The effect of the interplanetary magnetic field orientation in the Hermean magnetosphere structure

J. Varela[1,2], F. Pantellini[2] and M. Moncuquet[2]
[1](CEA Saclay, DSM/IRFU/SAp and LIMSI)
[2](LESIA, Paris Observatory)

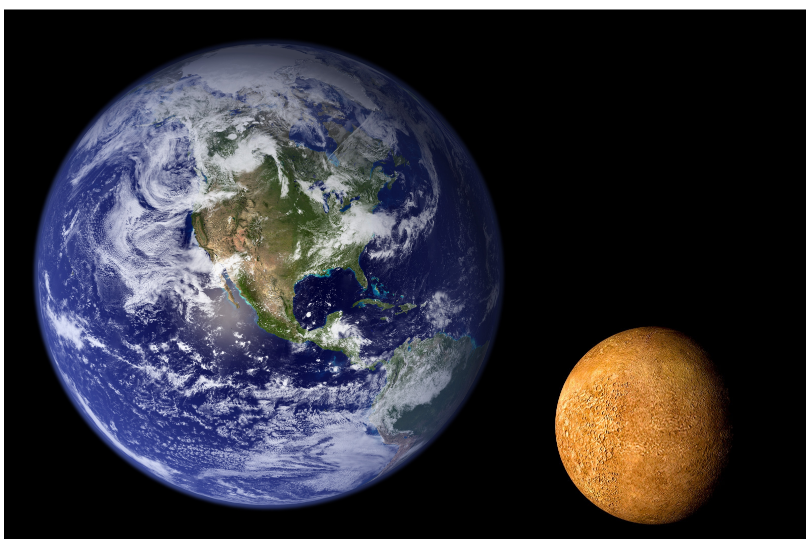
Introduction

· Simulation of the interaction of the solar wind (SW) with the Hermean magnetic field.

· Study the Hermean magnetosphere structure for realistic parameter of the solar wind.

- Effect of the solar wind magnetic field (IMF) orientation ?
- Extreme cases of the SW density, temperature and velocity ?

· Consequences for planet habitability ?



· Hermean magnetic field 150 times weaker. IMF is only 10 times weaker than the Hermean magnetic field.

· The solar wind sonic Mach number and the beta values are similar.

· Differences: magnetic and spin axis are aligned and perpendicular to the orbit of Mercury, Northward displacement dipolar field, etc ...

Plan

1. Code + setup of simulations

2. Effect of the IMF orientation

3. Extreme cases and parametric study

4. Aurora in Mercury?

The 3D MHD Code: PLUTO

- Equations in conservative form
- Solver used: HLL
  stable and diffusive
- Gradient limiter: minmod
- WEB: plutocode.ph.unito.it

$$\frac{\partial \rho}{\partial t} + \vec{v} \times \vec{\nabla} \rho + \rho \vec{\nabla} \times \vec{v} = 0$$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \times \vec{\nabla} \vec{v} + \frac{1}{\rho} \vec{B} \wedge \left(\vec{\nabla} \wedge \vec{B} \right) + \frac{1}{\rho} \vec{\nabla} p = \vec{a}$$

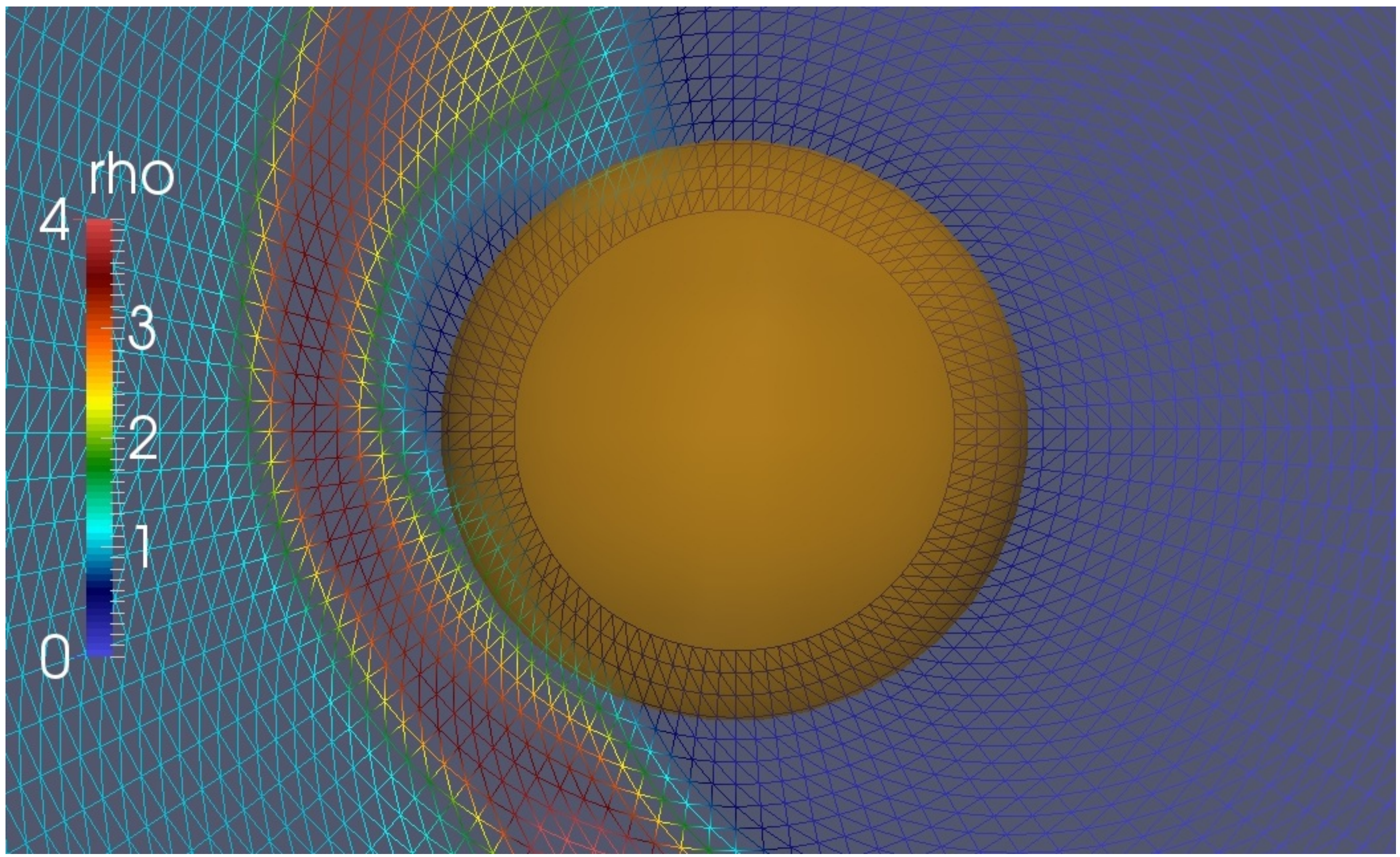
$$\frac{\partial p}{\partial t} + \vec{v} \times \vec{\nabla} p + \rho c_s^2 \vec{\nabla} \times \vec{v} = 0$$

$$\frac{\partial \vec{B}}{\partial t} + \vec{B} \left(\vec{\nabla} \times \vec{v} \right) - \left(\vec{\nabla} \times \vec{B} \right) \vec{v} + \left(\vec{v} \times \vec{\nabla} \right) \vec{B} = \vec{v} \left(\vec{\nabla} \times \vec{B} \right)$$

Simulation domain

Geometry, 3D spherical (r, θ, ϕ)

Grid resolution 192x48x96



Boundary conditions

Outer boundary

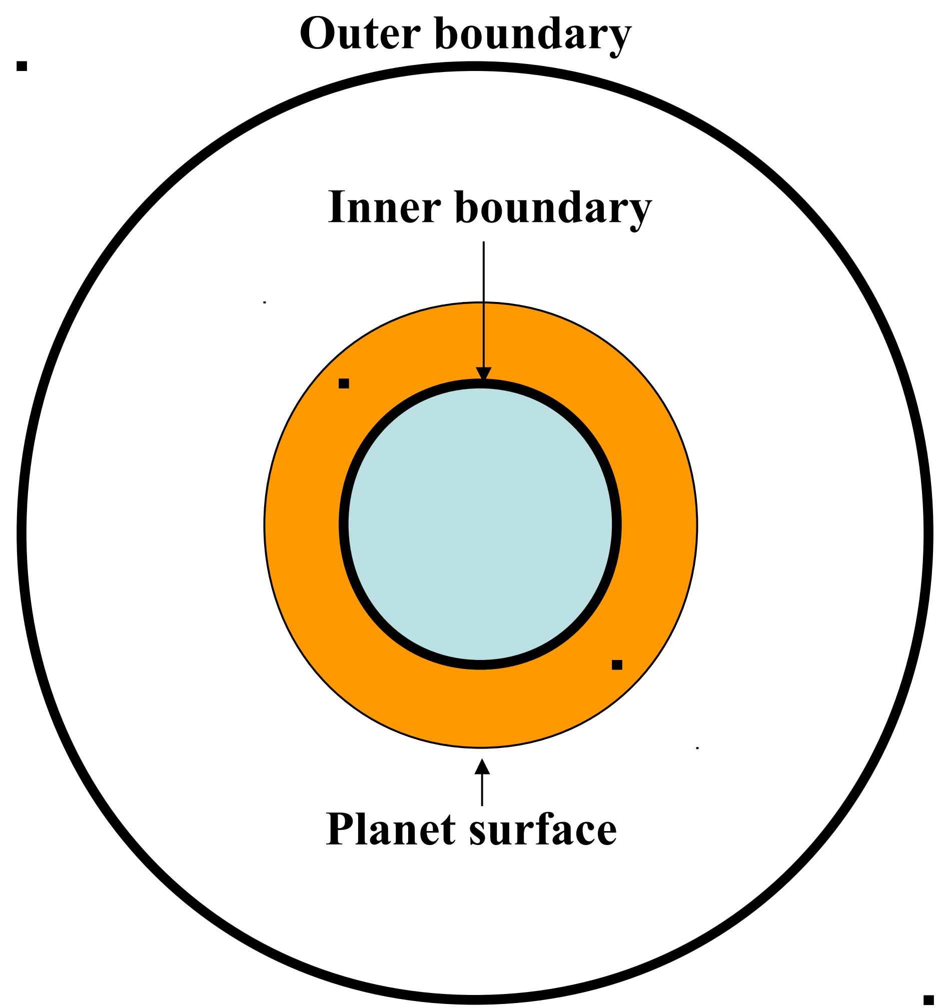
- Upstream: Solar wind parameters
- Downstream: $\partial/\partial r = 0$

Inner boundary

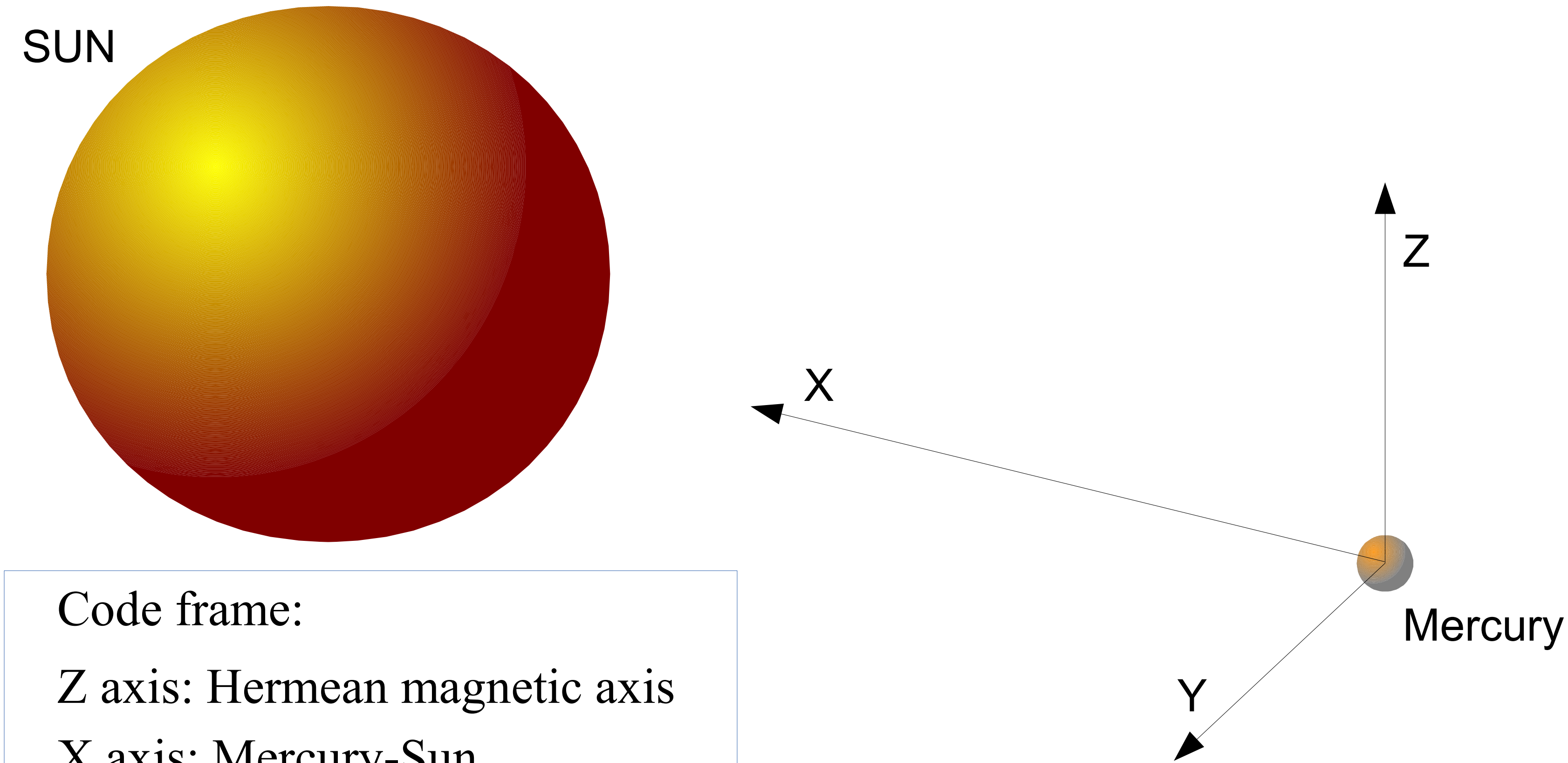
- Planetary intrinsic mag. Field
- Fixed density and pressure
- V = 0

Soft coupling region

- Smooth transition to make v||B at inner boundary
- V $\rightarrow$ 0
- $\mathrm{c} = \mathrm{v_A} = \mathrm{const}$



Coordinate system



Code frame:

Z axis: Hermean magnetic axis

X axis: Mercury-Sun

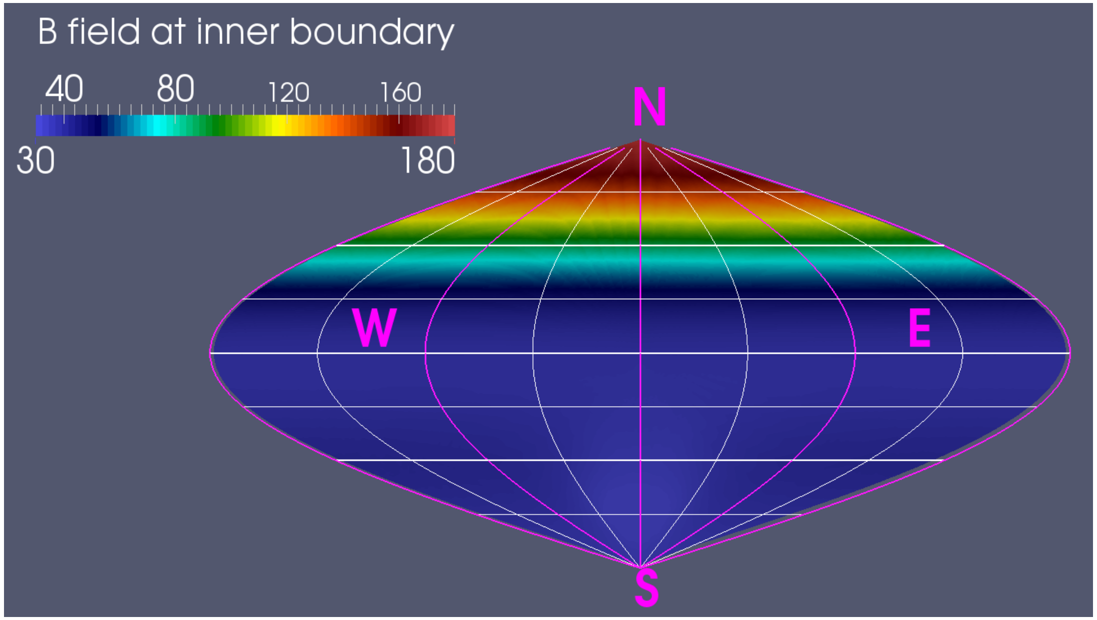
The simulation and MESSENGER data is compared in the MSO frame.

Mercury intrinsic field model
(from Anderson et al 2012)

$$\mathbf{B} = -\nabla\boldsymbol{\Psi}$$

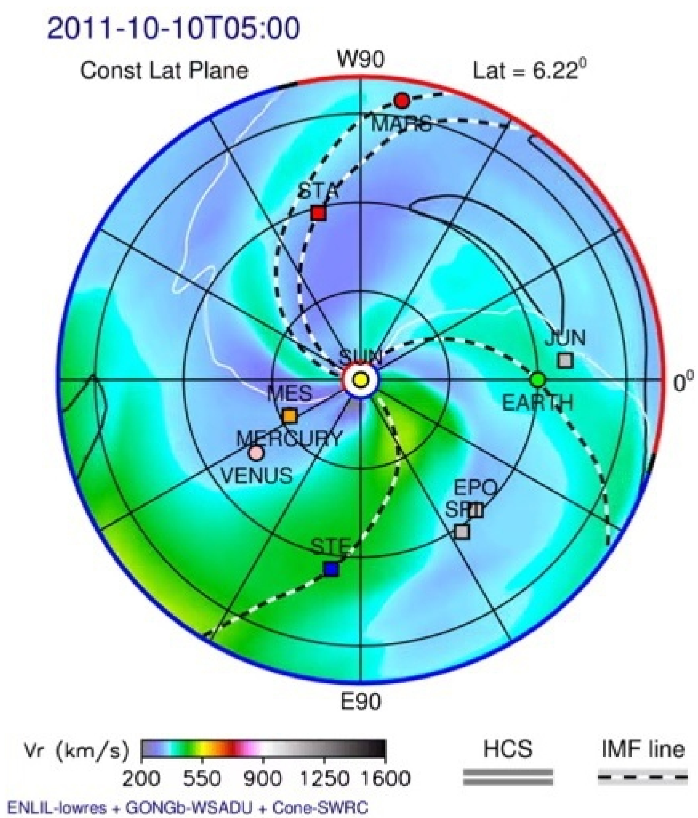
$$\Psi(r,\theta) = R_\mathrm{M}\sum_{l=1}^{4}\left(\frac{R_\mathrm{M}}{r}\right)^{l+1} g_{l0}\, P_l(\cos\theta)$$

$$\begin{aligned}
P_1(x) &= x\\
P_2(x) &= \tfrac{1}{2}(3x^2-1)\\
P_3(x) &= \tfrac{1}{2}(5x^3-3x)\\
P_4(x) &= \tfrac{1}{8}(35x^4-30x^2+3)
\end{aligned}$$

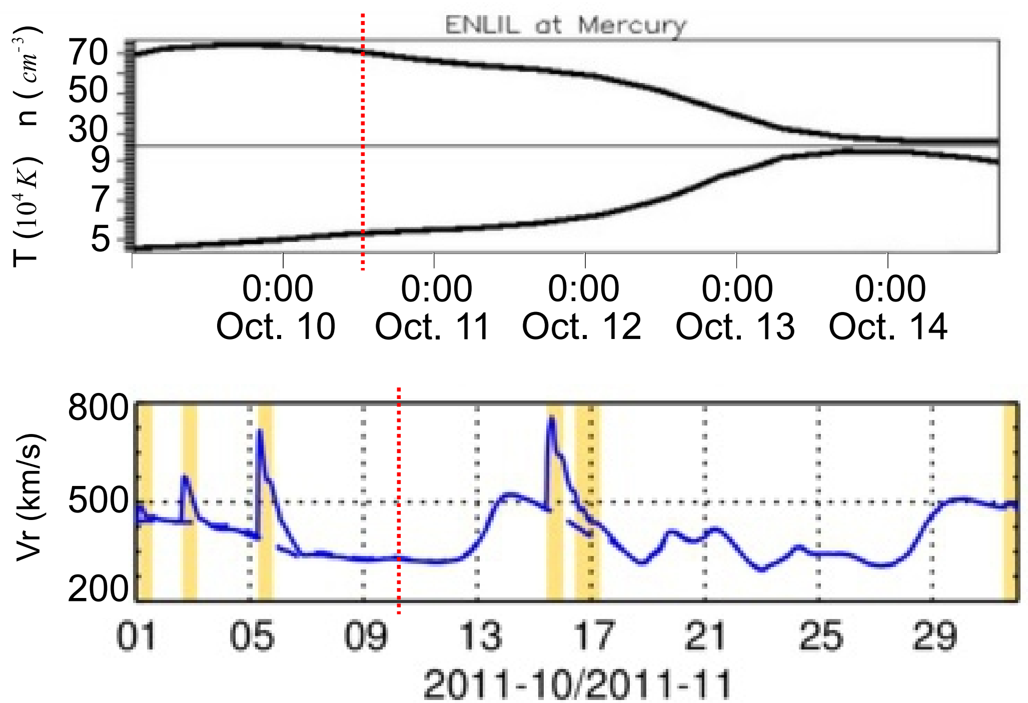


g_{10} [nT]	g_{20}/g_{10}	g_{30}/g_{10}	g_{40}/g_{10}
-200.0	0.393	0.1165	0.0295

Solar wind parameters
(WSA-ENLIL at Mercury)



Reference case (Bmin)



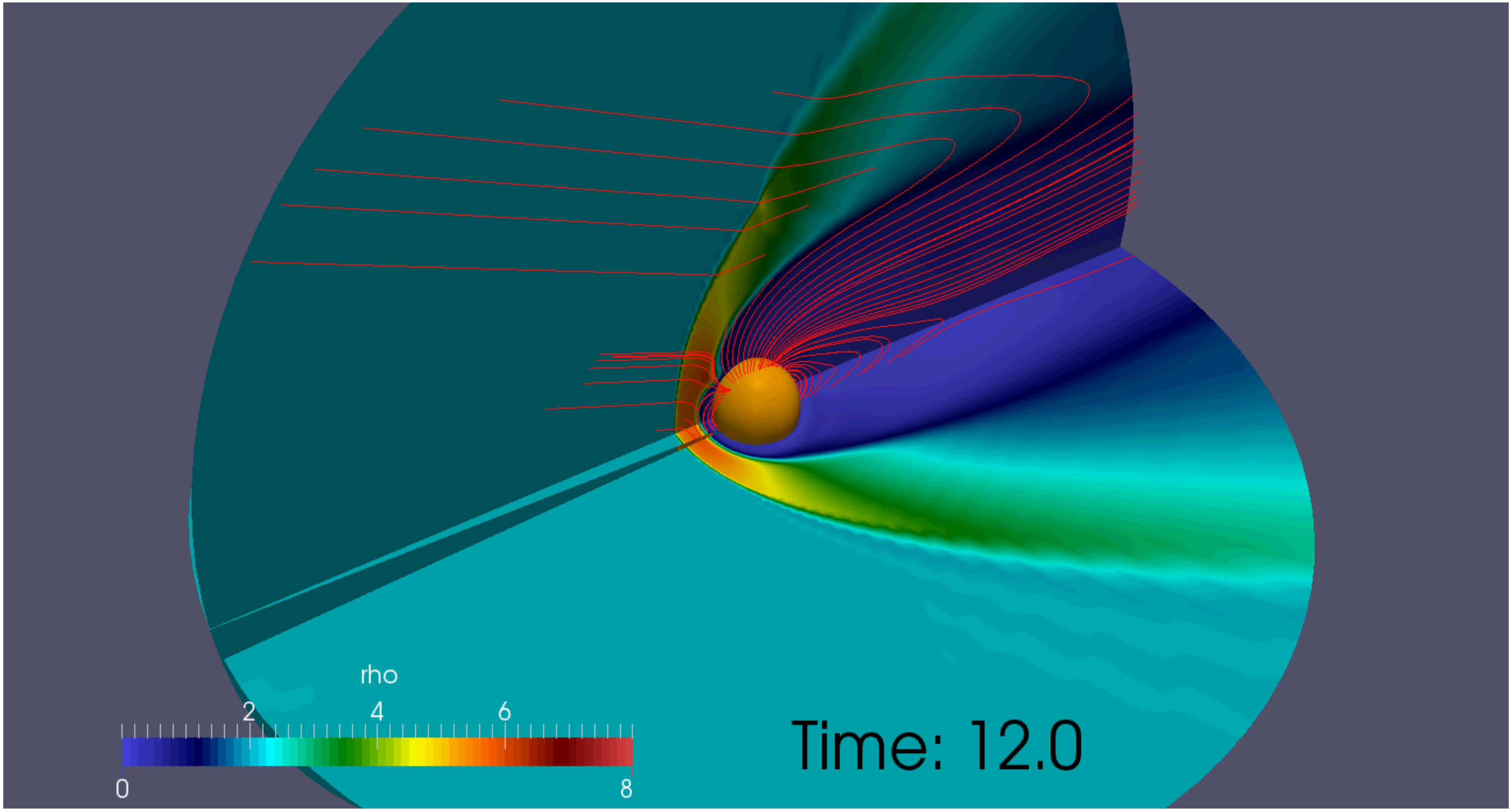
Get simulated profiles along real MESSENGER trajectories

Procedure

- Obtain coordinates of trajectory via horizons.jpl.nasa.gov
- Transform trajectory into simulation frame
- Extract simulated profiles along trajectory
- Transform vector quantities to MSO system.
- Get spacecraft data in MSO (for MESSENGER: pds-ppi.igpp.ucla.edu)
- Compare real and simulated data.

MHD Simulation

MHD simulation of the interaction of the solar wind with the Hermean magnetosphere



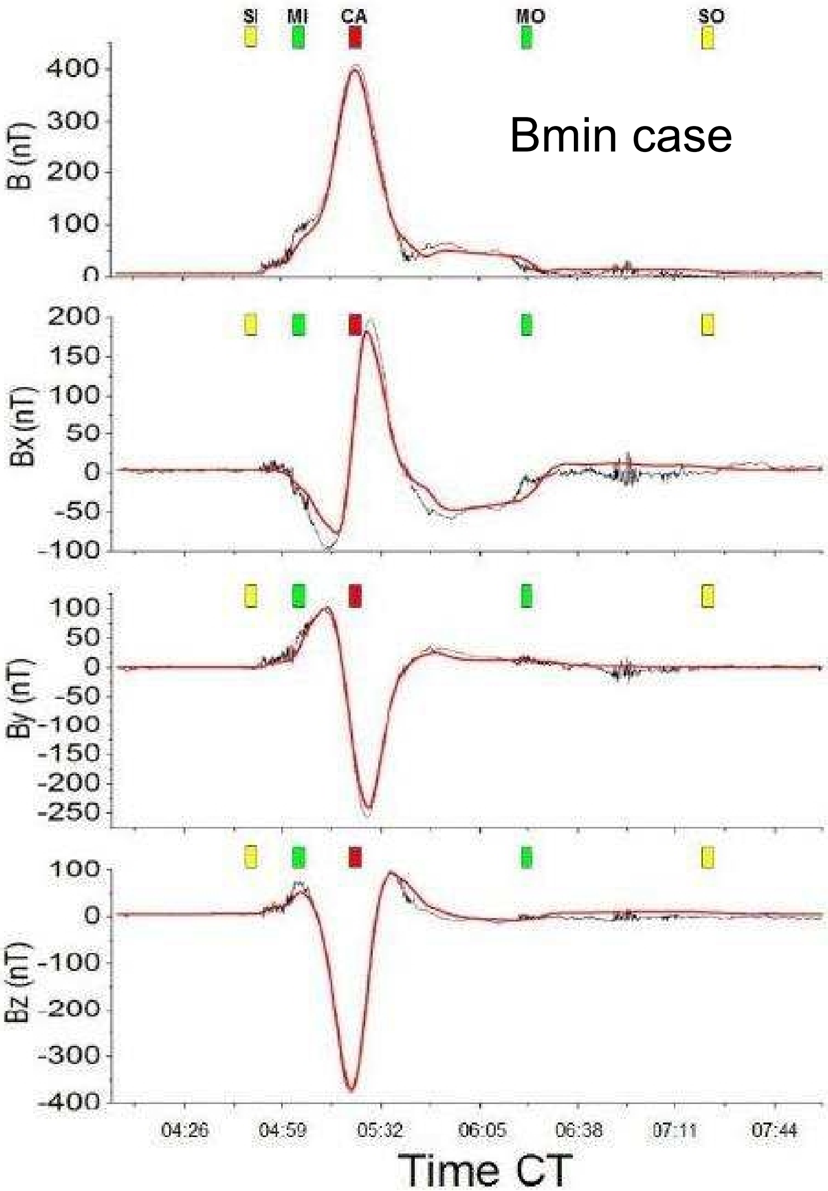
Effect of the IMF orientation
(Reconnection SW-Hermean mag.)

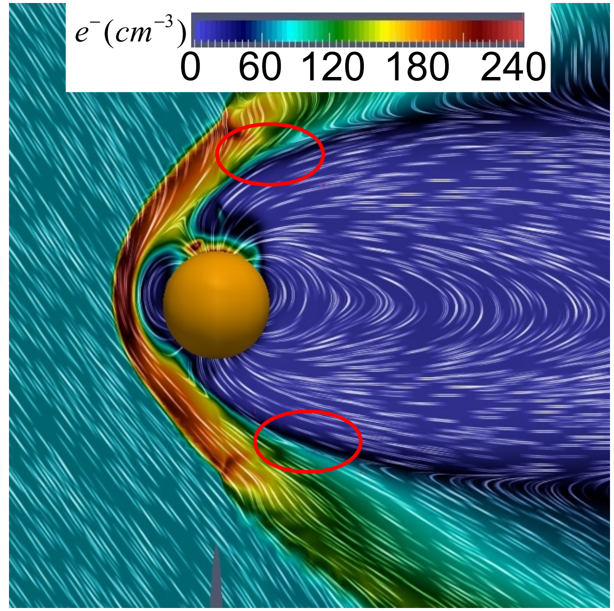
Simulations summary

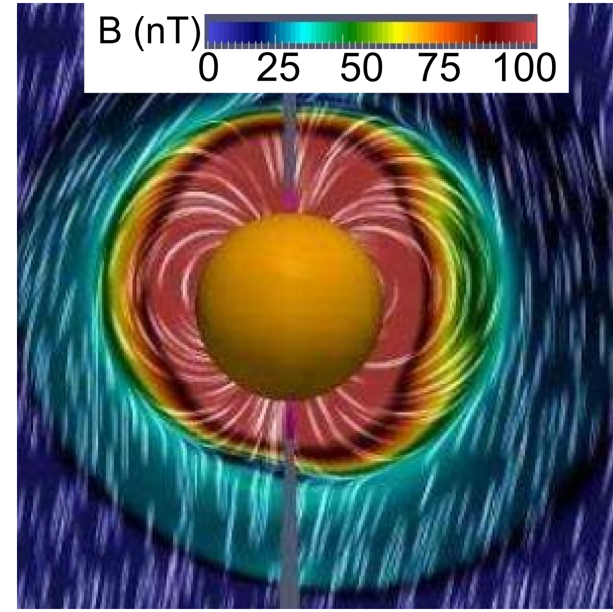
Name	Date	B field (nT)	$e^- cm^{-3}$	$T(K)$	β	V (km/s)	M_s
Bmin	2011/10/10	$(4, 1, 6)$	60	58000	2.27	250	6.25
Bx	2012/01/19	$(20, 0, 0)$	15	85000	0.11	320	6.67
Bxneg	2011/10/17	$(-18, 0, 0)$	20	90000	0.19	300	6
By	2012/03/24	$(-5, 15, 5)$	30	100000	0.38	400	7.69
Byneg	2012/03/03	$(8, -17, 0)$	70	115000	0.79	380	6.79
Bz	2011/09/06	$(0, -10, 41)$	90	110000	0.19	350	6.4
Bzneg	2011/09/29	$(8, 10, -26)$	30	60000	0.07	360	8.78

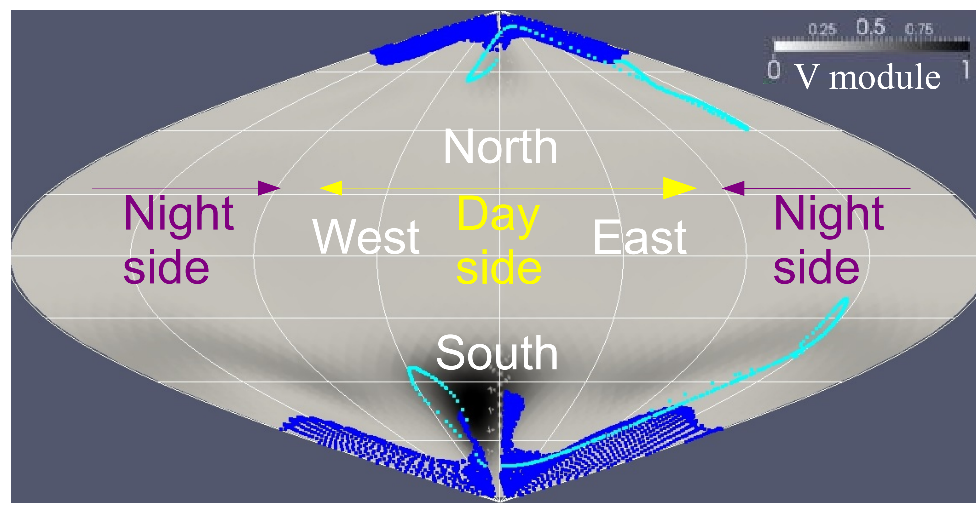
Bmin: weak IMF (reference case)

Hermean magnetosphere weak IMF







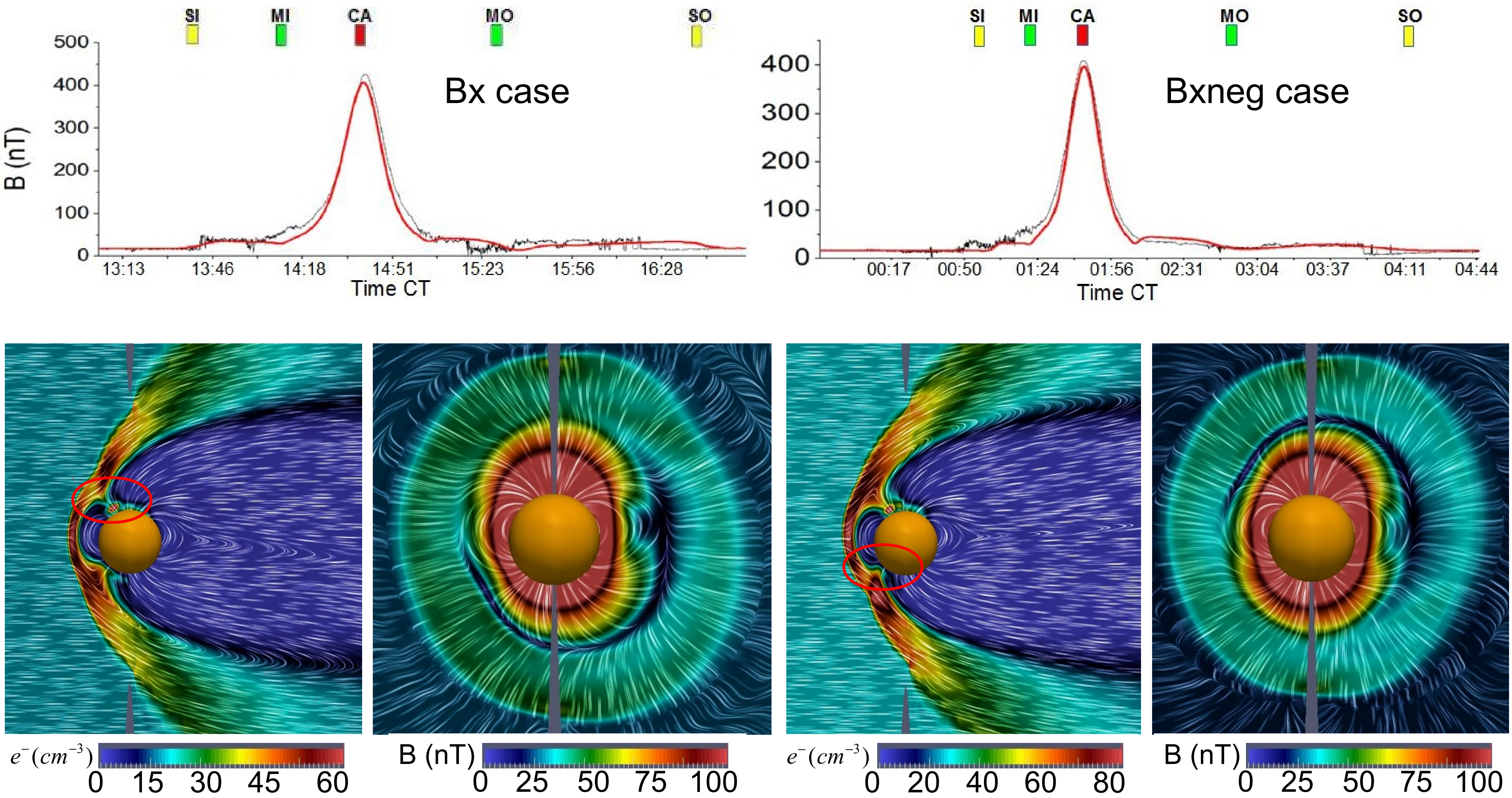


—	MESSENGER data
—	Simulation

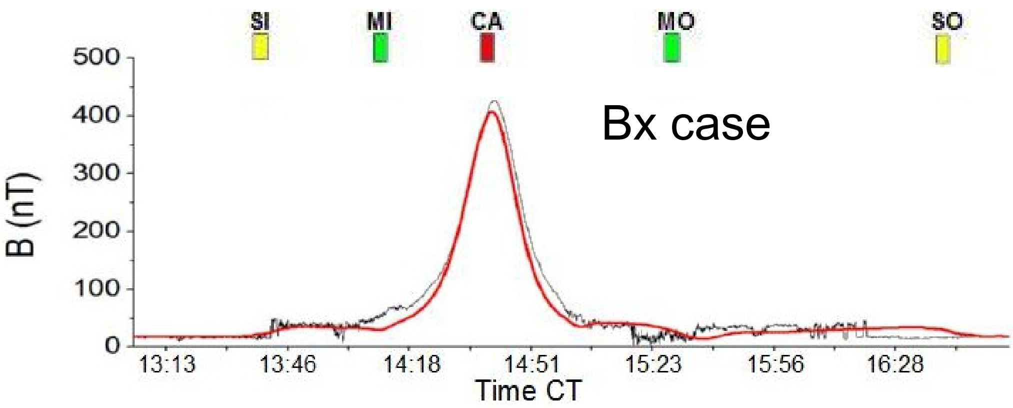
SPI 2014 workshop, Nov 2014, Saclay

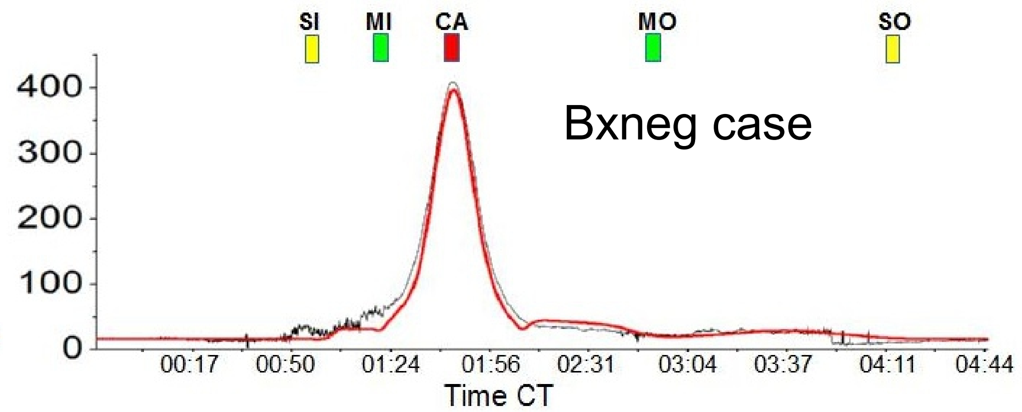
- Open field lines
- Lines in sat. trajectory

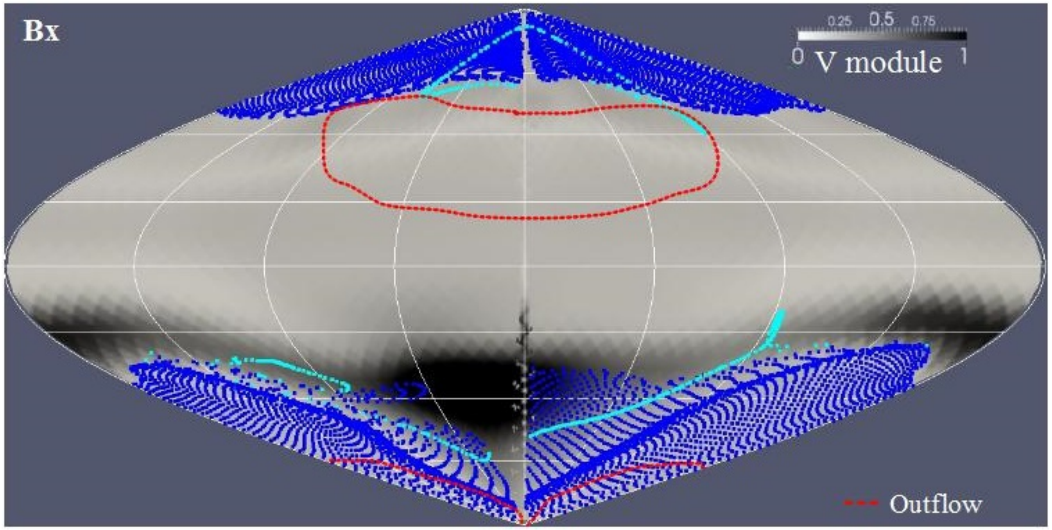
Hermean magnetosphere Bx/Bxneg IMF

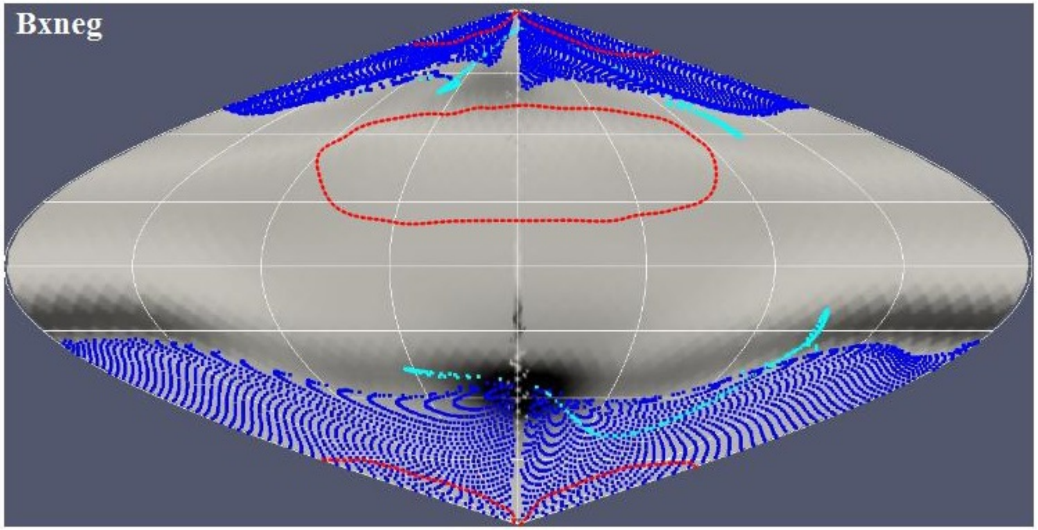


Hermean magnetosphere Bx/Bxneg IMF

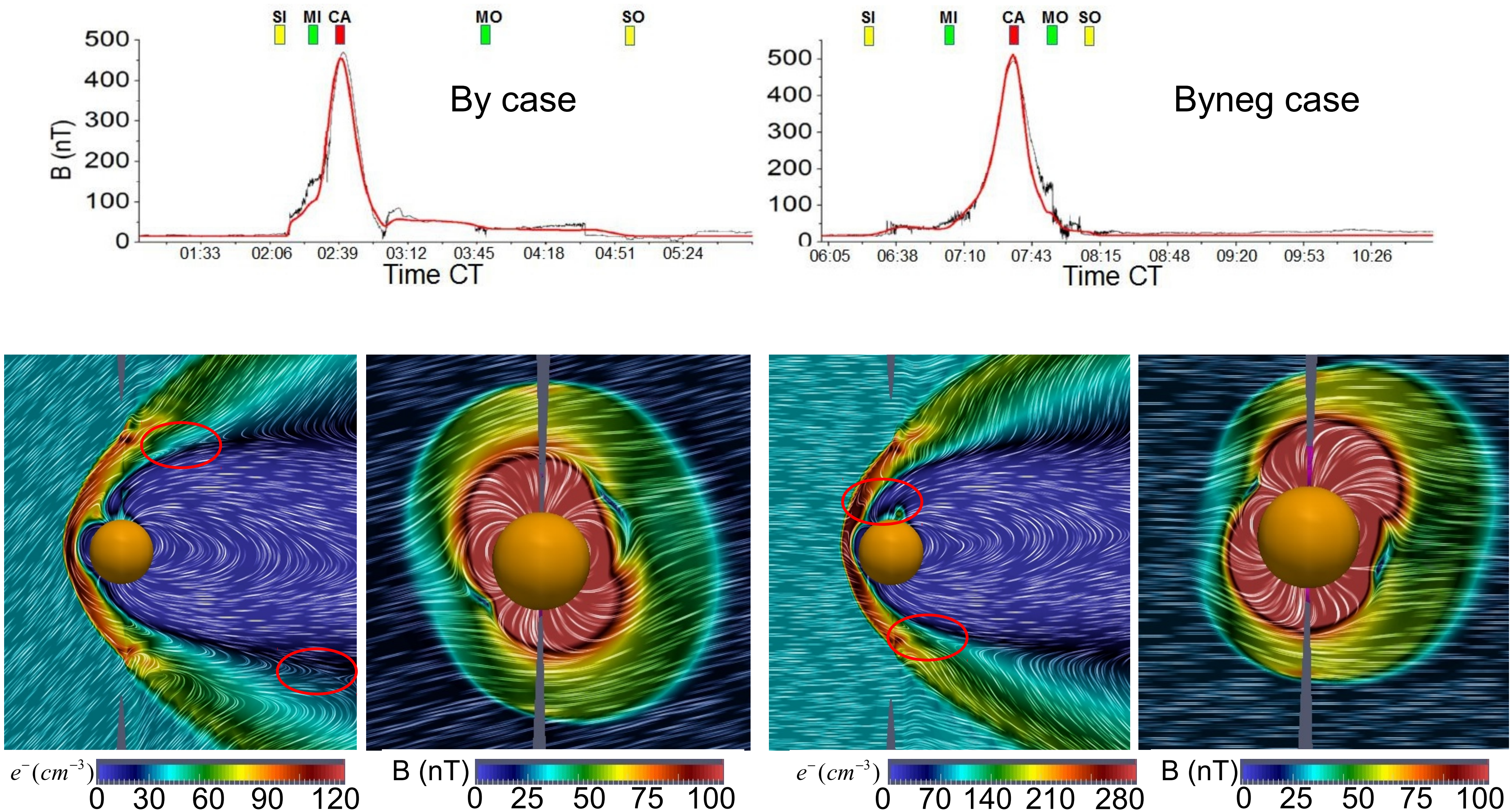




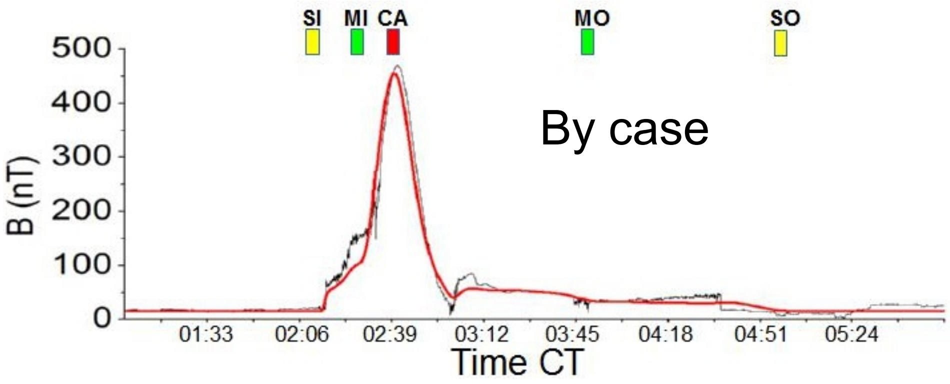


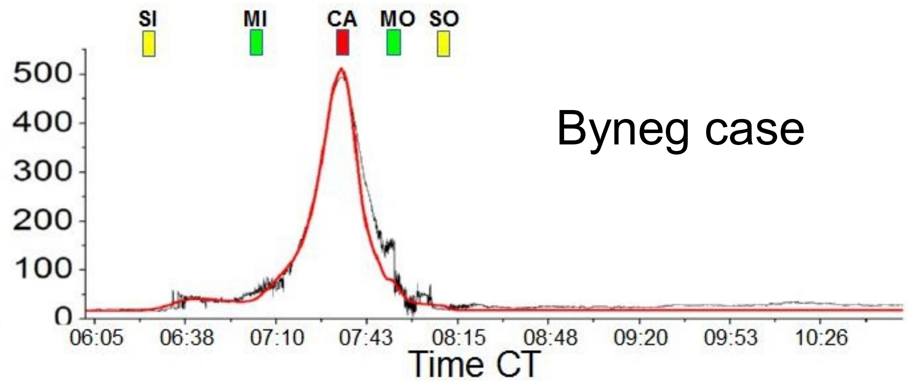


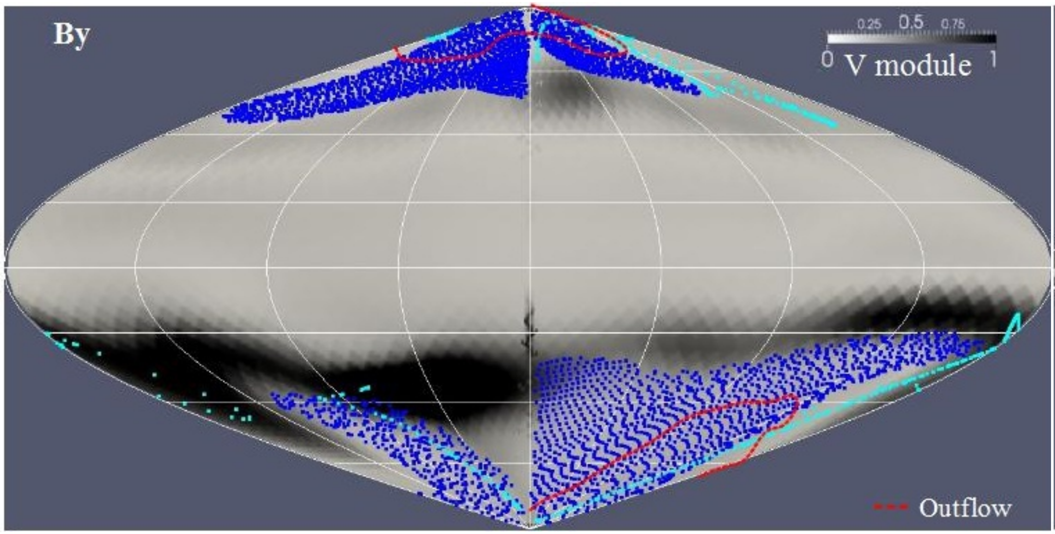
Hermean magnetosphere By/Byneg IMF

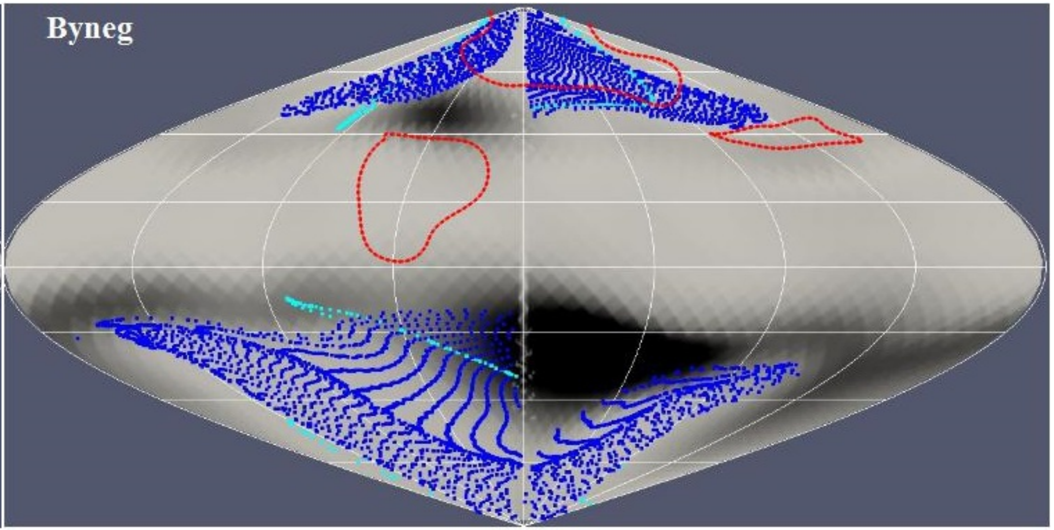


Hermean magnetosphere By/Byneg IMF

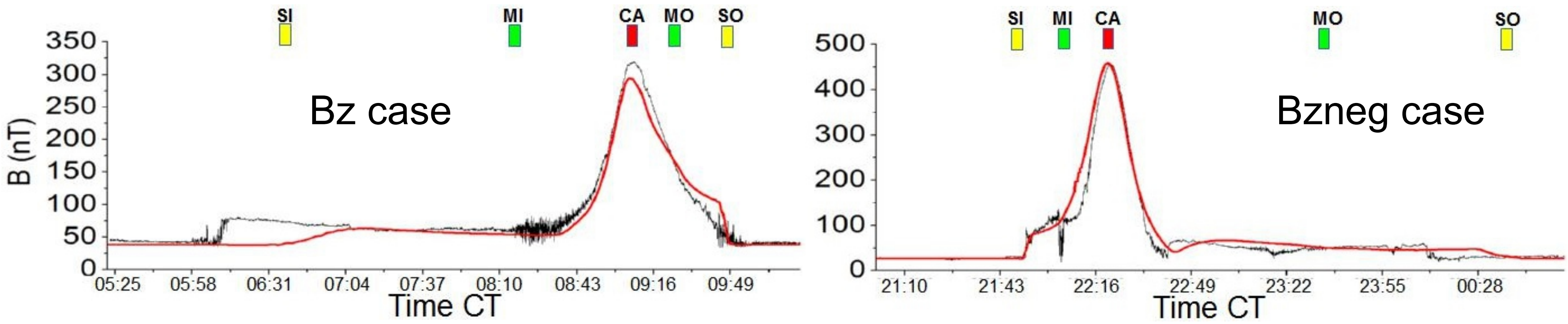


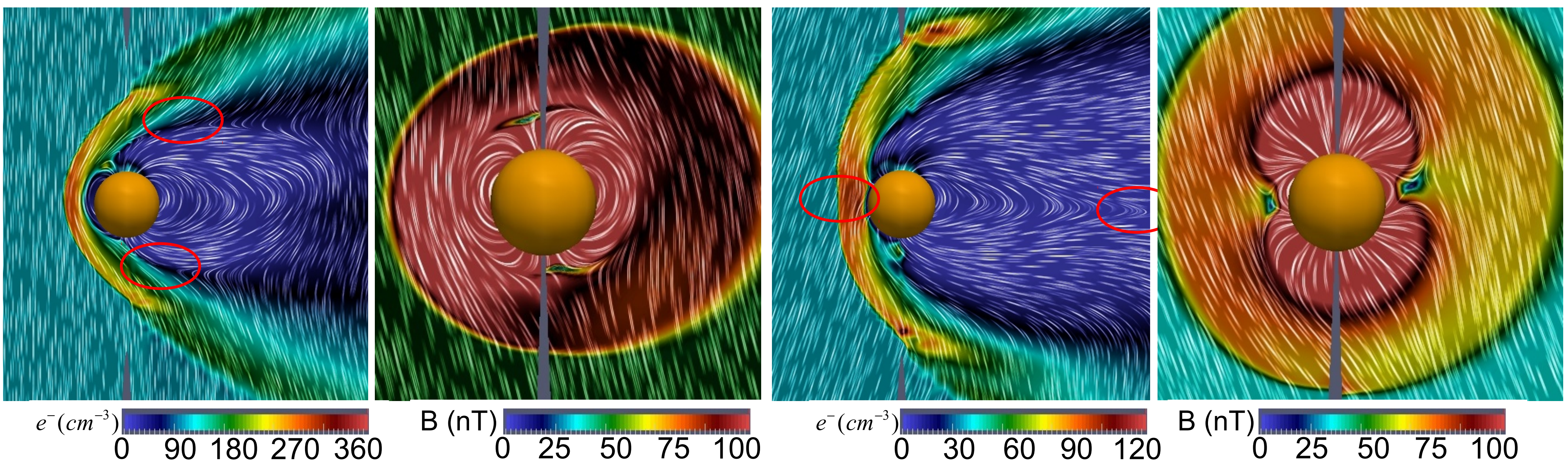




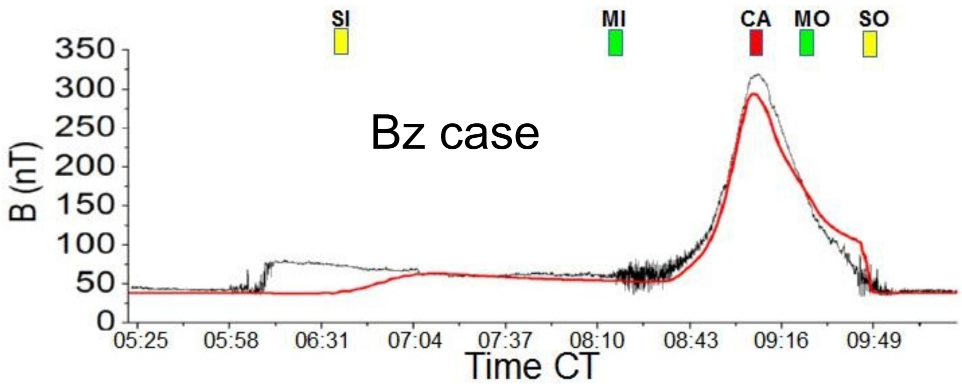


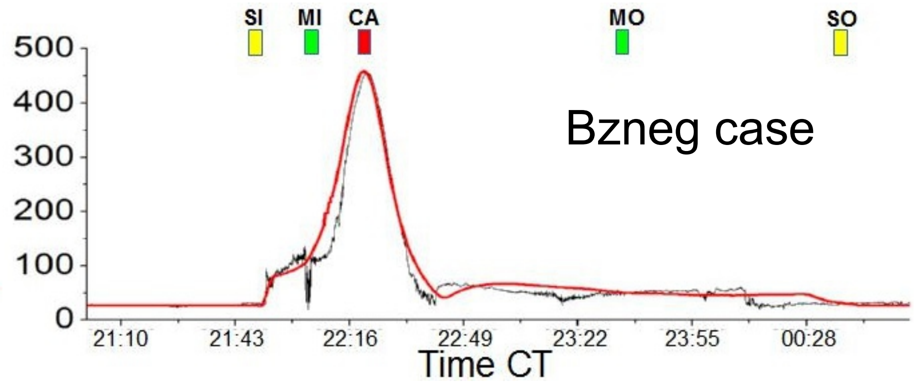
Hermean magnetosphere Bz/Bzneg IMF

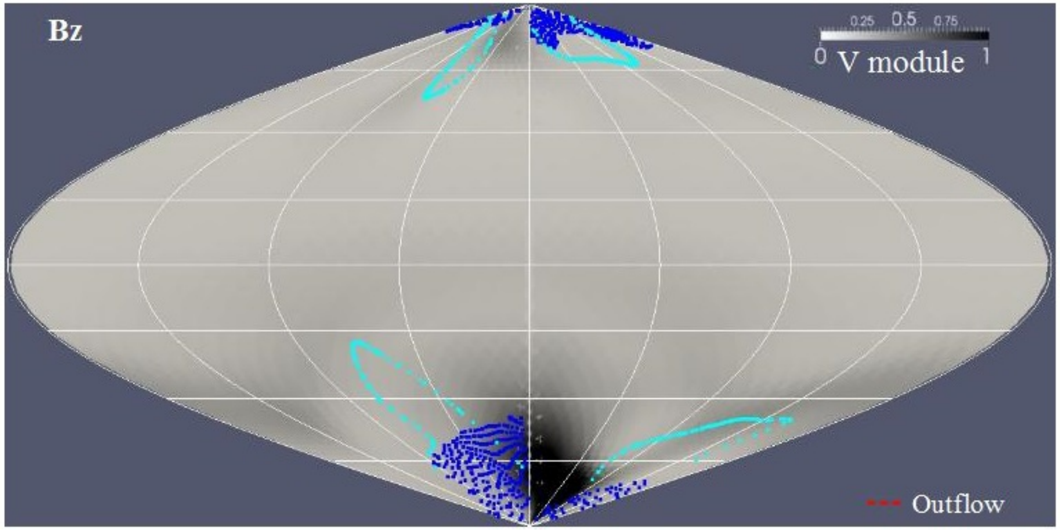


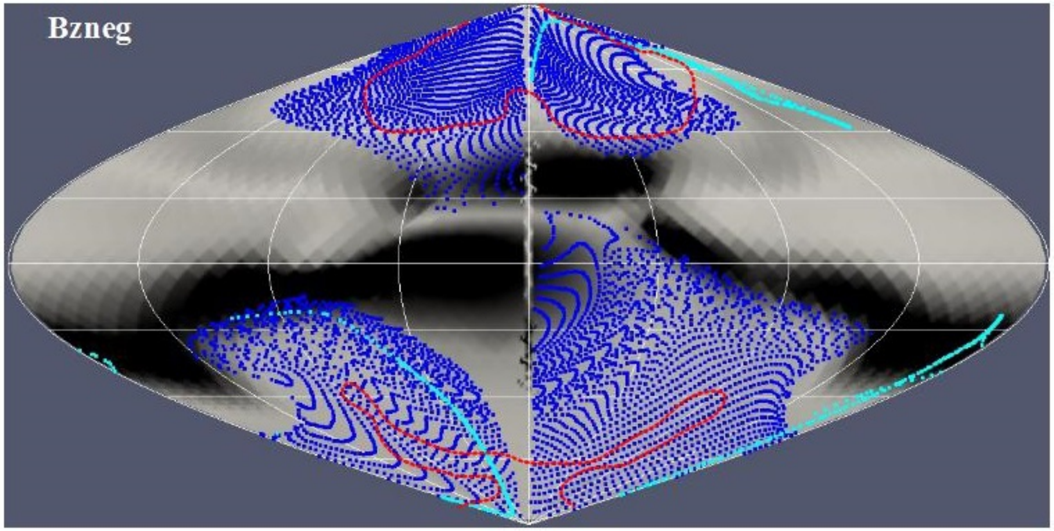


Hermean magnetosphere Bz/Bzneg IMF









IMF orientation results summary

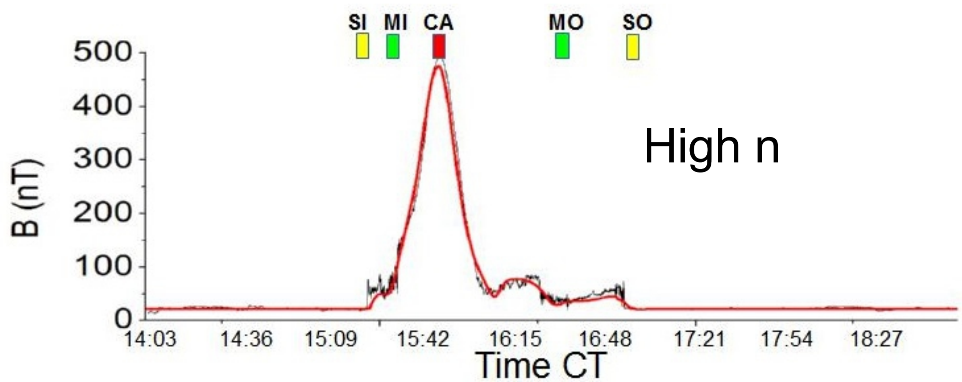
- Weak IMF:
  - Small regions of open magnetic field lines in the poles.
  - Strong inflow in the planet day side at the South Hemisphere.
- Bow shock nose, stand off:
  - Distortion near the South/North poles in the Bx/Bxneg cases.
  - The magnetosphere is tilt in the By/Byneg cases, BSN weakened.
  - Bz/Bzneg case, BSN enhanced/weakened.
- Open magnetic field lines:
  - Wide in the Bx/Bxneg cases, East/West asymmetry in the By/Byneg cases, Bz smallest region and Bzneg wide in the day side.
- Inflow regions day side:
  - Bx/Bxneg cases, enhanced in the South/North Hemisphere.
  - By/Byneg cases, enhanced in both Hemisphere and displaced.
  - Bz/Bzneg cases, weakened/enhanced in both hemisphere and displaced to the poles/equator.

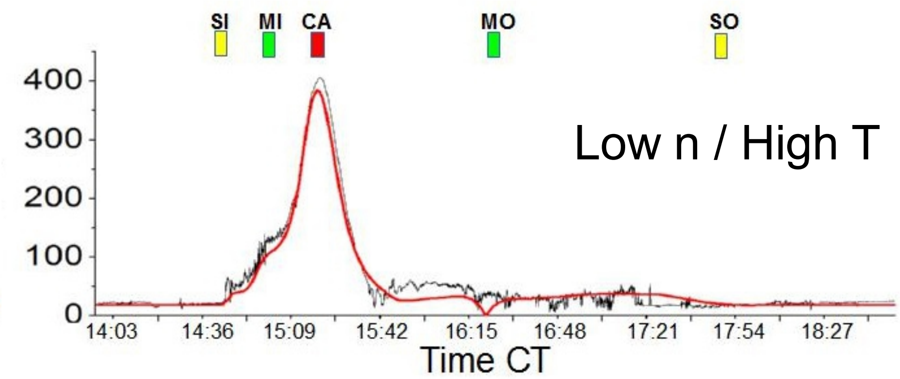
Extreme cases and parametric study

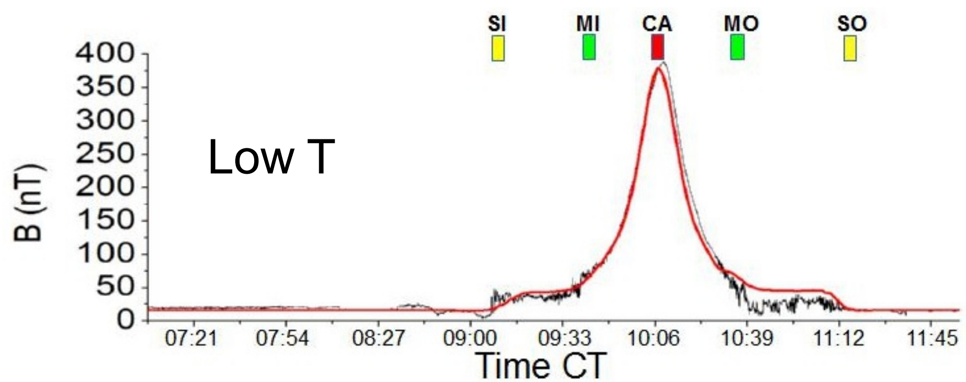
(Density, Temperature and velocity)

Simulations summary

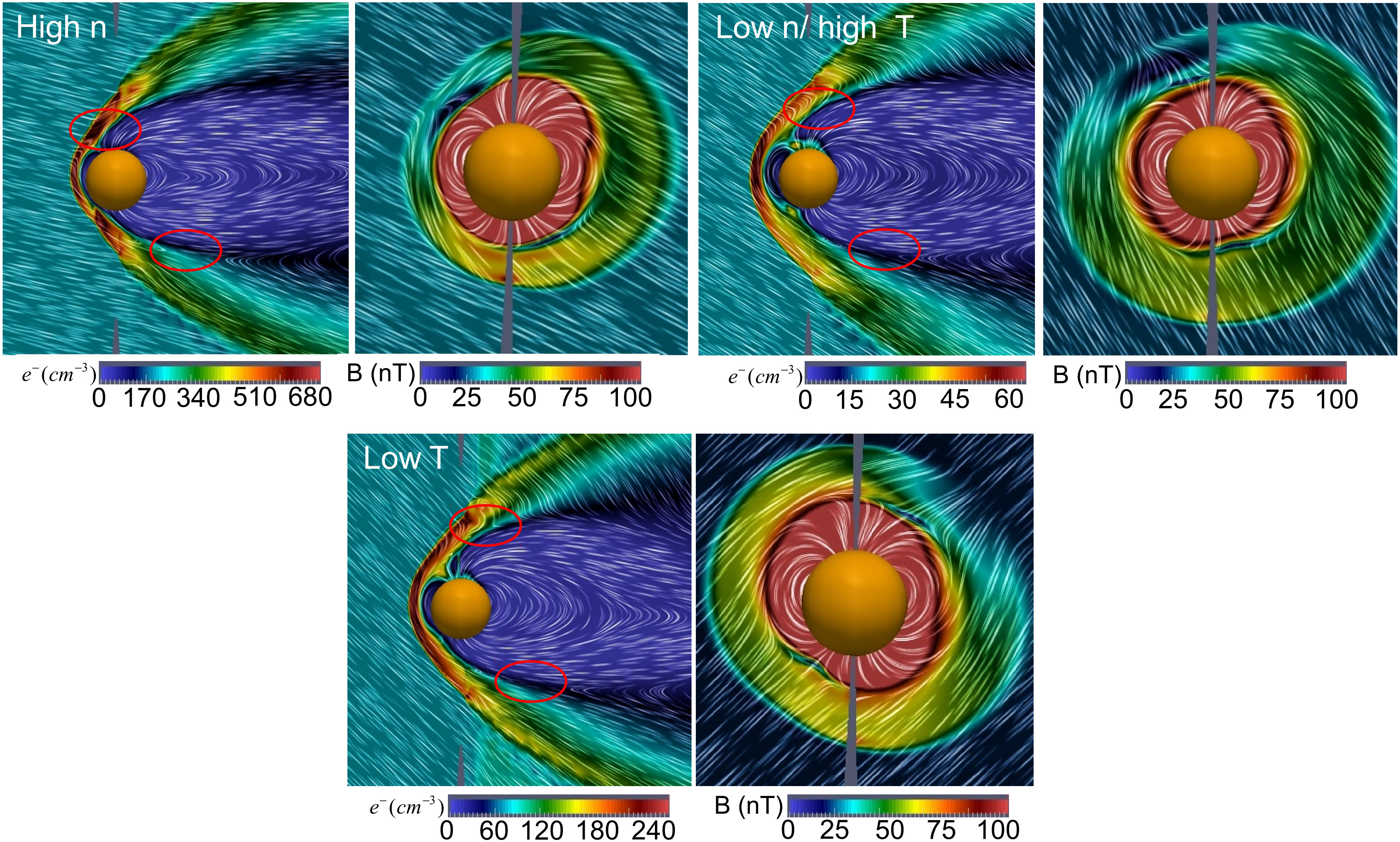
Name	Date	B field (nT)	$e^{-}cm^{-3}$	$T(K)$	β	V (km/s)	M_s
High n	2011/09/18	$(20, -10, 5)$	170	60000	0.69	270	6.58
Low n High T	2012/01/26	$(16, -6, 10)$	15	160000	0.21	500	7.58
Low T	2011/10/28	$(10, 10, 10)$	60	39000	0.27	340	10.61



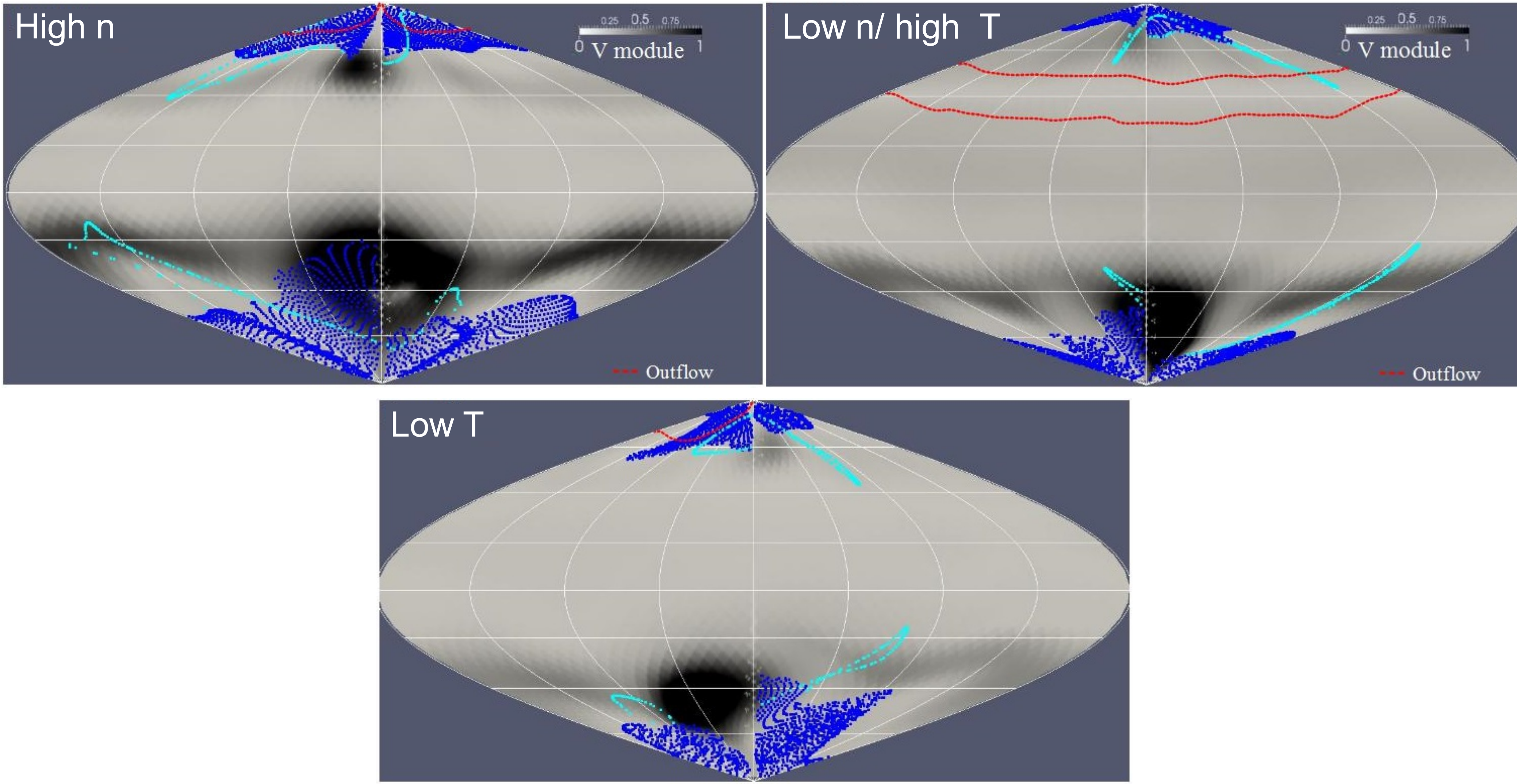




Hermean magnetosphere high/low density

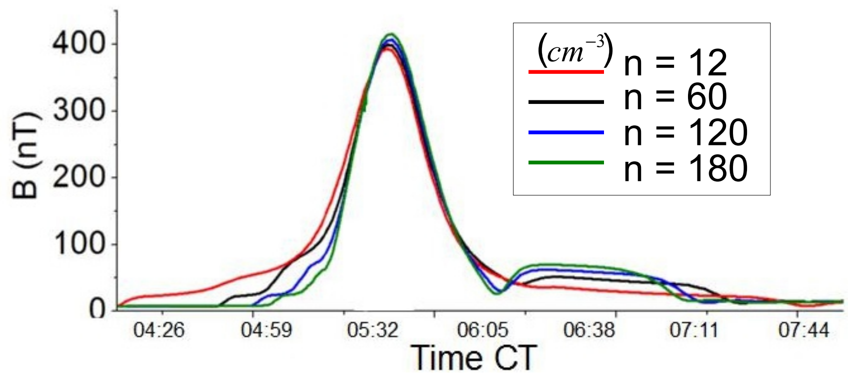


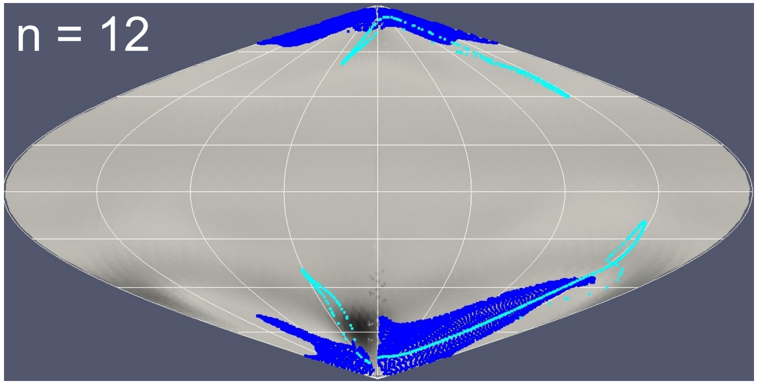
Hermean magnetosphere high/low density

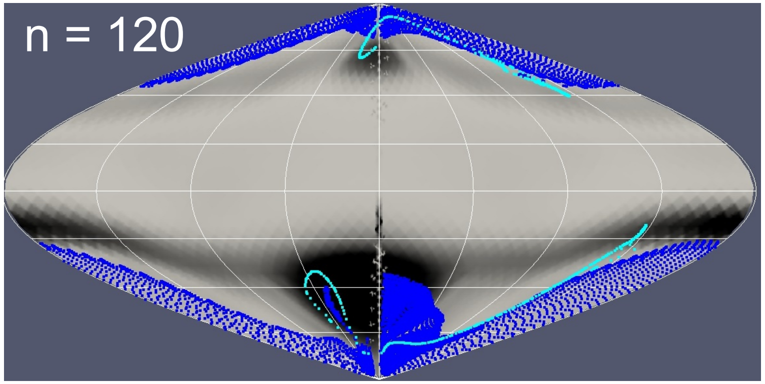


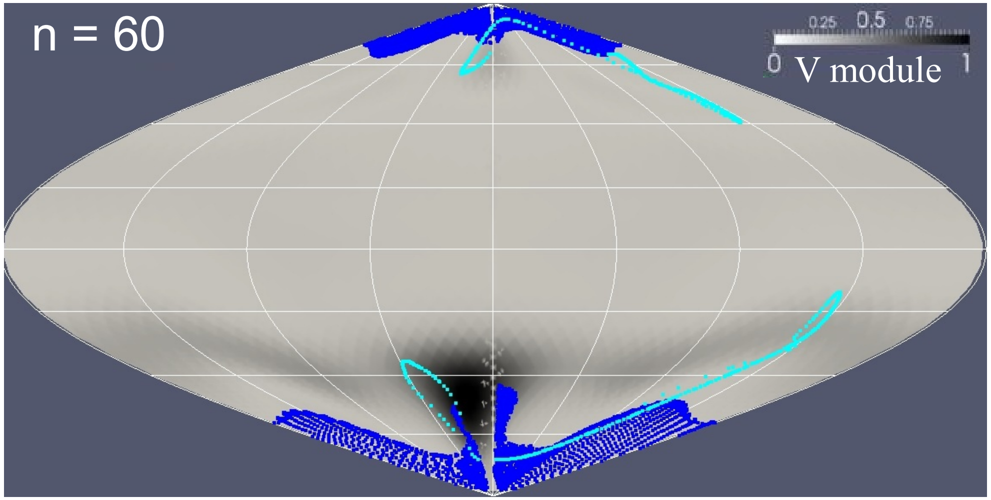
Parametric study: reference case

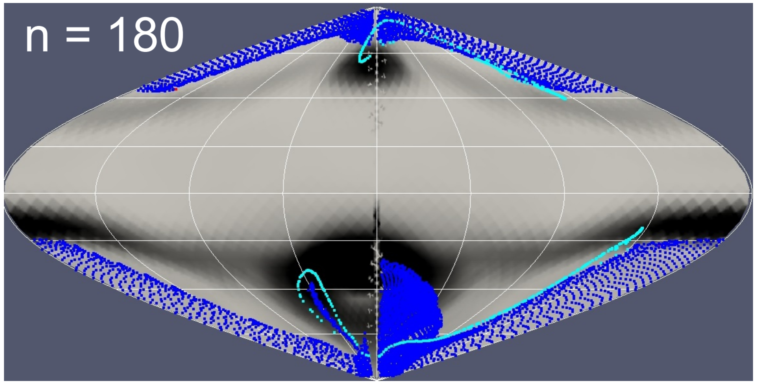
Bmin: density parametric study





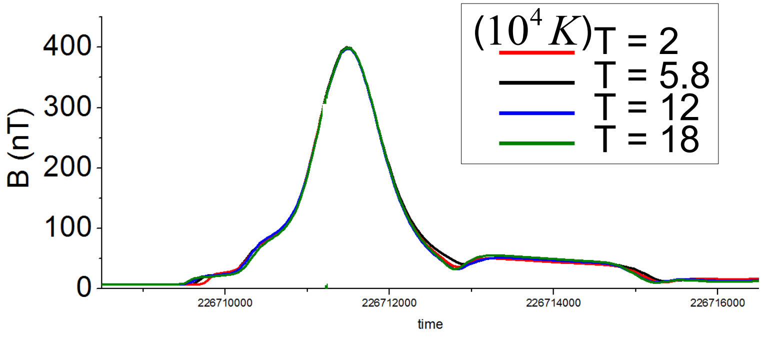


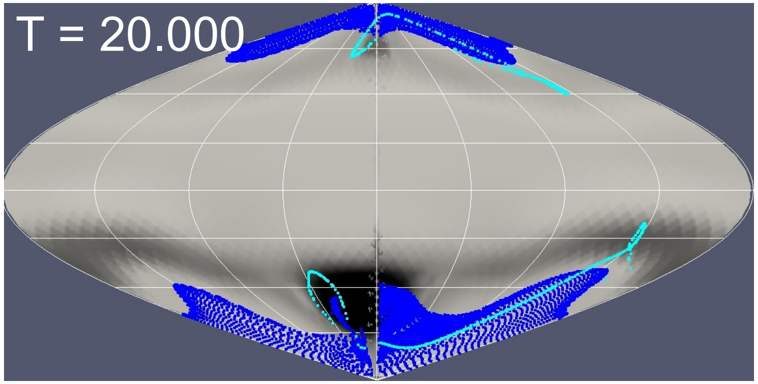


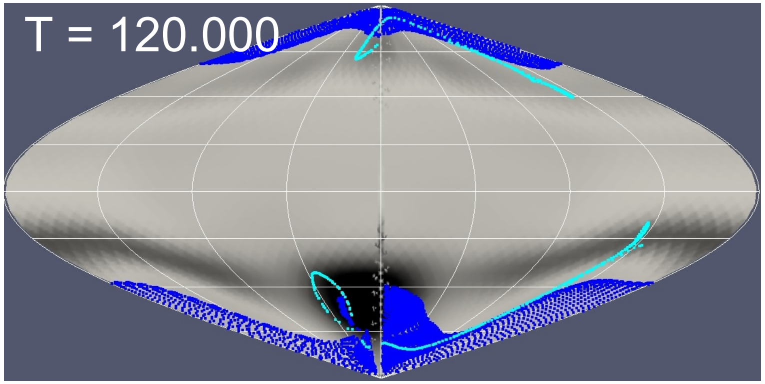


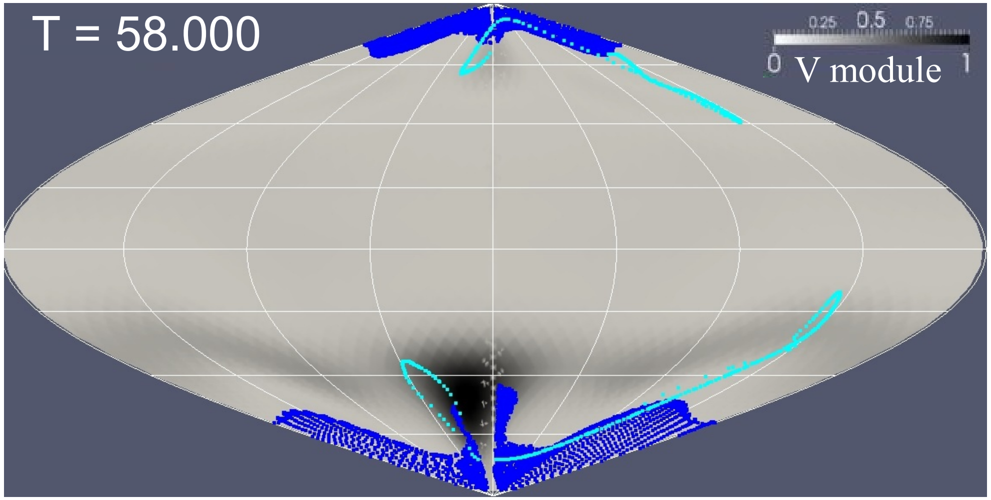
Parametric study: reference case

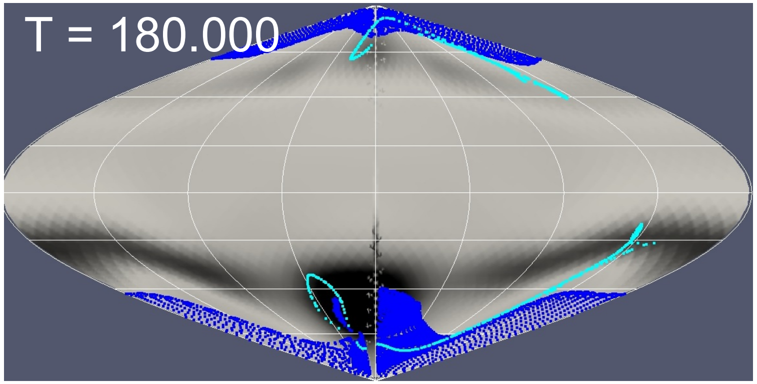
Bmin: temperature parametric study





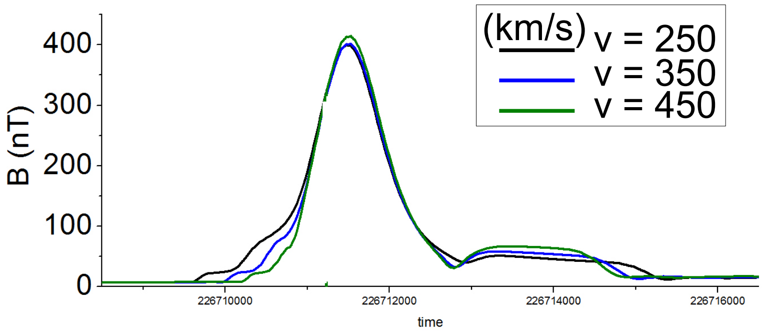


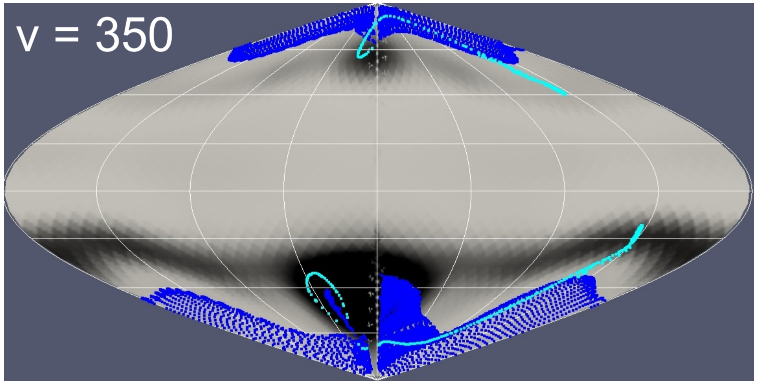


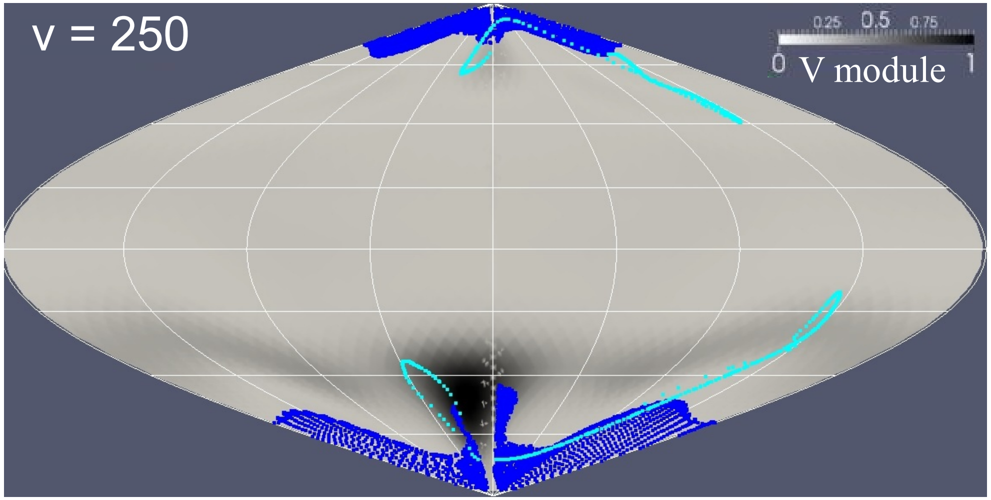


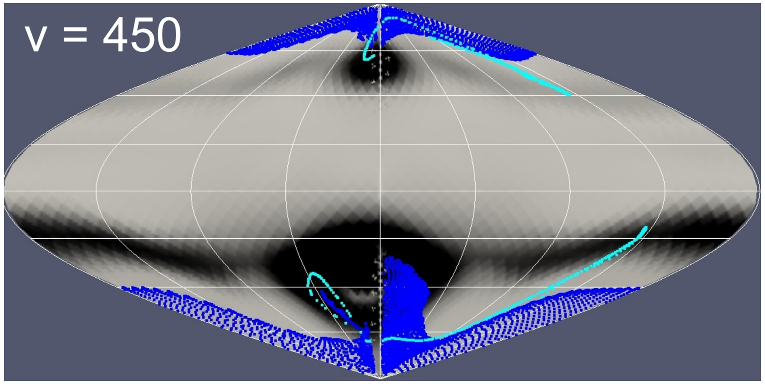
Parametric study: reference case

Bmin: velocity parametric study

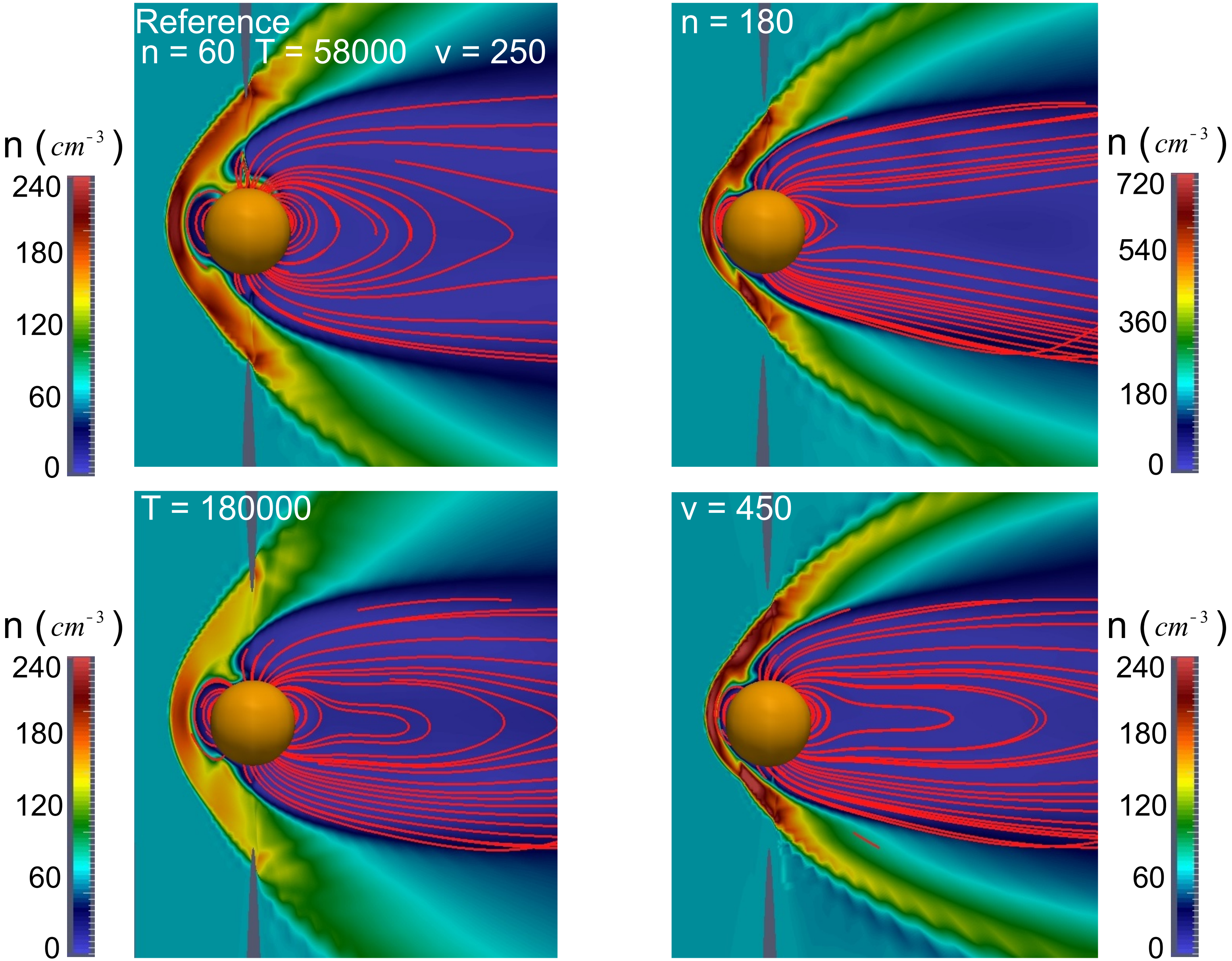








Parametric study: reference case



Parametric and extreme cases study results summary

- Magnetic field structure:
  - The reconnection region between the IMF and the Hermean magnetic field does not change
  - Different magnetotail structure.

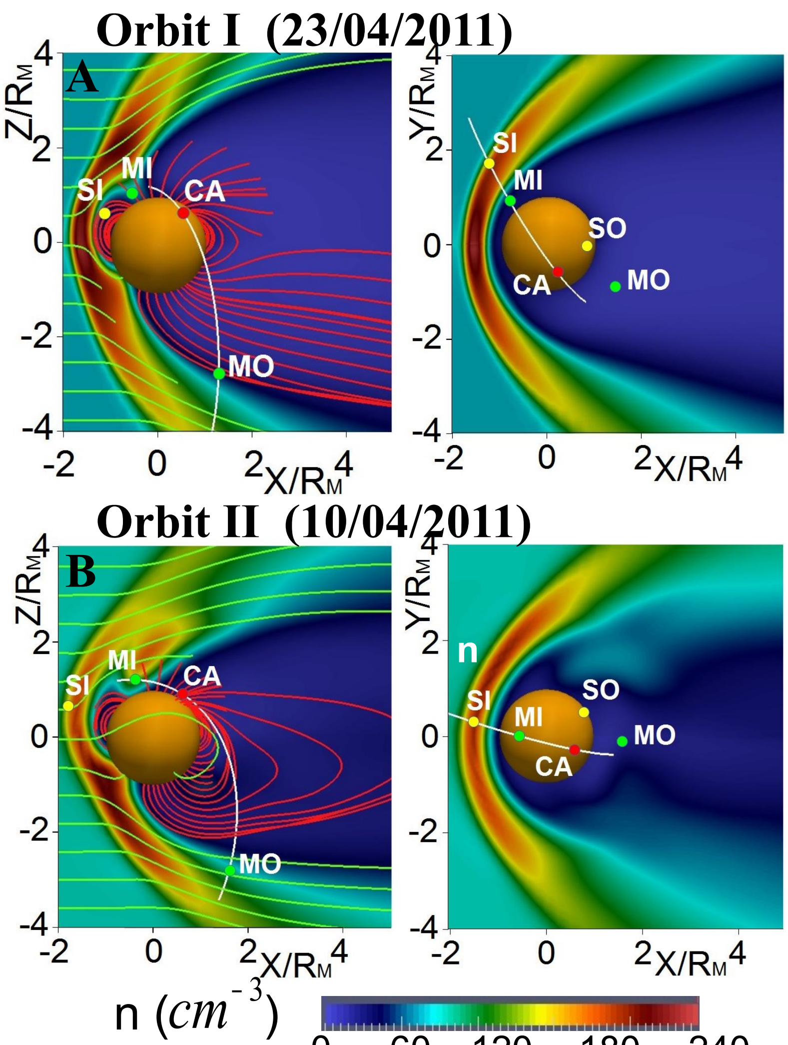
- Open magnetic field lines:
  - Large dependence with the density and weak with the temperature and velocity.
  - Largest regions observed in the high density case.

- Inflow regions day side:
  - Enhanced in the simulations with high density and velocity.
  - No dependence with the temperature.

Aurora in Mercury?

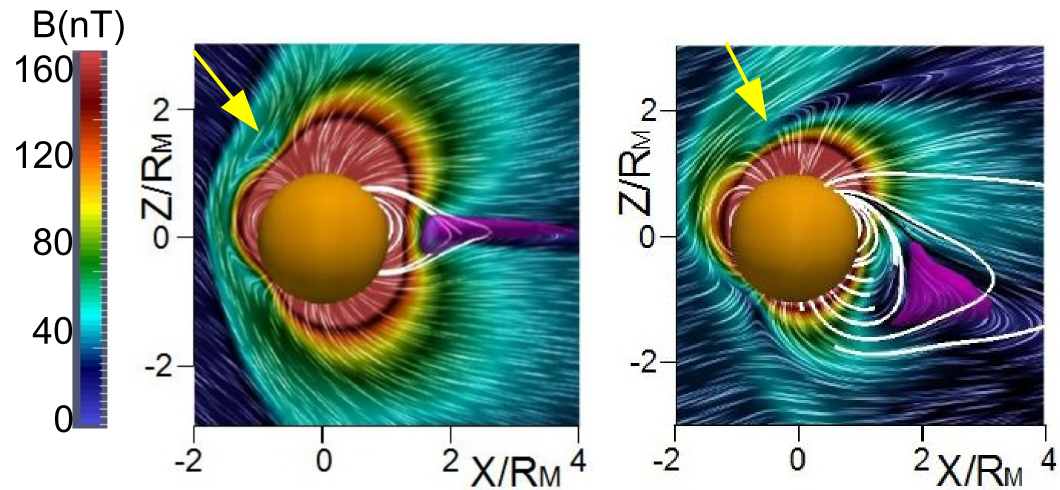
(Interaction of the BS with the planet surface in the North hemisphere)

Aurora in Mercury?

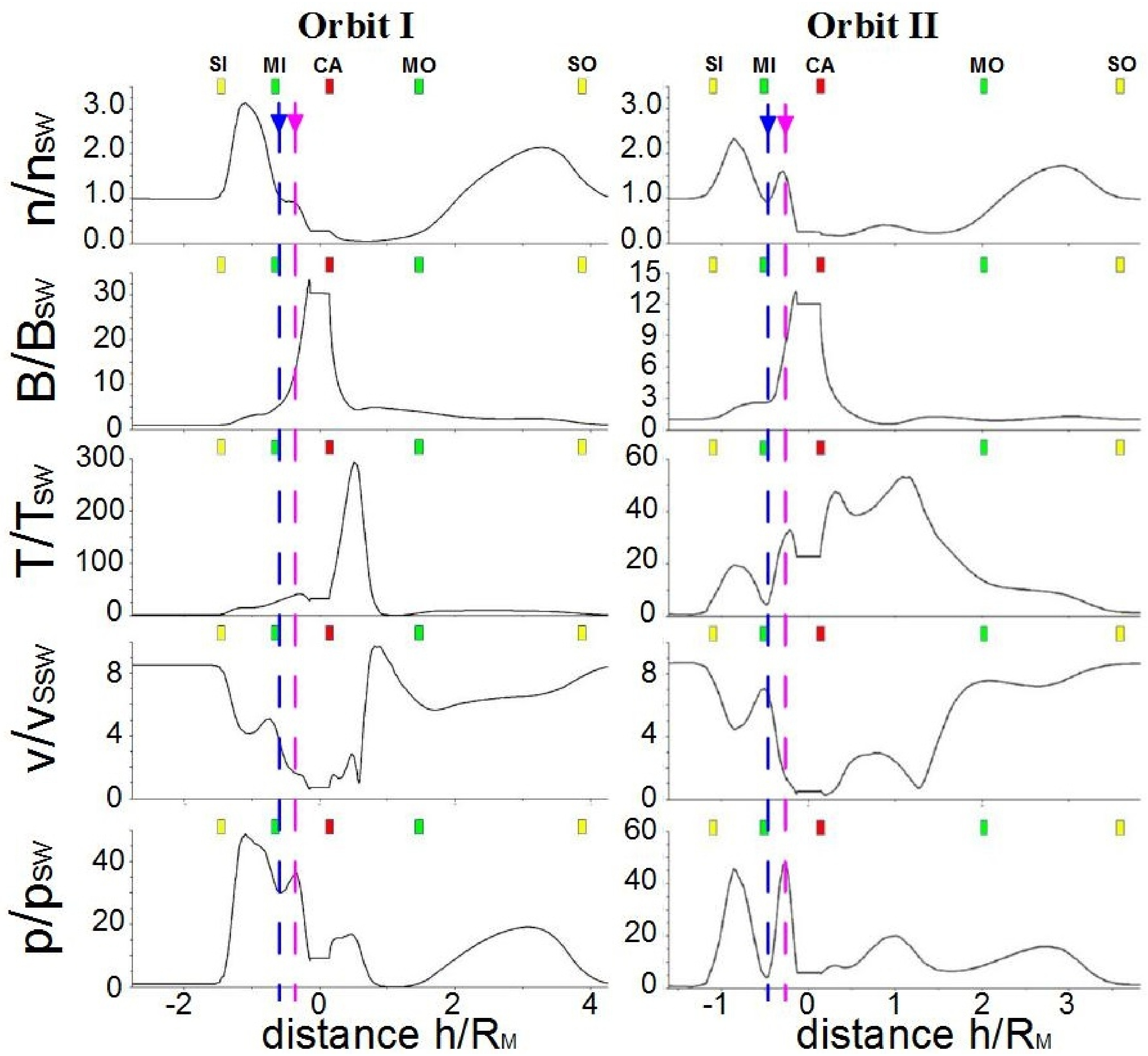


Name	B field (nT)	cm^{-3}	$T(10^3 K)$	β	V (km/s)	M_s
Orbit I	$(-5, 10, -5)$	60	43	0.597	290	8.53
Orbit II	$(-30, 13, 10)$	74	54	0.12	340	8.74

· Magnetospheric structure linking the back of the BS with the North Hemisphere of Mercury.



Aurora in Mercury?



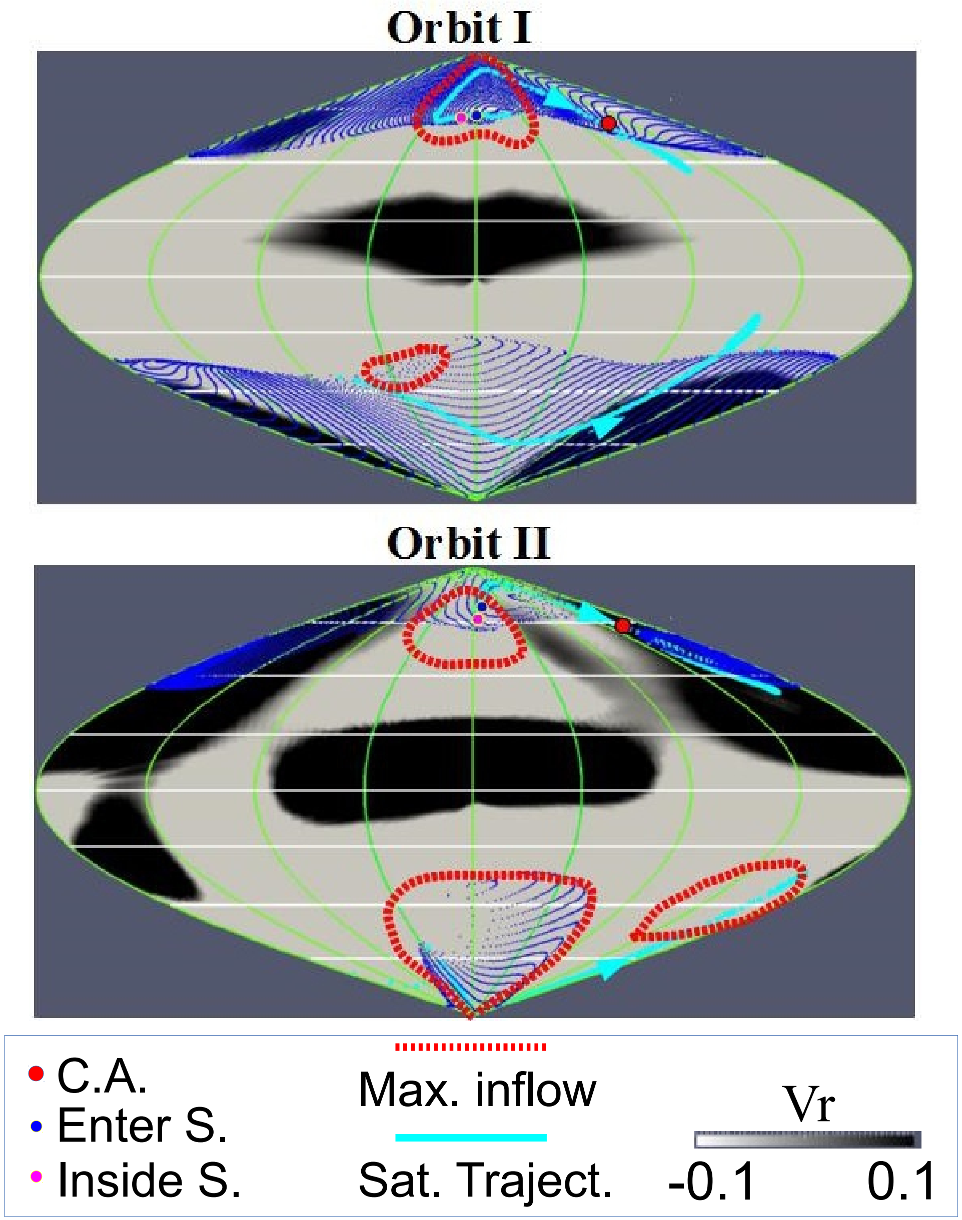
- Sat. enters in the mag. structure.
- Velocity reaches a local maximum.
- Density, temperature and pressure local minimum.

➢ Region of fast expansion and cooling down of the plasma.

- Inside the mag. structure.
- Velocity drops one order compared with the SW.
- Density, temperature and pressure local maximum.

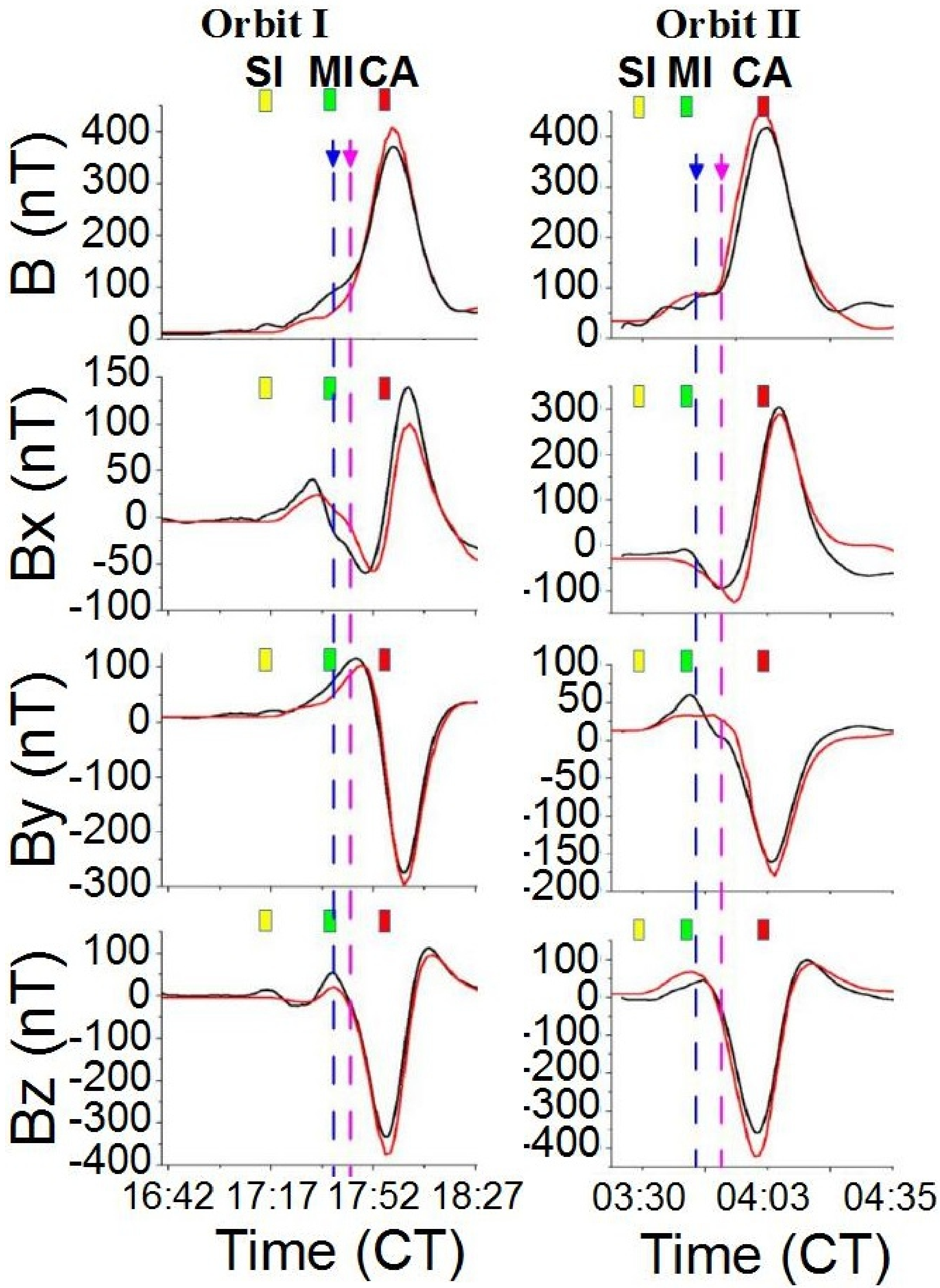
➢ Region of plasma accumulation nearby the planet pole.

Aurora in Mercury?



- Region of strong inflow in the planet surface.
- The back of the BS is connected with the planet surface by open magnetic field lines.
- It is located nearby the North pole almost in the middle of the day side of the planet.

Aurora in Mercury?



- There is a correlation between the magnetosphere structure and perturbations in the Hermean magnetic field ?

- The simulation results and MESSENGER data shows perturbations of the magnetic field when the satellite enters in the magnetosphere structure.

Smooth MESSENGER data
Simulation results

General conclusions

- IMF orientation and the location of the reconnection regions with the planet magnetic field is essential to study the planet habitability.

- SW density can lead to a strong distortion of the magnetosphere structure in the day and night side of the planet. SW high density the planet is more exposed (smaller stand off distance BS and narrow magnetotail).

- SW speed distorts the day side of the magnetosphere reducing the stand off distance but the effect in the night side is weak.

- SW temperature lead to a small distortion of the magnetosphere only in the night side.

Next steps

- Coronal ejection case; improve current closure (FAC).
- Time variable solar wind (not easy to implement in spherical geometry)
- New interesting experiments: magnetic blobs, test particle simulations ...
- Exoplanets (different SW conditions and planet magnetic field).
- Earth.
- Any suggestion...?