Exploration of the solar system: in situ measurements in planetary ionized environments by the mutual impedance method

Bellana CARME – 1st year PhD student
Thesis supervisors: Pierre HENRI (CNRS/LPC2E) & Gaëtan WATTIEAUX (CNRS/LAPLACE)

Context

Natural Laboratory

- Unique conditions to study plasma physics *in situ*
- Space missions enabling planetary plasma exploration:
  - **BepiColombo** (ESA/JAXA) – Mercury
  - **JUICE** (ESA) – Jupiter's Icy moons
- Requires adapted measurements tools to characterize Ionized environments

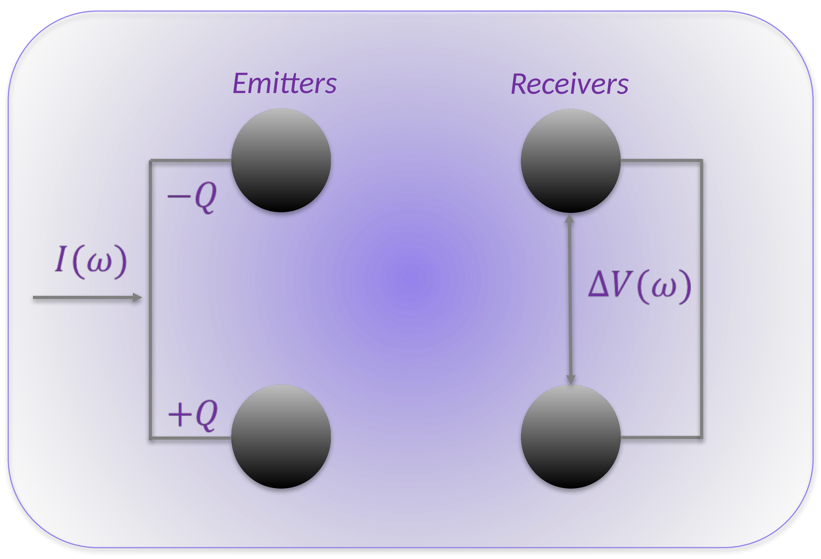
OBJECTIVES OF THIS WORK

Enable plasma diagnostics for space missions by developing tools for data interpretation**. Improve instrumental response models** and analysis methods**.** Enhance understanding of **(i) Sun-planet interactions** as well as **(ii) plasma-body interactions** and their impact on planetary physics.

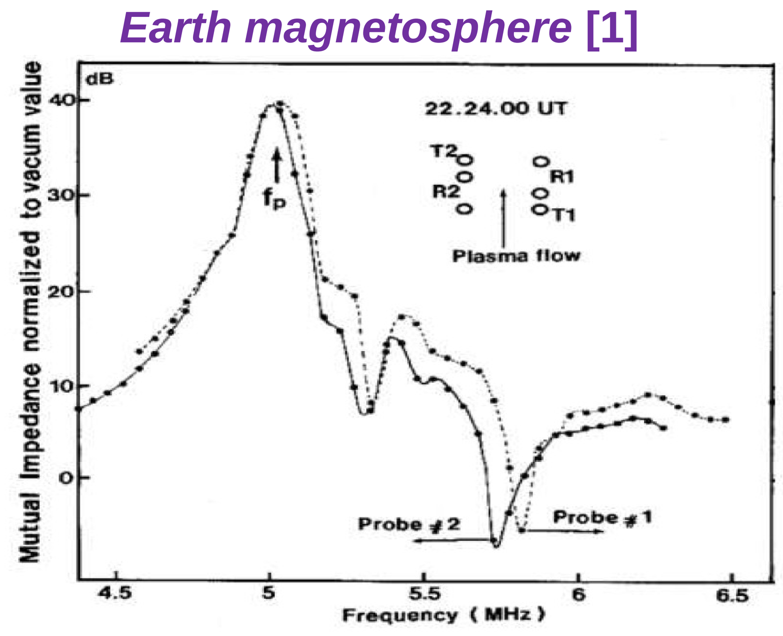
Mutual Impedance

- **Measures characteristic plasma frequencies** by triggering plasma resonances [2]
- Double dipole in emission/reception:
  - Emitter → Injecting an oscillating current $I(\omega)$ at frequency ω.
  - Receiver → Measure the induced potential $V(\omega)$ at the same frequency.
- Frequency sweep
- Mutal impedance calculations: $Z(\omega) = \frac{\Delta V(\omega)}{I(\omega)}$ (1)
- Dielectric properties of the plasma determine the mutual impedance response
- For unmagnetized plasma ($\omega_{pe} \ll \omega_{ce}$) resonance occurs near electron plasma frequency: $\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$ (2)

Quadripolar probe diagram immersed in a plasma



Mutual impdeance spectrum measured by the ISOPROBE-3 probe on ARCAD-3 in Earth magnetosphere [1]



Instrumental Response

Modeling the electrostatic Potential in Plasma

- Solve **the linearized Vlasov-Poisson** system for a plasma close to the environment to be diagnozed
- **Hypothesis**: Isotropic, homogeneous plasma
- **Potential induced**, at radial distance *r* form a pulsating point charge $Q\exp(i\omega t)$:

$$\phi(\omega, r) = \frac{Q}{4\pi\varepsilon_0}\frac{2}{\pi}\lim \mathrm{Im}(\omega) \to 0 \int_0^{\infty} \frac{\sin(kr)}{kr}\frac{dk}{\varepsilon_l(k,\omega)} \qquad (3)$$

- ε_l is the longitudinal **dielectric function**, for an unmagnetized plasma:

$$\varepsilon_l(k,\omega) = 1 + \frac{\omega_{pe}^2}{k^2}\int_0^{2\pi}\frac{k.\nabla_v f_0}{\omega - k.v}dv \qquad (4)$$

- f_0 is the electron velocity distribution function (evdf) at equilibrium

The instrumental response strongly depends on the evdf. Maxwellian [3]***, double Maxwellien*** [4]***, or Kappa*** [5] ***are the most communely use.***

DSCD (Discrete Surface Charging Distribution) Method [6]

- Account for **3D antenna and spacecraft geometry**, as well as the electric properties of emitting/receiving electronics.
- The system is divided into elements, each treated as a **perfect conductor** at potential:

$$V_{E_n} = V_{SC} + V_{B_n} - i\omega Z_{E_n} Q_n \qquad (5)$$

Elements E_n with n = 1,…,N , V_{SC} is the spacecraft potential, V_{B_n} the bias potential imposed on E_n , Z_{E_n} the equivalent impedance connecting the element to ground, Q_n the total electric charge present on the element

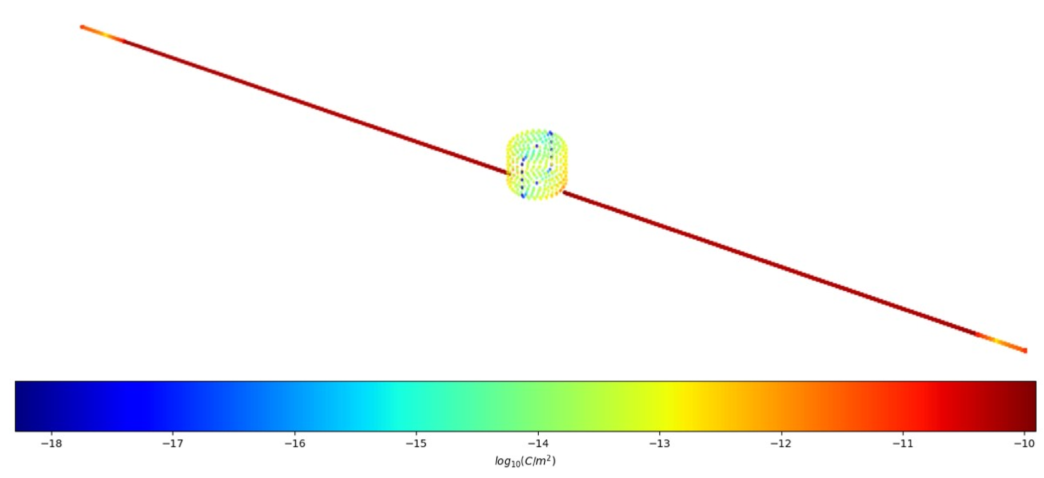
- Solve the linear system: $M \cdot q = 4\pi\varepsilon_0 V$ (6)

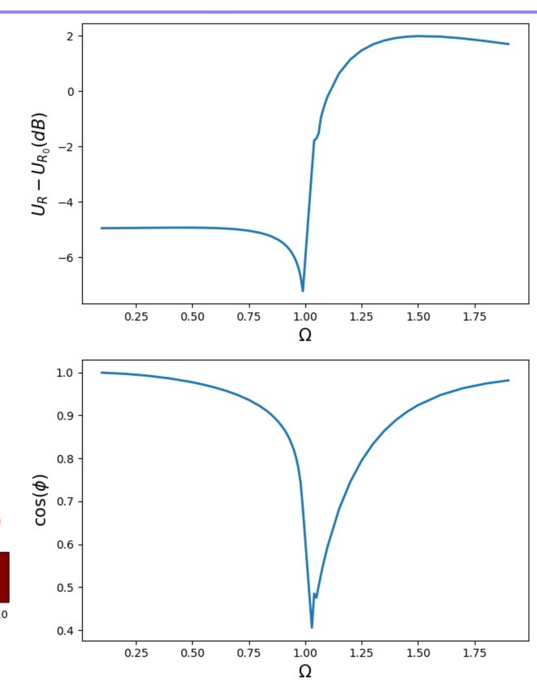
Where *M* is the discretization matrix, *q* is the charge

The DSCD model give the mutual impedance responce from the solution of linear system (6)

Current Work

Electrostatic modeling of Mio spacecraft/plasma interaction

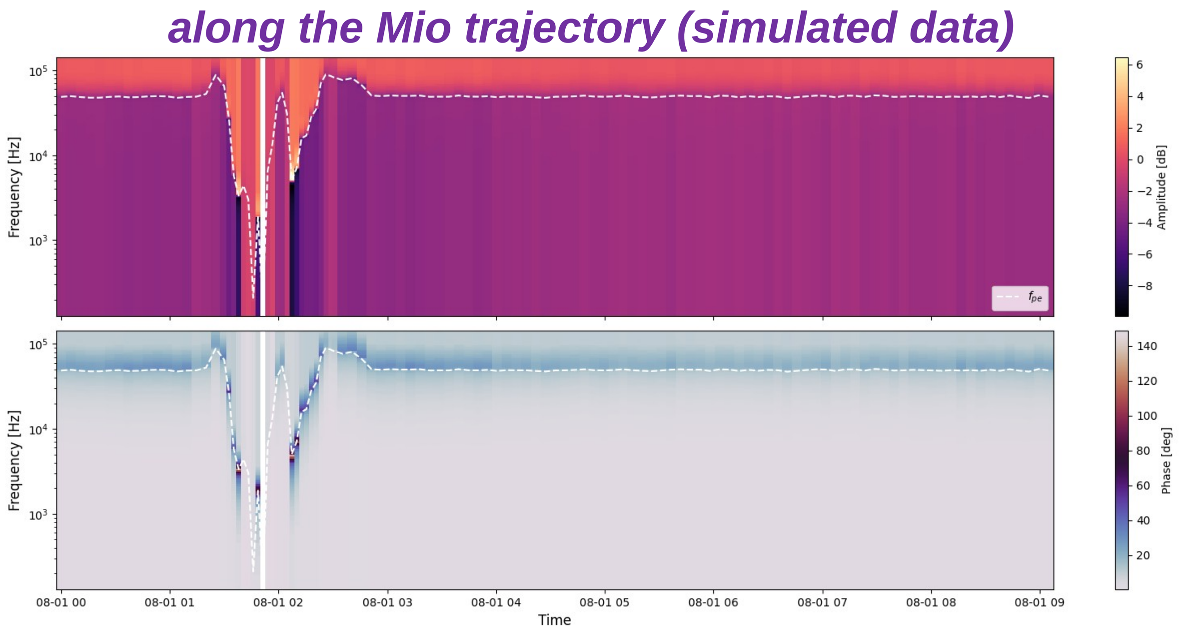




Spacecarft charge distribution from DSCD in a plasma

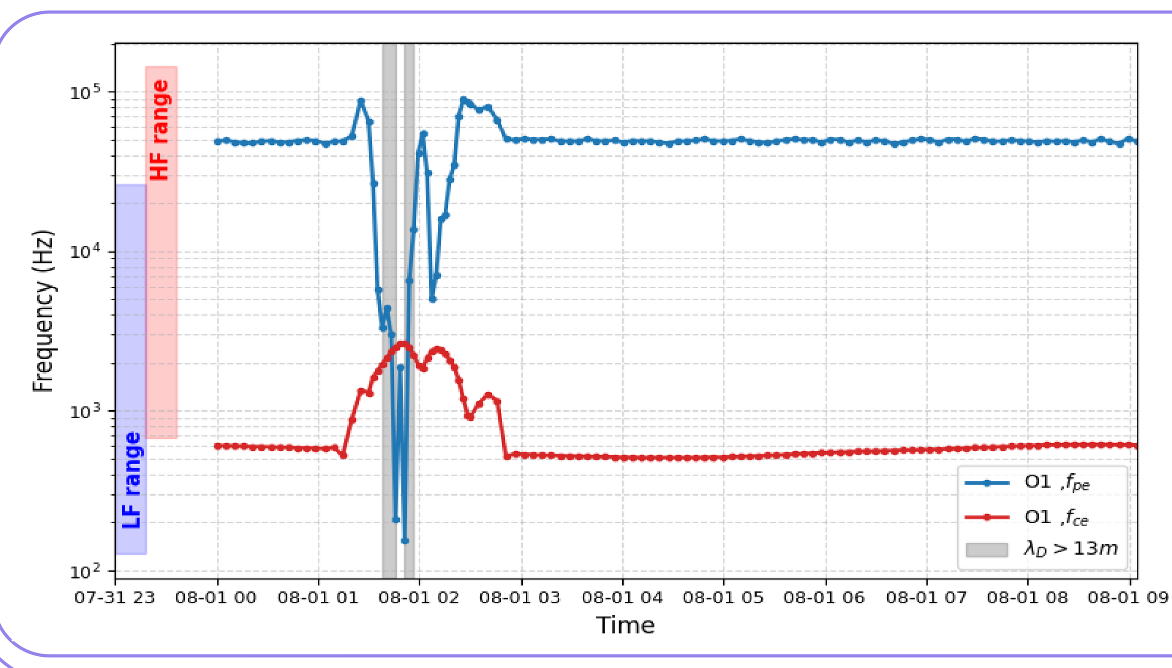
Instrumental response (dB/phase) normalized by vaccum response

Dynamical spectra of the mutual impedance signal along the Mio trajectory (simulated data)



Time and frequency map the evolution of the plasma environment, with color encoding mutual impedance spectral amplitude (top) and phase (bottom).

The white dashed line tracks the plasma frequency (f_{pe}), which appears as a clear resonance signature in both amplitude and phase, except where the Debye length exceeds 13 m



Comparison of plasma frequency (f_{pe} , blue) and electron cyclotron frequency (f_{ce} , red) along the Mio trajectory (simulated data)

The operational frequency ranges (LF in blue, HF in red) are shown on the left. The gray-shaded region indicates where the Debye length exceeds 13 m, corresponding to weakened plasma resonance detection.

Next/Objectives/conclusion

- Continuing the study of BepiColombo in magnetized plasma conditions to refine our understanding of its instrumental response.
- Extending a similar analysis to JUICE, comparing results with data from its first Earth flyby, and conducting studies in magnetized environments.
- Expanding these investigations using a hybrid DSCD + PIC model (currently under development) to further validate and enhance our simulations

Ref

[1] Beghin, C. (1992). Advances in Space Research, vol. 2, p. 61–66
[2] Grard, R. (1969). *Alta Freq.*, vol. 38, p.97–101
[3] Beghin, C. (1995). Radio Science 30.2, pp. 307–322.
[4] Gilet, N. et al. (2017). Radio Science 52.11, pp. 1432–1448.
[5] Gilet, Nicolas et al. (2019). Frontiers in Astronomy and Space Sciences 6, p. 16.
[6] Beghin, C.et al (1998). Radio Science 33.3, pp. 503–516.