Solar wind – magnetopshere coupling: small scales and large scales dynamics

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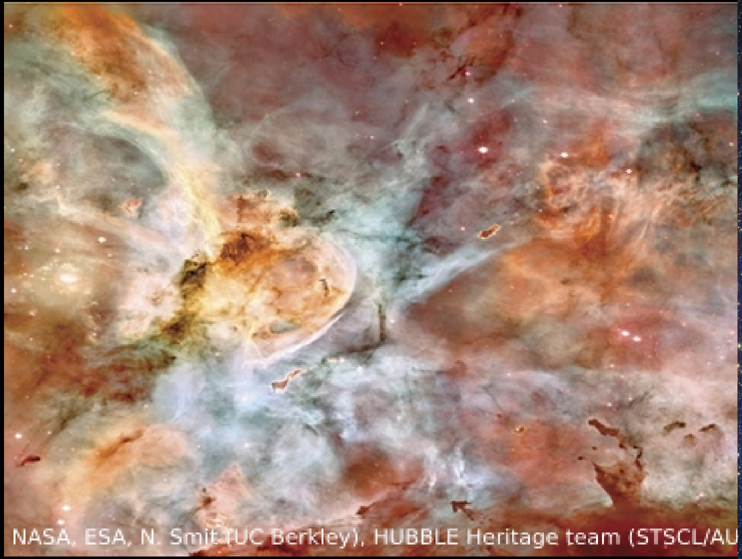
Part I: How do we observe space plasmas ?

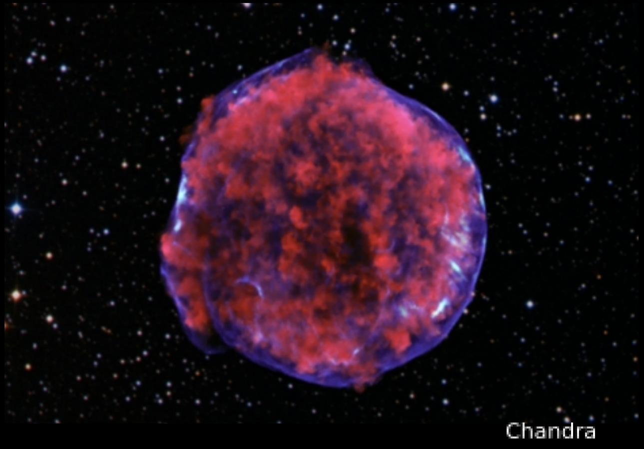
Part II: Turbulence properties at the MHD scales

Part III: Planetary ionospheres - Saturn

Part I:
How do we observe space plasmas ?

Plasma make up over 99% of the visible universe !





Plasma observations from space

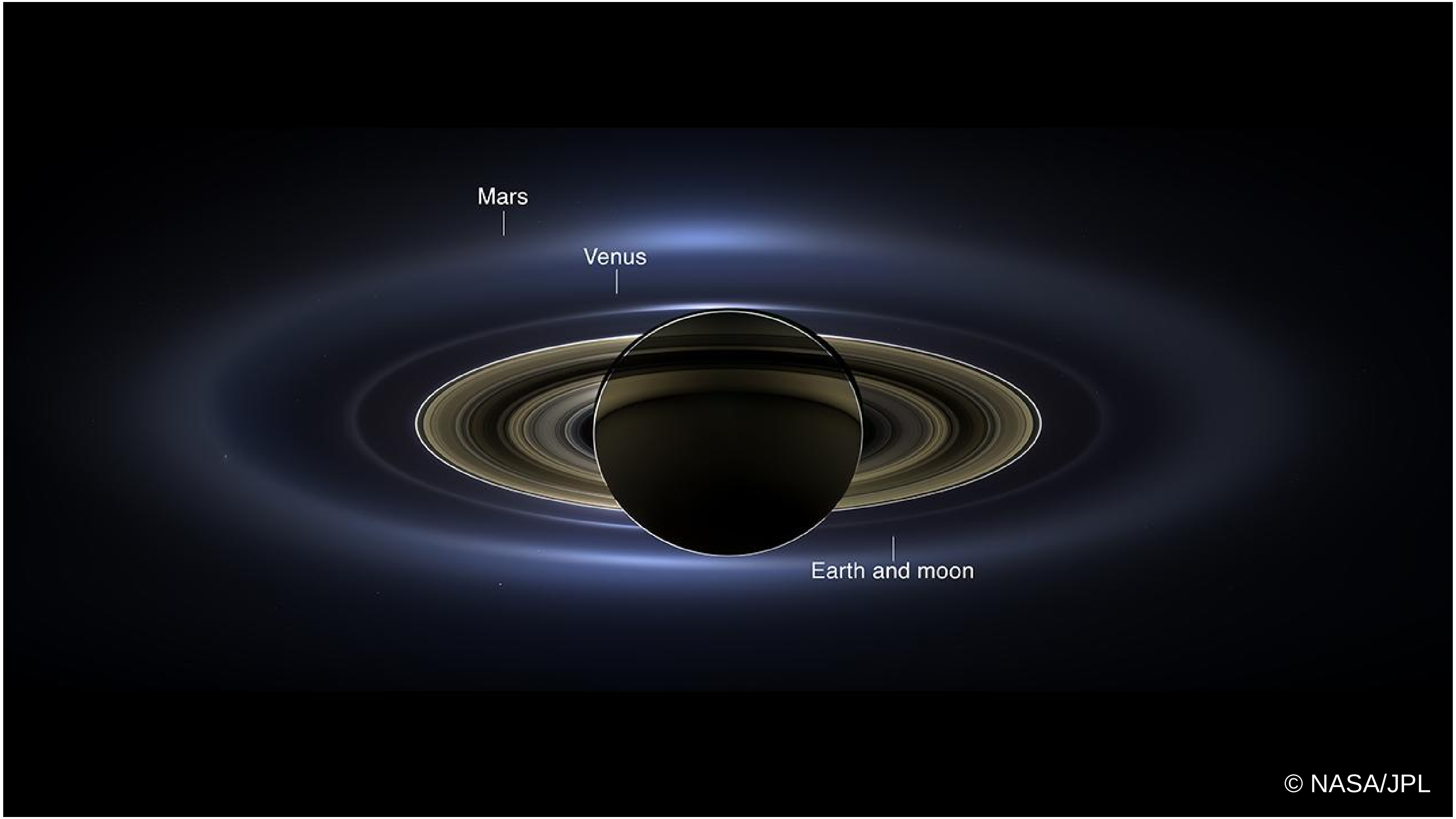
1. **Remote sensing**
   → General properties and global dynamics of the system

2. ***In situ***
   → Detailed information on the plasma at the location of the satellite.
   → Plasma parameters of the system (E, B, ne, Te, Ti, etc.) that we can use in the equations.

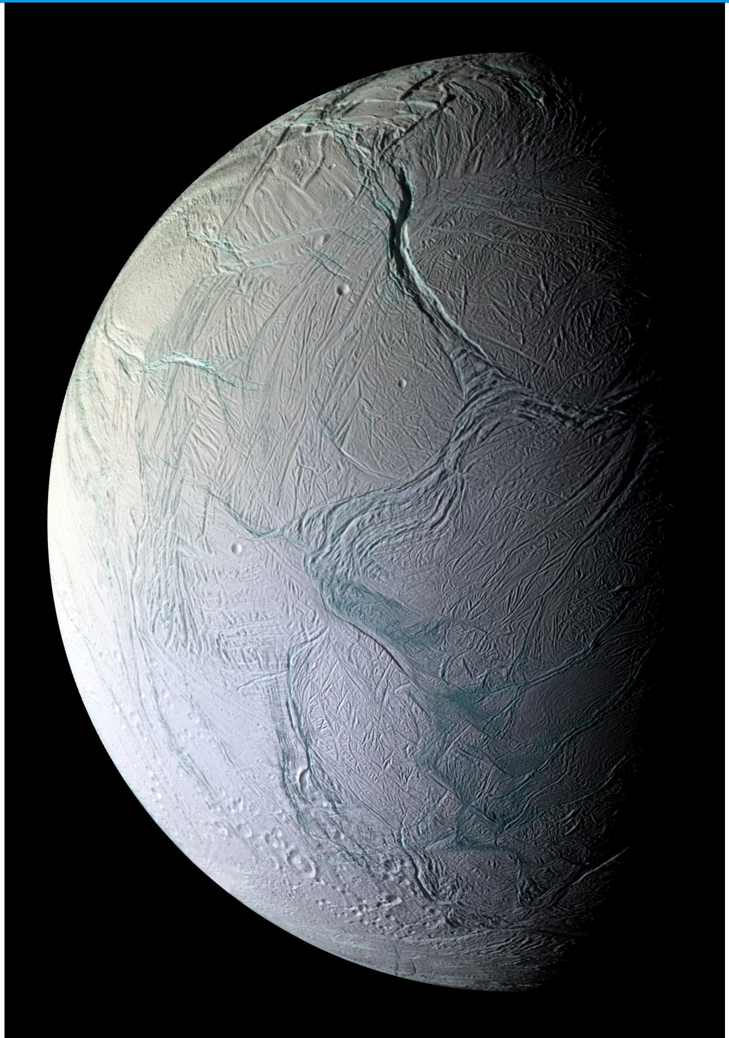
Plasma observations from space

Remote sensing observations

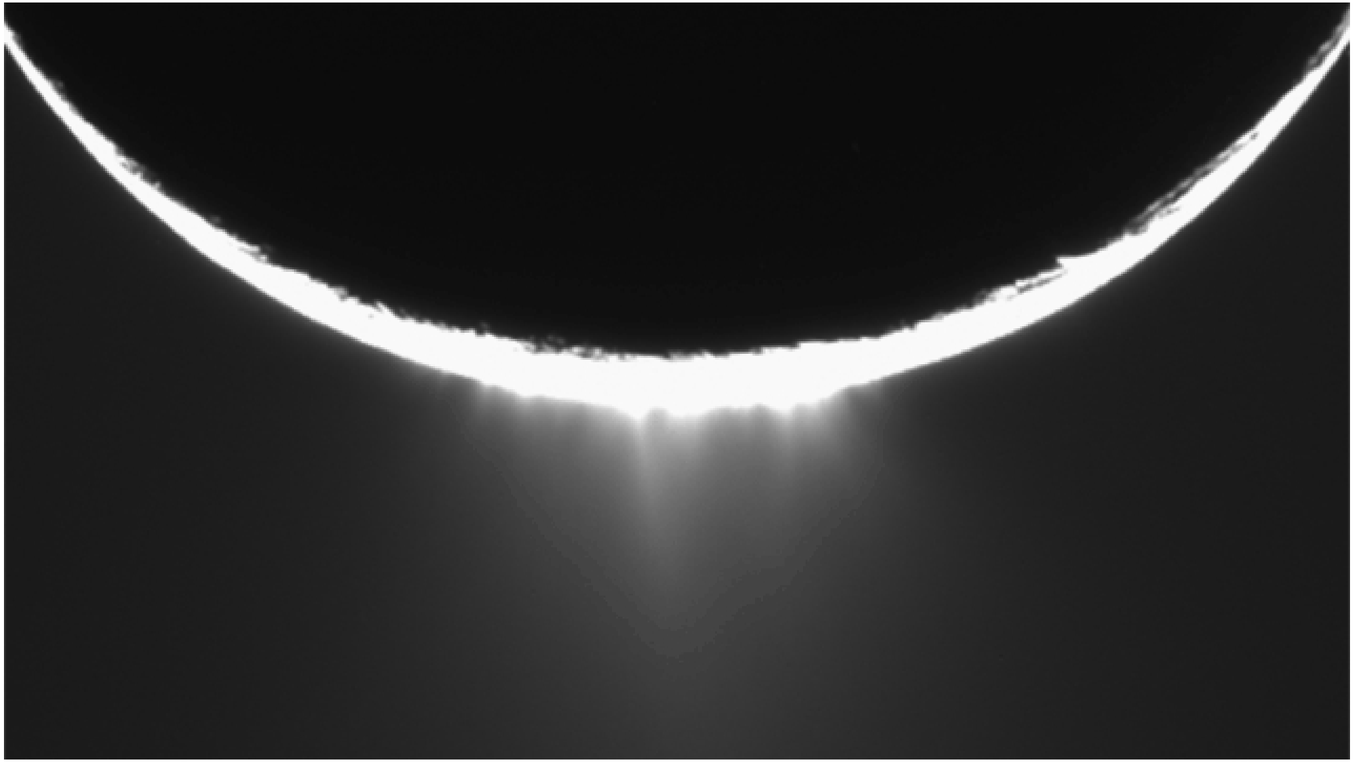
Images



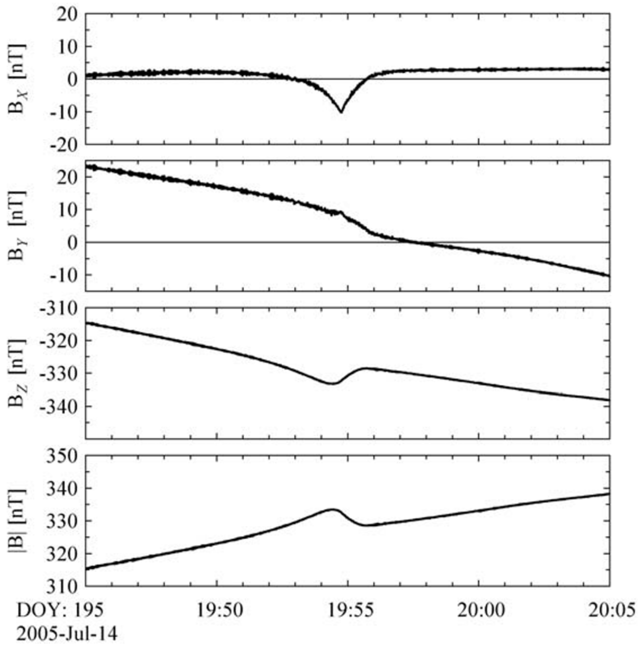
Encaladeus icy moon around Saturn

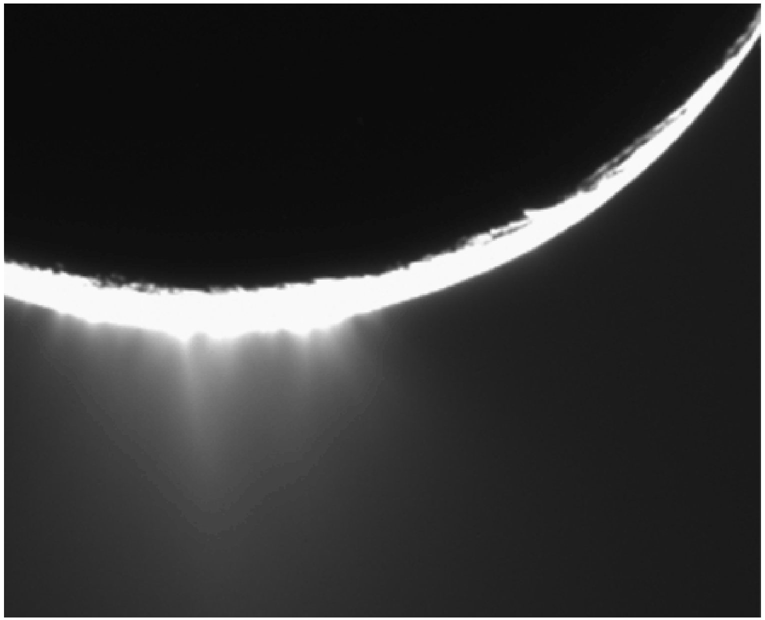


Encaladus active jets



Encaladus active jets





2005: first flyby of Enceladus is 1000 km, unusual comet like magnetic field signature detected.
Second flyby, altitude decreased to 175 km [Dougherty el al., Science, 2006]

Spectroscopy

Measure the spectrum of electromagnetic radiation, including visible light, IR, UV, X-rays and radio waves that radiate from stars and other celestial objects. The spectrum can reveal many properties such as the chemical composition, temperature, density, mass distance and luminosity.

→ Planets, asteroids, and comets all reflect light from their parent stars and emit their own light. For cooler objects, including Solar System planets and asteroids, most of the emission is at infrared wavelengths we cannot see, but that are routinely measured with spectrometers.

Spectroscopy

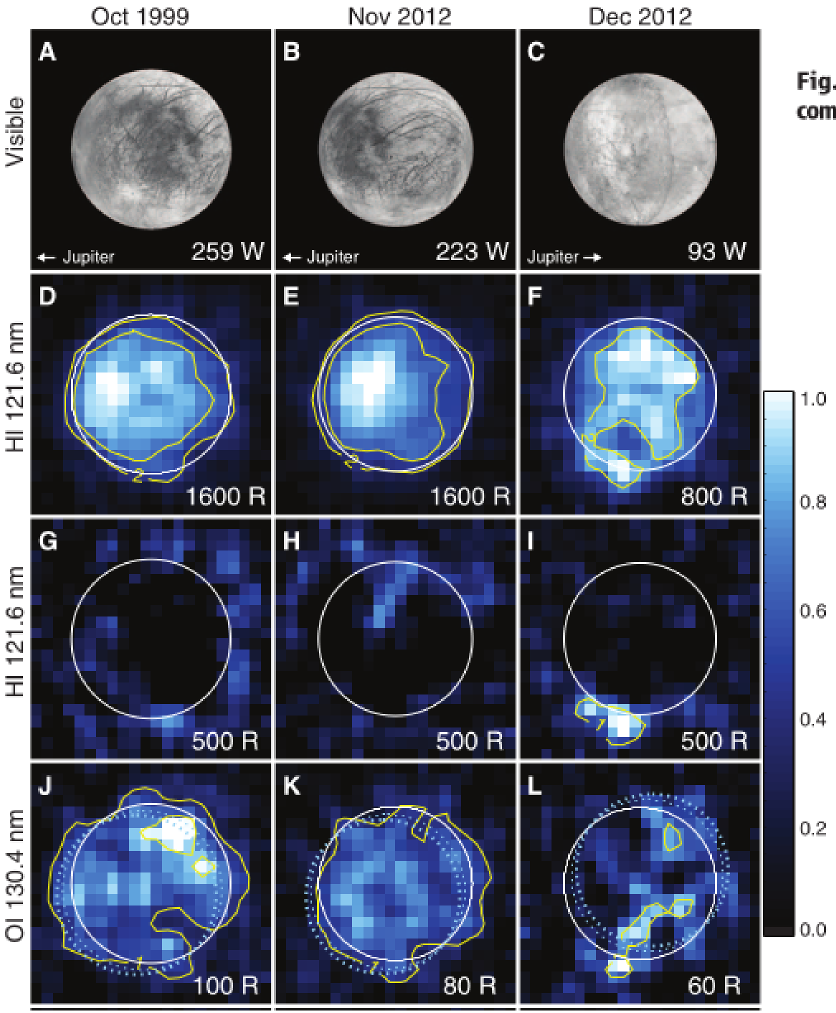


Fig. 1. Visible images of the observed hemispheres (A to C) with sub-observer longitudes listed and combined STIS images of the H and O emissions (D to O) (Table 1).

December 2012, the Hubble Space Telescope (HST) imaged Europa's ultraviolet emissions in the search for vapor plume activity.

Detection of water vapor above the southern pole of the icy moon Europa → Presence of water plume.

Roth et al., *Nature* 2014

Magnecti field measurements: Zeeman effect

The Zeeman effect is the effect of splitting of a spectral line into several components in the presence of static magnetic field. It was observed for the first time in 1896 by the Dutch physicist, Pieter Zeeman in laboratory experiment.

→ Since the distance between the Zeeman sub-levels is a function of the magnetic field strength, the Zeeman effect can be used to measure the magnetic field strength (Sun, stars formation or in laboratory plasmas)

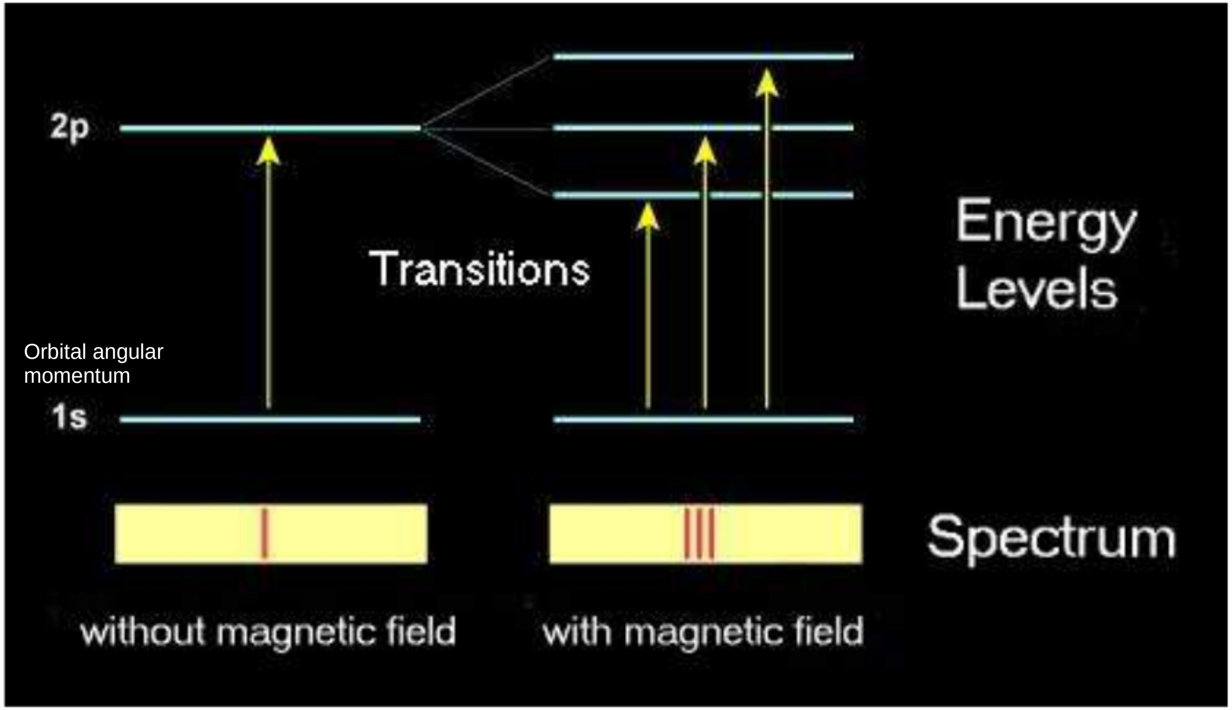
$$\nu = \nu_0 \pm \frac{\mu_B B}{h}$$

Predicted frequencies

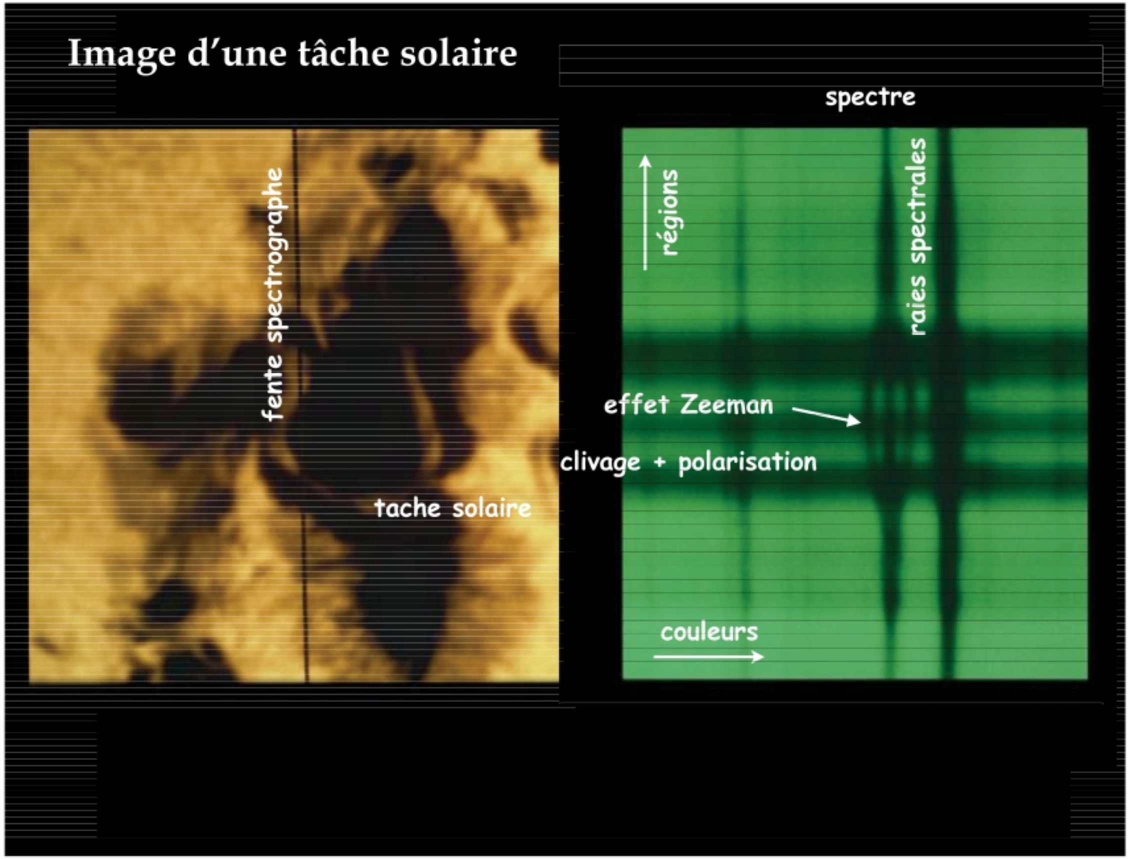
Unshifted line frequency

μ_B = Bohr magneton (the magnetic moment of an electron caused by its orbital or spin angular momentum).

h = Planck constat



Magnecti field measurements: Zeeman effect



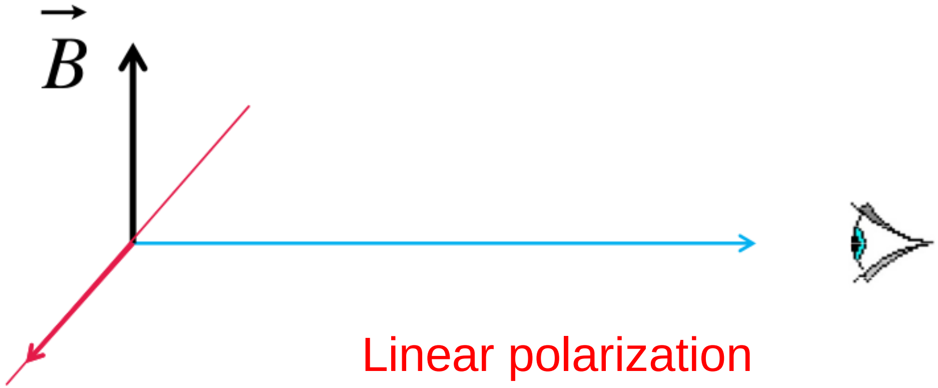
J-F. Donati

The Sunspots are regions of Sun's atmosphere with strong magnetic field

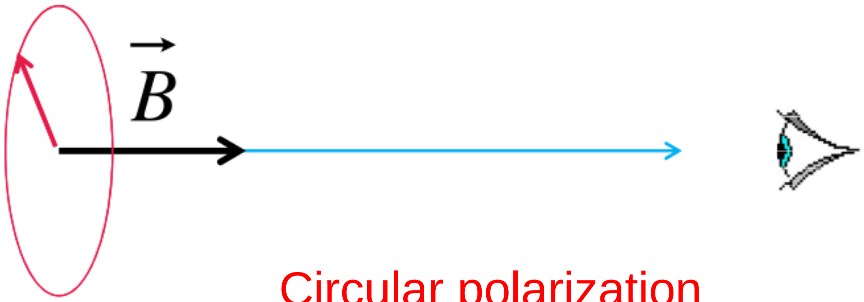
Magnecti field measurements: Zeeman effect

The separartion in the energy level is followed by A polarisation of the light emitted (or absorbed) during the transition between the different levels.

→ The type and intensity of the polarisation depends on the orientation of the magnetic field with respect to the observer.



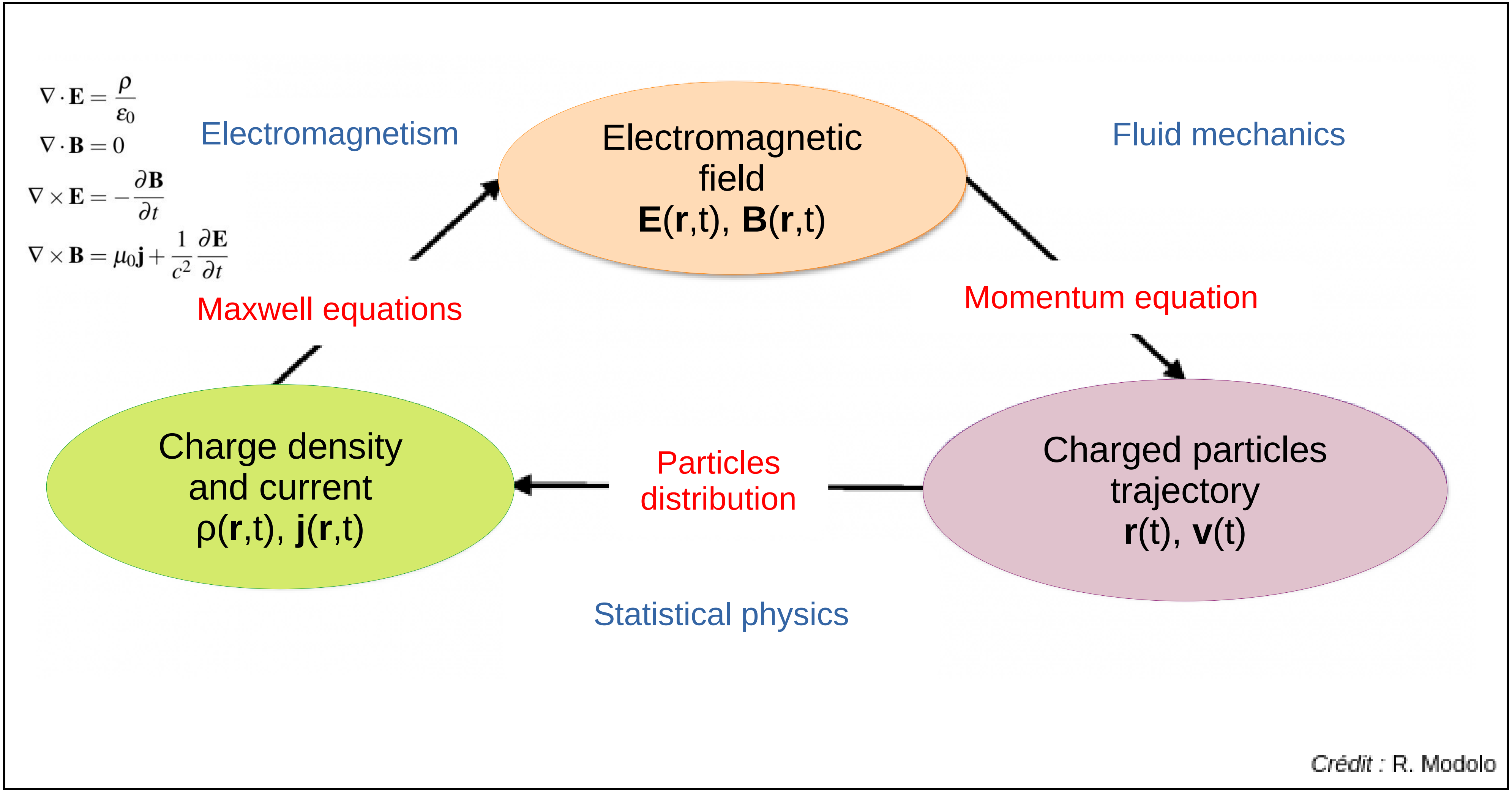
Linear polarization



Circular polarization

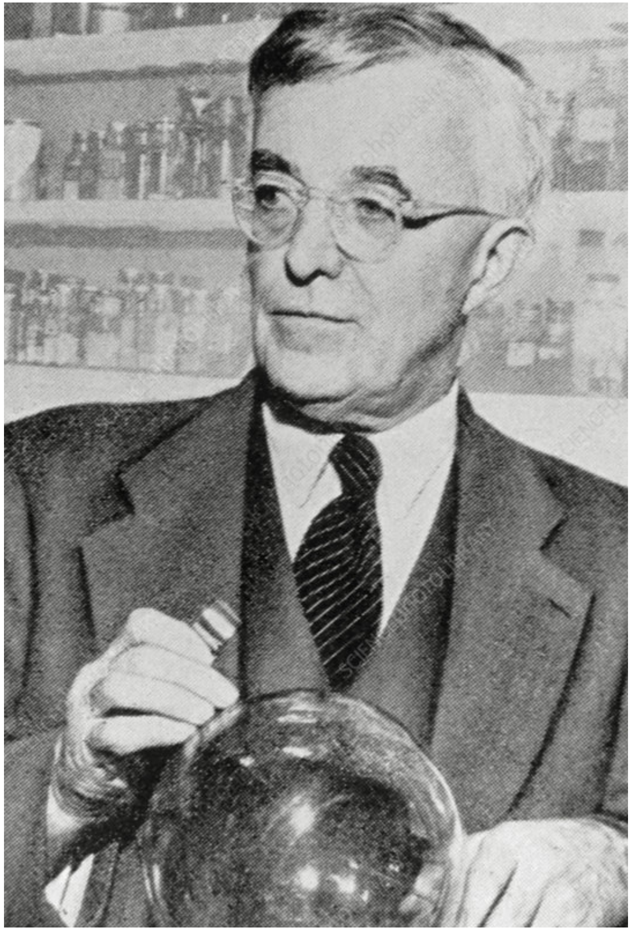
Plasma observations from space

In situ observations



$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$
Electromagnetism
Electromagnetic field
E(**r**,t), **B**(**r**,t)
Fluid mechanics
Maxwell equations
Momentum equation
Charge density and current
ρ(**r**,t), **j**(**r**,t)
Particles distribution
Charged particles trajectory
r(t), **v**(t)
Statistical physics
Crédit : R. Modolo

Langmuir probe



Irving Langmuir (1881 - 1957)

Active measurements perturbing the surrounding plasma.

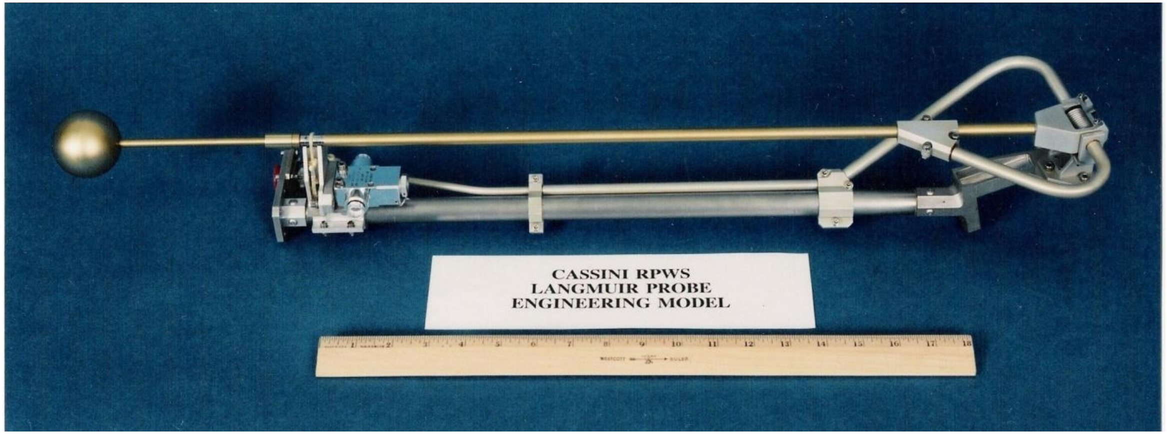
→ ~**1920:** Invention the Langmuir probes to measure the electron plasma density (n_e) and the electron temperature $K_B T_e$ in cold low density laboratory plasmas.

→ **1928:** Coined the term “plasma” in relation to the physics of partially ionized gases.

→ ~ **1950:** Langmuir probes are used on rockets and satellites to measure the electron and ion densities, the electron temperature in the ionospheres and the spacecraft potentials.

Langmuir probe

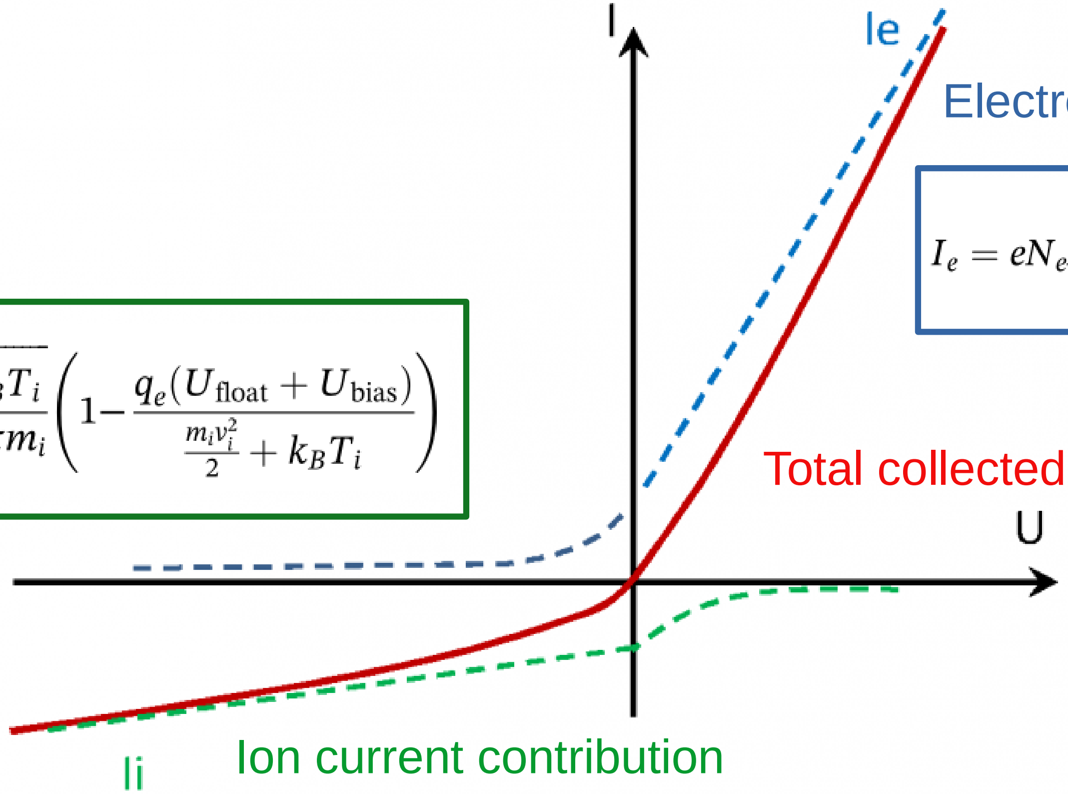
Langmuir probe onboard the Cassini spacecraft (Diameter ~5cm)



IRFU, Uppsala, Sweden

Langmuir probe

The Langmuir Probe samples the total electrical current from the plasma. The caracteristical Current-Voltage (I-V) curve gives estimates of several thermal plasma parameters:



$$I_e = eN_eA_{LP}\sqrt{\frac{kT_e}{2\pi m_e}}\exp\left(\frac{-e(U_{\text{float}}+U)}{kT_e}\right)$$

$$I_i \approx -A_{\text{LP}}n_iq_i\sqrt{\frac{v_i^2}{16}+\frac{k_BT_i}{2\pi m_i}}\left(1-\frac{q_e(U_{\text{float}}+U_{\text{bias}})}{\frac{m_iv_i^2}{2}+k_BT_i}\right)$$

M. Morooka et al., JGR, 2019

Example: ion current

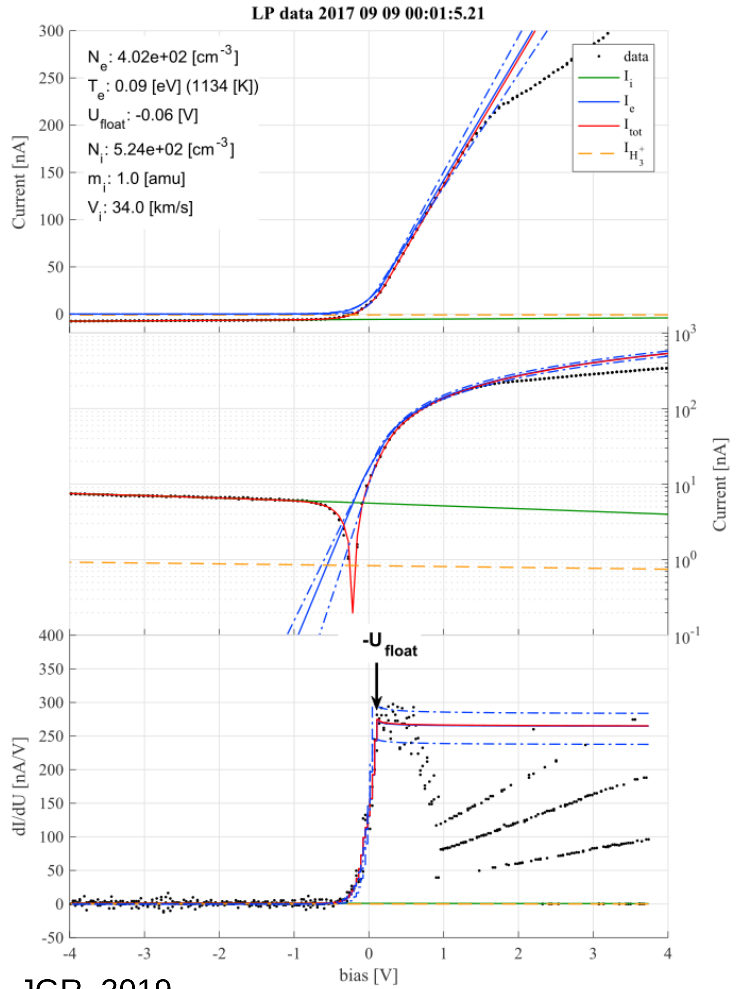
The ion current can be expressed as a linear function:

$$I_i = m + bU_{\text{bias}},$$

Where: $m \approx \frac{1}{4} A_{LP} q_i n_i v_i$ and $b \approx A_{LP} q_i n_i \frac{q_e}{2 m_i v_i}$

↓ Intercept ↓ Slope

A_{LP} is the surface area of the LP, and qi, Ti, ni, vi, and mi are the charge, temperature, density, drift velocity, and mass of the ion species, respectively. U_{float} is the floating potential. It is where the probe electrical potential balances with the ambient plasma.



M. Morooka et al., JGR, 2019

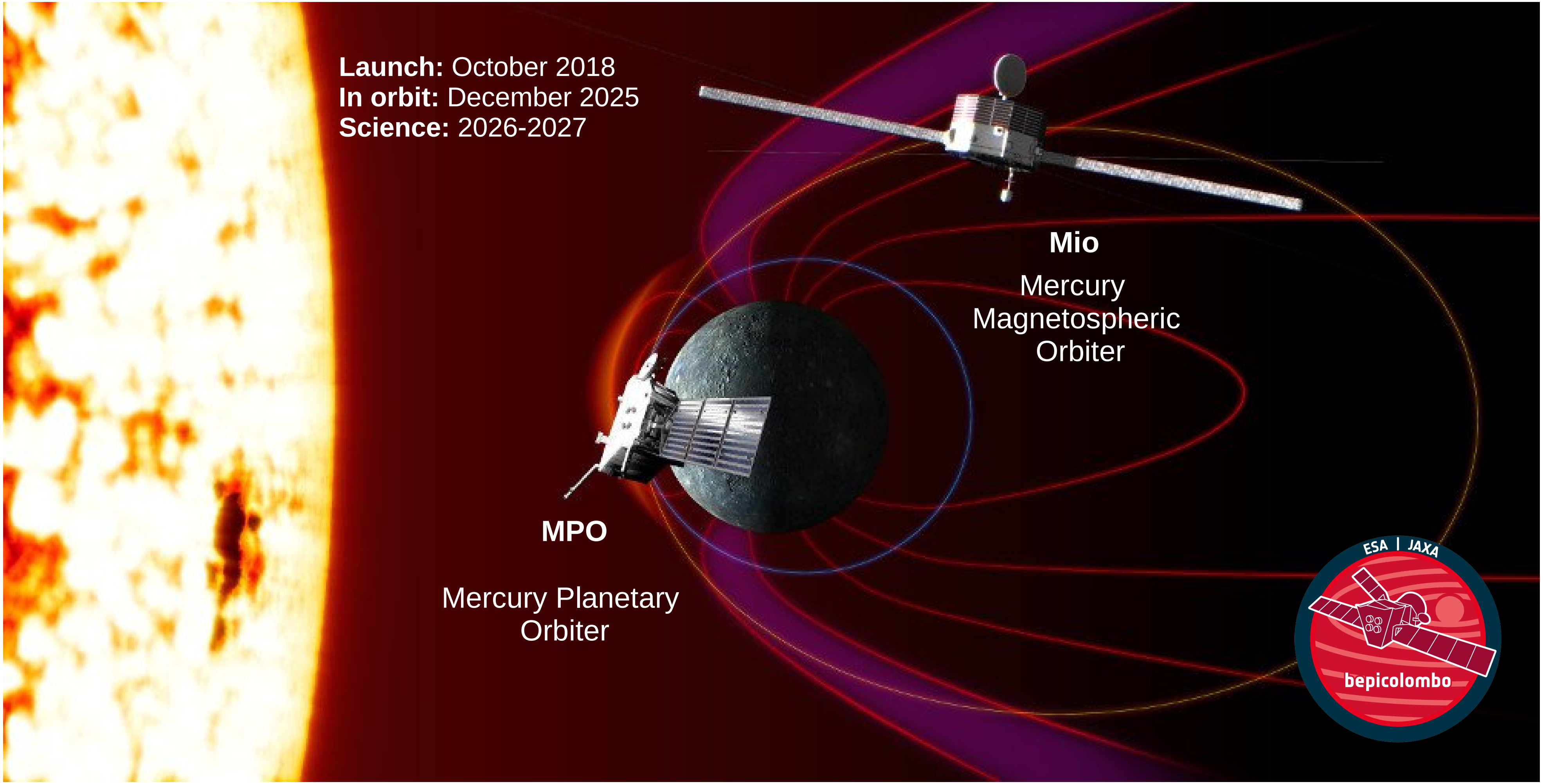
Ion mass spectrometers

Calculate the ion counts and some properties:

- Direction
- Energy
- Ion species (ratio m/q)

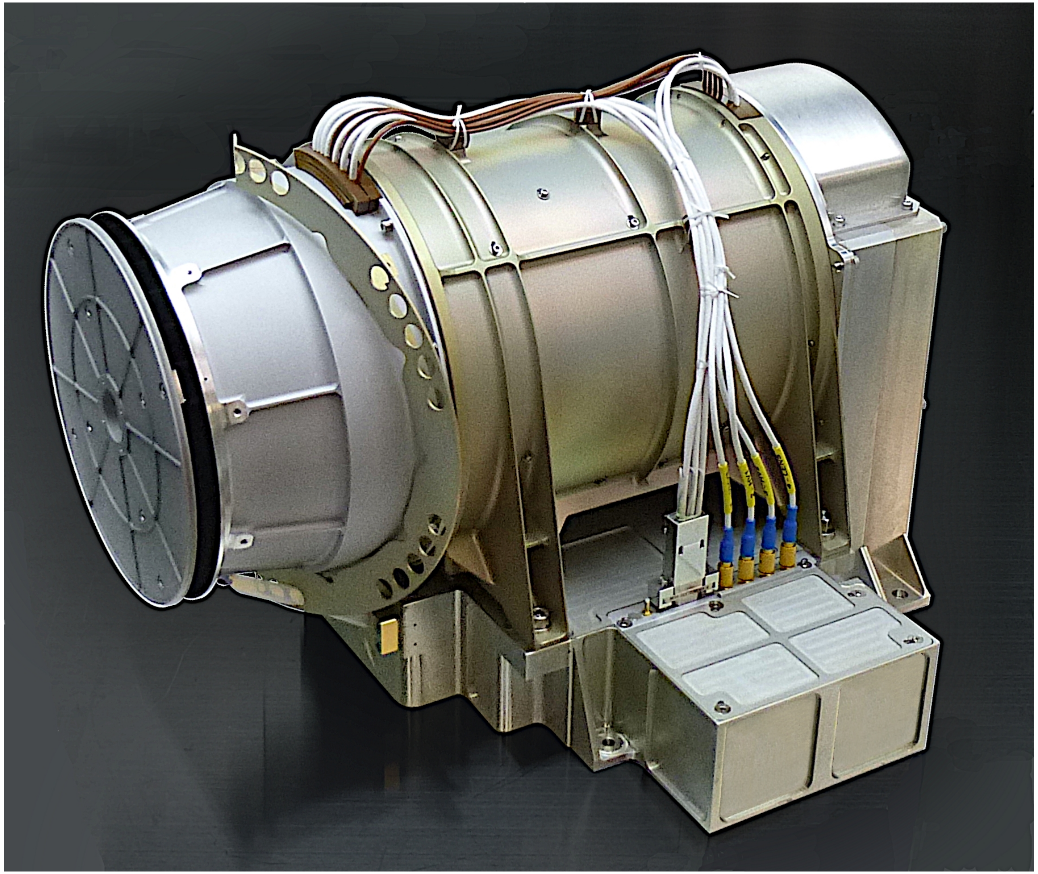
→ Example: Mass Spectrum Analyzer (MSA) onboard the **BepiColombo Spacecraft mission**

BepiColombo ESA/JAXA mission to MERCURY

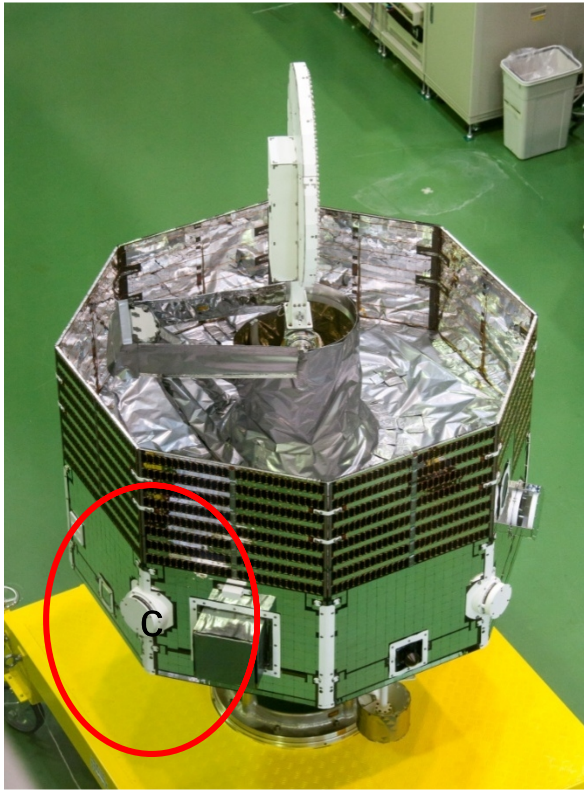


Ion mass spectrometers

BepiColombo Mass Spectrum Analyzer (MSA) developped at LPP



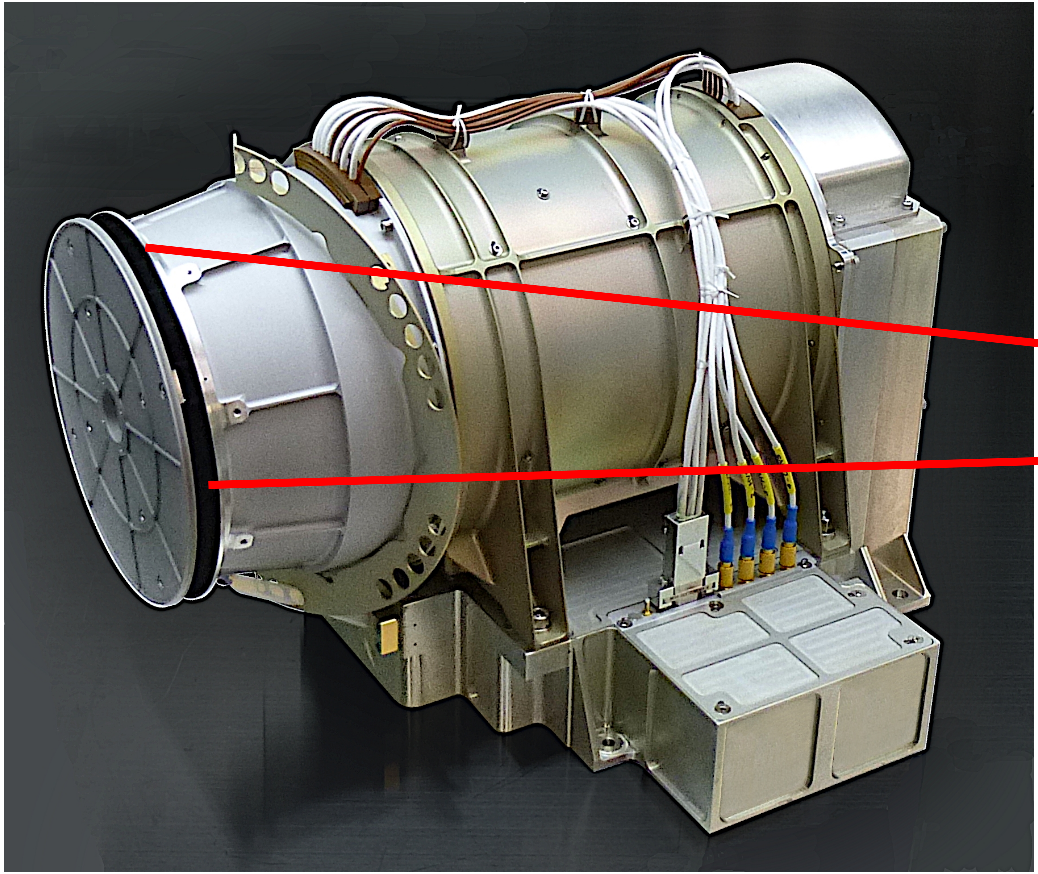
Delcourt et al., JGR, 2016

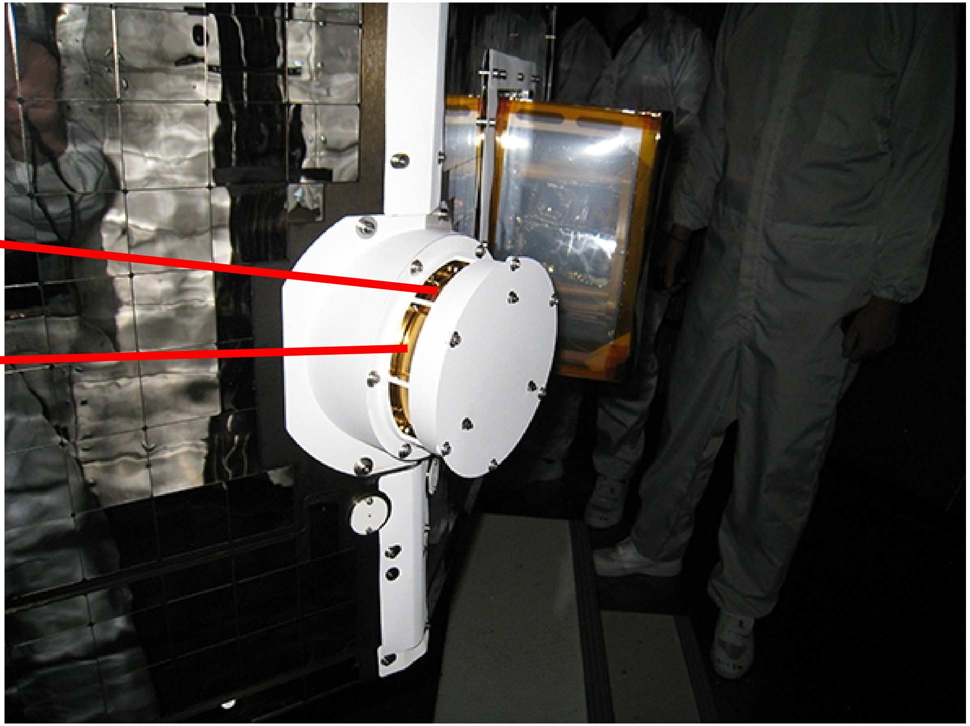


Saito et al. SSR, 2021

Ion mass spectrometers

BepiColombo Mass Spectrum Analyzer (MSA) developped at LPP





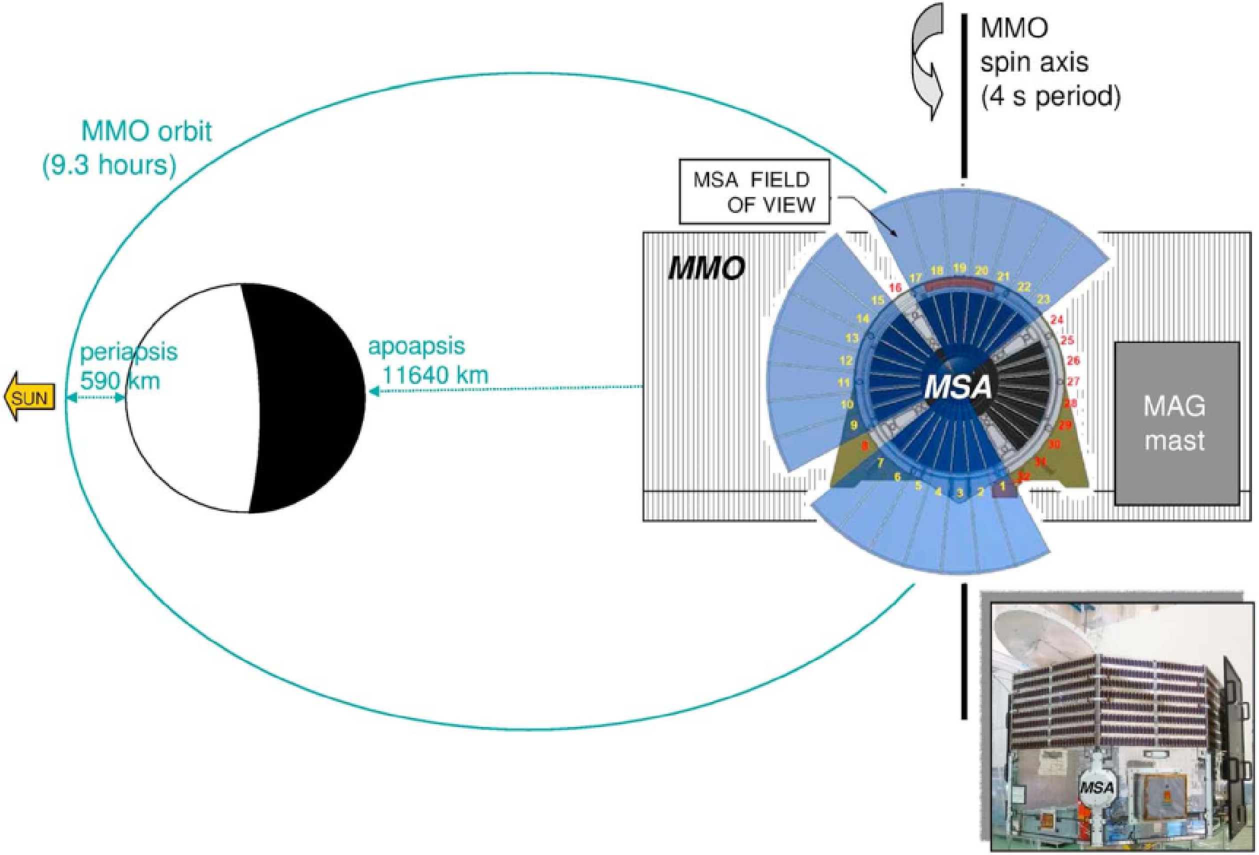
Saito et al. SSR, 2021

Delcourt et al., JGR, 2016

Ion mass spectrometers

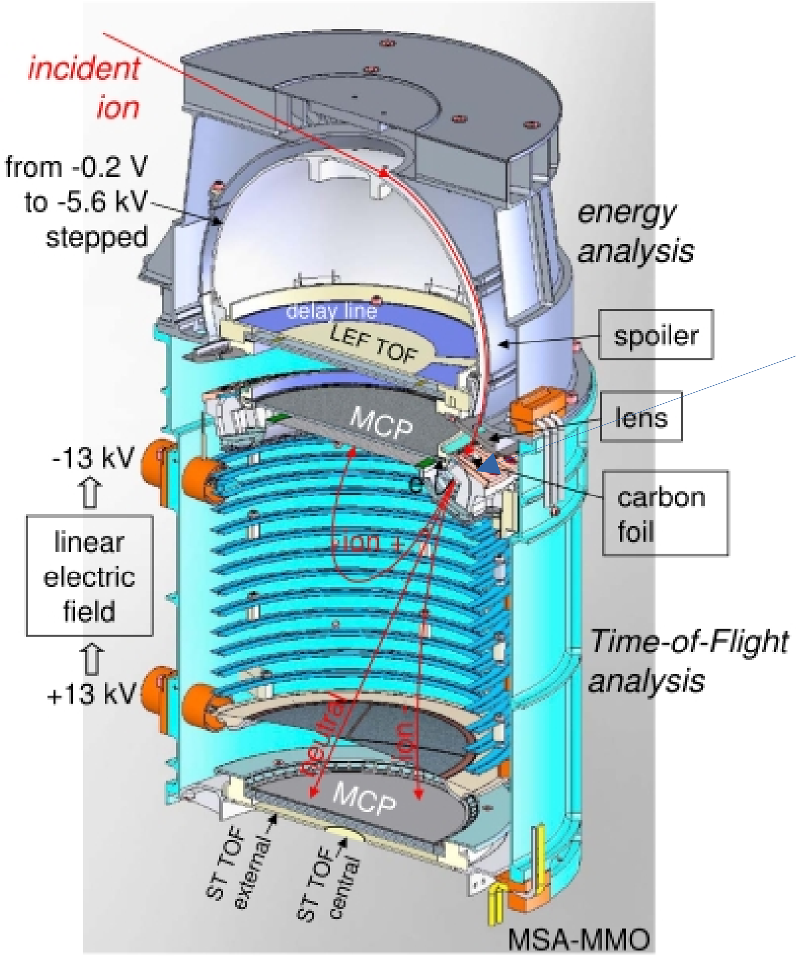
BepiColombo Mass Spectrum Analyzer (MSA)

Field of View:
32x11.25°

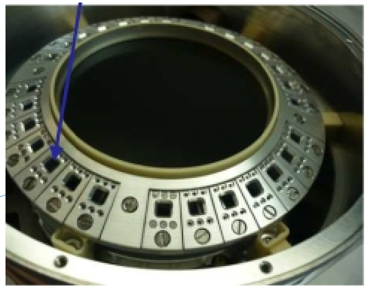


Delcourt et al., JGR, 2016

Ion mass spectrometers



Carbon foil

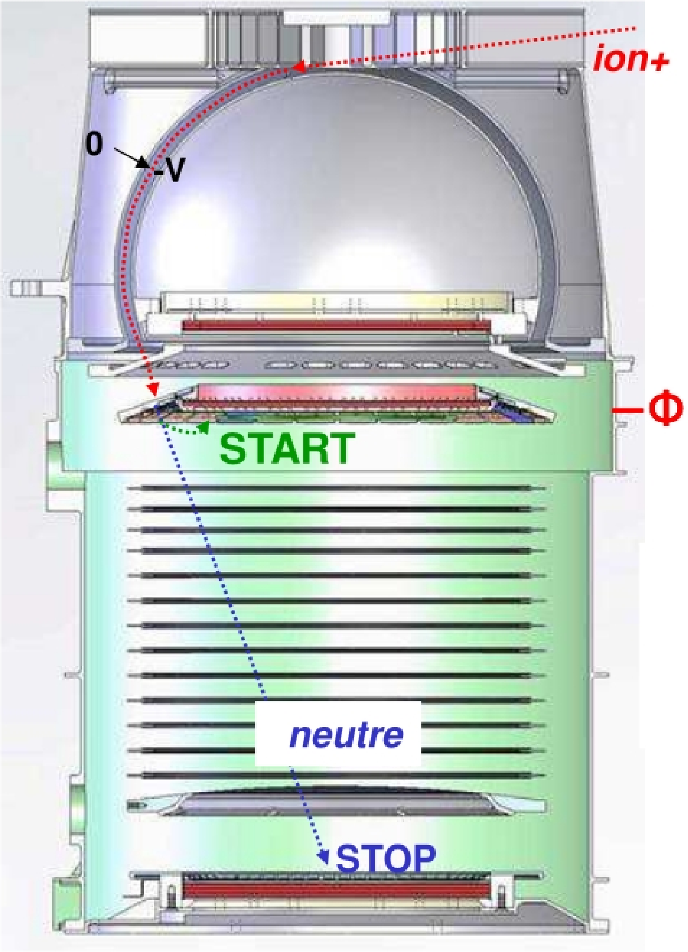


Delcourt et al., JGR, 2016

Ion mass spectrometers

Neutrals and negatively charged ions inside the TOF chamber:

Straight Trough (ST) detector



$$E_0 + q\,\Phi = \frac{1}{2} m v^2$$

$$\frac{E_0}{q} + \Phi = \frac{1}{2}\frac{m}{q}\left(\frac{L}{T}\right)^2$$

Ion mass spectrometers

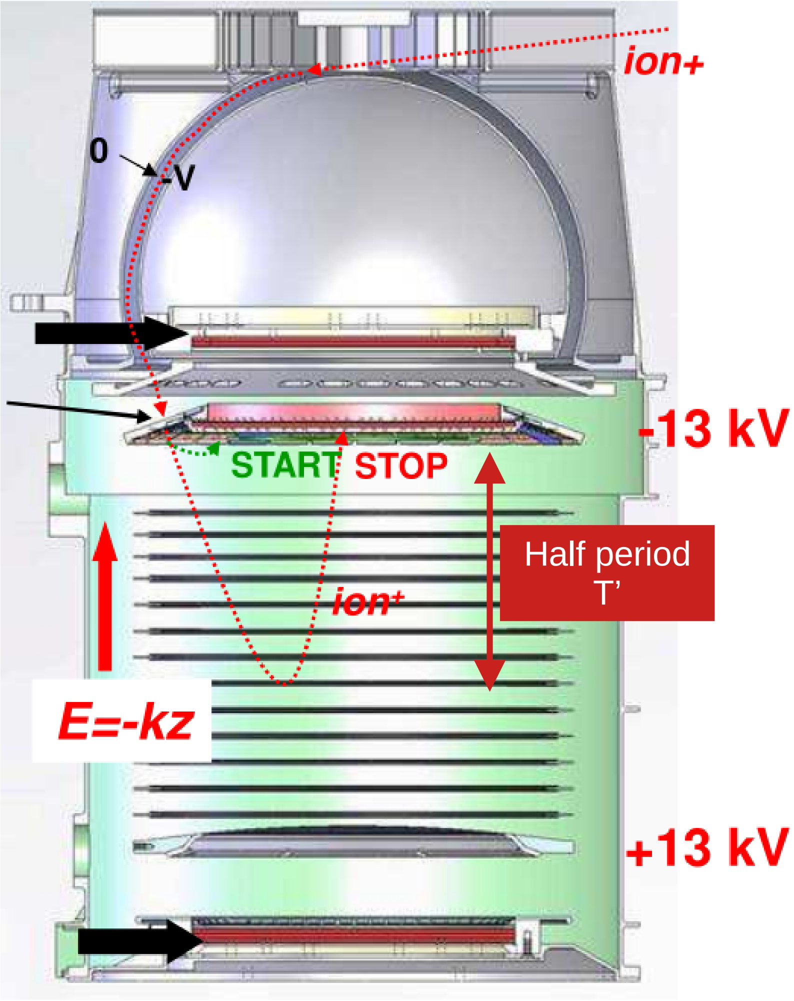
Positively charged ions
Inside the TOF chamber:

Linear Electric Field (LEF)
detector

$$m\frac{dz^2}{dt^2}=-qkz$$

$$\frac{dz^2}{dt^2}+\frac{qk}{m}z=0$$

ω^2 (Angular frequency)



$$\frac{m}{q}=k\left(\frac{T'}{\pi}\right)^2$$

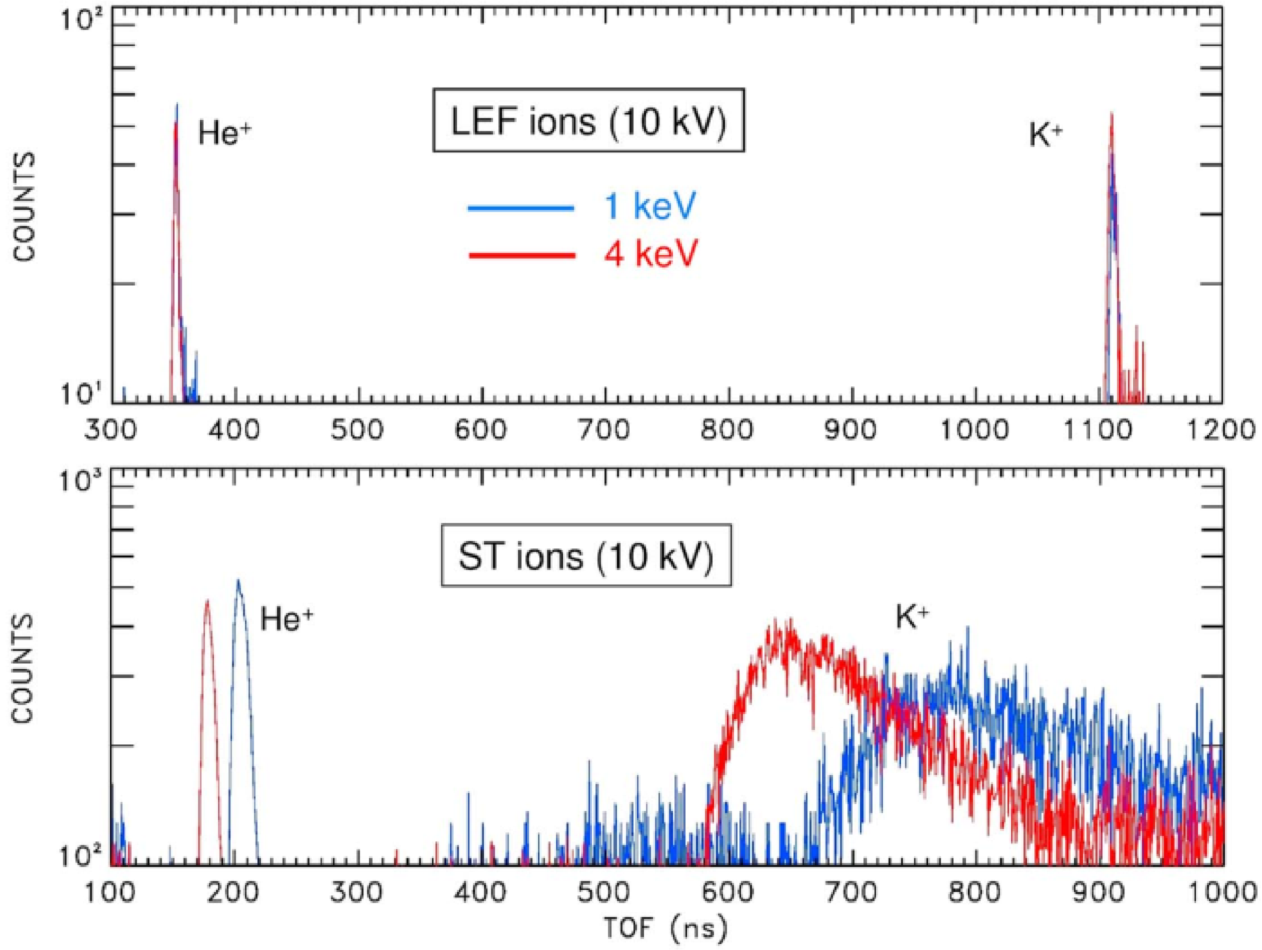
Ion mass spectrometers

LEF → No dependence on energy

$$m/q = CT^2/\pi^2$$

ST → Dependent on the energy

$$m/q = 2(E/q)T^2/L^2$$



Delcourt et al., JGR, 2016

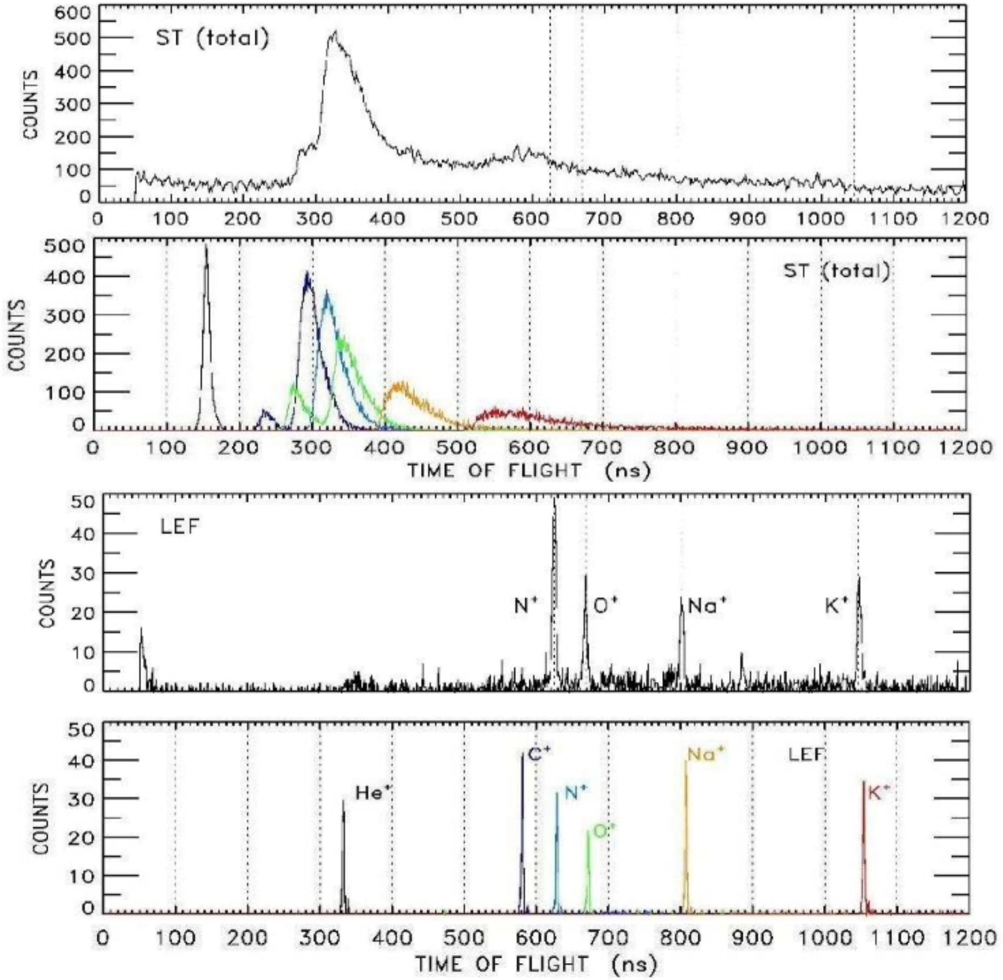
Ion mass spectrometers

Ion beam test using
the flight model of MSA →

Simulated data →

Ion beam test using
the flight model of MSA →

Simulated data →

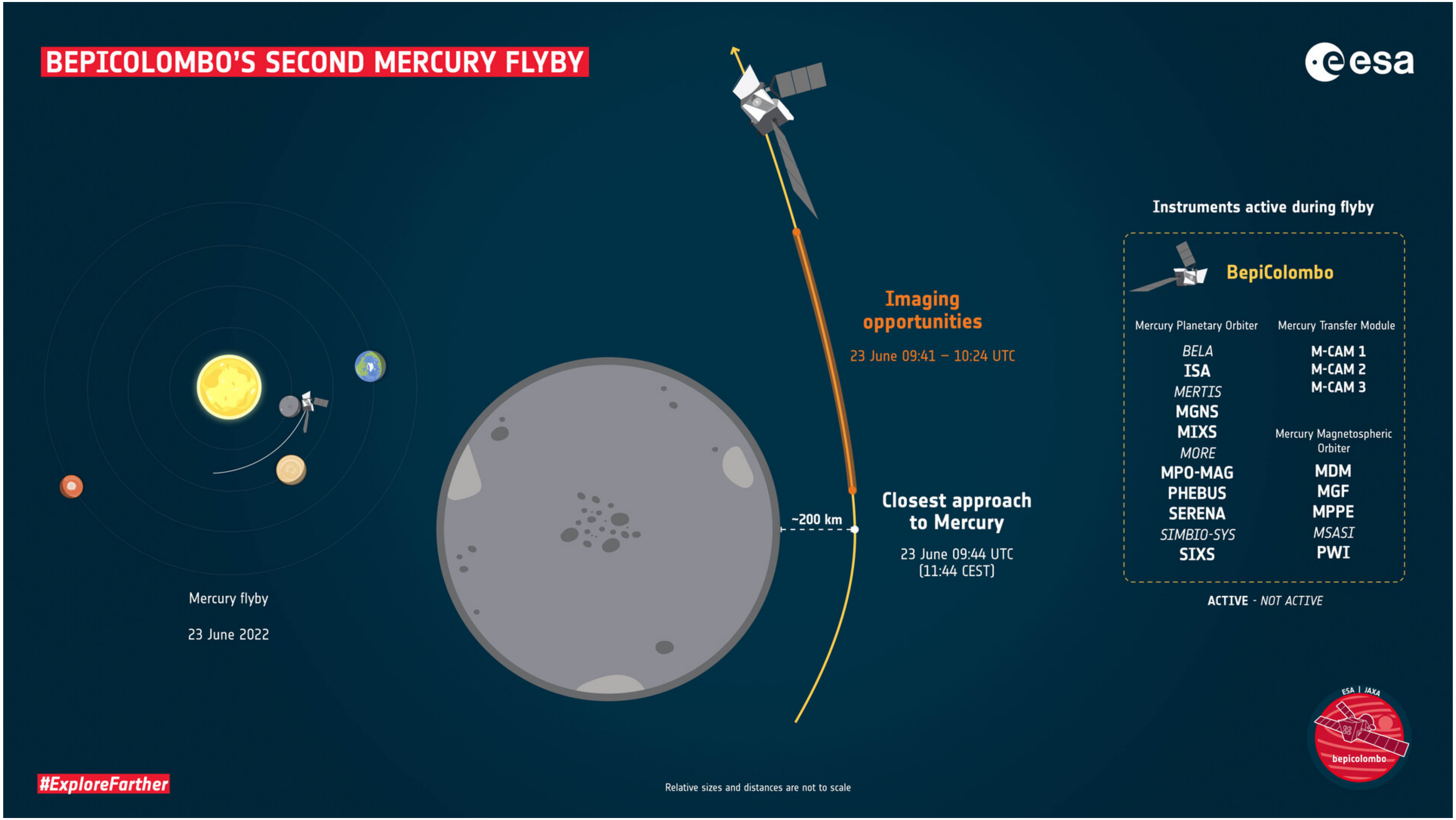


ST

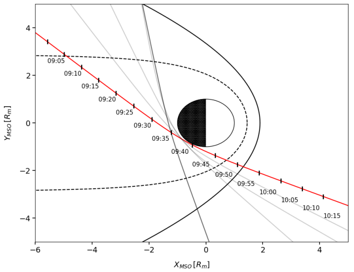
LEF

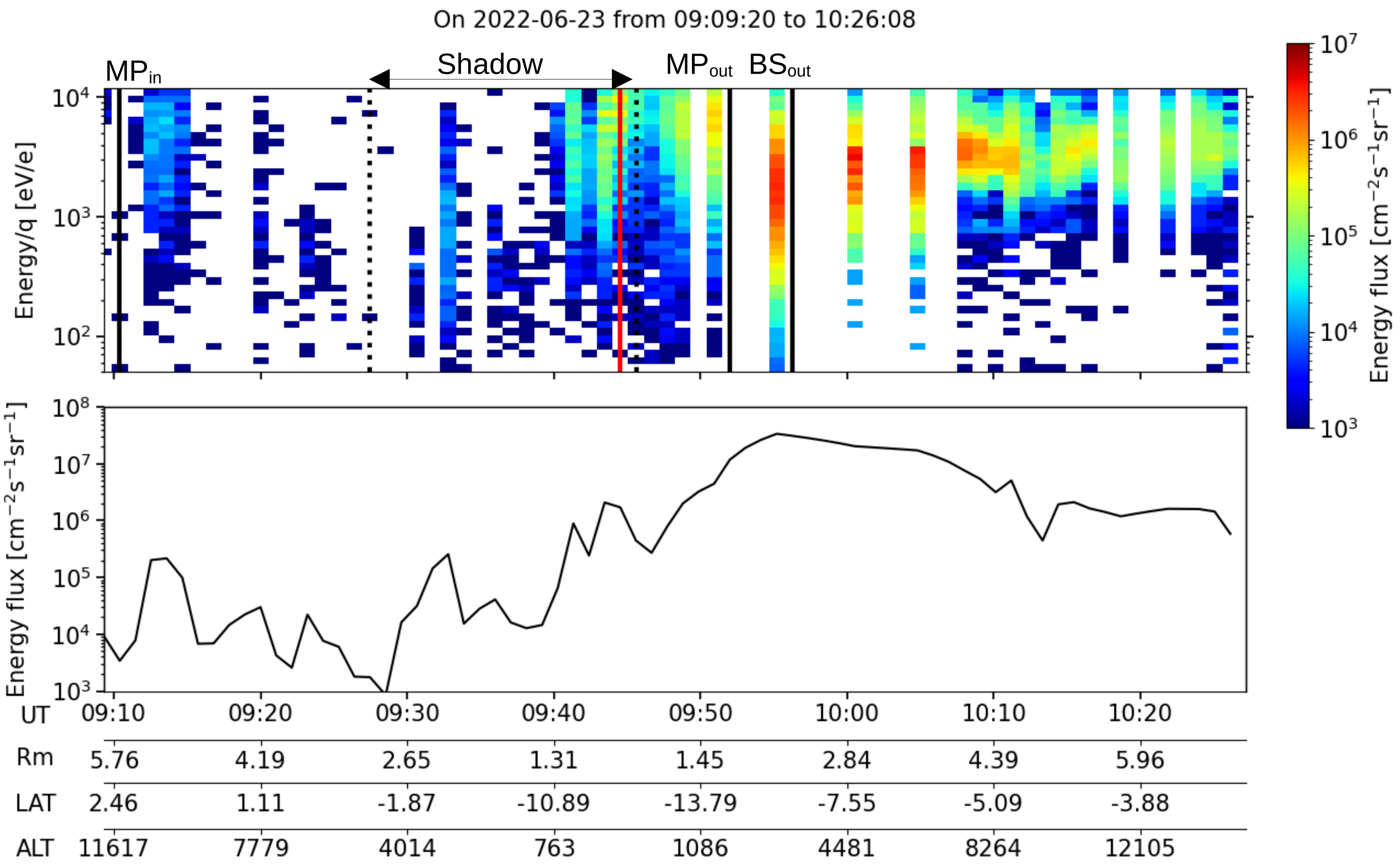
Delcourt et al., JGR, 2016

MSA data at Mercury – June 23, 2022



Overview of MSA observations



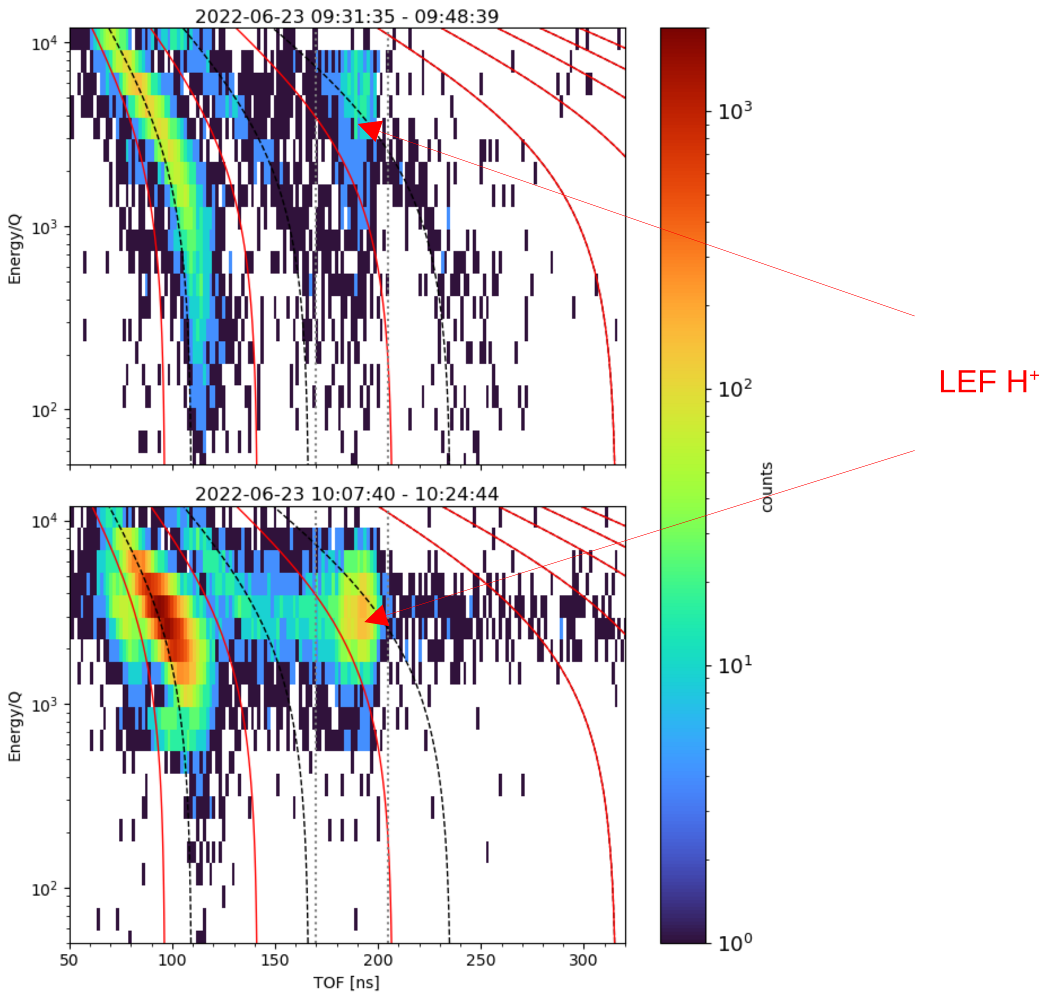


Observation of planetary He^{2+} and He^{+}

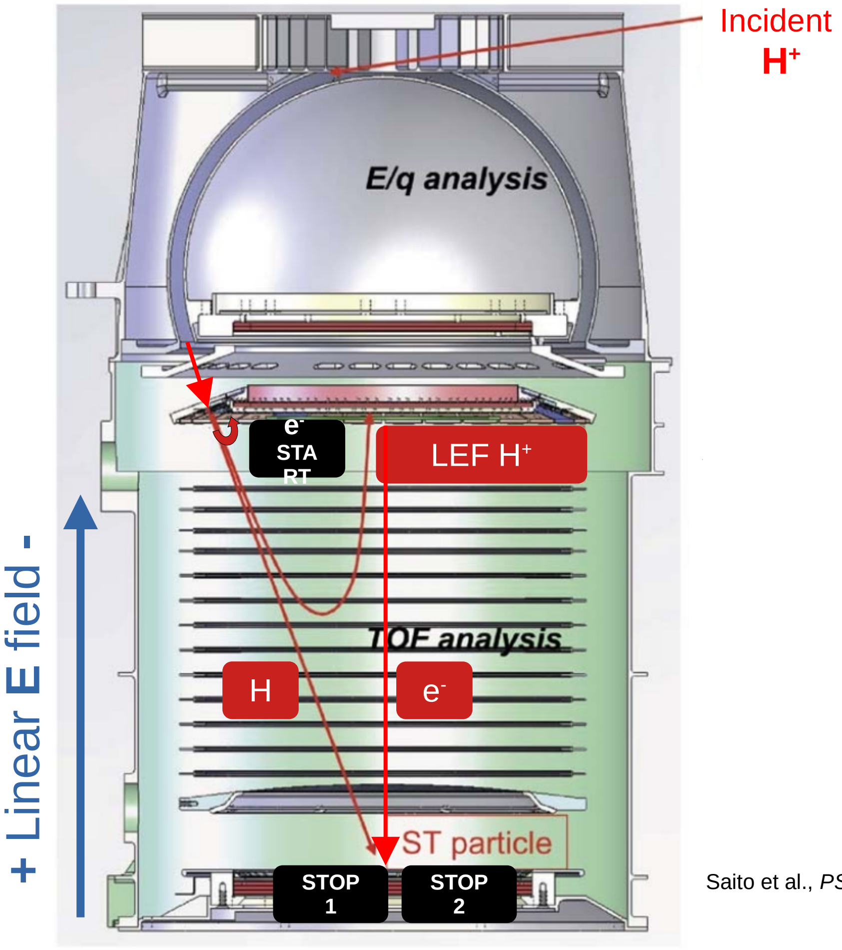
MSA TOF spectra:

Around the CA

Foreshock/Solar wind



Observation of planetary He^{2+} and He^{+}



During Carbon foil crossing:

$H^{+} \rightarrow H$

TOF1= STOP1 – START (50 – 100 ns depending upon energy)

During Carbon foil crossing:

$H^{+} \rightarrow H^{+}$

TOF2= STOP2 – START (~ 200 ns regardless of energy)

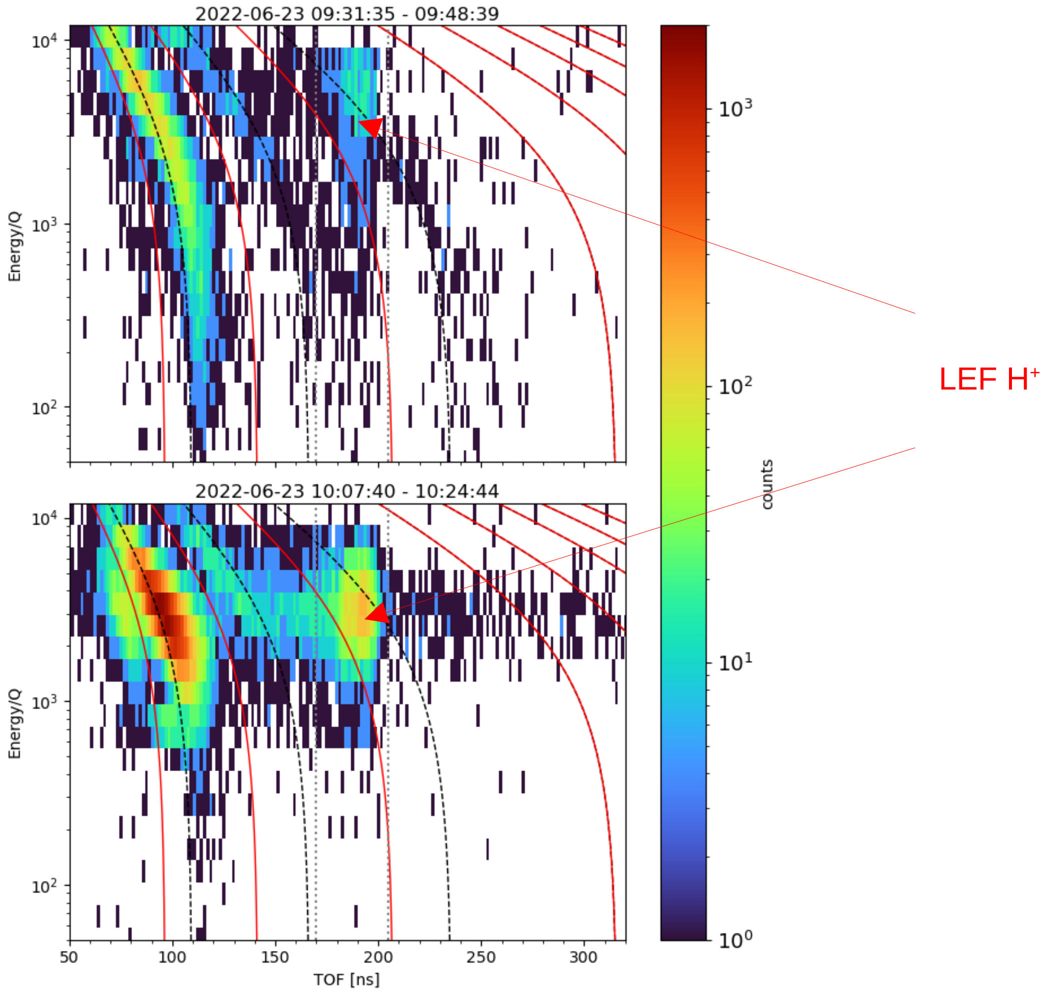
Saito et al., *PSS*, 2010

Observation of planetary He^{2+} and He^{+}

MSA TOF spectra:

Around the CA

Foreshock/Solar wind

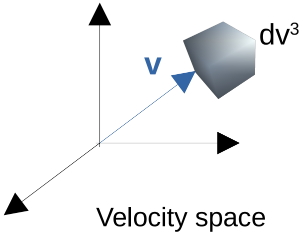


Ion distribution function

Number of counts/second

$$J = \frac{c(E,\varphi,\vartheta)}{G(E,\varphi,\vartheta)\tau\Delta E}$$

Differential flux (J) for a given energy and direction



$$J dE d\Omega = v f d^3 v$$

$$J m v dv d\Omega = v f dv\, v^2 d\Omega$$

Calculate the ion distribution function

$$f = \frac{mJ}{v^2}$$

Ion distribution functions

Number density
(0-th order moment)

$$n = \int_{-\infty}^{\infty} f(v)\,dv$$

Flow velocity
(1st order moment)

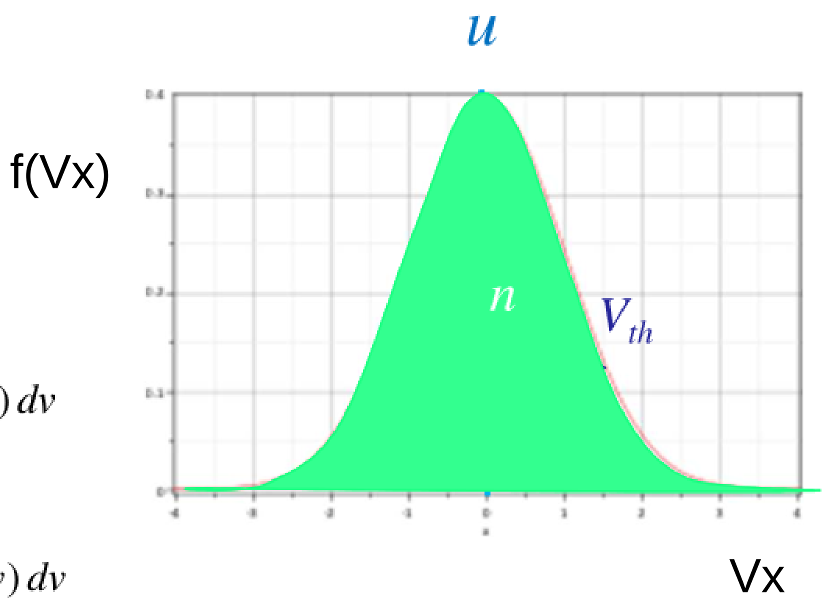
$$u = \langle v \rangle = \frac{1}{n}\int_{-\infty}^{\infty} v\, f(v)\,dv$$

Pressure
(2nd order moment)

$$V_{th}^2 = \langle (v-u)^2 \rangle = \frac{1}{n}\int_{-\infty}^{\infty} (v-u)^2 f(v)\,dv$$

Heat flux
(3rd order moment)

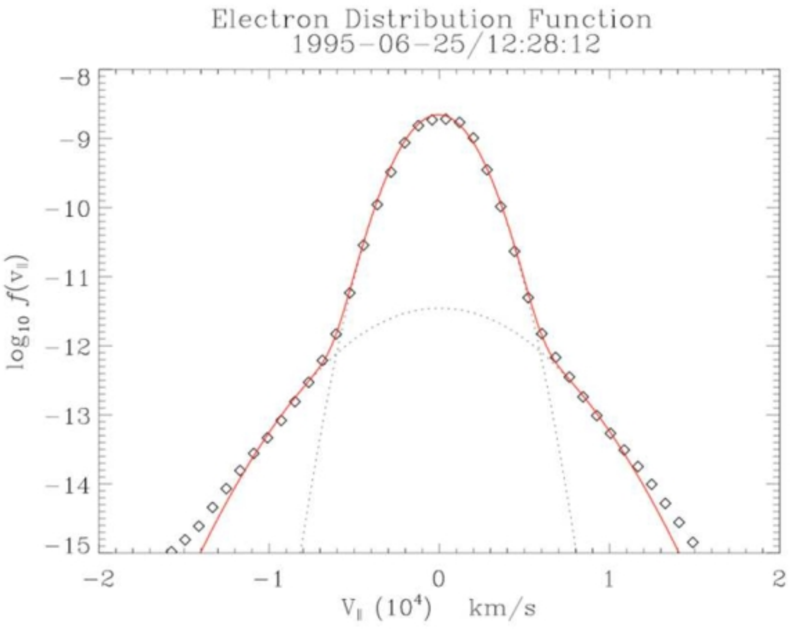
$$\frac{q}{nm} = \langle (v-u)^3 \rangle = \frac{1}{n}\int_{-\infty}^{\infty} (v-u)^3 f(v)\,dv$$

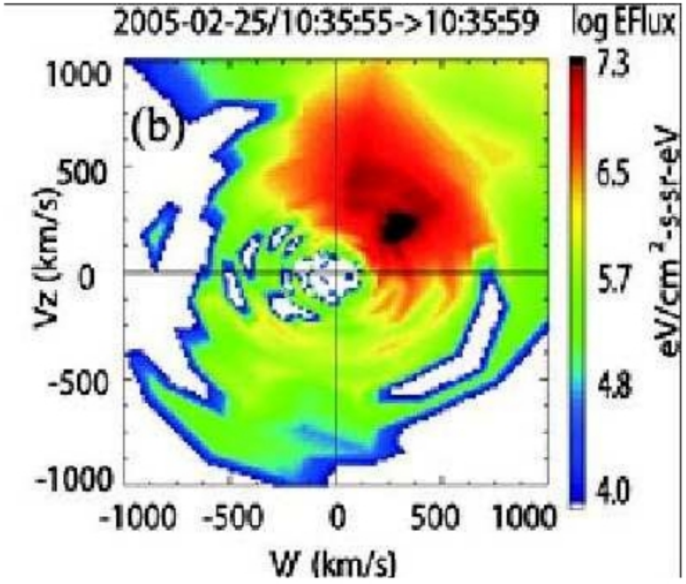


Ion distribution functions

Electron distribution function

Ion distribution function

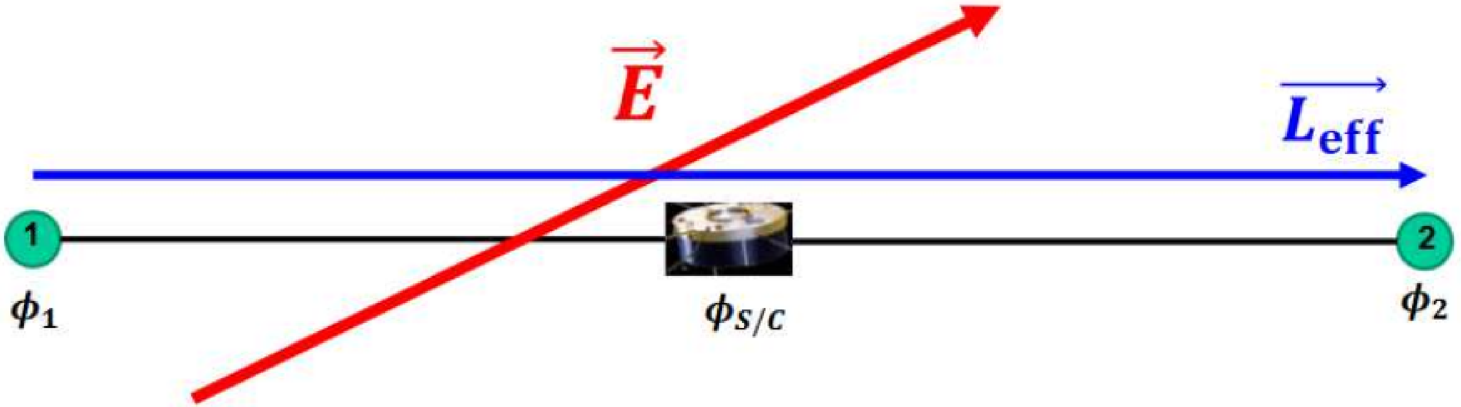




Electron distribution function in the solar wind using Wind spacecraft data (C. Sulem, PhD thesis).

Cluster data, Wang et al. 2014

Electric field measurements



$$\Phi_2 - \Phi_1 = \vec{E}.\overrightarrow{L_{eff}}$$

Magnetic field measurements

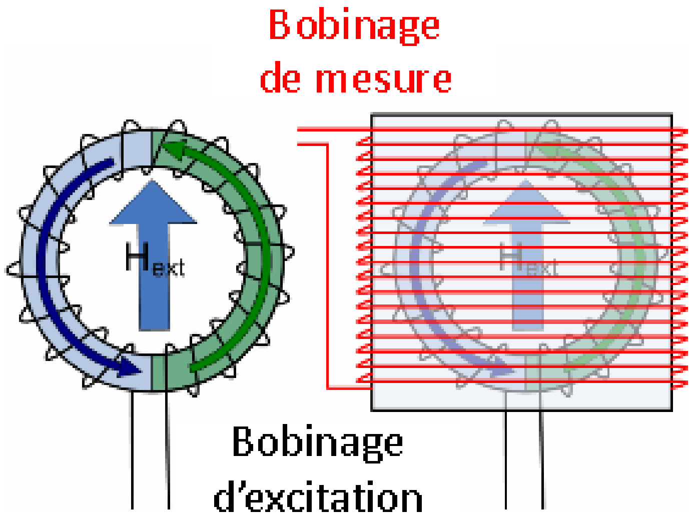
Lenz's law

$$e = -N\frac{d\Phi}{dt} = -NS\frac{dB}{dt}$$

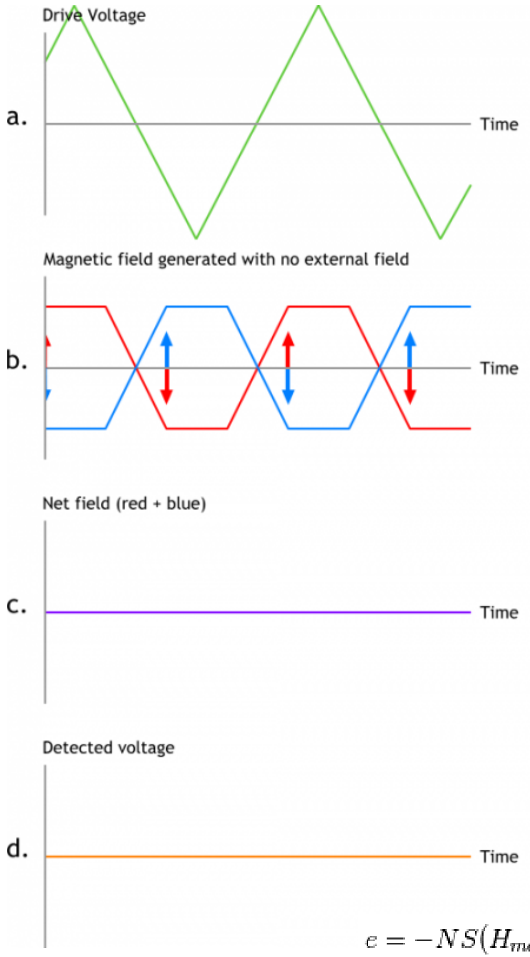
e= induced electric current
Φ=magnetic flux
N= number of turns in a coil of wire

Fluxgate magnetometer: [DC – 1 Hz]

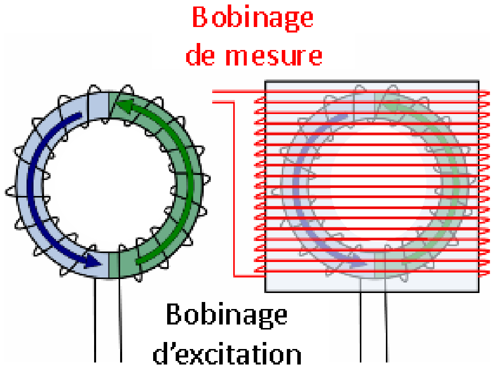
A fluxgate magnetometer consists of a ferromagnetic metal core wrapped by two coils of wire. An alternating electric current is passed through the **primary "drive" coil**, driving the core through an alternating cycle of magnetic saturation; i.e., magnetised, unmagnetised, inversely magnetised, unmagnetised, magnetised, and so forth. This constantly changing field induces an electric current in **the secondary "sense" coil**, and this output current is measured by a detector. In a magnetically neutral background, the input and output currents match. However, when the core is exposed to a background field, it is more easily saturated in alignment with that field and less easily saturated in opposition to it. Hence the alternating magnetic field, and the induced output current, are out of step with the input current. The extent to which this is the case depends on the strength of the background magnetic field.



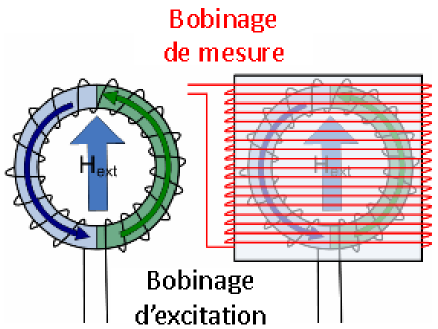
Magnetic field measurements

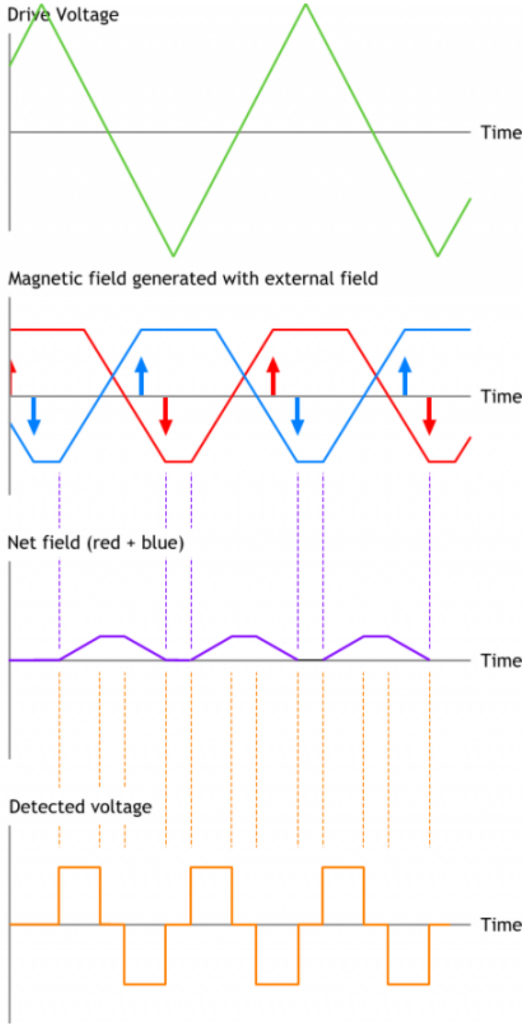


No external magnetic field



External magnetic field





$$e = -NS\left(H_{max}\omega_0 \cos(\omega_0 t)(a_1 - 3a_3 H_{ext}) + \boxed{3a_3 H_{ext} H_{max}^2 \omega_0 \sin(2\omega_0 t)} + \frac{3}{2} a_3 H_{max}^3 \omega_0 \cos(3\omega_0 t)\right)$$

Magnetic field measurements

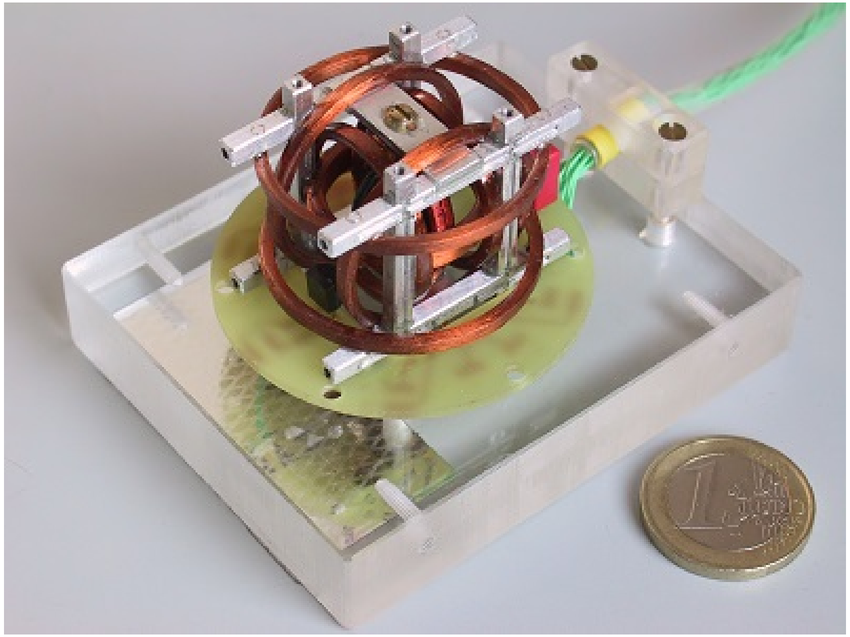
Lenz's law

$$\epsilon = -N\frac{d\Phi}{dt} = -NS\frac{dB}{dt}$$

Tri-axial fluxgate magnetometer on board the BepiColombo spacecraft (MPO/MAG)

Fluxgate magnetometer: [DC – 1 Hz]

A fluxgate magnetometer consists of a ferromagnetic metal core wrapped by two coils of wire. An alternating electric current is passed through the **primary "drive" coil**, driving the core through an alternating cycle of magnetic saturation; i.e., magnetised, unmagnetised, inversely magnetised, unmagnetised, magnetised, and so forth. This constantly changing field induces an electric current in **the secondary "sense" coil**, and this output current is measured by a detector. In a magnetically neutral background, the input and output currents match. However, when the core is exposed to a background field, it is more easily saturated in alignment with that field and less easily saturated in opposition to it. Hence the alternating magnetic field, and the induced output current, are out of step with the input current. The extent to which this is the case depends on the strength of the background magnetic field.



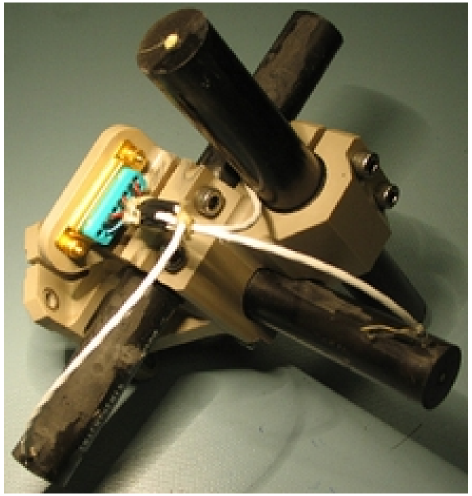
TU Braunschweig

Magnetic field measurements

Search-Coil magnetometer: [~0.1Hz ~1 MHz]

Magnetometer that will measure the varying magnetic flux.

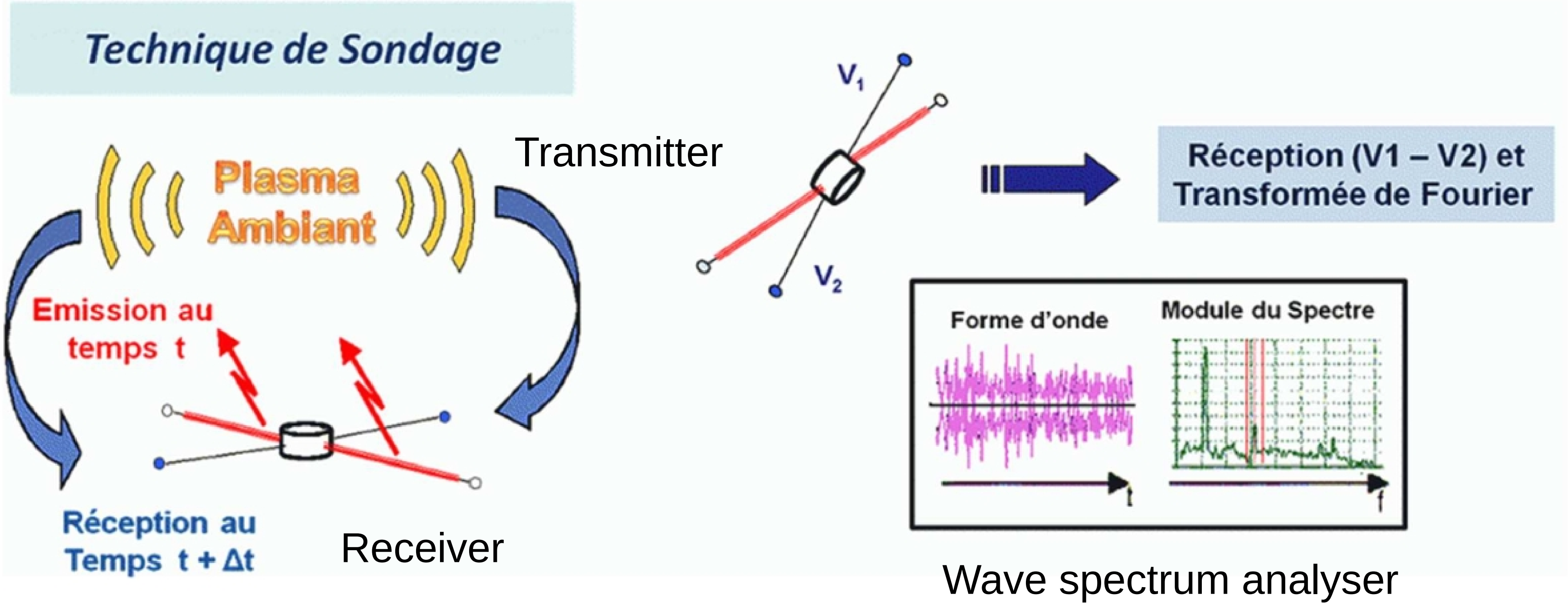
Lenz's law (induced voltage): $V_C = -N\frac{d\Phi}{dt} = -j2\pi f\, N\, S\, \mu_{eff}\, B\cos\theta$



THEMIS and Cluster/STAFF Search-Coils

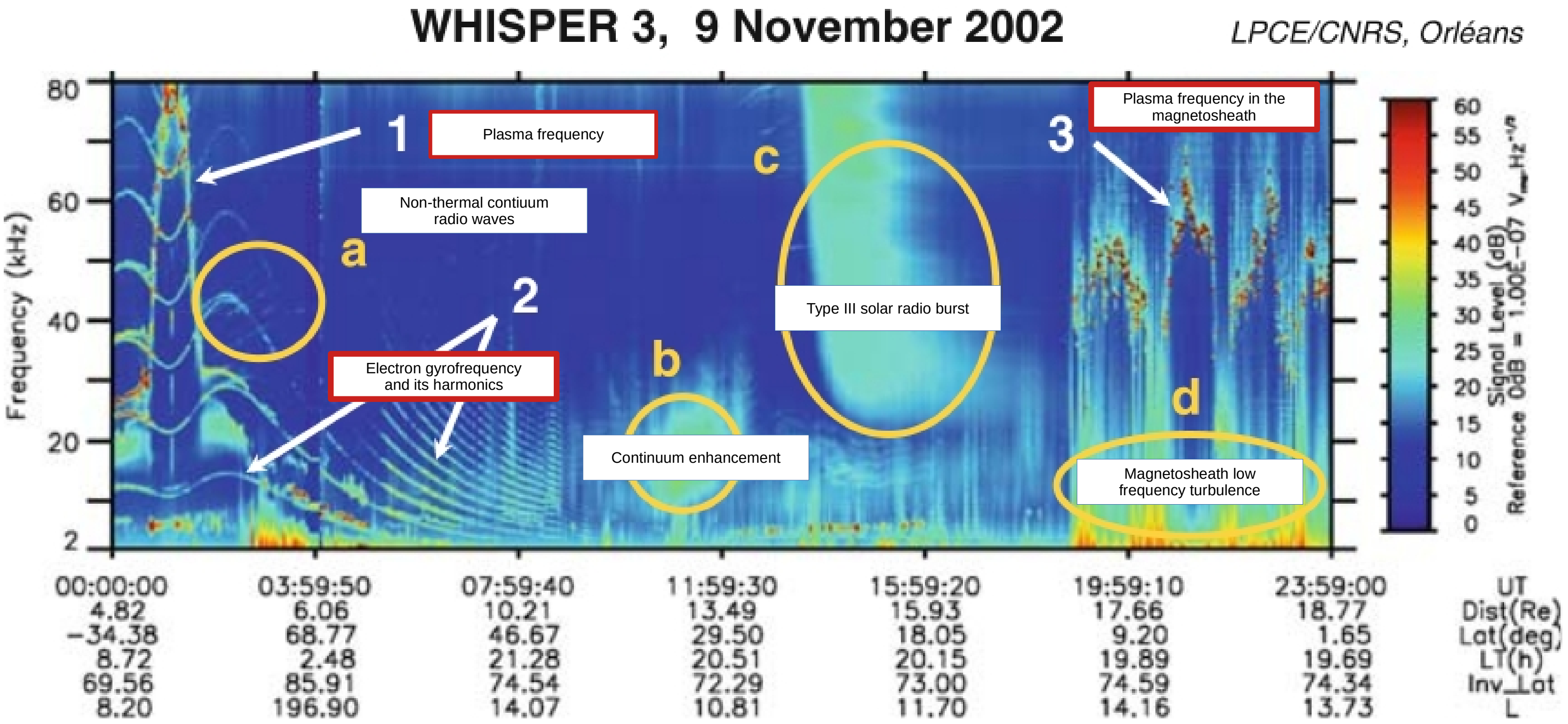
Passive and active measurements

Relaxation sounder: allows to measure the plasma frequency and infer an absolute value of the electron density + measurements of the electrostatic and electromagnetic natural emissions



Passive and active measurements

Dynamic spectrogram of the electric field intensity and triggered characteristic resonnances by the sounder of the Cluster/ESA spacecraft mission.

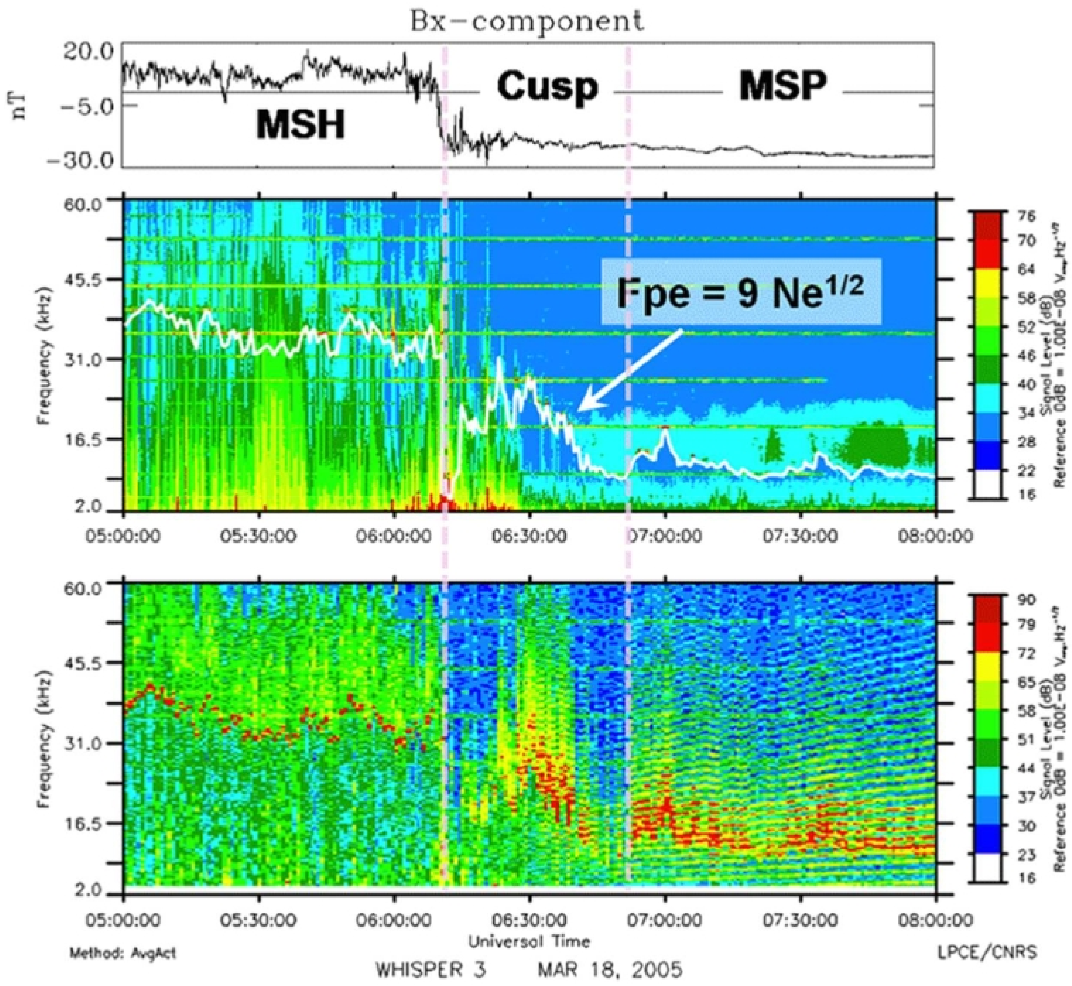


J.G. Trotignon et al., 2010

Passive and active measurements

Passive mode

Active mode



Plasma observations

Combining
Remote Sensing & in situ observations

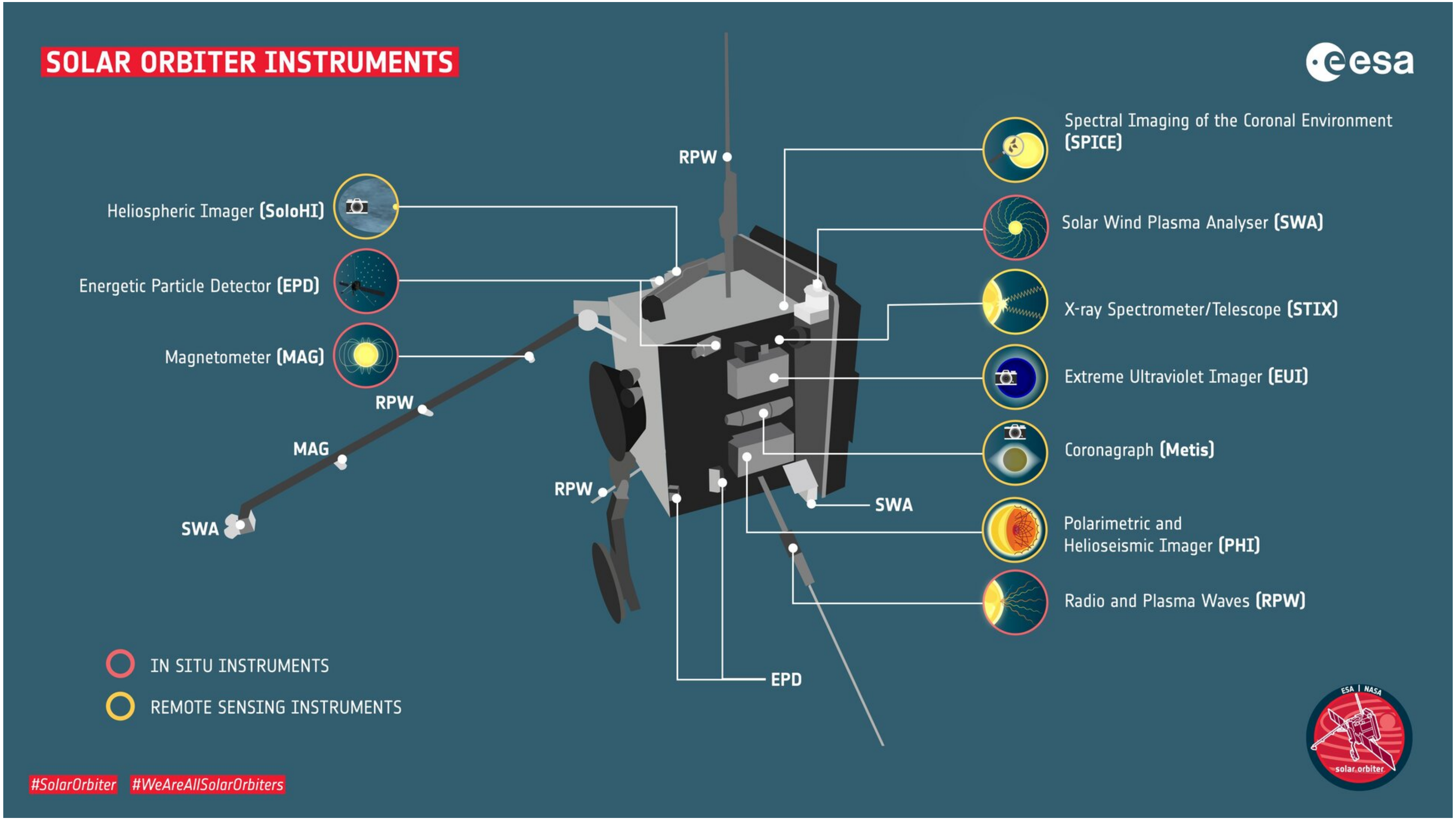
Solar Orbiter ESA/NASA mission

Launch: Februray 2020

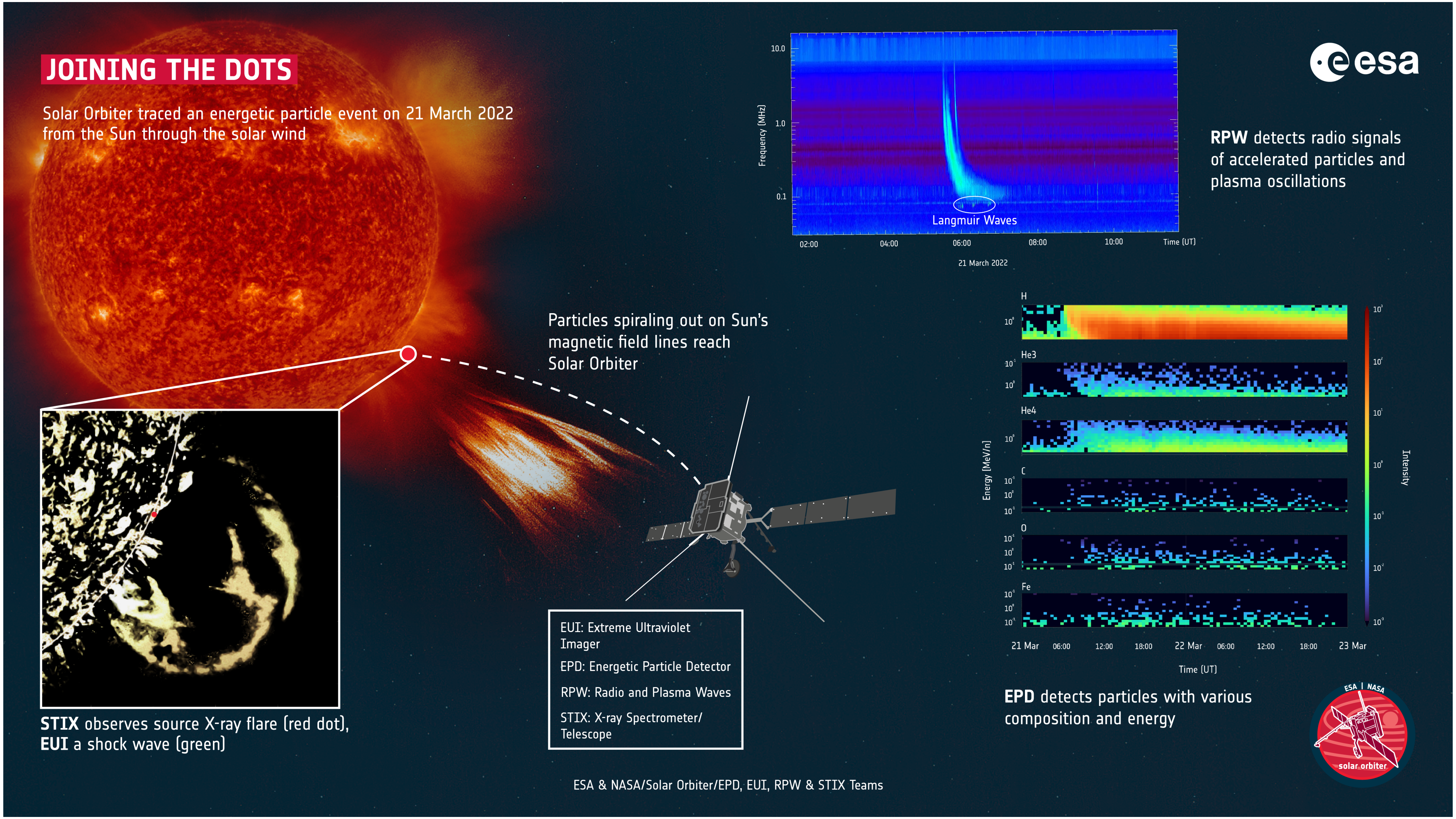
→ Make significant breakthroughs in our understanding both of how the inner heliosphere works, and of the effects of solar activity on it.

→ The spacecraft will take a unique combination of measurements: in situ measurements will be used alongside remote sensing close to the Sun to relate these measurements back to their source regions and structures on the Sun's surface.

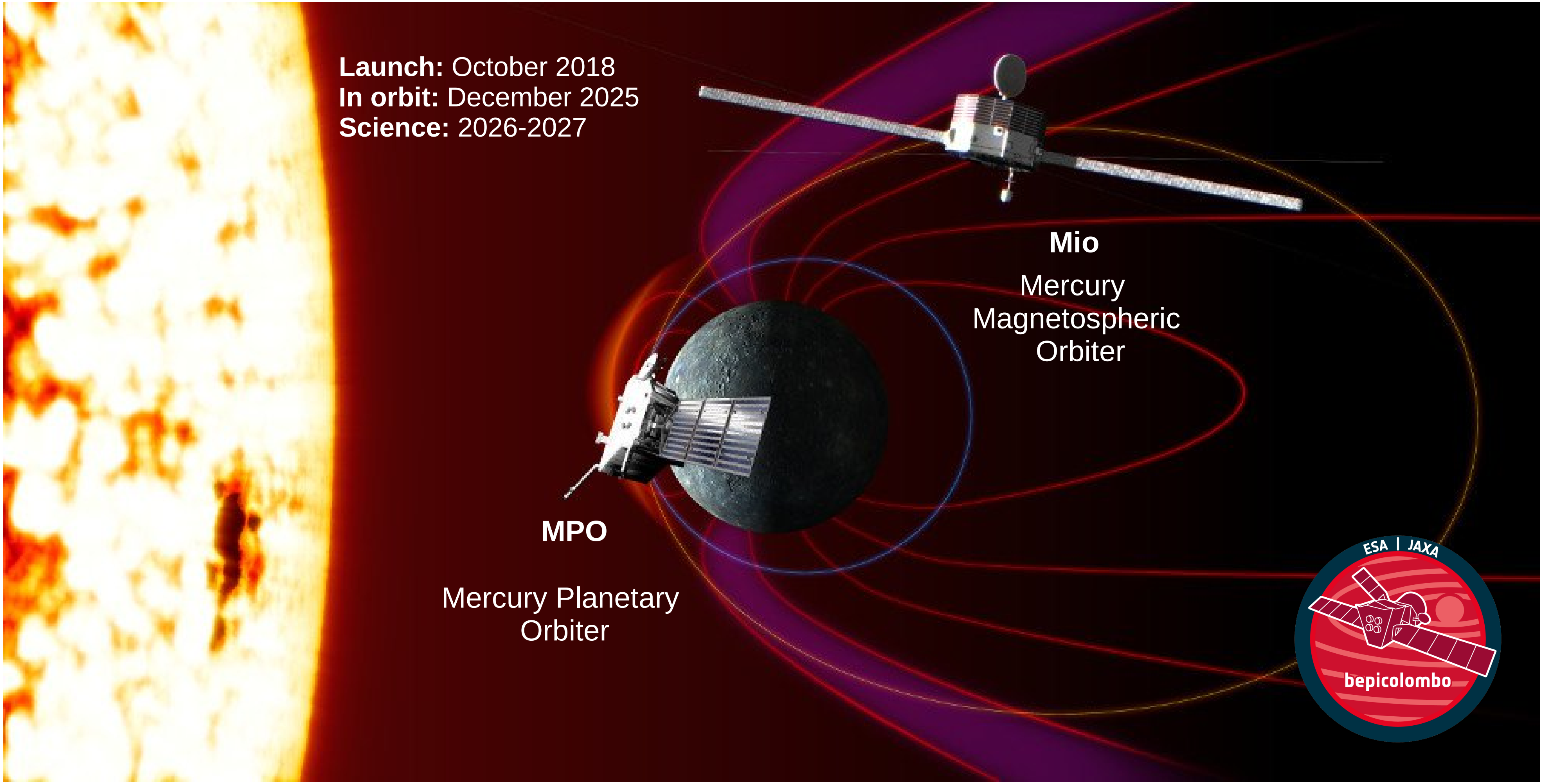
Solar Orbiter ESA/NASA mission



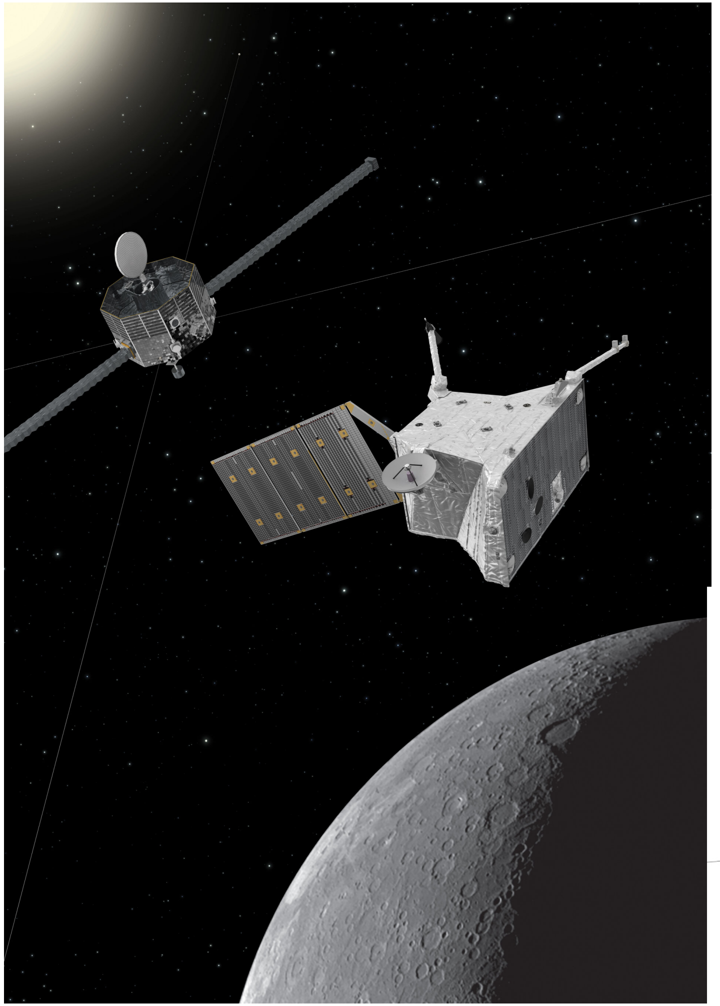
Solar Orbiter ESA/NASA mission



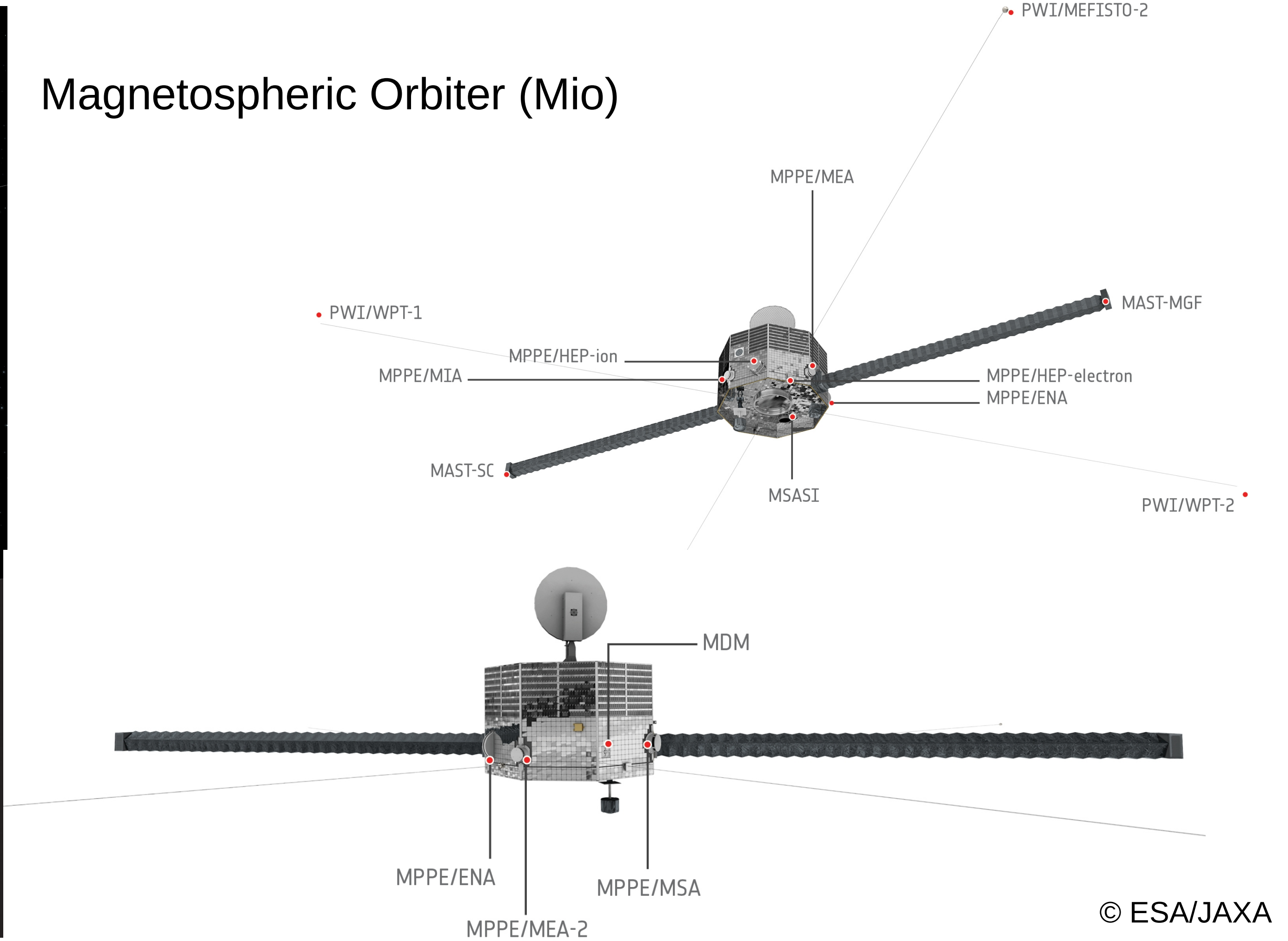
BepiColombo ESA/JAXA mission to MERCURY



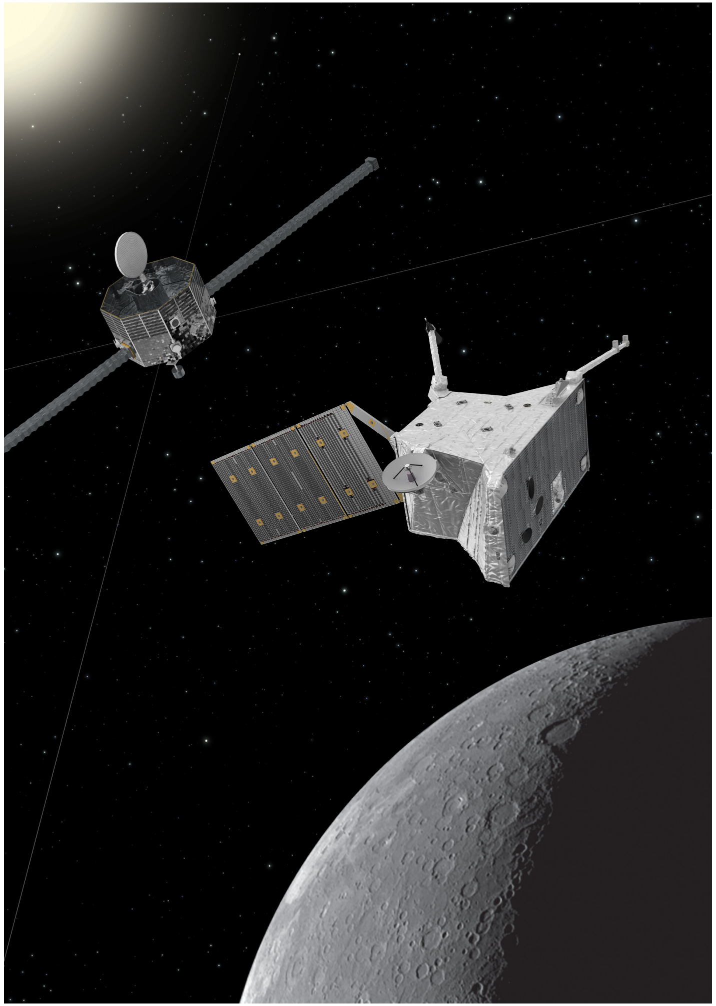
BepiColombo ESA/JAXA mission to Mercury

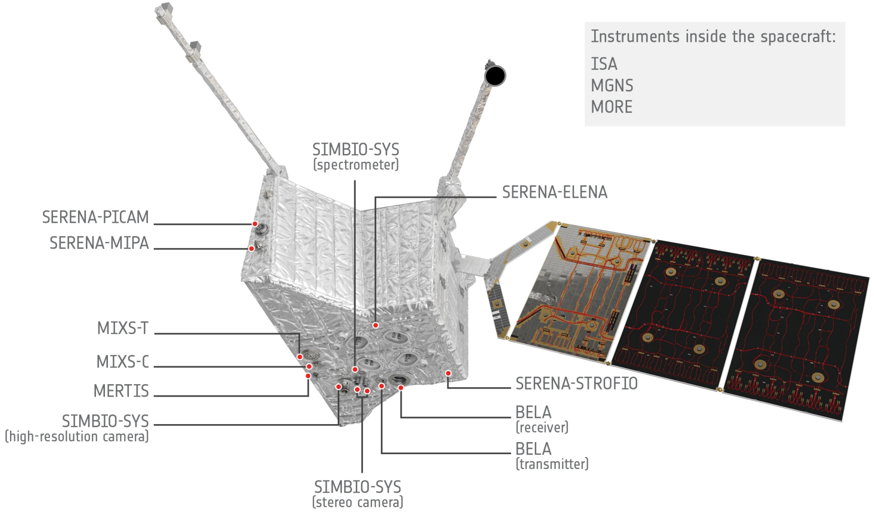


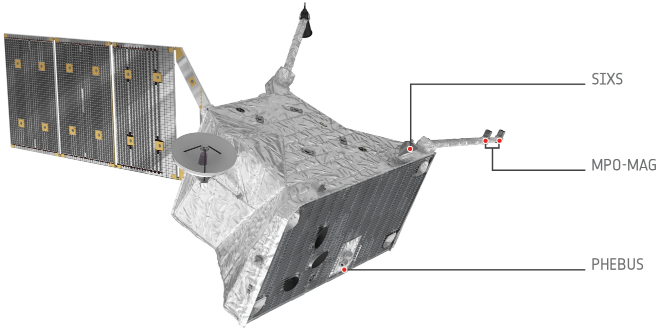
Magnetospheric Orbiter (Mio)



BepiColombo ESA/JAXA mission to Mercury







Planetary Orbiter (MPO)

End of Part I