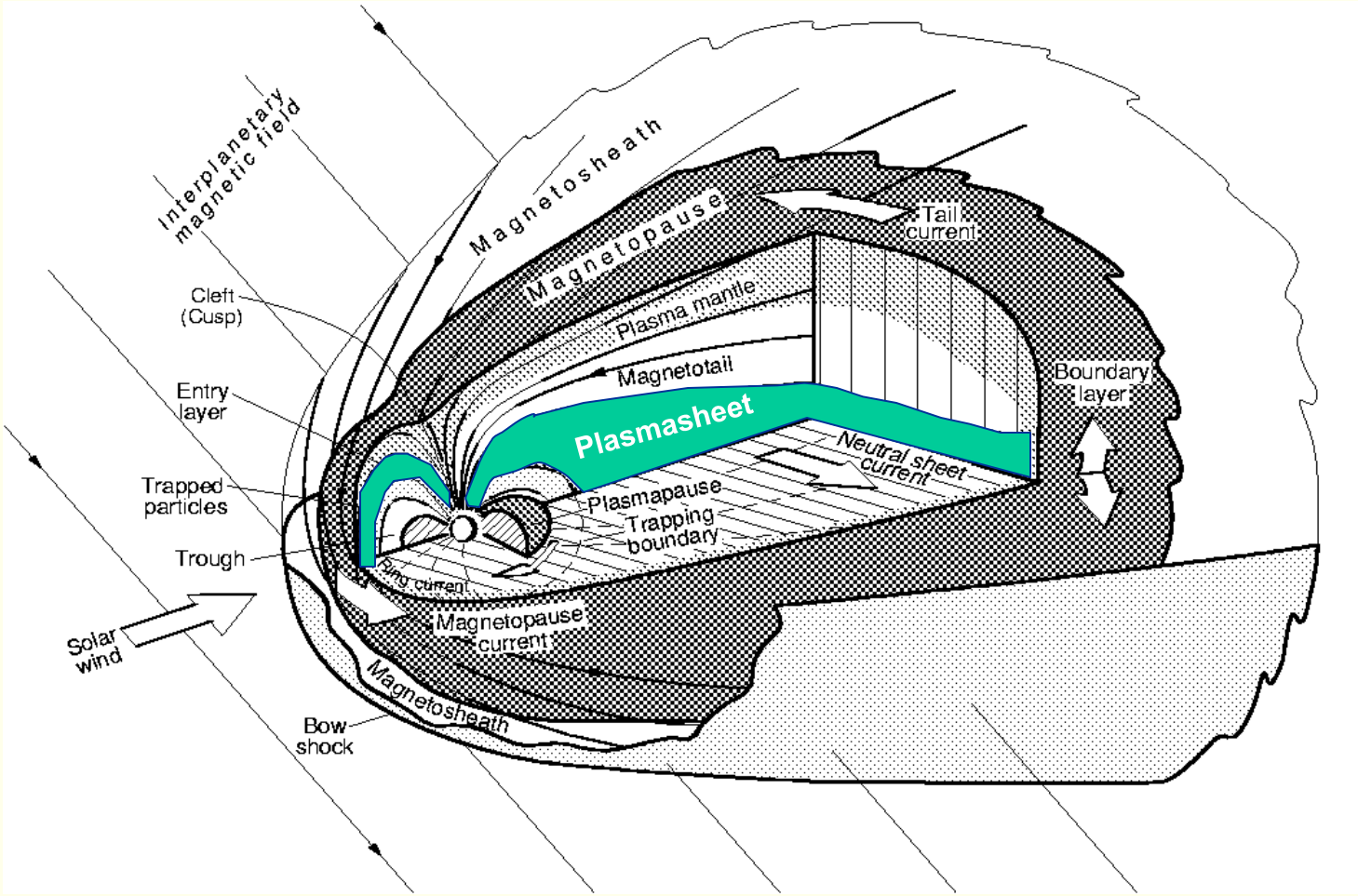
2015-04-16


V1 V2
V probe (V)
-V sc (V)
E (mV/m)
3.5
3
2.5
2
1.5
1
0.5
20
0
-20
-40
12:44:00
12:44:10
12:44:20
16-Apr-2015

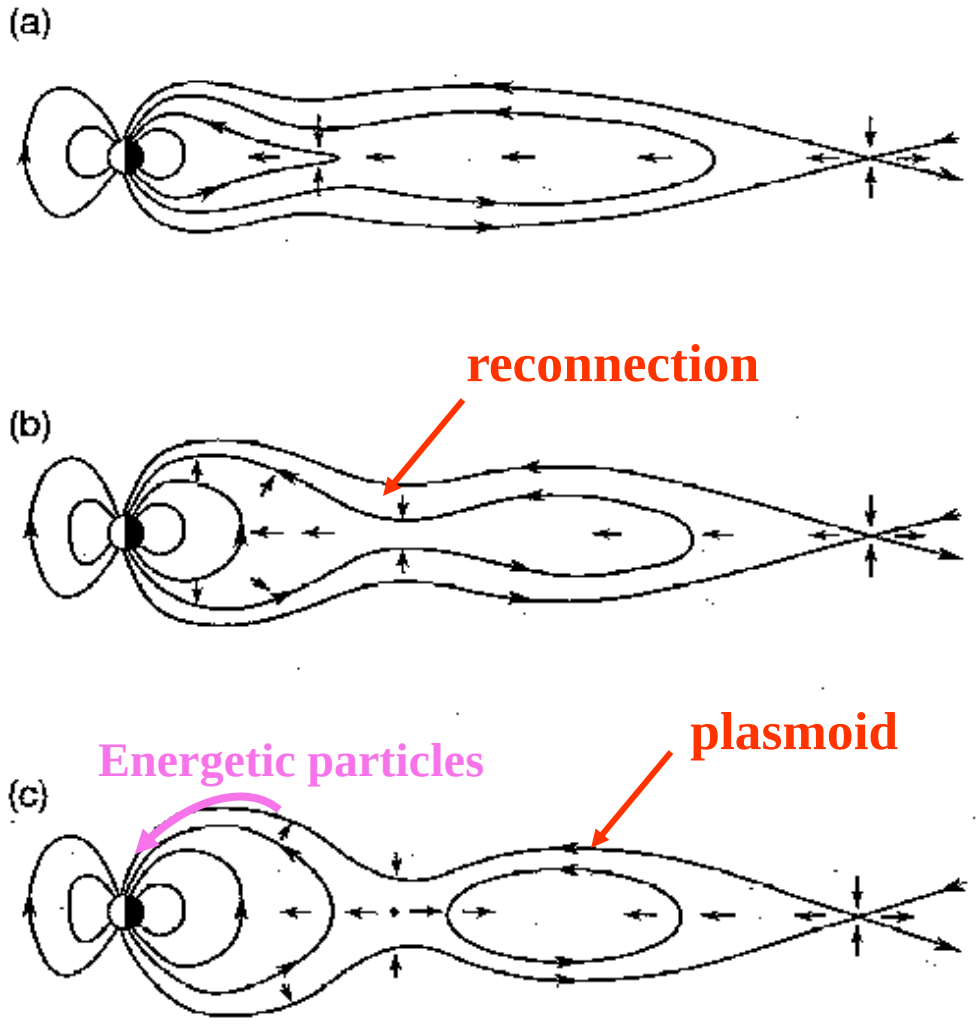

V1 V2
V probe (V)
-V sc (V)
E (mV/m)
3.5
3
2.5
2
1.5
1
60
40
20
0
-20
-40
12:45
12:46
12:47
16-Apr-2015

Some unsolved problems

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



Substorms



How do they start?

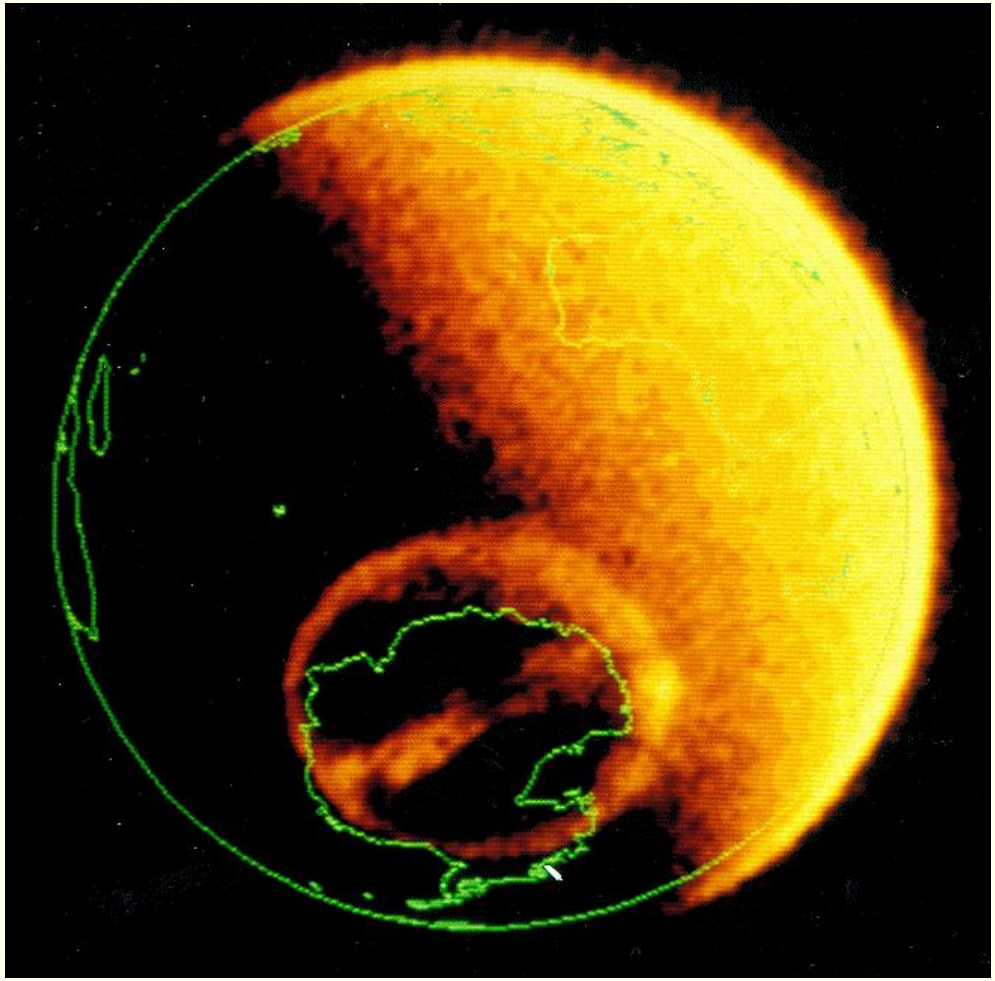
•An internal instability? ("Rubber band breaks")

or

• An external trigger, e.g. IMF turns from northward to southward? ("Rubber band released")

Theta-aurora

How is it created?



Why is the corona so hot?

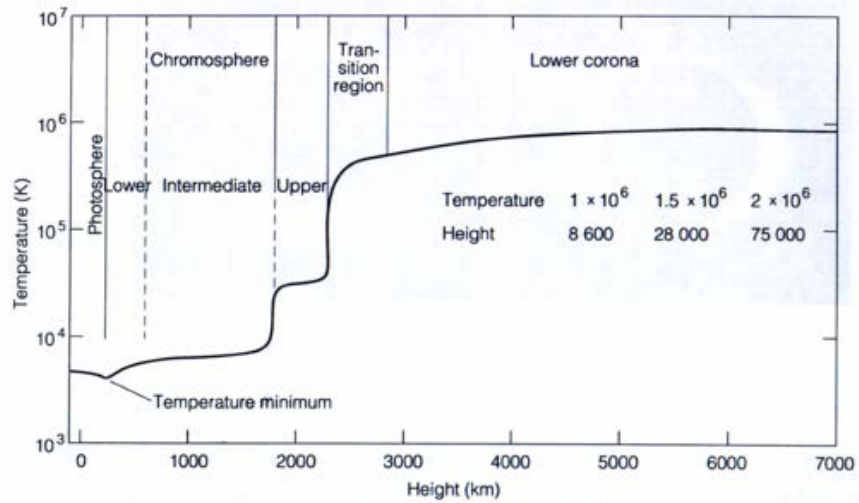
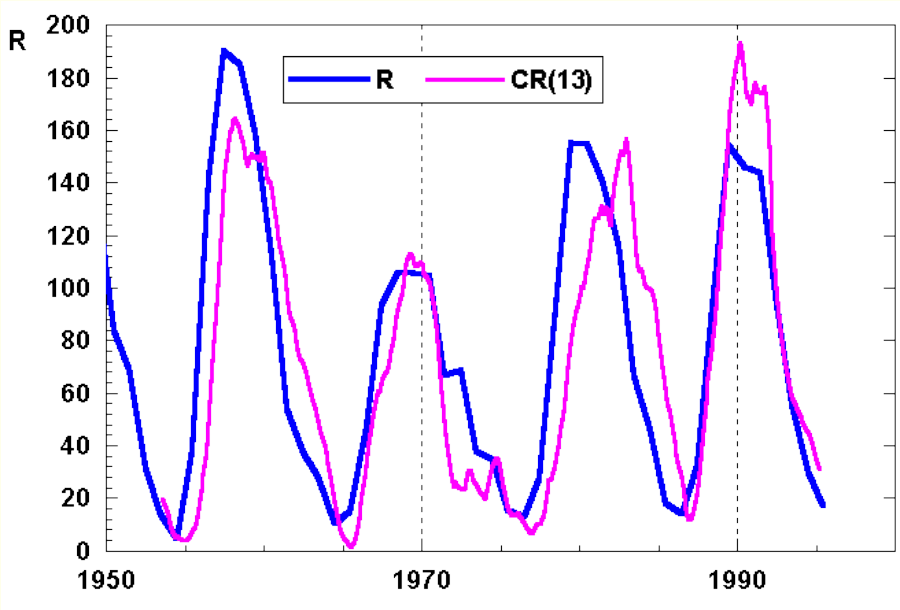


Figure 5.3. Distribution of average temperature in the solar atmosphere (Athay 1976).

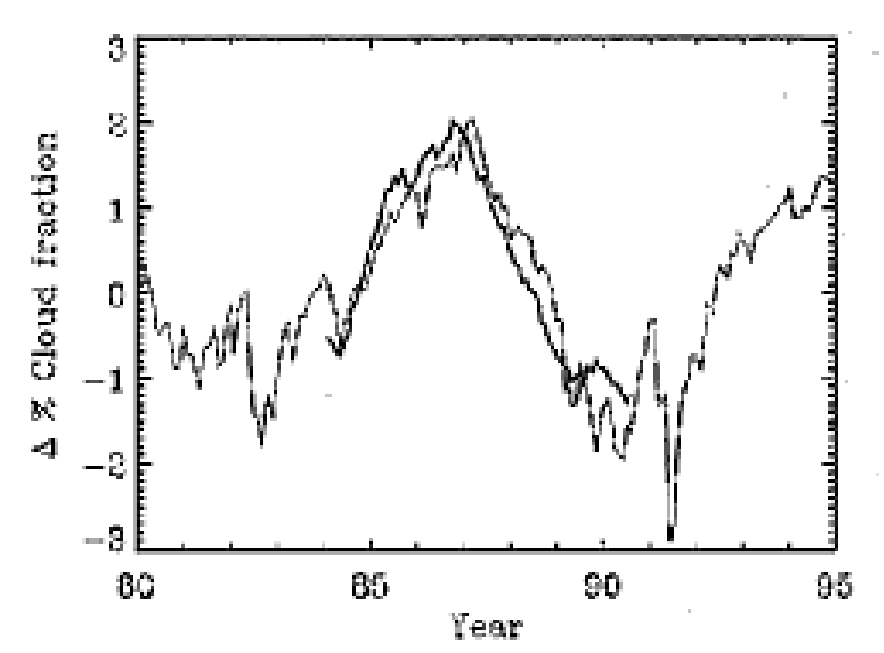
Two main theories:

1) Energy transported by plasma waves
2) Reconnection frees magnetic energy

Cosmic radiation and climate

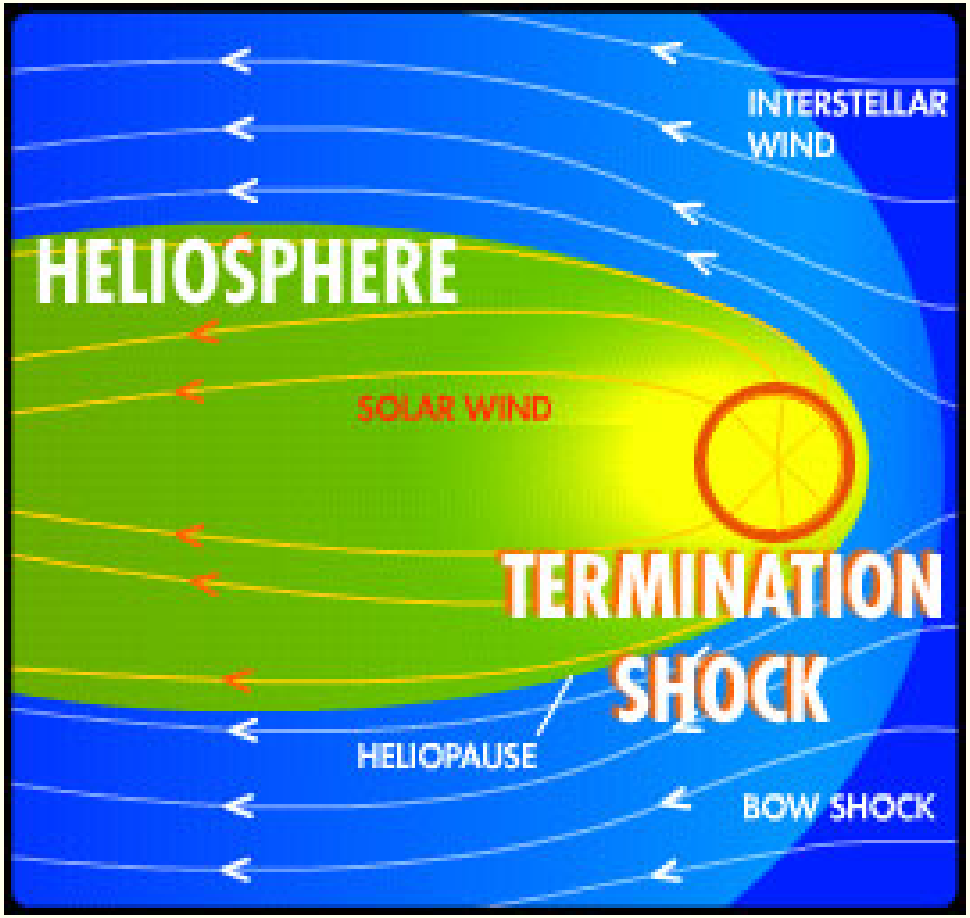


Sun spot number (R) and flux of cosmic radiation



Variations in cloud cover and cosmic radiation

Heliosphere



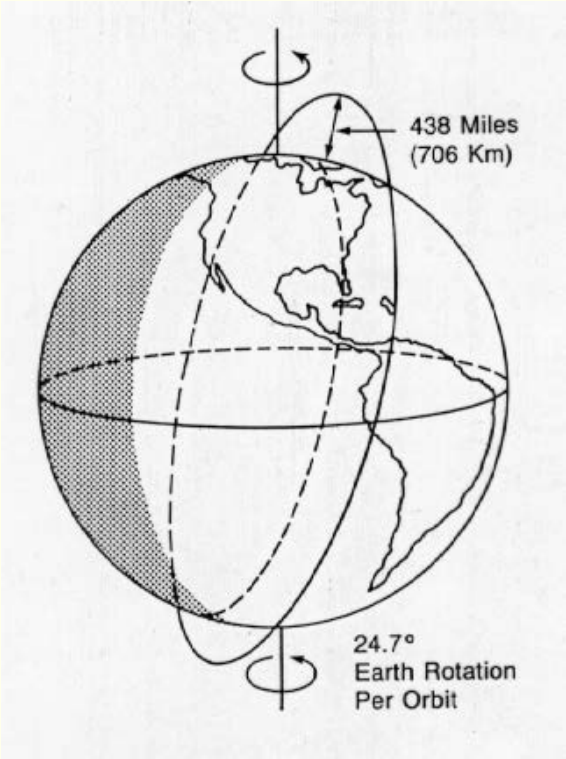
How is the heliosphere/heliopause created by the interaction of the solar wind and the interplanetary medium?

What is the role of the 'termination shock', where the solar wind is abrubtly deccelerated to below 100 km/s?

Swedish space research

Satellites

Rockets

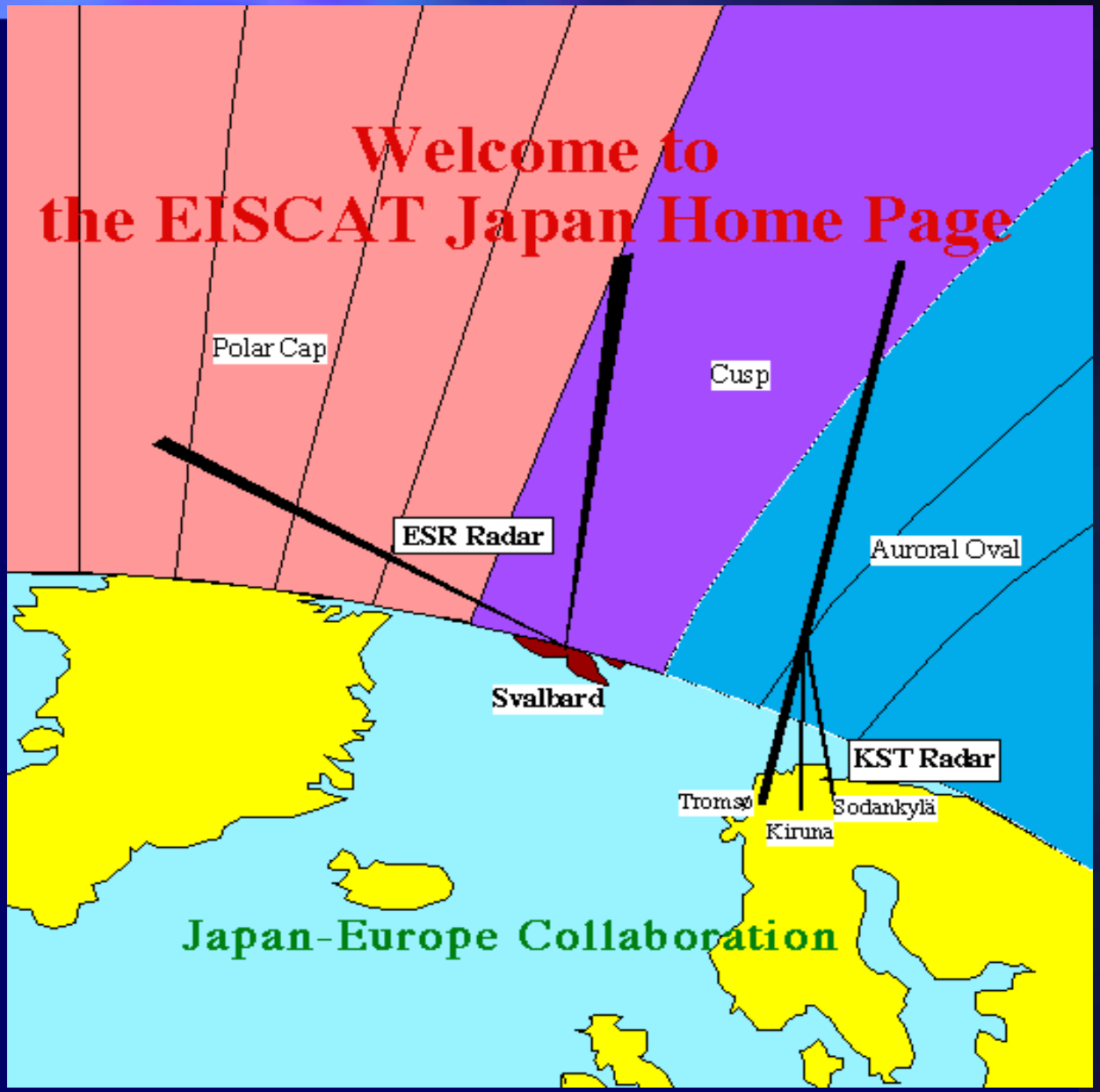


Ground-based measurements: *radar, optical instruments*

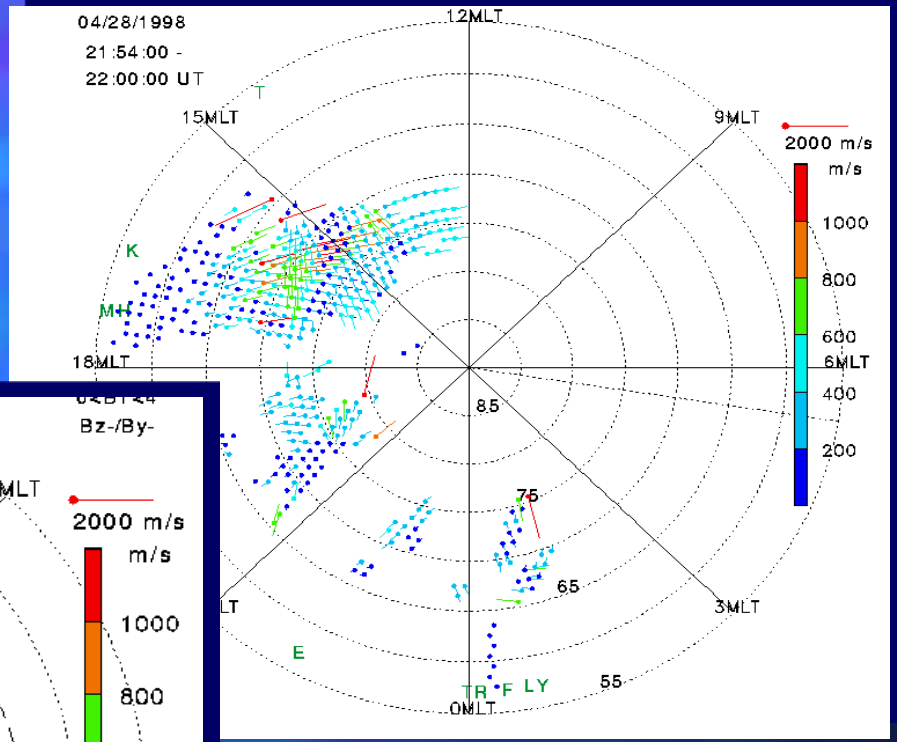
Three IS Radars

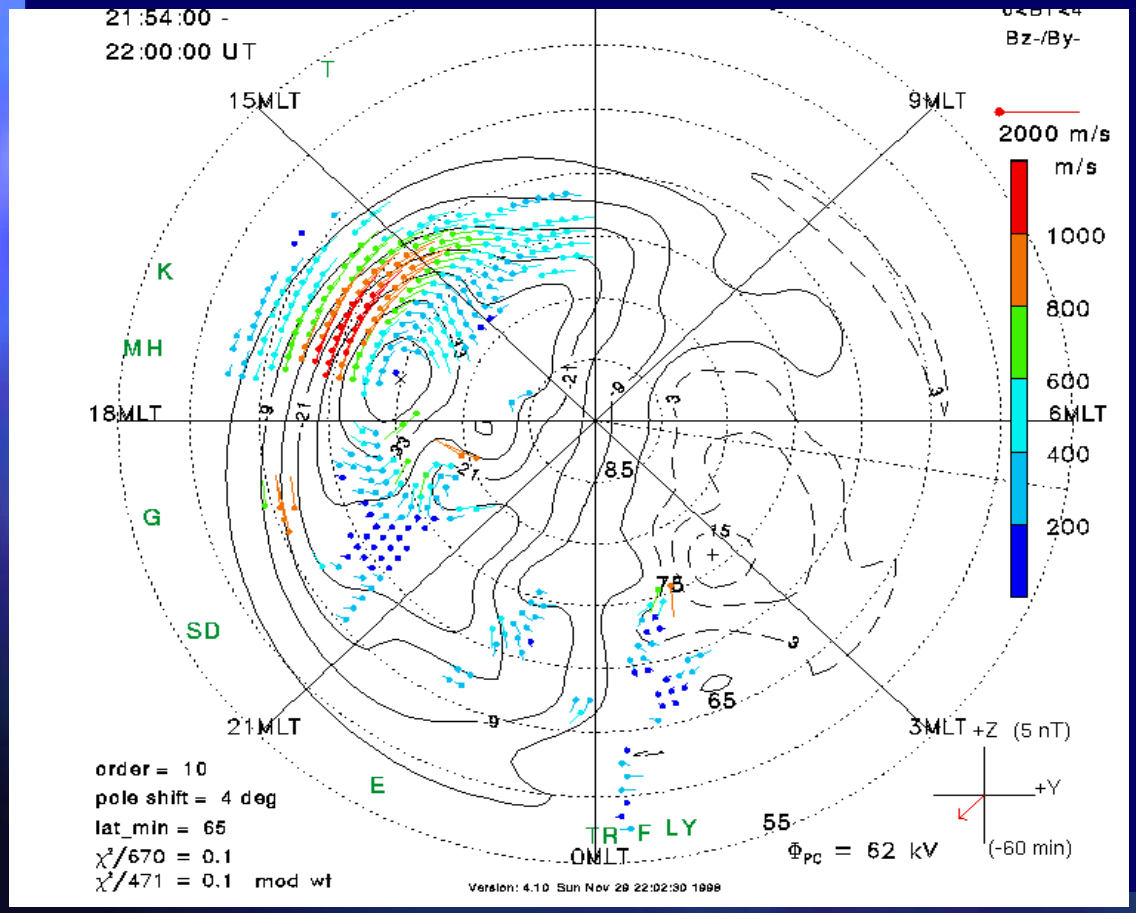
Location

- World's only multistatic IS radar
- Three co-operating installations
- Heater
- Other instruments
  - Optical
  - Satellite
  - Radio wave



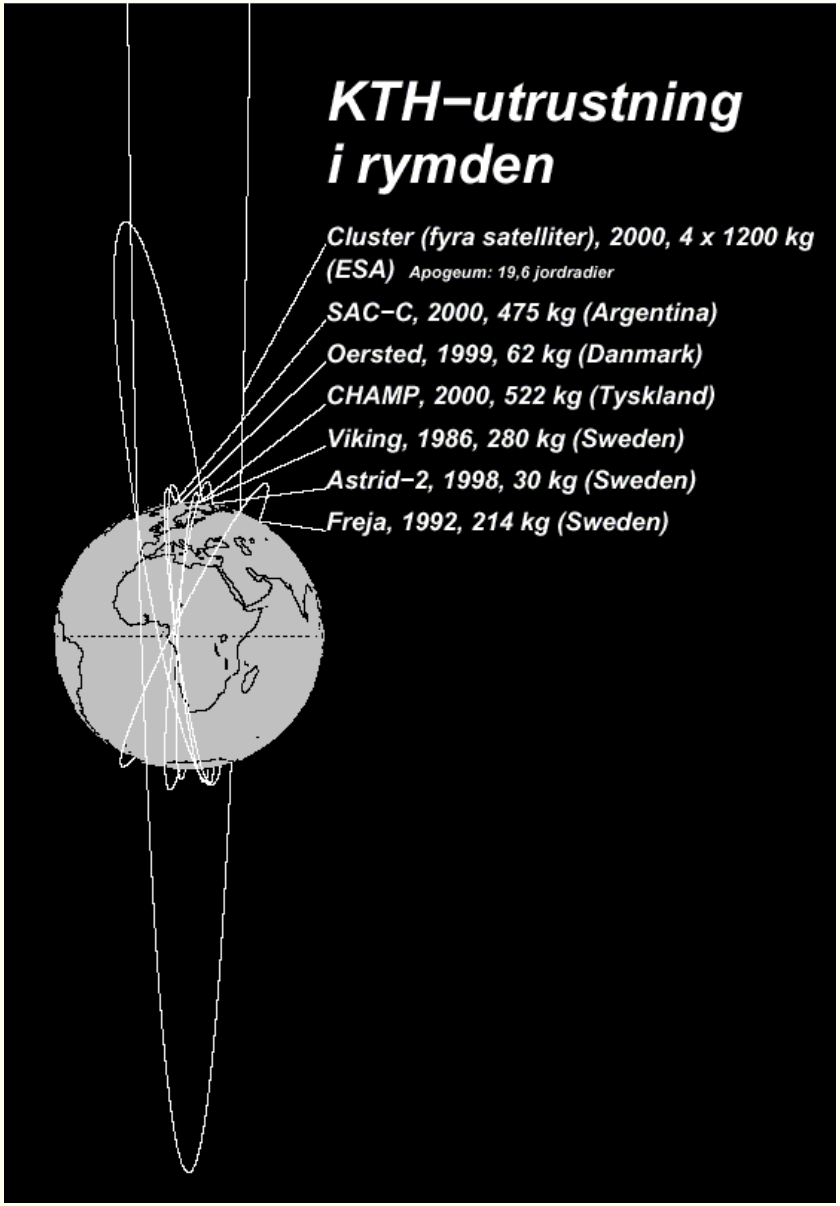
SuperDARN + ISR's



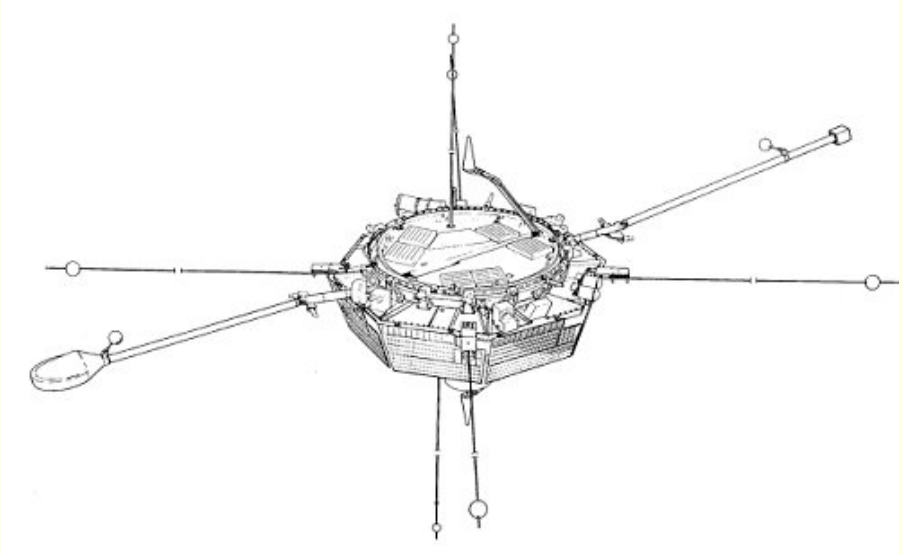


Swedish research satellites

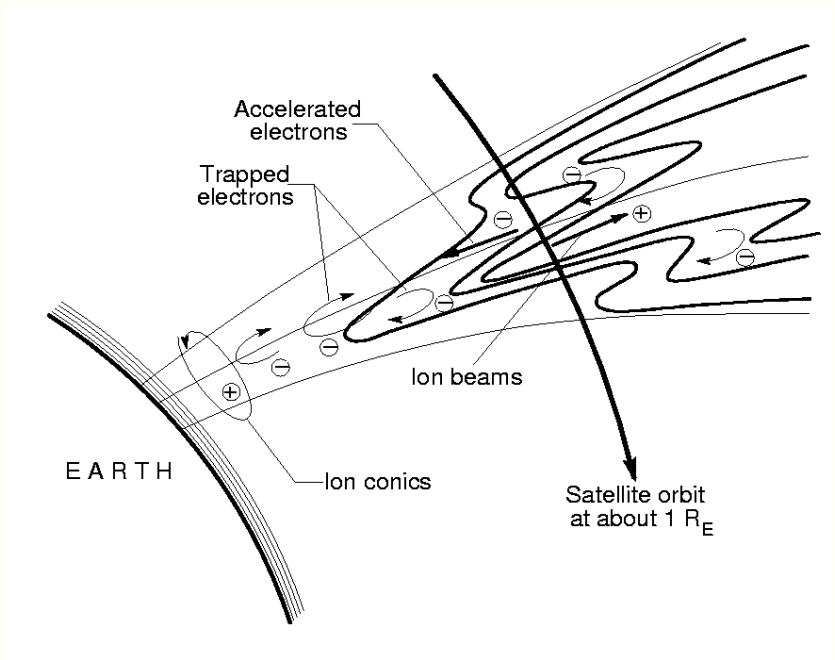
KTH equipment in space



Viking



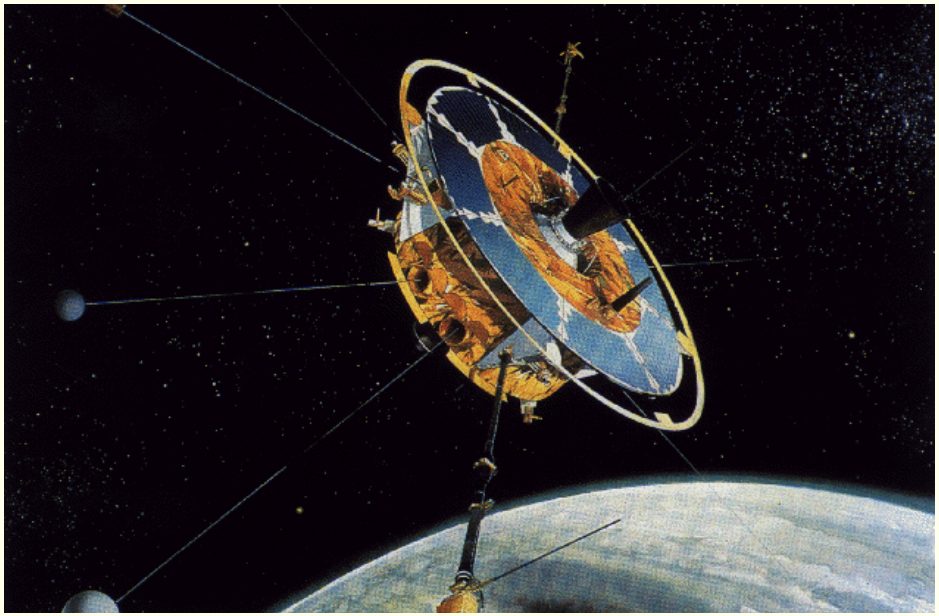
Auroral acceleration region

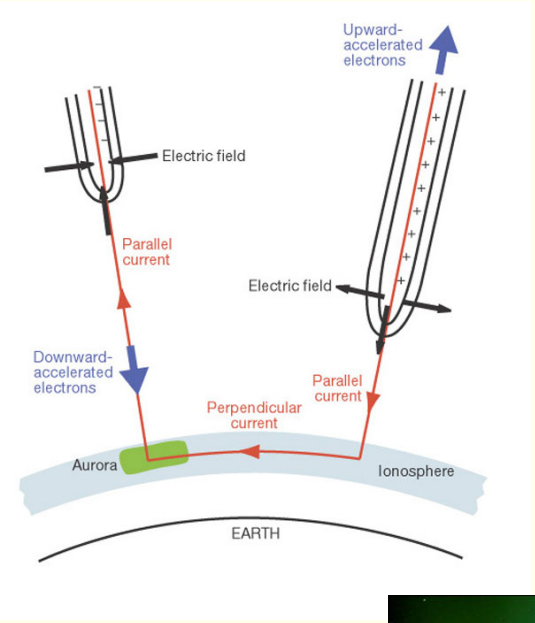


- Launch: 1986
- Apogee: 13500 km
- Perigee: 800km

Freja

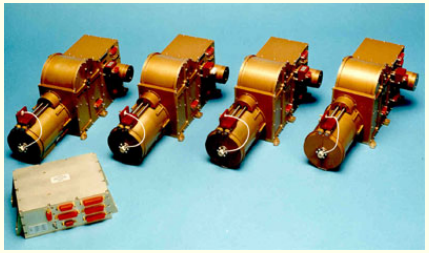
The mirror image of the aurora – the black aurora





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

Freja instrumentation

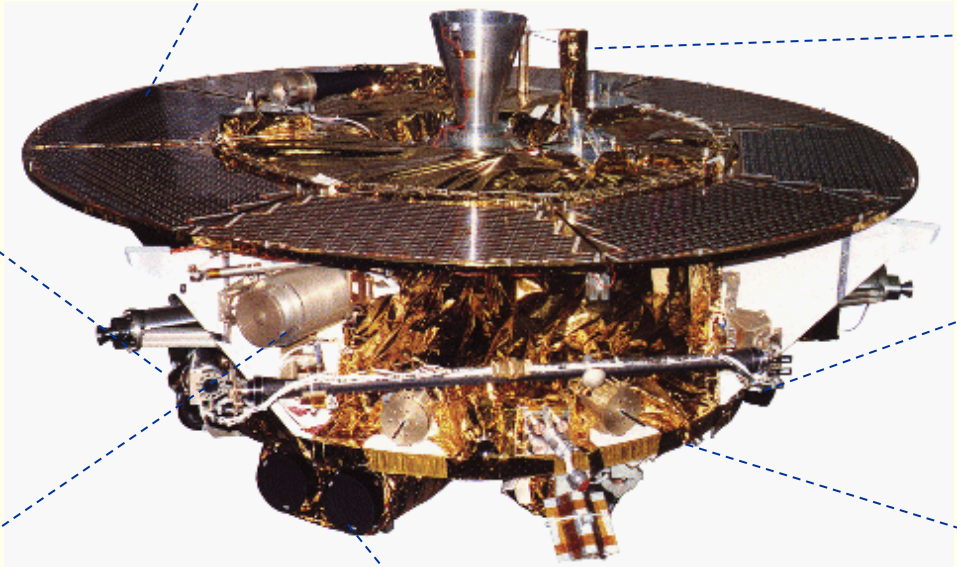


E-field instrument

Solar panel

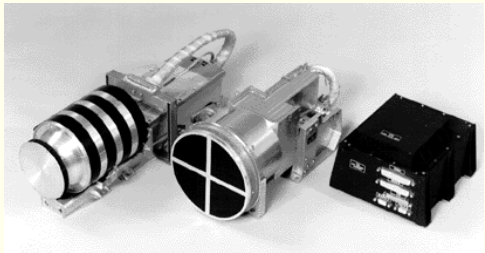
Rocket engine

Antenna

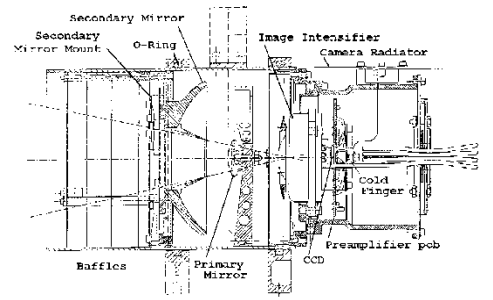


Magnetometer

Langmuir probe
(n_e measurement)

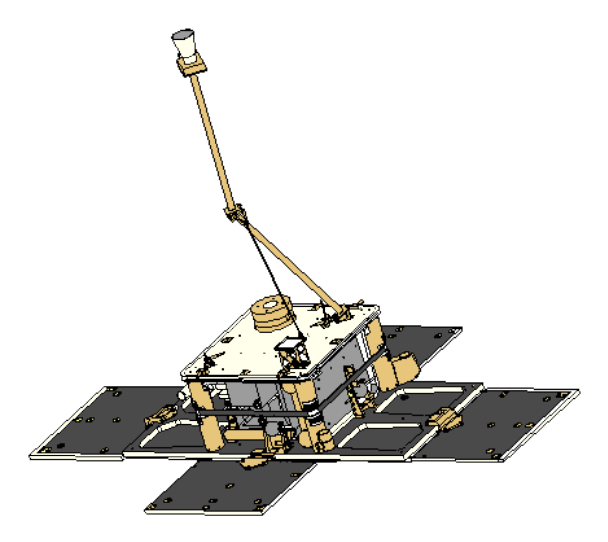


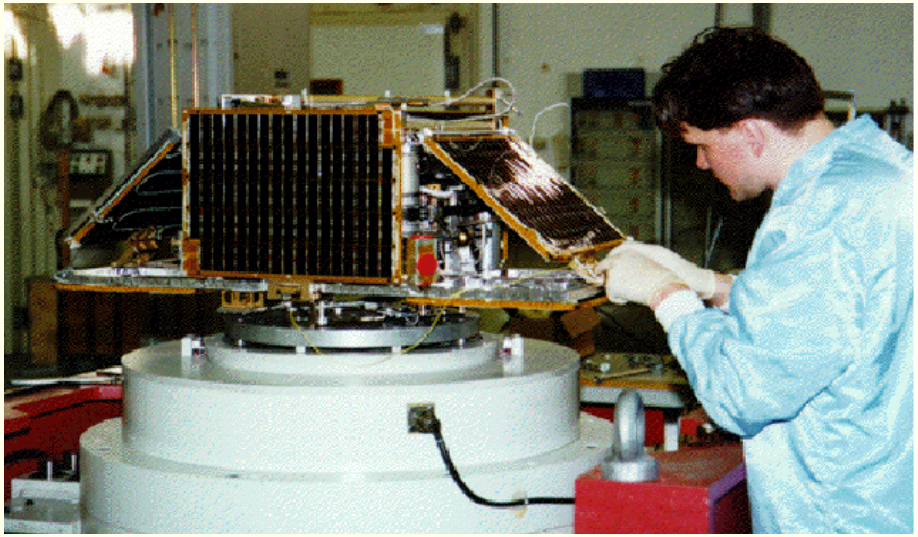
Particle instrument



UV camera

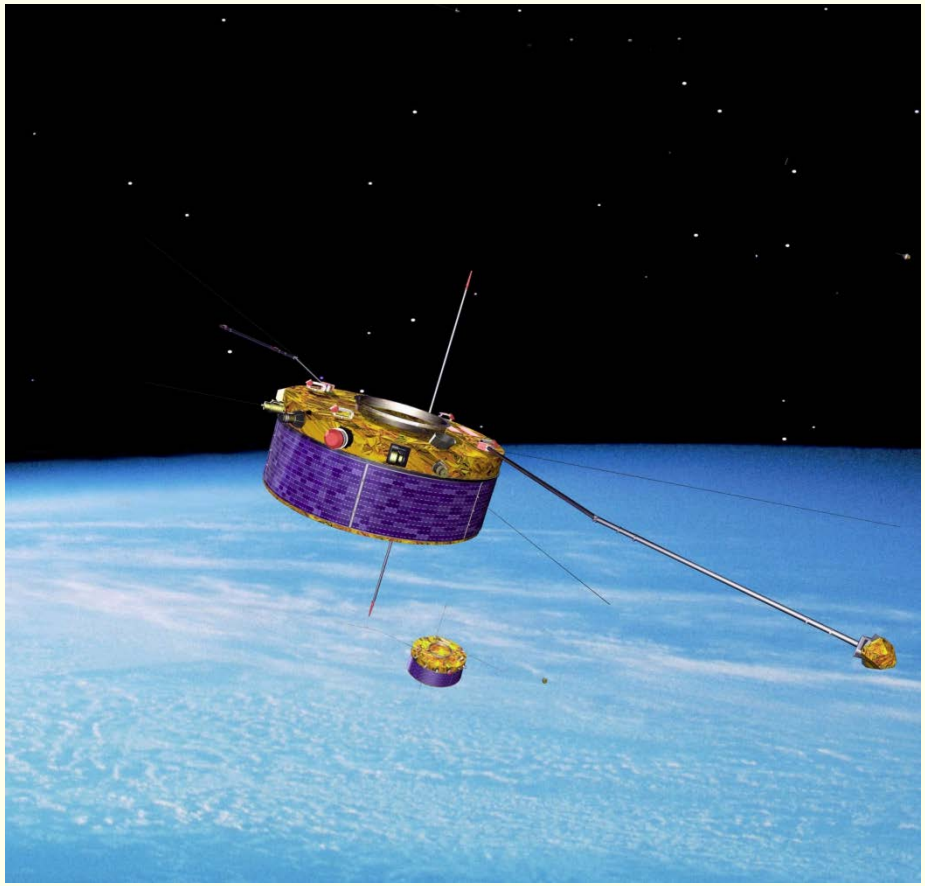
Micro satellite Astrid II





Minituriazation of the payload gave a very cheap mission

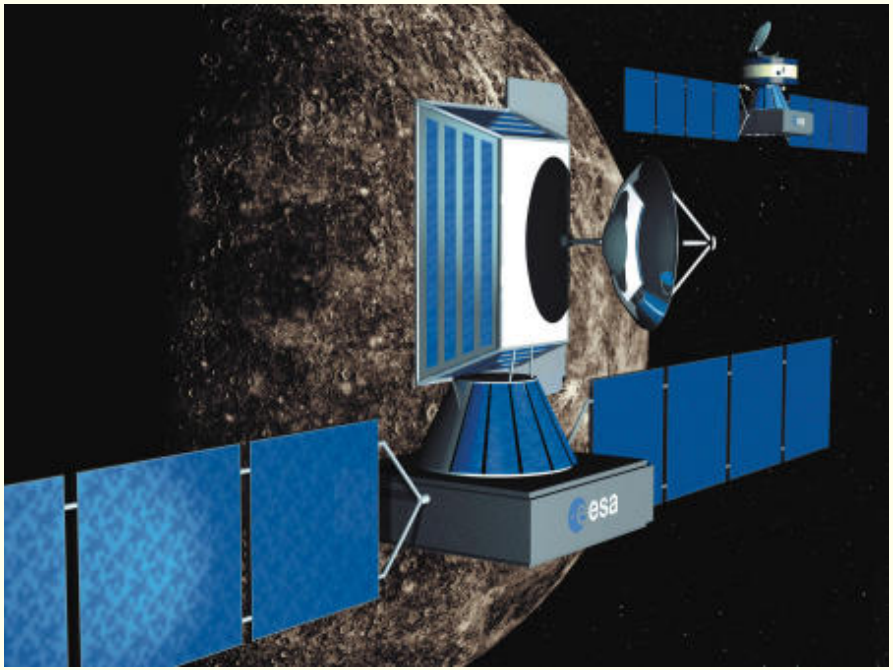
- Launched 1998
- Apogee: 1000 km
- Perigee: 1000 km



Cluster

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

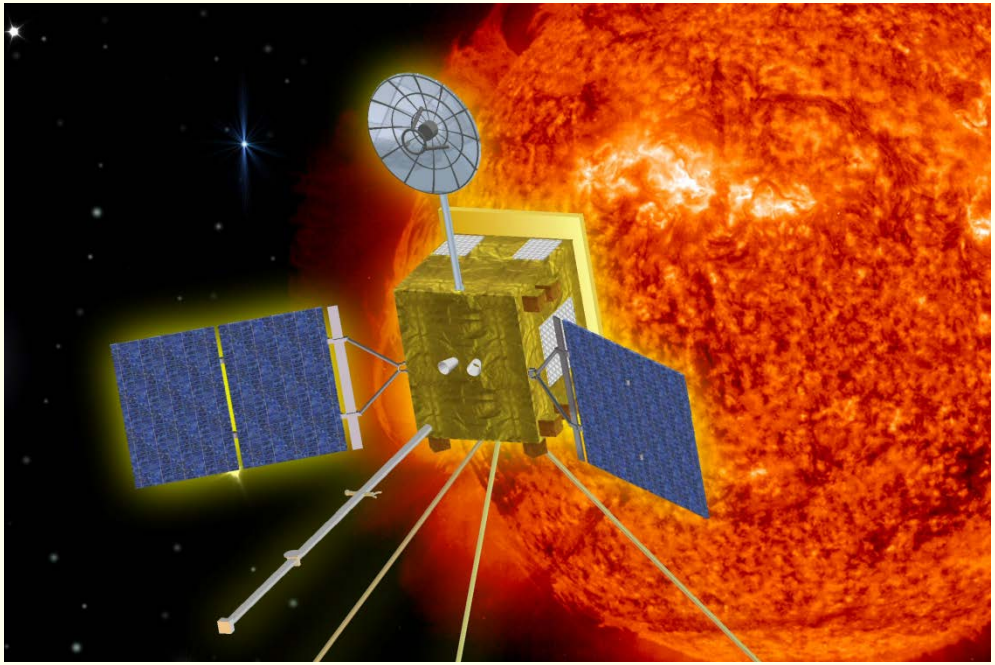
Future mission



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

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

My own research

Spatial or temporal variations?

t_1

Slussen

t_2

Tekniska högskolan

Interpretation 1: temporal variation

t_1

Slussen **Tekniska högskolan**

t_2

Slussen **Tekniska högskolan**

Interpretation 2: spatial variation

t_1

Slussen

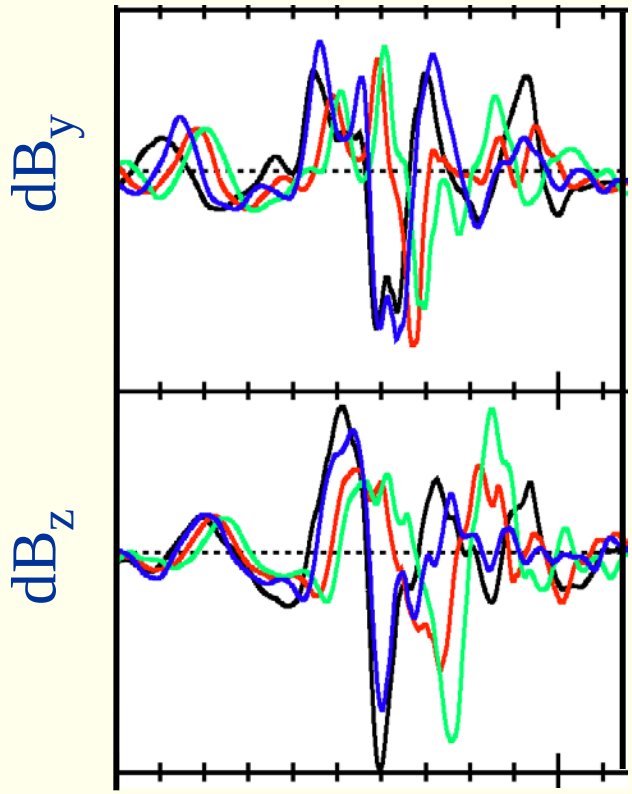
Tekniska högskolan

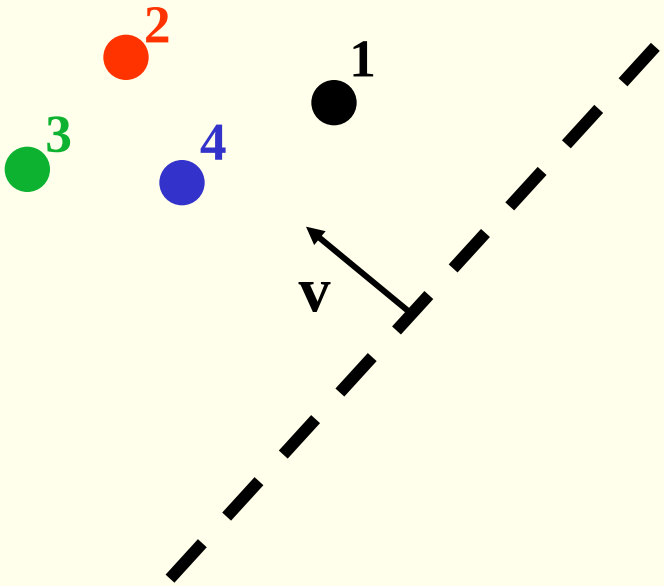
t_2

Slussen

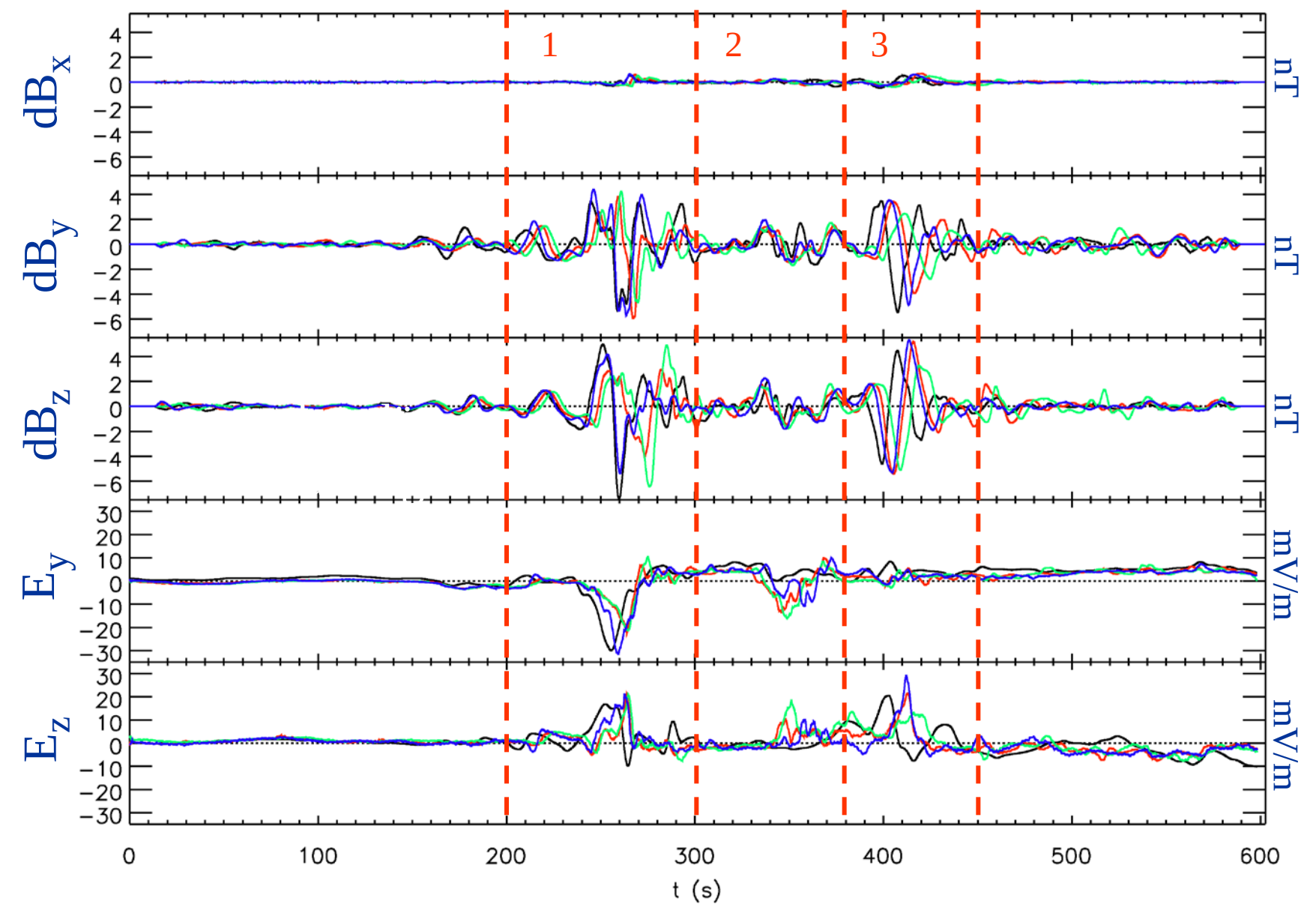
Tekniska högskolan

Interpreting Cluster multipoint measurements





Cluster field data

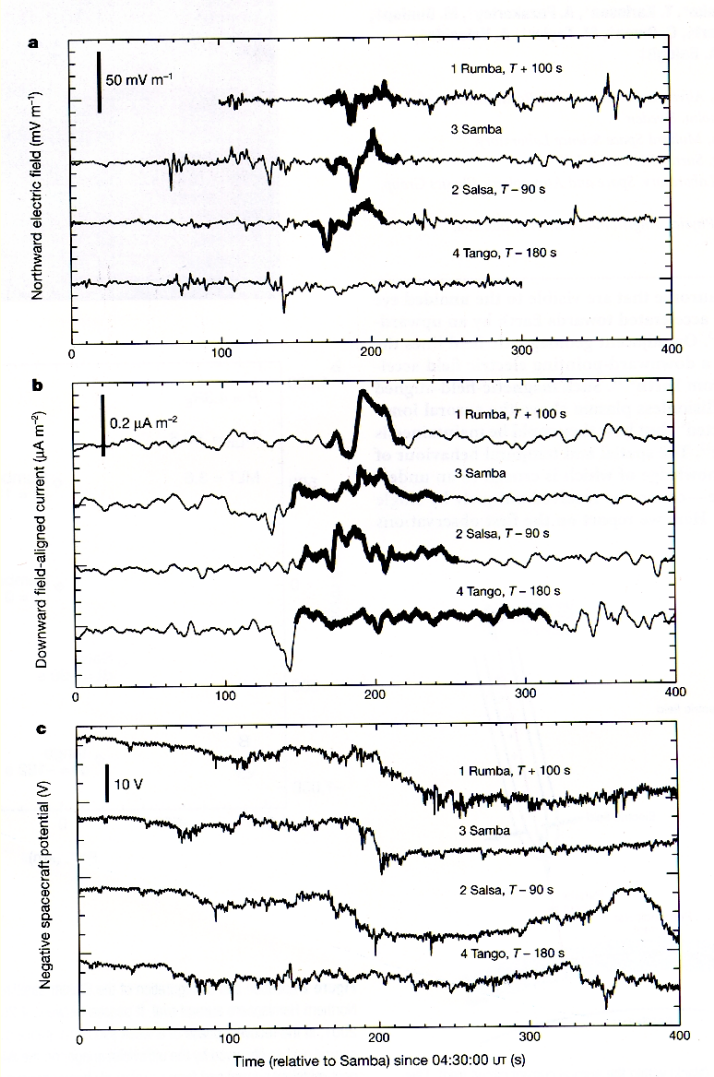


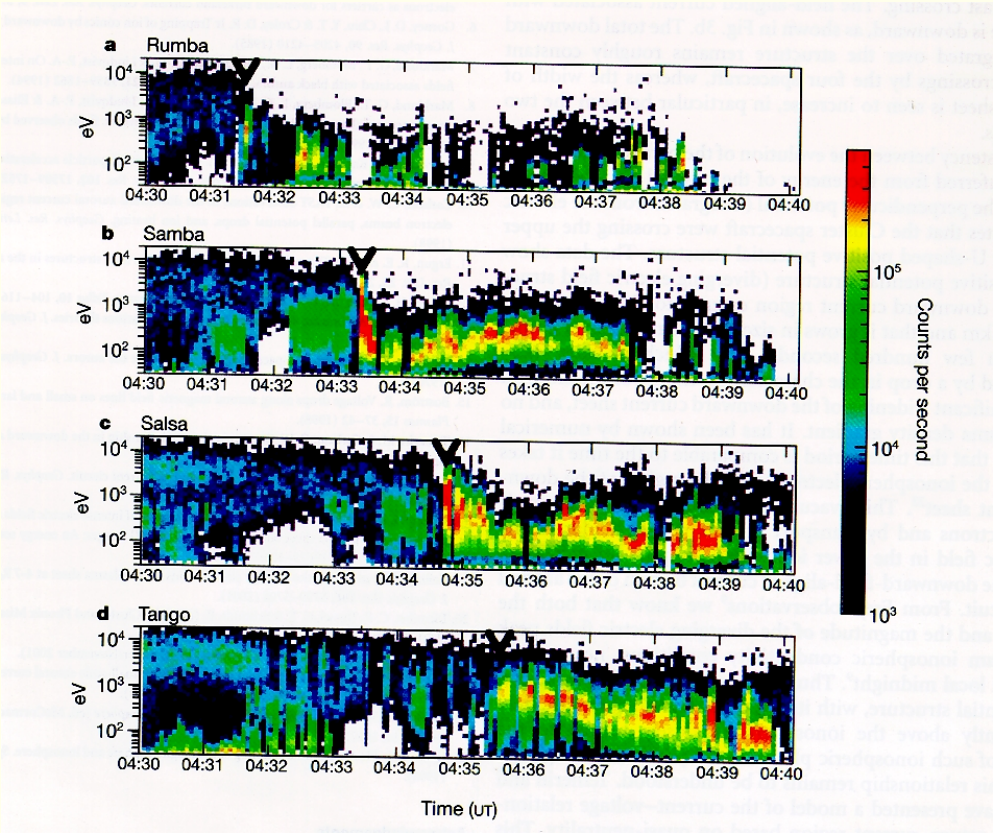
CLUSTER multipoint measurements (1)

E

current

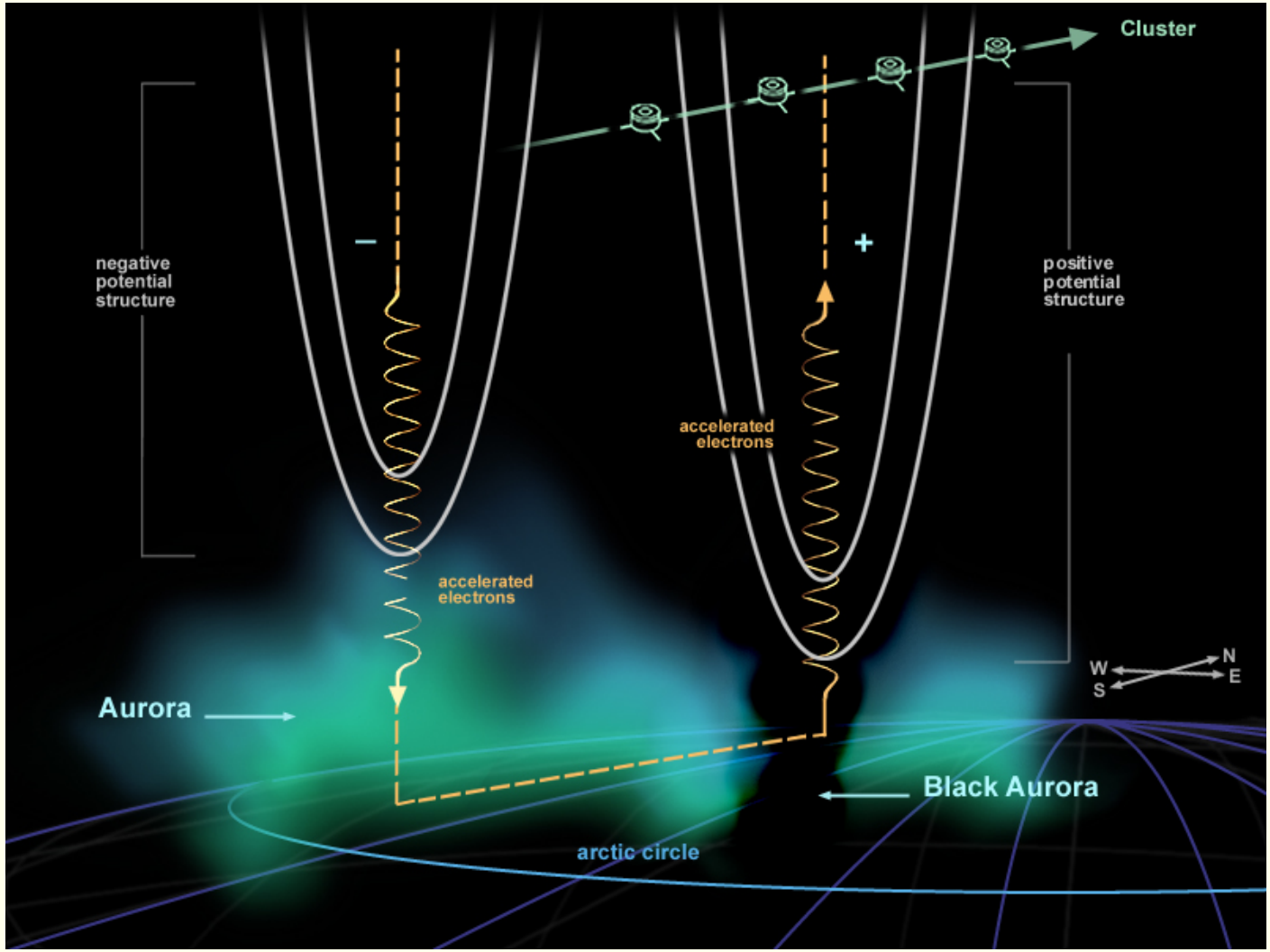
plasma density



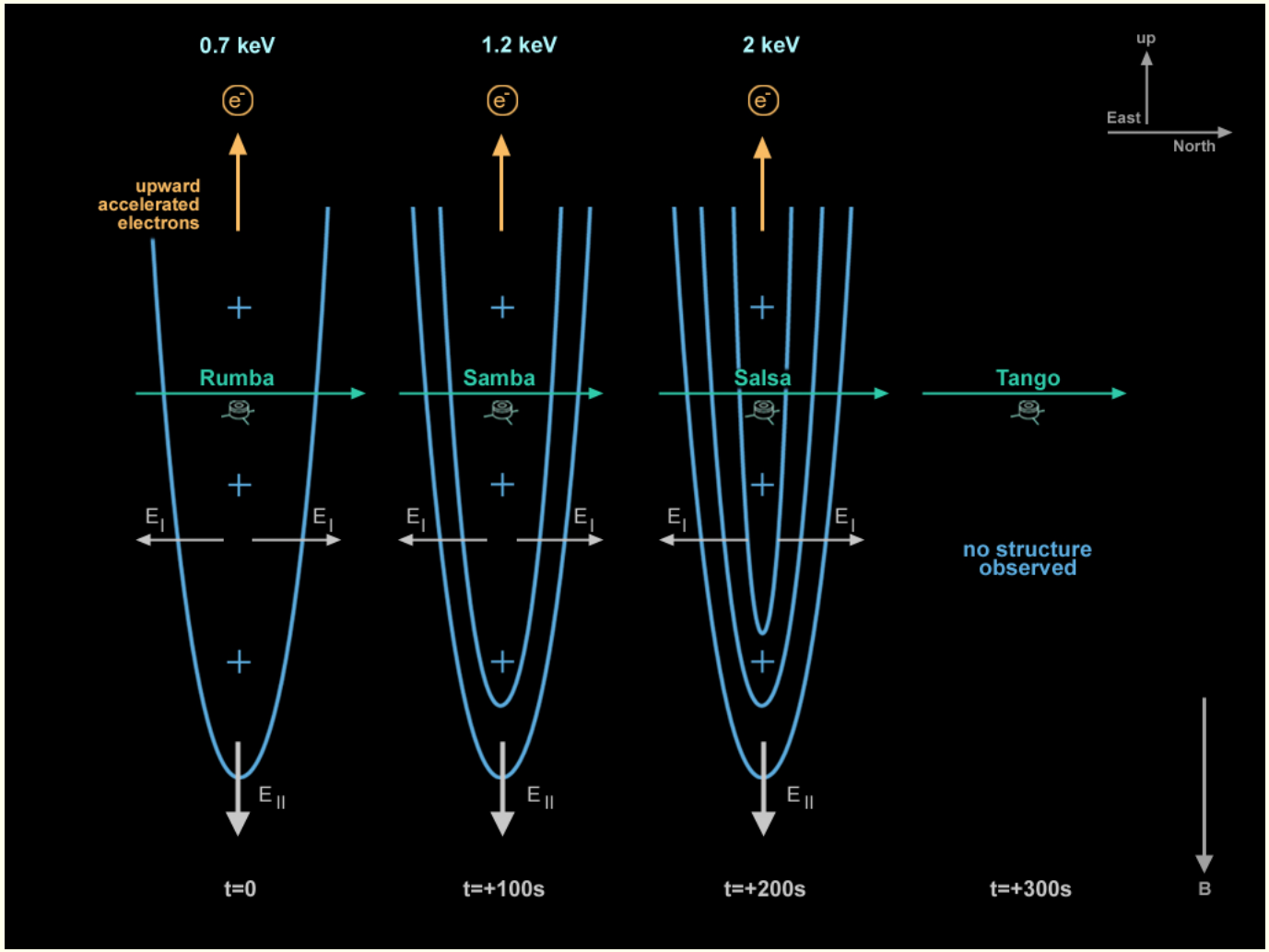


Marklund et al, 2001

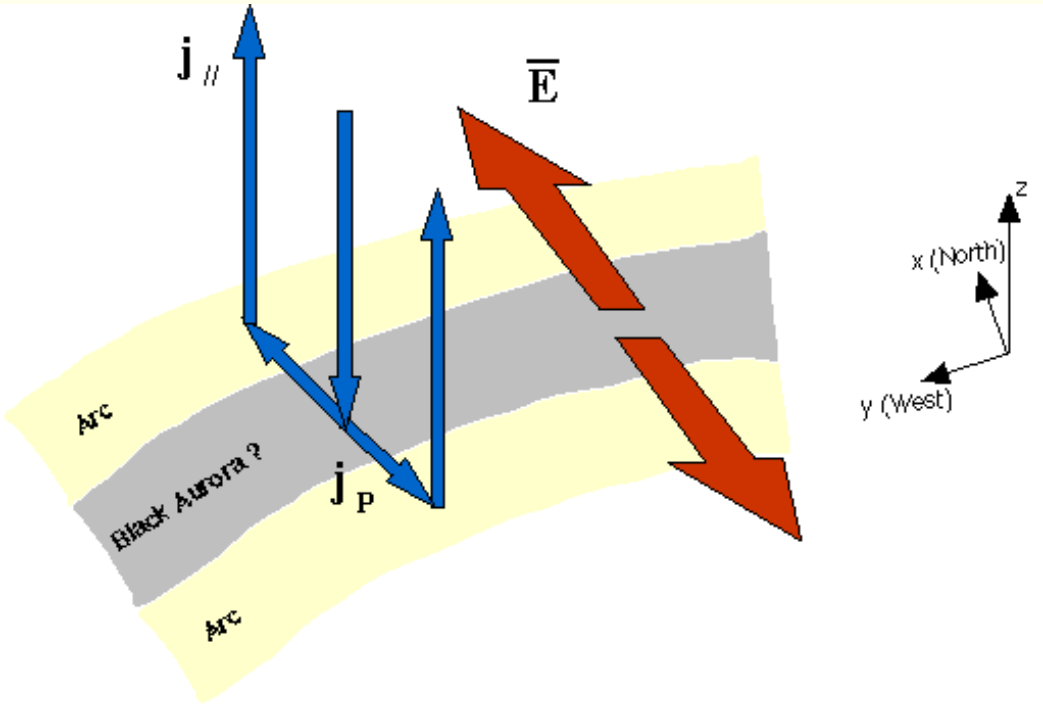
Cluster passage through black aurora

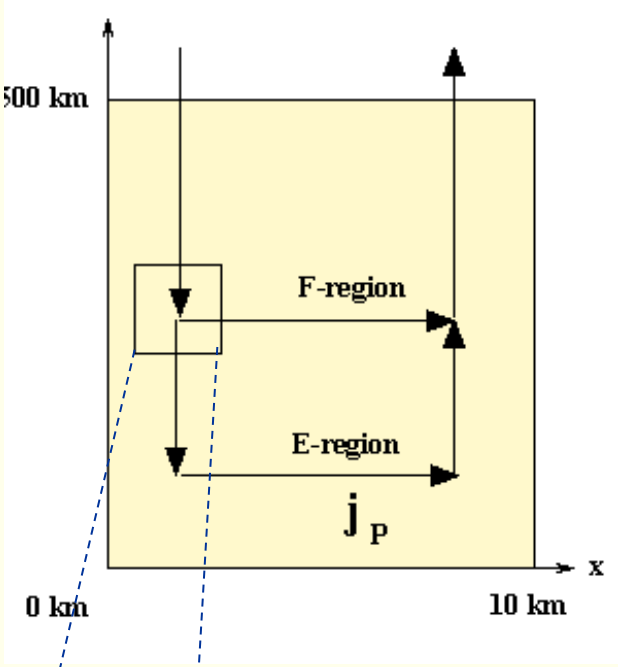


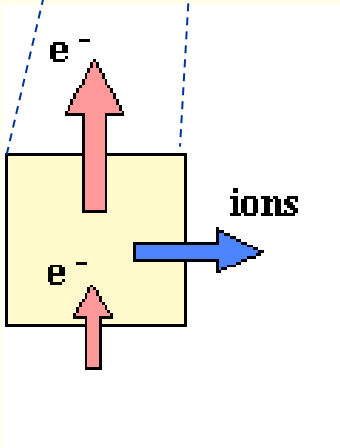
Temporal evolution of acceleration potential over black aurora



Model of ionospheric evacuation by currents



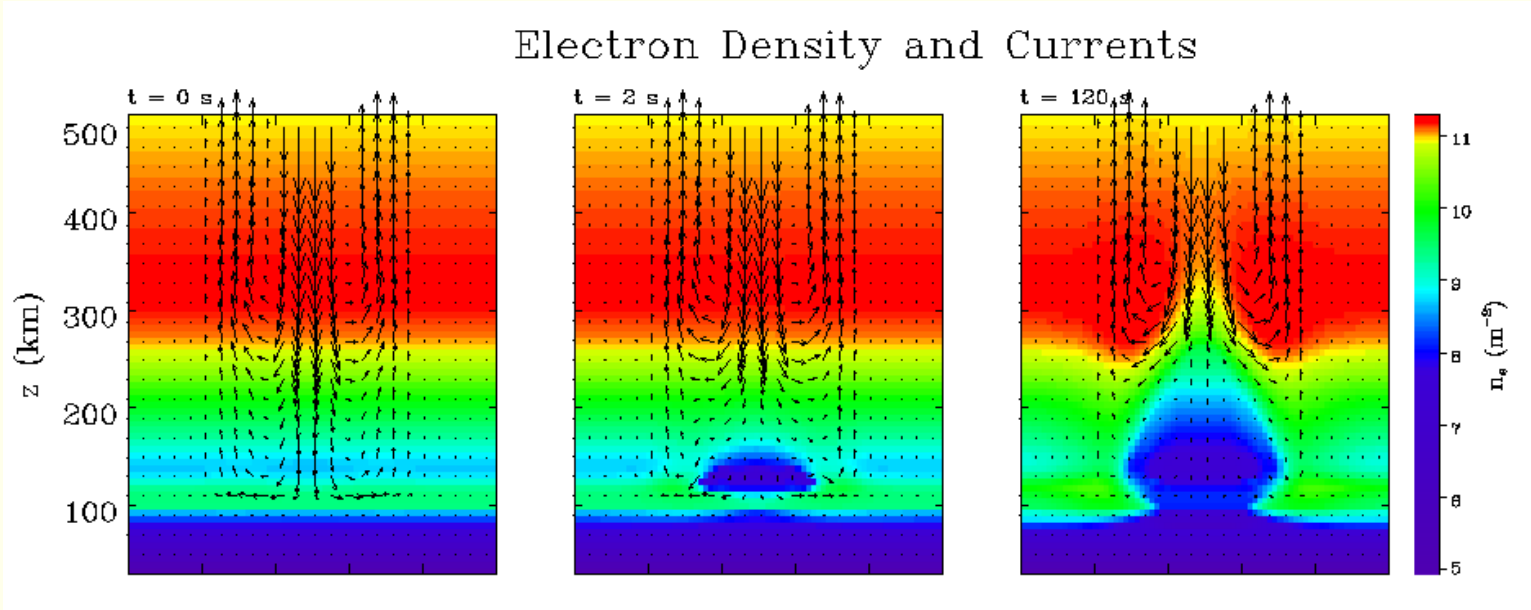


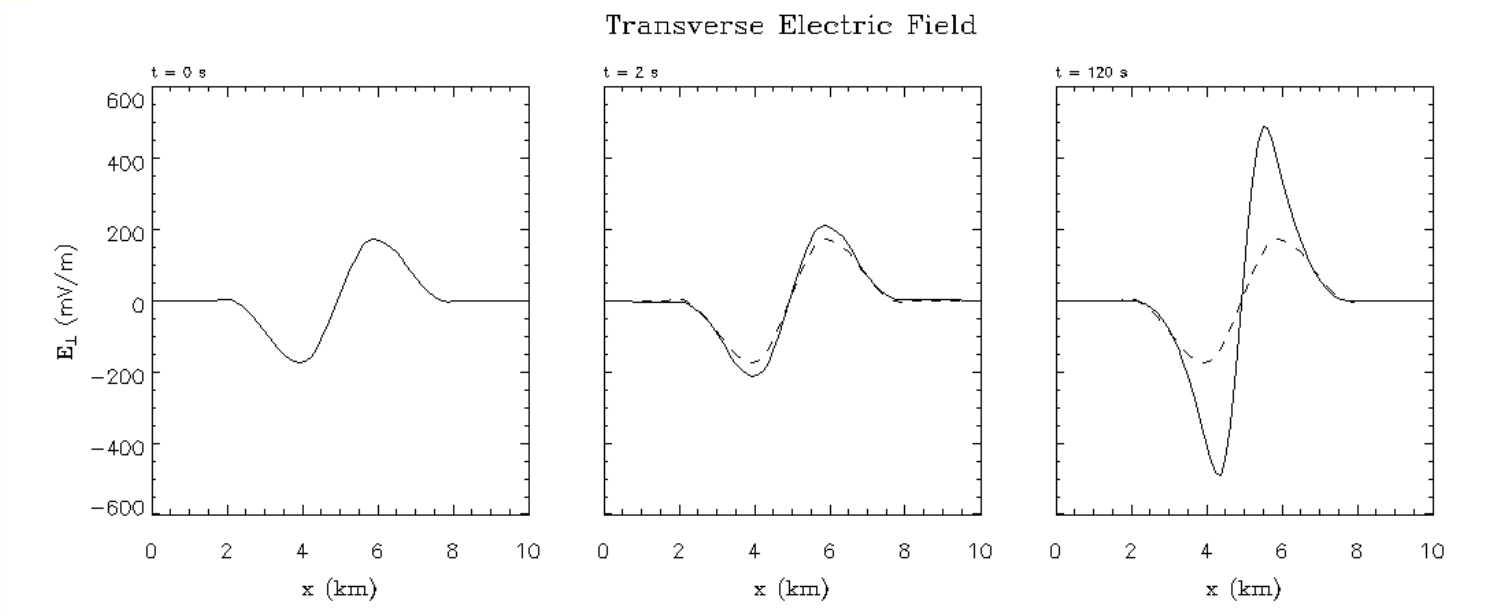


Assumptions:

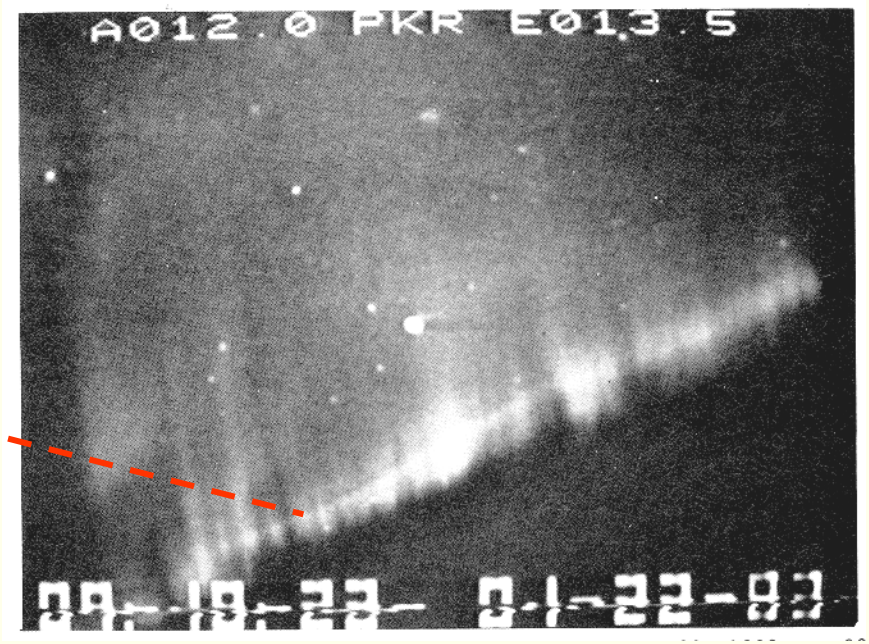
$j_{//}$ carried by e^-
j_P carried by ions

$$\Longrightarrow \quad \frac{\partial n_e}{\partial t} = -\frac{1}{q}\frac{\partial j_{//}}{\partial z}$$


Electron Density and Currents
t = 0 s
t = 2 s
t = 120 s
z (km)
500
400
300
200
100
11
10
9
8
7
6
5
n_e (m^{-3})


Transverse Electric Field
t = 0 s
t = 2 s
t = 120 s
$E_\perp$ (mV/m)
600
400
200
0
−200
−400
−600
0
2
4
6
8
10
x (km)

Observations of "Enhanced Aurora"

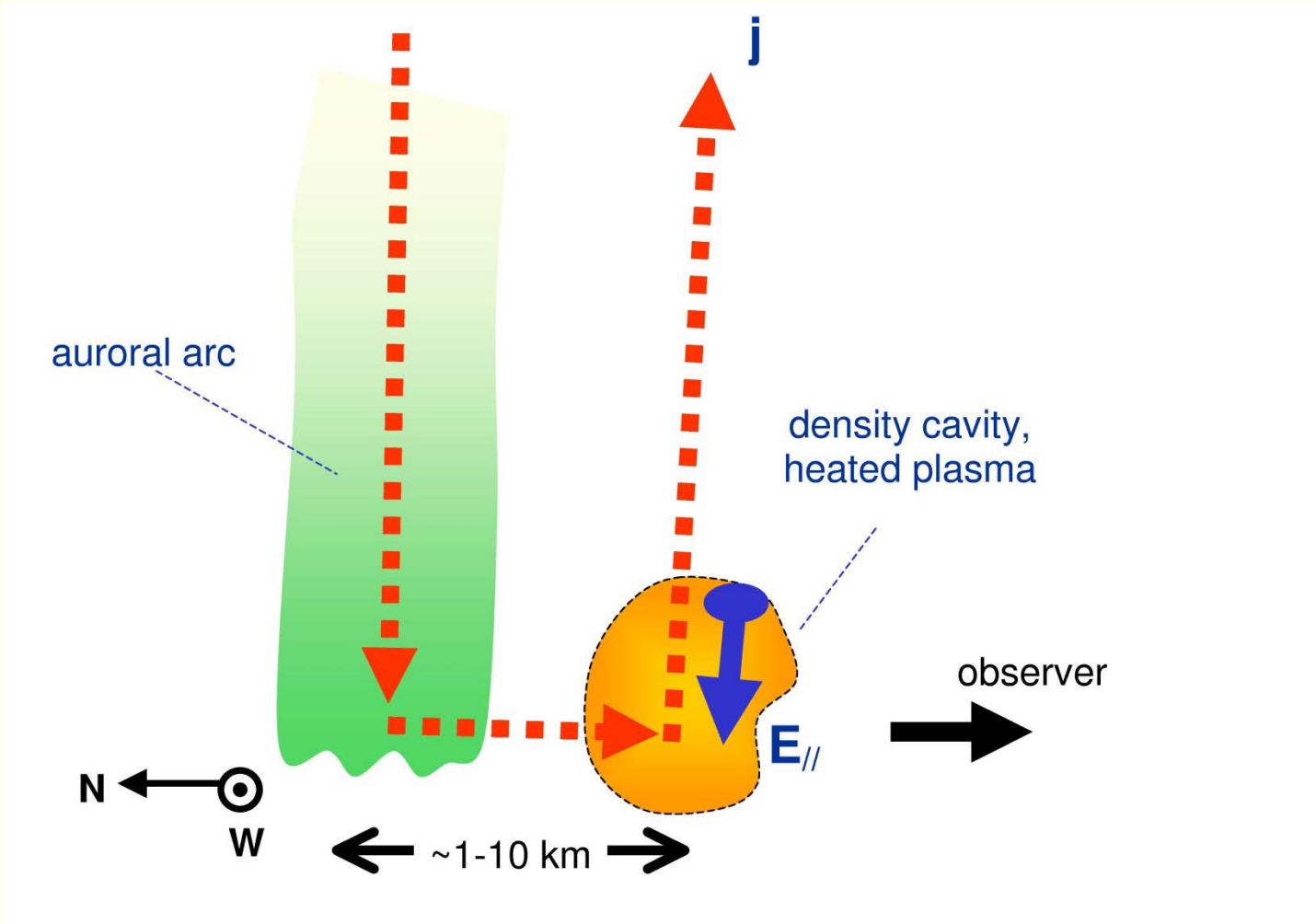


Enhanced layer

[Hallinan et al., 1985]

Discrete auroral arcs sometimes exhibit intensity enhancements in thin horizontal layers at the bottom of the arc.

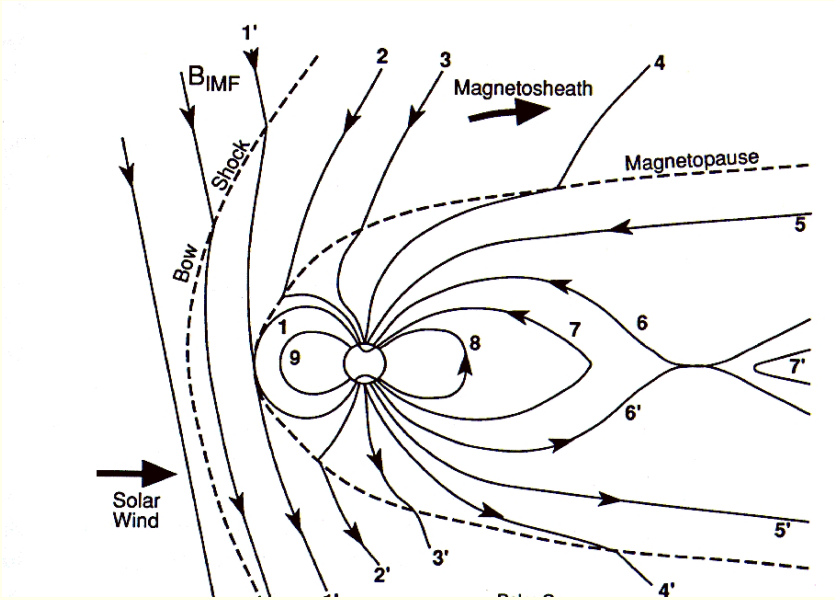
Enhanced Aurora theory

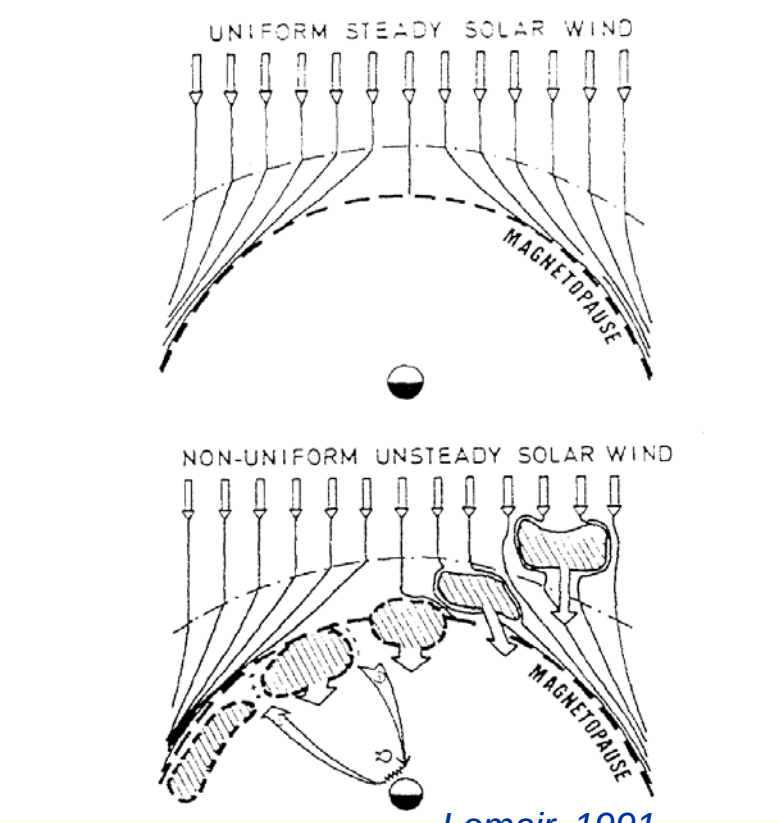


Introduction

Reconnection
Dominating process for transfer of energy and plasma

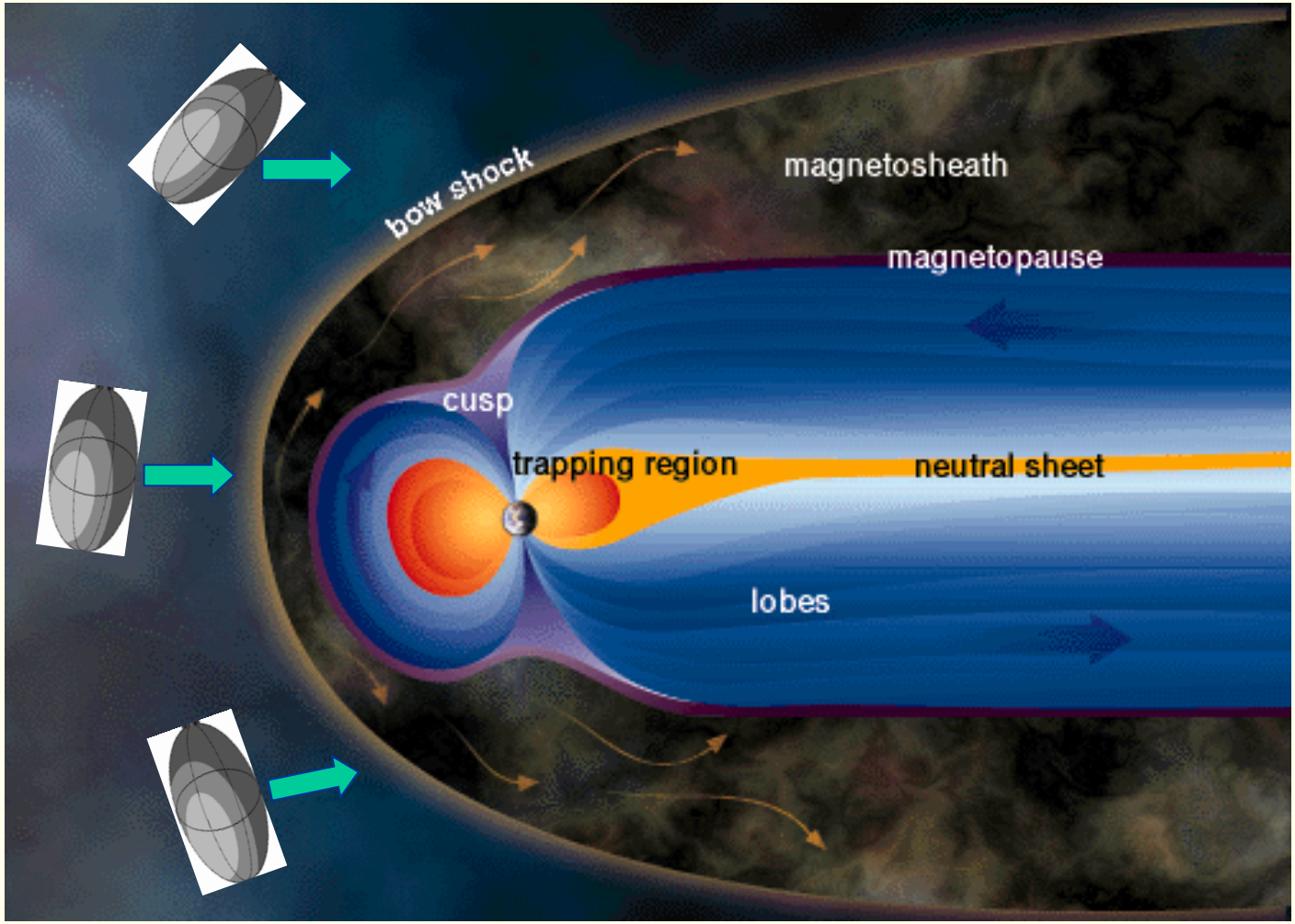
Impulsive penetration
Alternative/complementary model proposed by Lemair ca 1976





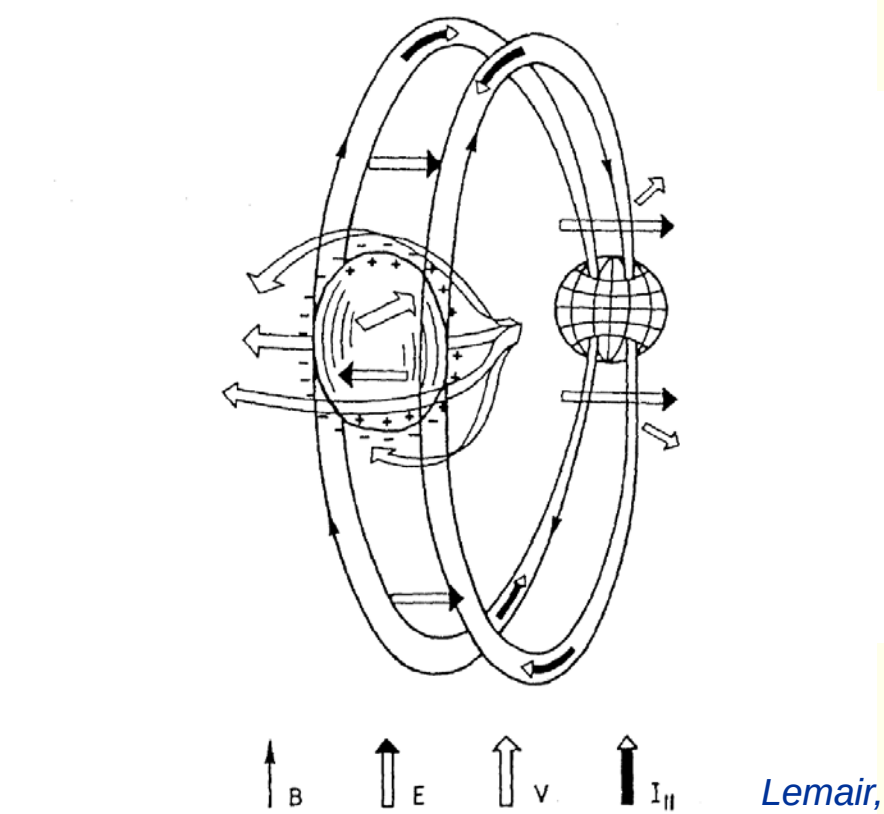
Lemair, 1991

Plasmoids and magnetosphere

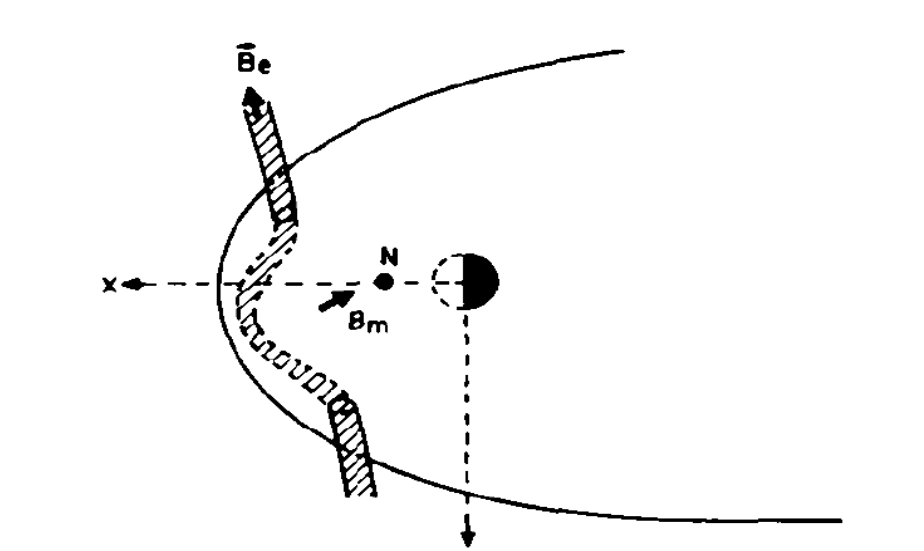


Impulsive penetration

Geometry of penetrating elements unclear



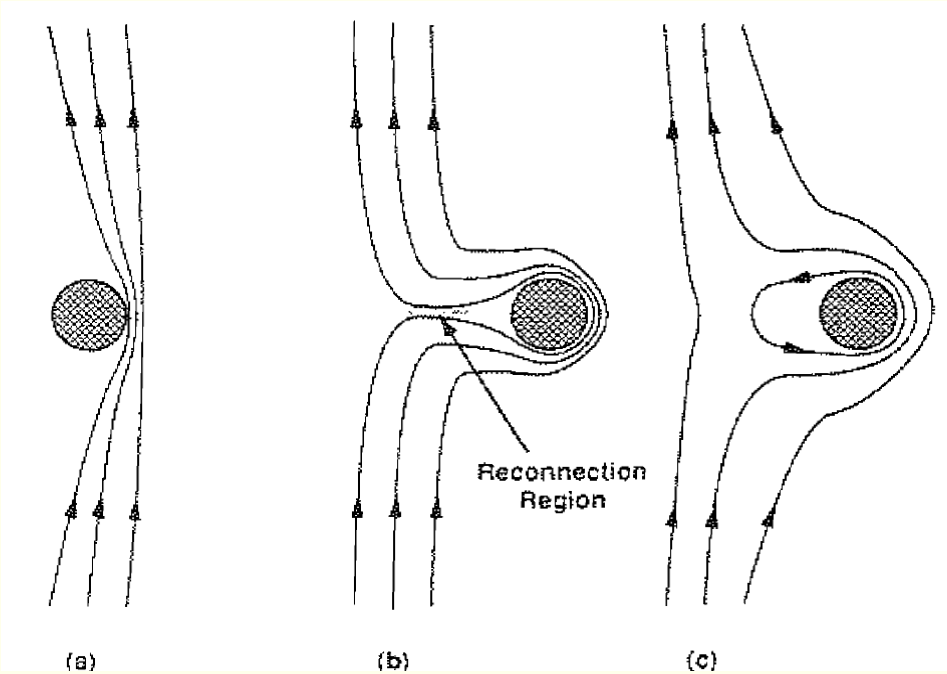
Lemair, 1991



Lemair, 1977

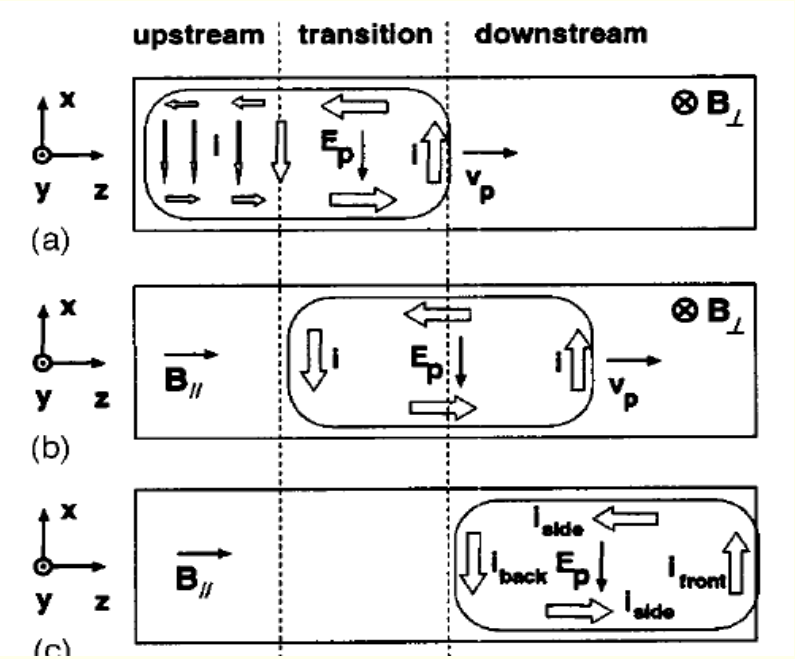
Penetration mechanisms

Magnetic expulsion
(followed by localized reconnection)



Ma, 1991

Self-polarization
$\mathbf{E_p} = -\,\mathbf{v} \times \mathbf{B}$

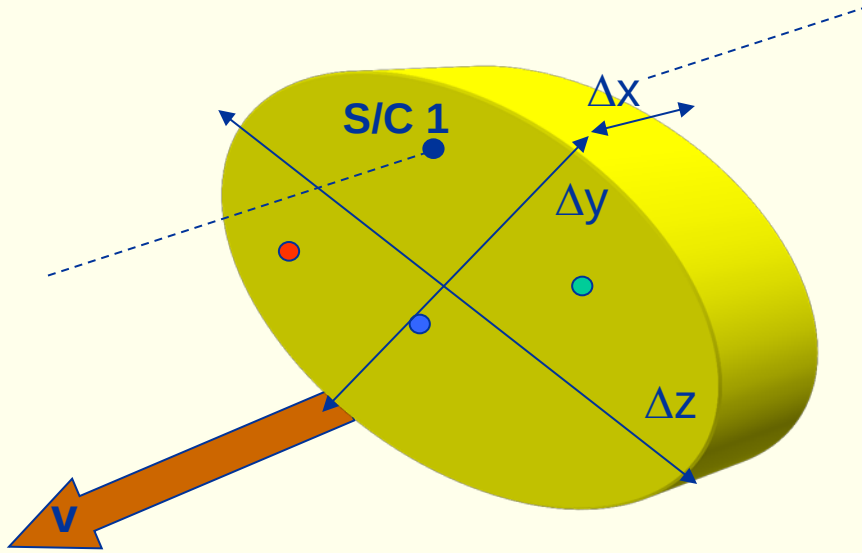


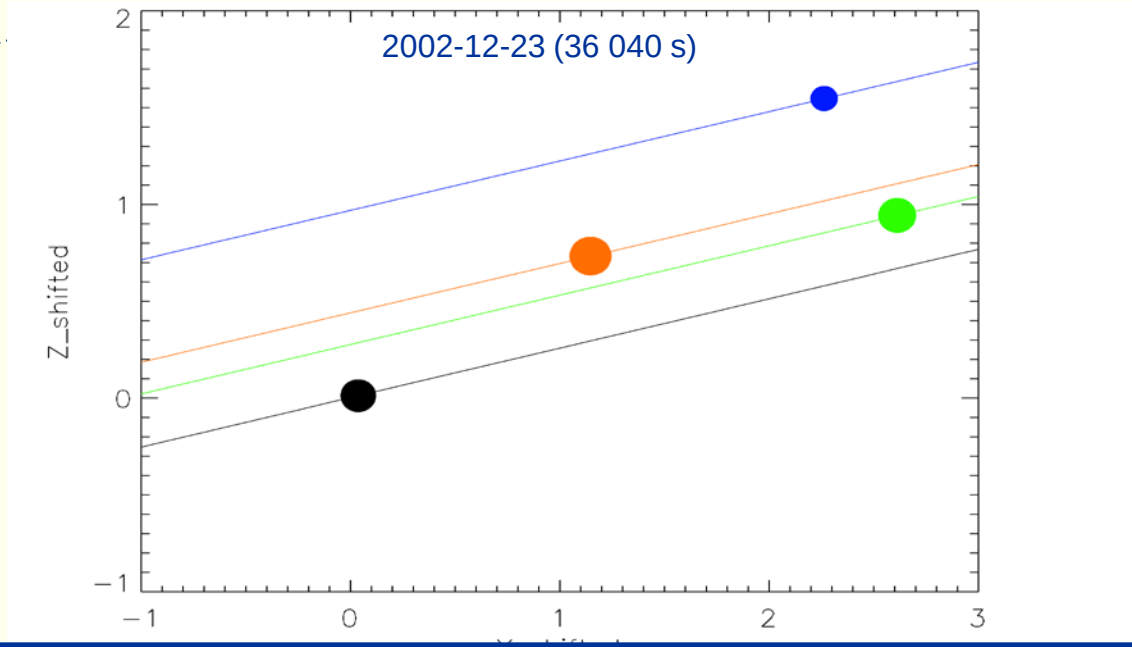
Brenning, 2005

Estimation of scale sizes

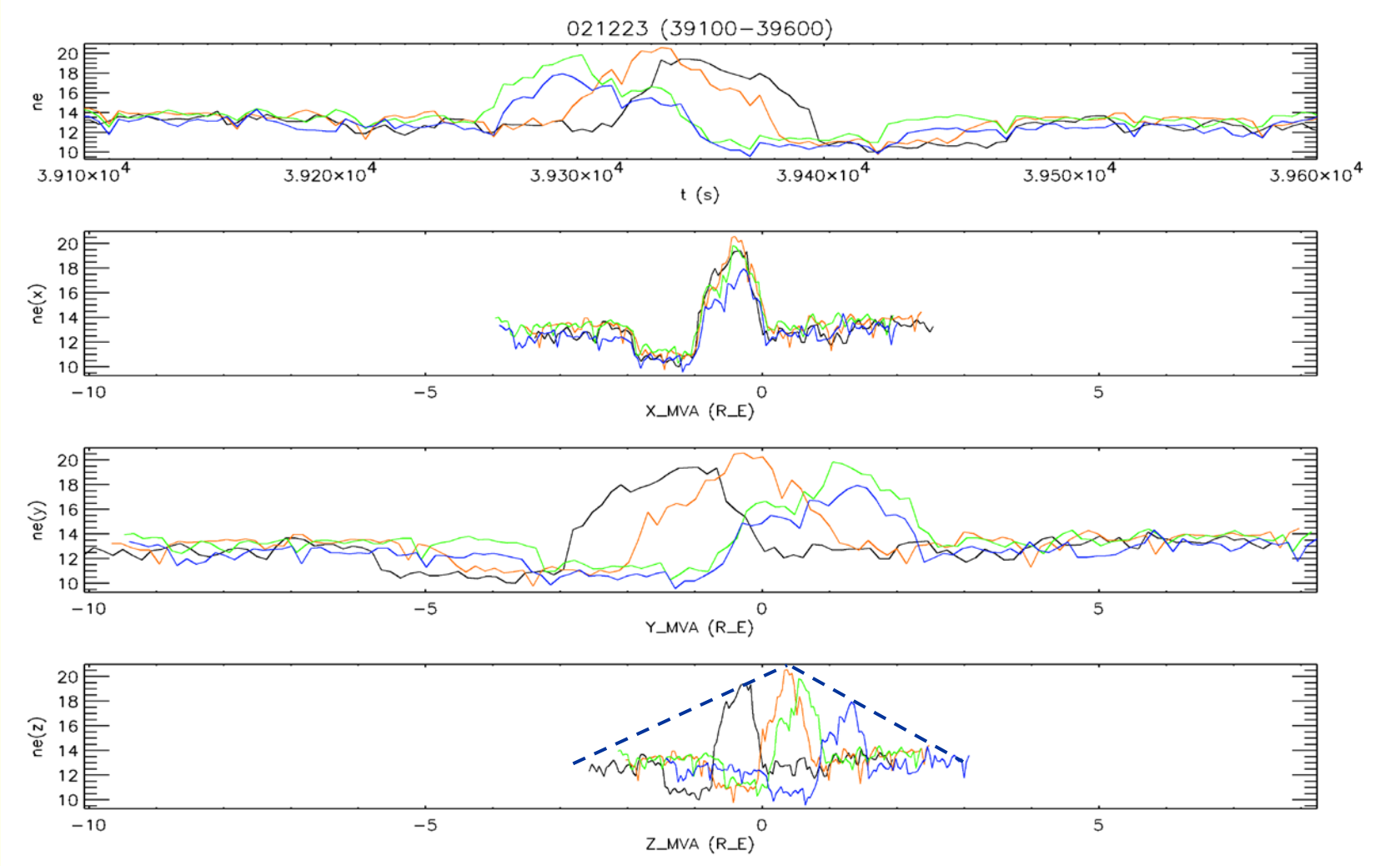
1. Along x-direction: width of half maximum of Δn_e

2. y and z: in effect only four measurement points



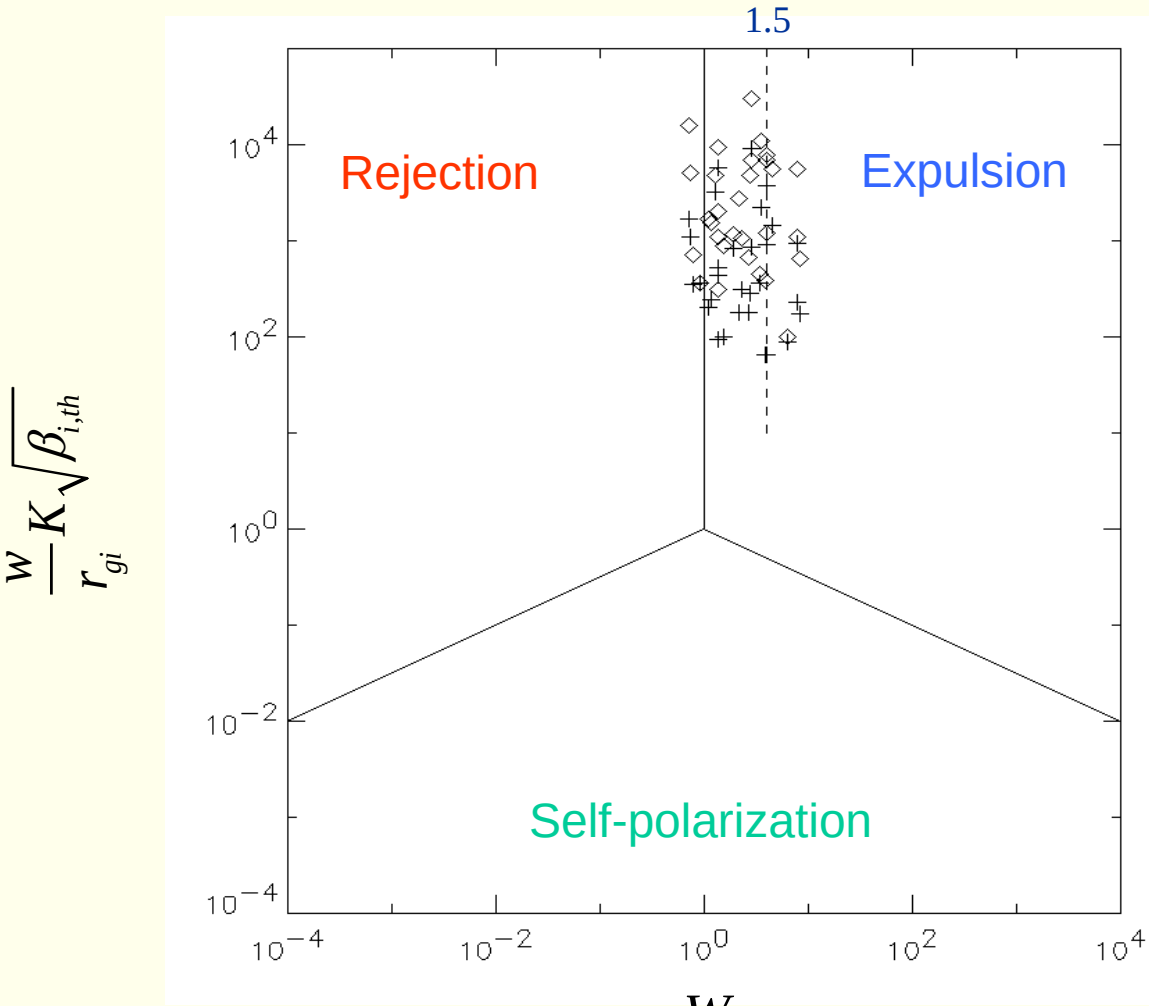


2002-12-23 (39 315 s)



Method 1a

Penetration parameters



$$W_k = \frac{m_i n_e v_d^2}{2}$$

$$W_{i,th} = \frac{m_i n_e v_{i,th}^2}{2}, \quad T = 321\,\text{eV}$$

$$W_B = \frac{B_0^{\,2}}{2\mu_0}, \quad B_0 = 50\ \text{nT}$$

$$\beta_k = \frac{W_k}{W_B}$$

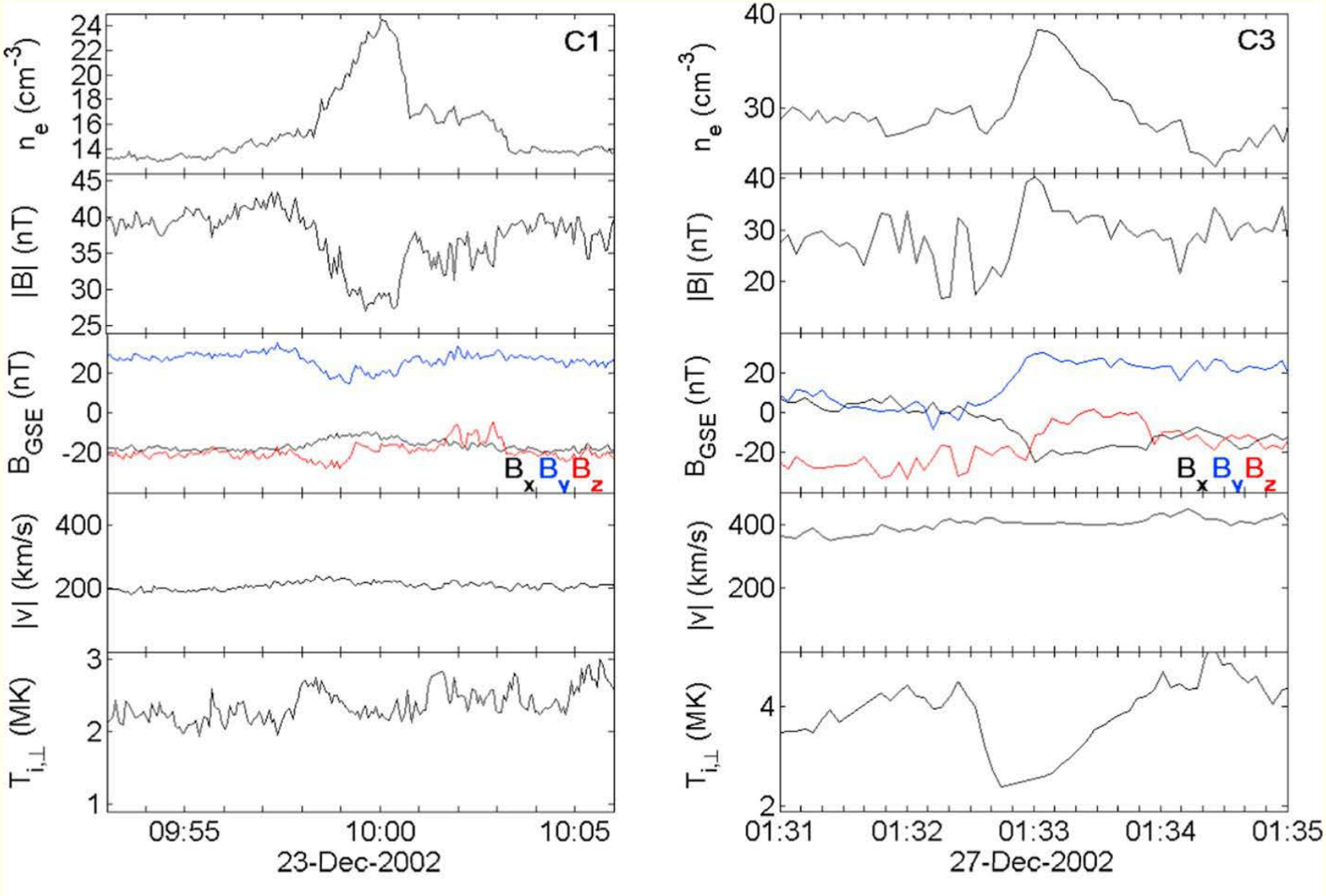
$$\beta_{i,th} = \frac{W_{i,th}}{W_B}$$

$$w = l_x$$

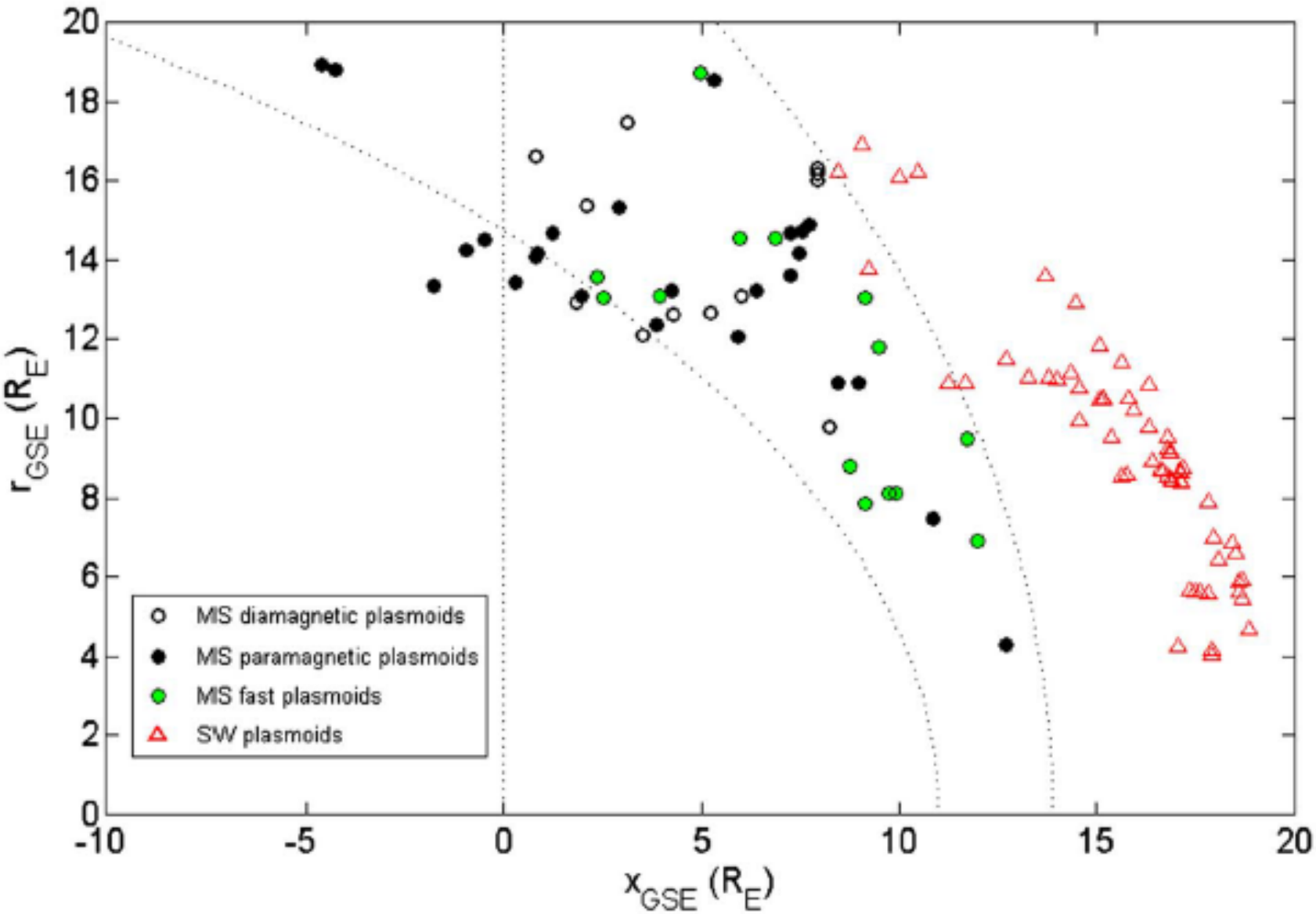
$$r_{gi} = \frac{m_i v_d}{eB_0}$$

$$K = 2.3$$

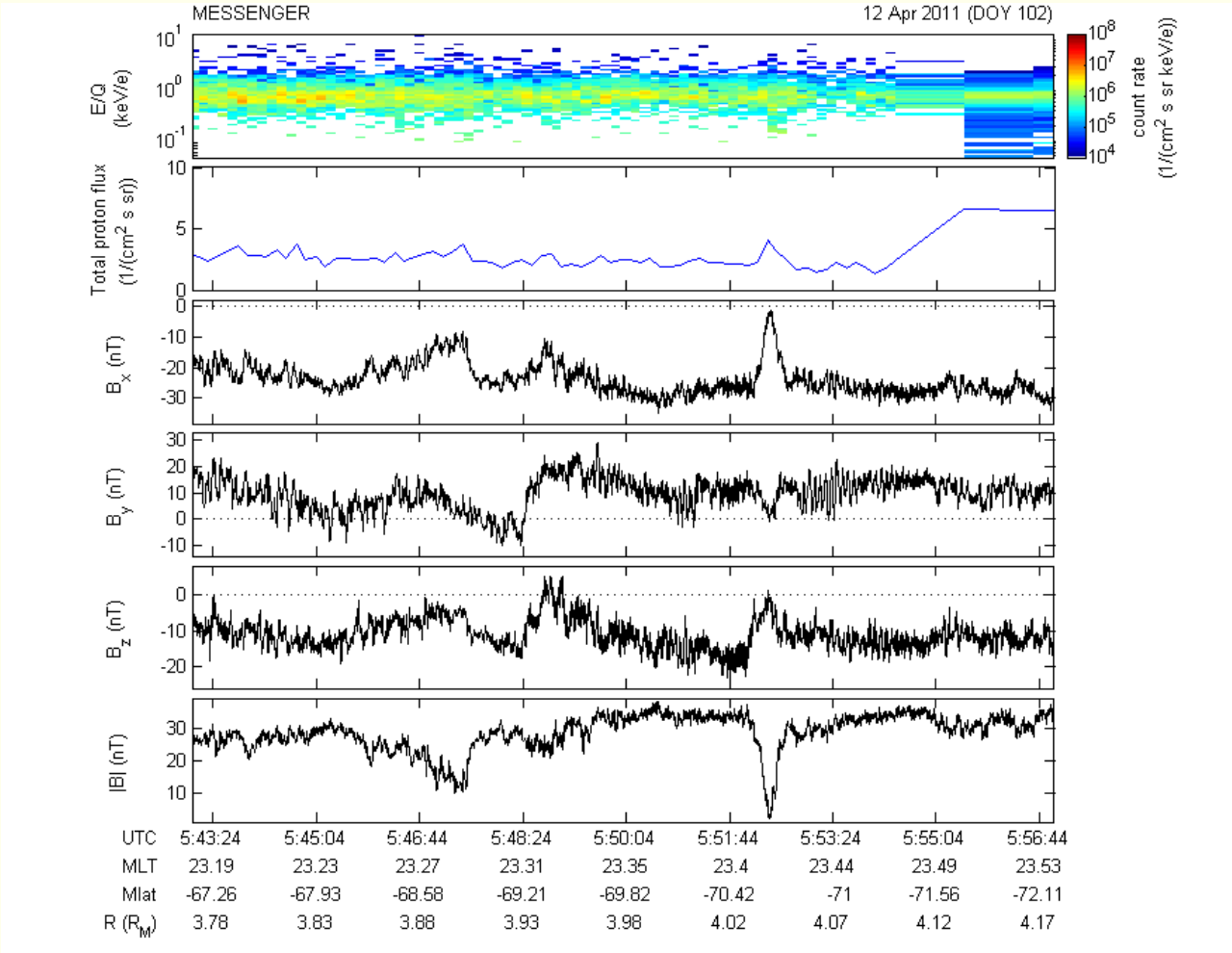
Where do they come from?



Where do they come from?



Do they exist at other planets?



MESSENGER data from Mercury