The Magnetopause: an almost tangential interface between the magnetosphere and the magnetosheath

LPP

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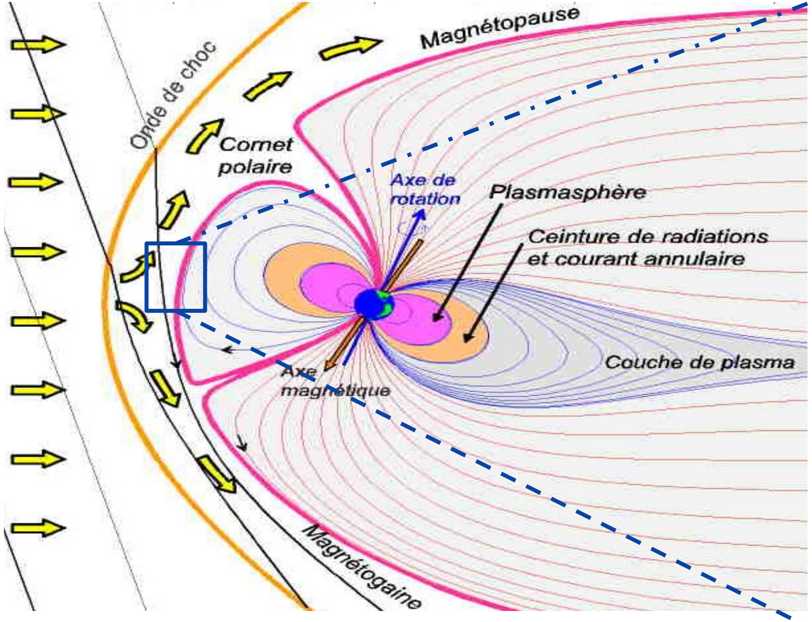
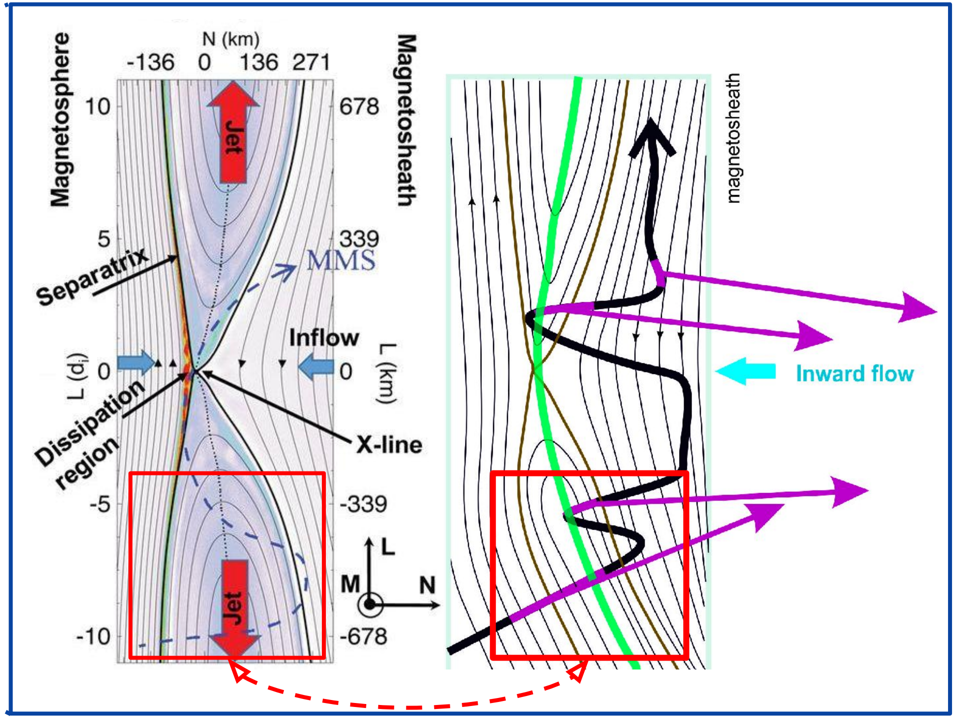
Magnetopause: Global vs Local





In this study we focus on studying the internal structure of the discontinuity

What is the nature of the magnetopause?

Classic Theory of Discontinuities

Compressive Discontinuities (shocks)

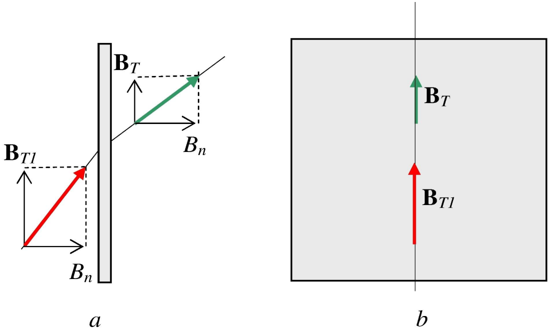
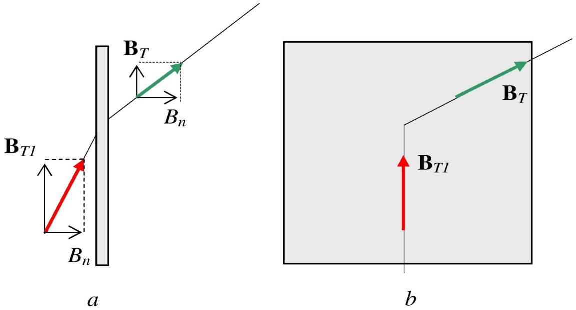


Image Credit: **Belmont et al, *Introduction to Plasma Physics***

Rotational Discontinuities



*The linear version of the rotational discontinuity correspond to the MHD shear Alfven wave

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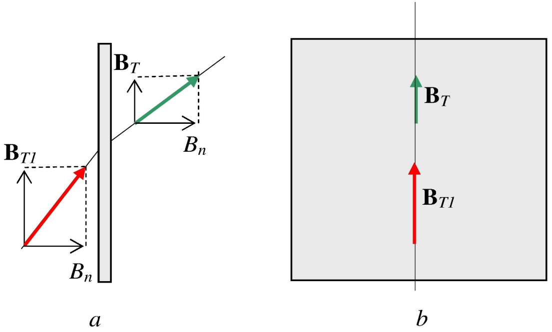

Tangential Discontinuity

- Only exception which mixes rotational and compressive features
- Requires $B_n=0$ and $V_n=0$

From data: Compressional and rotational features mixed or observed in a close vicinity

Rotational Discontinuities

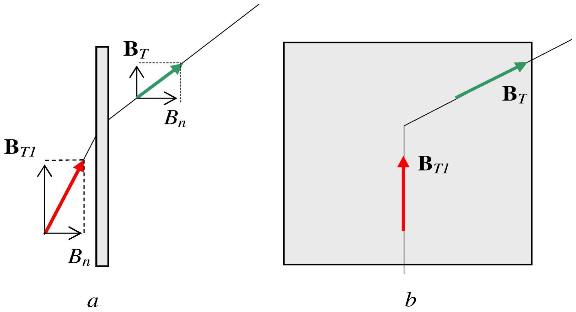

Image Credit: **Belmont et al, *Introduction to Plasma Physics***

Classic theory of discontinuities is insufficient for describing the magnetopause

Classic Theory of Discontinuities: equations

The separation between rotational and compressive discontinuities comes from:

We defined:

$$V_{n0} = \frac{B_n^2}{\mu_0 \rho V_n} = \text{cst}$$

$$(V_{n2} - V_{n0})\mathbf{B}_{t2} = (V_{n1} - V_{n0})\mathbf{B}_{t1}$$

Comes from the tangential projections of

- The momentum equation
- the Faraday-Ohm equation

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Compressive discontinuity

$$\mathbf{B}_{t2} = \frac{V_{n1} - V_{n0}}{V_{n2} - V_{n0}}\mathbf{B}_{t1}$$

Rotational discontinuity

$$V_{n1} - V_{n0} = V_{n2} - V_{n0}$$

$$\Downarrow$$

$$V_{n1} = V_{n2} = V_A$$

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- ➢ The $\nabla \cdot$ P term is purely along the normal direction (isotropic assumption)
- ➢ $\nabla \cdot$ P does not appear in the equation
- ➢ This term comes into play for the anisotropic or non-gyrotropic case

Equations in the **anisotropic** case

As shown in Hudson [1971], the equation is changed in the anisotropic case:

$$(V_{n2} - \alpha_2 V_{n0})\mathbf{B}_{t2} = (V_{n1} - \alpha_1 V_{n0})\mathbf{B}_{t1}$$

We defined:

$$\alpha = 1 - \frac{p_{\parallel} - p_{\perp}}{B^2/\mu_0}$$

- ➢ Coplanar solutions still exists
- ➢ The equivalent of the tangential discontinuity implies compression if $\alpha_1 \neq \alpha_2$
- ➢ No universal result giving the downstream state as a function of the upstream one independently of the phenomena inside the layer
- ➢ For thin layers (kdi ~ 1), the FLR effects are to be taken into account

The magnetopause normal

An accurate determination of the magnetopause **local** normal proves to be fundamental

For each time step inside the magnetopause

- **Separate tangential and normal components** of conservation laws and the magnetic field
- Determine which terms are experimentally significant but not included in Classic Theory of discontinuities

Momentum Equation

$$\rho \partial_t \mathbf{u} + \rho \mathbf{v}.\nabla \mathbf{u} = -\nabla \cdot \mathbf{P} + \mathbf{J} \times \mathbf{B}$$

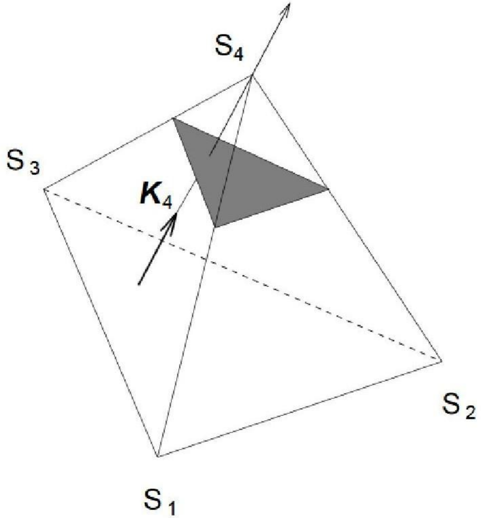
Has a component only along the normal in Classic Theory

The local normal using MMS satellites

- **Reciprocal vectors**
  - Firstly introduced in space plasma physics by **Chanteur [1998]**
  - Use to linear estimate the gradient of a vector field

$$\mathbf{G} = \text{grad}\,\mathbf{B} \sim \sum_s \mathbf{k}_s \mathbf{B}_s$$

$$k_4 = \frac{\mathbf{r}_{12} \times \mathbf{r}_{13}}{\mathbf{r}_{14}.(\mathbf{r}_{12} \times \mathbf{r}_{13})}$$



- **The Minimum Directional Derivative (MDD) method**
  - **Shi et al [2005]**
  - Normal as the eigenvector with maximum eigenvalue of $\mathbf{G}.\mathbf{G}^T$

A new magnetopause normal tool

Assume that the structure can be fitted locally (*i.e.* in each small sliding window), by a **two dimensional model:**

$$\mathbf{G}_{fit} = \mathbf{e}_0 \, \mathbf{B}'_{e0} + \mathbf{e}_1 \, \mathbf{B}'_{e1}$$

We defined:

- $\mathbf{e}_0$ and $\mathbf{e}_1$ as two unit vectors in the plane perpendicular to the invariance direction
- $\mathbf{B'}_{\mathbf{e0}}$ and $\mathbf{B'}_{\mathbf{e1}}$ as the variation of the magnetic field along these two directions
- We choose here the M direction given by MVA as the invariant direction

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As for the MDD, the dyadic tensor is obtained from the 4-point measurements via the reciprocal vector method

$$\mathbf{G} = \sum_s \mathbf{k}_s \mathbf{B}_s$$

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Minimizing the difference between **G** and $\mathbf{G}_{fit}$ by imposing $\nabla . \mathbf{B} = 0$, we obtain the values of $\mathbf{B}'_{e0}$ and $\mathbf{B}'_{e1}$.

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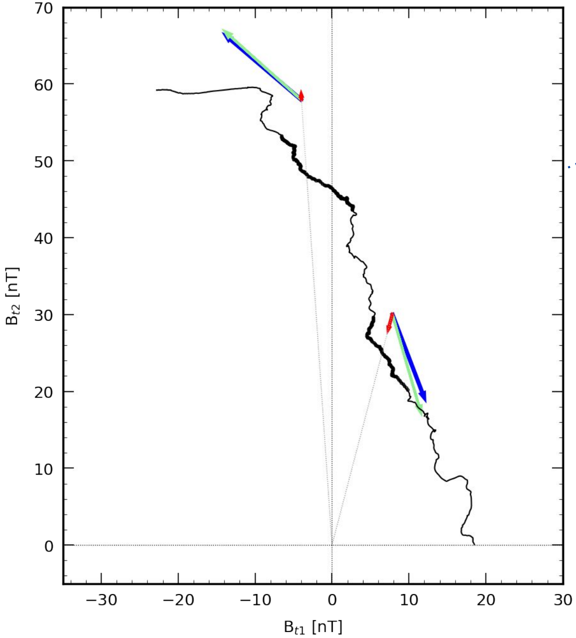
Minimizing the difference between **G** and $\mathbf{G}_{fit}$ by imposing **∇**. **B** = 0, we obtain the values of $\mathbf{B'}_{\mathbf{e0}}$ and $\mathbf{B'}_{\mathbf{e1}}$.

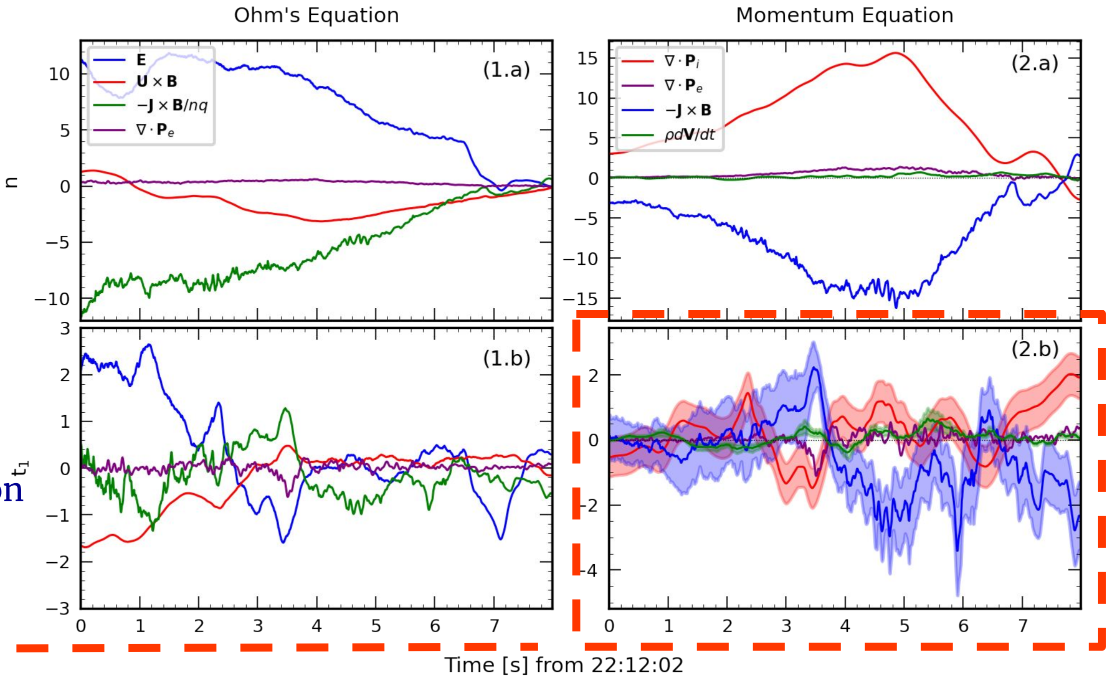
Obtain a precise estimation of the **magnetic** normal and intermediate direction by applying the MDD to the fit matrix.

Finite Larmor radius effects on the magnetopause equilibrium



Hodogram in the tangential plane

"Linear" variation in **B**, not explained in classic theory



Tangential components of the momentum equation

$\nabla \mathbf{P}_{i,tang}$ term of the same order of the $\mathbf{J\times B}_{tang}$ term

➔ **∇Pi** plays a fundamental role in the magnetopause equilibrium

Data from MMS, 28.12.2015

A statistical study

A database of 149 crossings has been selected from the one in Michotte De Welle et al. (2022).

From these database, we found the following distribution:

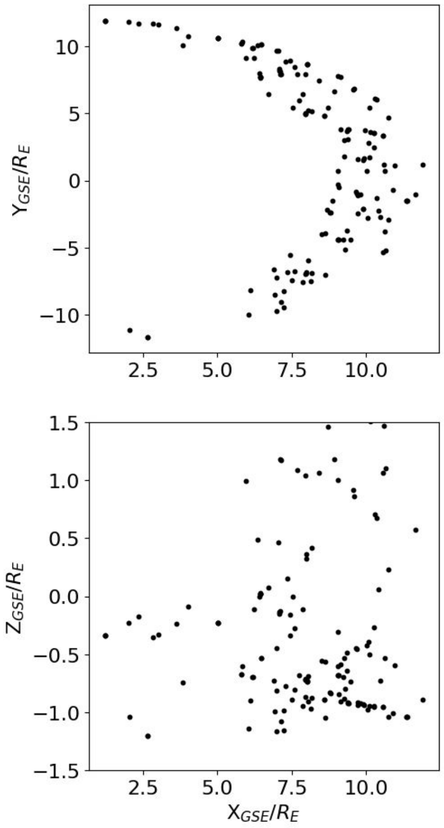
- **36.2%** (54/149) of the crossings presents **linear features**.

- 3.4% (5/149) of the crossings presents circular features (rotational discontinuity).

- 18.8% (28/149) of the crossings presents radial features (compressional discontinuity).

- 41.6% (62/149) of the crossings could not be interpreted definitely as either of the three before.

Spatial distribution



Conclusions and Future works

Magnetopause is a typical example of “quasi-tangential” discontinuity where Finite Larmor radius (FLR) effects have a fundamental role on the magnetopause equilibrium.

The magnetopause is to the rotational discontinuity what the Kinetic Alfven wave (KAW) is to the standard MHD Alfven wave.

Future work

- Include FLR terms in the magnetopause model
- Study the structure by using global numerical simulations (using the **Menura** solver)

The Menura solver [Behar et al, 2022]

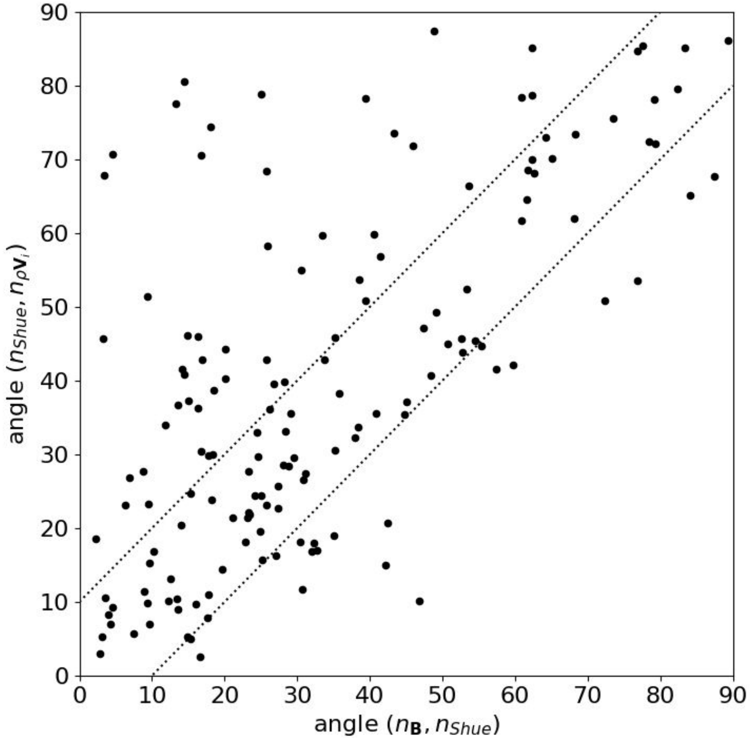
Menura is an hybrid particle-in-cell (PIC) solver

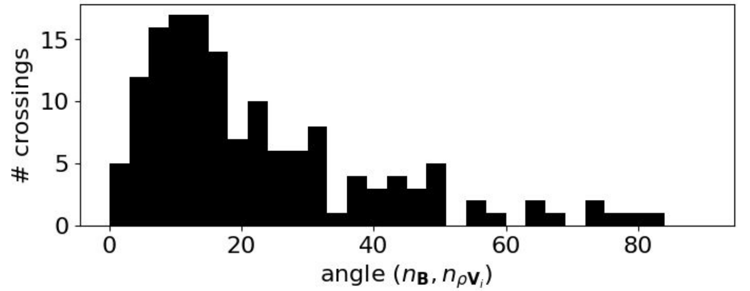
- Kinetic description for ions
- Fluid description for electrons
- Strongly parallelized and executed on multiple GPUs
- Written so that it is possible to work in the solar wind reference frame

Thank you for any feedback

Giulio Ballerini, Laurence Rezeau, Gerard Belmont,
Francesco Califano

Statistics: magnetic vs particles normal





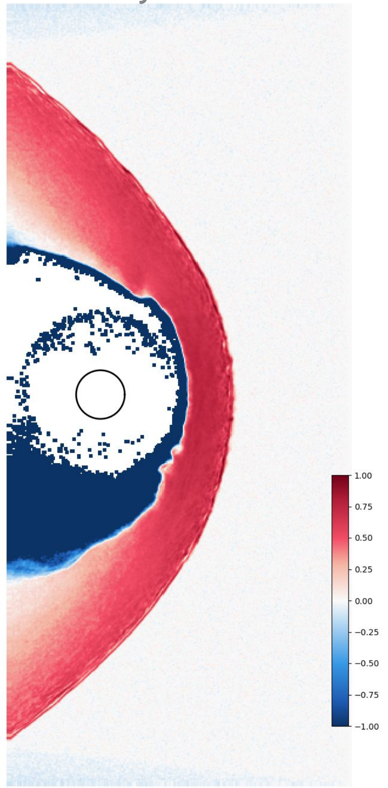
Simulations: current status

Global 3D simulations:

- ➢ Grid size dx=2.5di
- ➢ Box size 700x1500x1600 d_i
- ➢ Standoff magnetopause distance: $200d_i$
- ➢ Waiting for resources to increase the mesh resolution

Density plots

Plane xy



Plane xz