Indirect measurements of slow modes in the Hermean magnetosphere

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Abstract

The aim of this study is to simulate slow mode structures in the Hermean magnetosphere. We use the single fluid MHD code PLUTO and a multipolar expansion of the Northward displaced Hermean magnetic field, to perform simulations mimicking the solar wind and interplanetary magnetic field conditions during 08/09/2011 MESSERGER orbit, susceptible to cross a slow mode structure [F. Pantellini et al, PSS, 112, 1 (2015) and J. Varela et al, PSS, 125, 80 (2016)]. The simulation shows the presence of a slow mode structure nearby the North pole. The comparison with the MESSENGER data shows a decrease of the magnetic field module in the trajectory region where the slow mode structure is predicted by the simulation.

Numerical model

We use the MHD version of the open source code PLUTO [Mignone, A. et al, ApJS, 170, 1 (2007)] in spherical coordinates to simulate a single fluid polytropic plasma in the inviscid limit. The simulation domain consist of 256 radial points, 48 in the polar angle θ and 96 in the azimuthal angle ϕ (the grid poles correspond to the magnetic poles). The simulation domain is confined within two spherical shells centered on the planet, representing the inner and outer boundaries of the system. The shells are at $0.6R_M$ and $16R_M$. Between the inner shell and the planet surface (at $R_M = 1$ in the domain) there is a "soft coupling region" where special conditions apply. The outer boundary is divided in two regions, upstream part where solar wind parameters are fixed and downstream part where we consider null derivative condition $\frac{\partial}{\partial r} = 0$ for all fields. At the inner boundary the value of the intrinsic magnetic field of Mercury is specified. In the soft coupling region the plasma velocity is smoothly reduced to zero when approaching the inner boundary, setting magnetic and velocity fields parallel. We use a multipolar expansion of the planet magnetic field assuming an axisymmetric model. The magnetic potential Ψ is expanded in dipolar, quadrupolar, octupolar and hexadecapolar terms:

$$\Psi(r,\theta) = R_M \sum_{l=1}^{4} (\frac{R_M}{r})^{l+1} g_{l0} P_l(cos\theta) \quad (1)$$

The current free magnetic field is $B_M = -\nabla\Psi$. r is the distance to the planet center, θ the polar angle and $P_l(x)$ the Legendre polynomials. The numerical coefficients g_{l0} taken from Anderson et al. 2012 are $g_{01} = -182$ nT, $g_{02}/g_{01} = 0.4096$, $g_{03}/g_{01} = 0.1265$ and $g_{04}/g_{01} = 0.0301$. The simulation frame is such that the z-axis is given by the planetary magnetic axis pointing to the magnetic North pole and the Sun is located in the XZ plane with $x_{sun} > 0$. y-axis completes the right-handed system. The solar wind parameters of the simulations are summarized in Table 1. We assume fully ionized proton-electron plasma. $\vec{v}_u$ is the unitary vector of the velocity. The dynamic pressure is defined as $q = \rho v^2/2$.

Date	B field (nT)	n (cm^{-3})	T (K)	q (10^{-9} Pa)	v (km/s)	$\vec{v}_u$
2011/09/08	(-25,30,25)	50	155000	5.40	360	$(-0.988, 0.154, 0)$

Table 1: Simulation parameters

Slow modes structures

Fig. 1A shows a polar cut of the density distribution. The bow shock (BS) is identified as the region with high plasma density. The inner magnetosphere is identified as the low plasma density region. The closest approach of MESSENGER orbit (black line) is nearby the North pole. Fig. 1B shows the pressure distribution in the satellite's orbital plane. The local maximum of the pressure in the inner magnetosphere shows the compressional front of the slow mode structure.

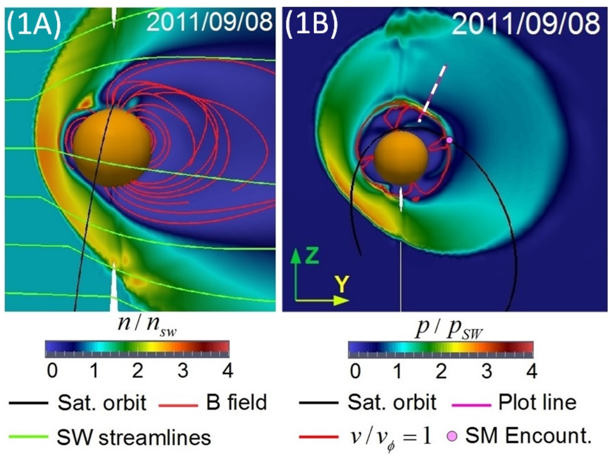

Figure 1: *(A) Polar cut of the density distribution. (B) Pressure distribution in the plane of the satellite orbit. The white dashed line identifies the strip of the model plotted on Figure 2C.*

The local maximum of the pressure is linked with a region of strong magnetic shear, due to the large bending of the magnetic field lines that connect IMF and Hermean magnetosphere (Fig. 2A). Large rotation of the velocity and magnetic fields in the region of the compressional front (Fig. 2B). The compressional front is identified as a sharp increase of the pressure and a local maximum of the density in anti-phase with the velocity and magnetic field modules (Fig. 2C). The rarefaction front shows almost flat profiles between the magnetosheath and the magnetopause.

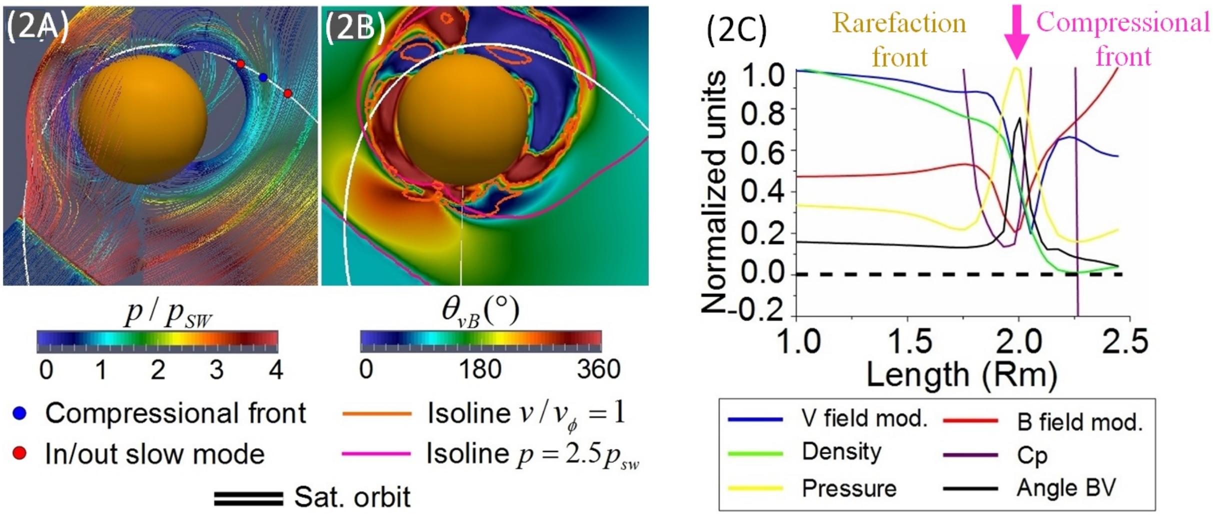

Figure 2: *(A) Magnetic field lines crossing the satellite's trajectory with the pressure imprinted on the field lines by a color scale. (B) Angle between velocity and magnetic field in the plane of the satellite trajectory. (C) Normalized module of magnetic and velocity fields, density, pressure, C_p parallel compressibility and the angle between velocity and the magnetic fields θ_{vB}.*

Slow mode signs in MESSENGER data

There is a local minimum of the B field module in MESSENGER data (red) on the planet nigh side also reproduced in the simulation (black), between 08:10 to 08:25 CT (Fig. 3A to D). The blue dashed lines indicate the MESSENGER orbit inside the slow modes structure according to the simulation.There is a local maximum of the pressure correlated with a local minimum of the magnetic field and a sharp decrease of the velocity: satellite's encounter with the slow mode compressional front at $R/R_M = 0.9$ (Fig 3E to G). The plasma temperature increase inside the slow mode structure: heating mechanism associated with the strong magnetic shear (Fig 3I).

Conclusions

The analysis suggests the presence of a slow mode structure in the North of the magnetosphere during the MESSENGER orbits of the 2011/09/08. MESSENGER data shows a drop of the B field module in the orbit region where the slow mode structure is formed according to

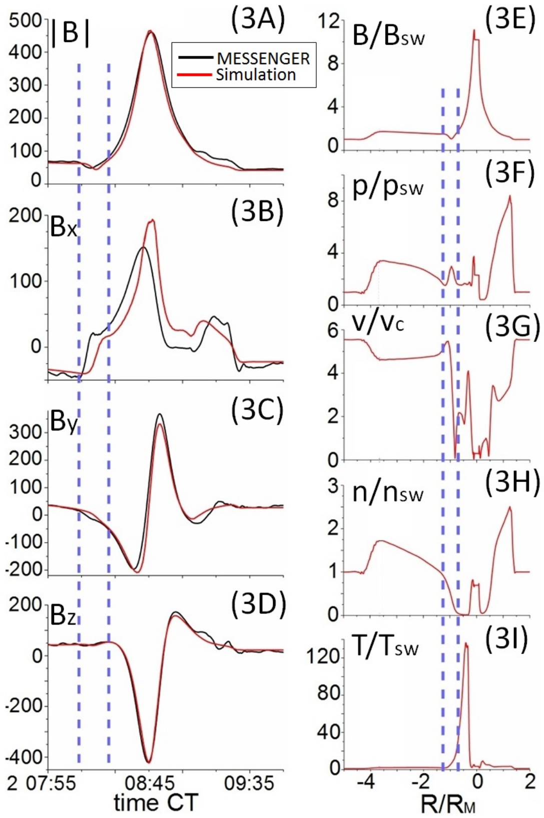

Figure 3: *(Panels A to D) Comparison between smoothed MESSENGER magnetometer data (black line) and simulation magnetic field (red line) along satellite's trajectory. Blue dashed lines indicate the satellite's trajectory inside the slow mode structure in the simulations. (Panels E to I) Density, magnetic field, temperature, velocity and pressure in the simulation along the satellite's trajectory. Blue dashed lines indicate the satellite's trajectory inside the slow mode structure in the simulation. Negative R/R_M values indicate a trajectory position before the satellite's closest approach.*

the numerical model. In 2011/09/08 orbit, IMF orientation has a large Northward component and the dynamic pressure smaller than $6.25\dot{1}0^{-9}$ Pa, optimal conditions for the formation of slow modes nearby the Hermean North pole [J. Varela et al, PSS, 125, 80 (2016)]. The satellite is inside the slow mode structure between 08:10 to 08:25 CT. The satellite encounter with the compressional front takes place at 08:21 CT.

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