BepiColombo SHOTS Project: A Comparative Study of Mercury's Magnetosphere Using MHD and Hybrid Particle Simulations

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After the successful launch of MIO and MPO in 2018, we now need to prepare for the measurement of Mercury’s environment. The MESSENGER mission provided us many outstanding scientific findings on Mercury’s environment. However, the scientific knowledge obtained on Mercury’s magnetosphere is still incomplete. It is because not only of the limited specifications of science instruments but also of dynamic variation of the magnetosphere which is approximately 1/20 smaller than that of Earth. As a result, many scientific issues remain unsolved on the physics in Mercury’s magnetosphere. To achieve the holistic understanding of Mercury’s magnetosphere, the success of the BepiColombo (BC) mission is essential.

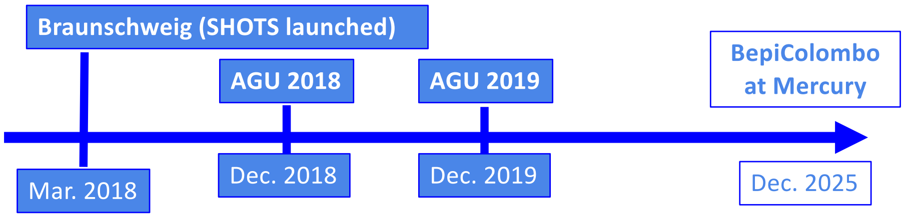
Previously, numerical simulations using hybrid particle and MHD models have been performed and compared with the MESSENGER data. However, the comparison was made on a case study basis. Thus, the comprehensive understanding of Mercury's magnetosphere hasn't been attained yet. Contrary to MESSENGER, the BC satellites will provide us a large number of measurement data along north-south symmetric orbits. This implies that we will be able to investigate more details of plasma dynamics in Mercury's magnetosphere. To obtain the maximum understanding of the measurement data, the collaboration with numerical simulations is inevitable.

Toward the mission’s success, it is extremely important that we need to increase the number of young scientists who get interested in Mercury’s physics and participate in the BC mission. In the cruising phase when no measurement on Mercury’s magnetosphere is conducted, numerical simulation is essential for the study of Mercury’s magnetosphere. In this situation, we should encourage young scientists, who will be the next leading players in the mission, to participate in the mission and start plasma simulations for Mercury's mission and beyond.

Some members of Young Scientists WG (YSWG) in the BC project started an international simulation collaboration called SHOTS (Studies on Hermean magnetosphere Oriented Theories and Simulations). It aims to figure out which model is more suitable to describe particular environments or physical processes in Mercury’s magnetosphere, and how and where the kinetic effect has significant influence. SHOTS has been very actively working, and the members are currently writing a collaboration paper on the comparison of Mercury’s magnetosphere with different simulation models. In the present paper, as the first step of the SHOTS activities, we examined the formation of Mercury’s magnetosphere in terms of the locations of magnetopause and bow shock by performing numerical simulations with different models such as MHD and hybrid particle. We used academic parameters (purely north/south IMF) to highlight the main capabilities of each simulation code.

What is SHOTS?

Studies on Hermean magnetosphere Oriented Theories and Simulations



Active members in 2019 (alphabetical order)

Name	Institute
Sae Aizawa	IRAP/Tohoku Univ.
Jorge Amaya	KU Leuven
Nicolas André	IRAP
Jan Deca	LASP
Willi Exner	TU-Braunschweig
Shahab Fatemi	IRF
Léa Griton	IRAP
Daniel Heyner	TU-Braunschweig
Go Murakami	ISAS/JAXA
Hideyuki Usui	Kobe Univ.
Manabu Yagi	RIKEN

+ support members

Simulation codes used within the SHOTS project

Fluid description

Scale

Particle description

MHD

- **MPI-AMRVAC, Spherical grid**
- **YAGI's CODE, Cartesian grid**

Hybrid

- **AIKEF, Adaptive Cartesian grid**
- **AMITIS, GPU, Cartesian grid**
- **LatHyS, Cartesian grid**

Particle-In-Cell (PIC)

- **EMSES, Explicit, Cartesian grid**
- **ECsim, Semi-implicit, Cartesian grid**
- **iPIC3D, Semi-implicit, Cartesian grid**

Ion ・ Electron : One fluid
Describing a large structure

Ion kinetics

Ion: Particle, Electron : Fluid
Reconnection, Exosphere

Electron kinetics

Ion ・ Electron : Particle
Micro-scale physics

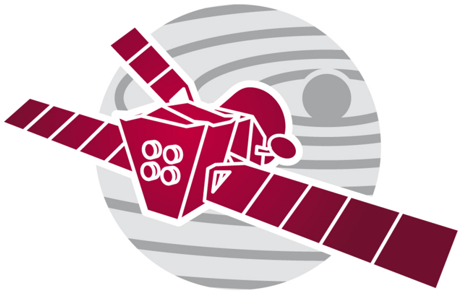
+ local codes

Our objective – being ready for the BepiColombo observations!

- Structure of magnetosphere
- Highly dynamic physical processes
- Dawn-dusk asymmetry

Simulation
(MHD, Hybrid, PIC, Test particle)

- **Which model is more suitable to describe particular environments or physical processes?**
- **How and where do the kinetic effect have significant influence?**
- **Can we connect global and local simulations?**

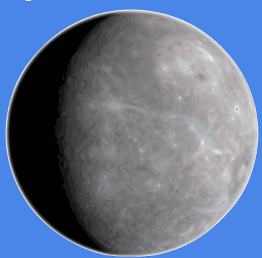


- Virtual data along the MIO path (Help for measurement requirements)
- Catalog of simulations for different sets of SW parameters
- Develop the tools

A comparative study of Mercury's Magnetosphere

We started with academic parameters (purely north/south IMF) to highlight the main capabilities of each code

Input Parameters – Purely North/Southward IMF

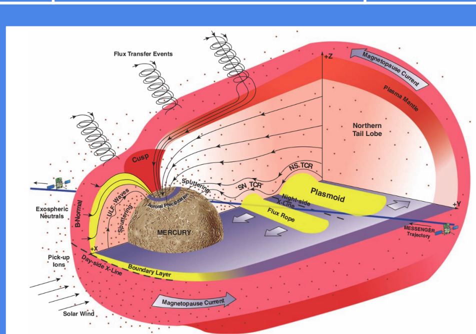


Mercury

Radius of Mercury (R_M)	2440 [km]	Dipole offset	$0.2R_M$
Resistivity of Mantle	$1.2\times10^{+7}$ [Ω · m]	Exosphere	None
Core Size	$0.80R_M$	Minimum grid Resolution	85 [km]
Dipole Moment	200 [nT-R_M^3]	Minimum Timestep	0.001 [s]

Solar wind

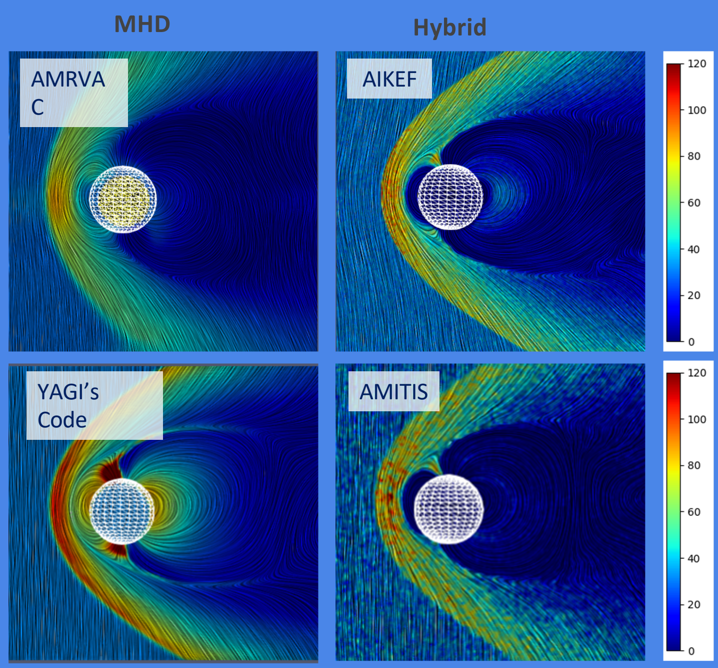
Plasma density	30 [cm^{-3}]	Plasma velocity	400 [km/s]
Temperature	0.25 [MK]	IMF magnitude	20 [nT]
Plasma beta	0.6	**IMF direction**	**+/- Z**
Alfvèn Mach	5	Sonic Mach	4.8



Southward IMF condition [Slavin et al., 2009]

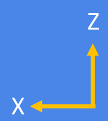
A comparative study of Mercury's Magnetosphere

Current pictures – Northward IMF



All data are in the same
- format (netCDF)
- visualization tool (here Paraview)

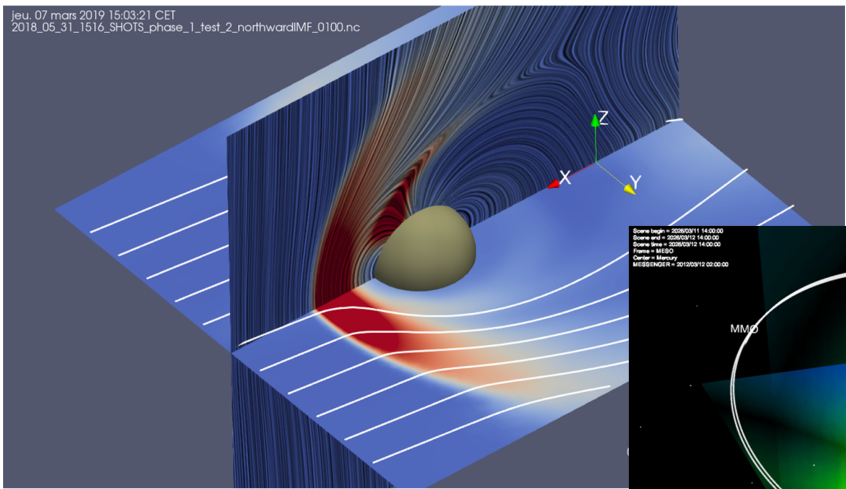
Quick Look
- Density in the magnetosheath/nightside
- Diffusive cusp in MHD, clear cusp in hybrid
- Sharpness of bowshock



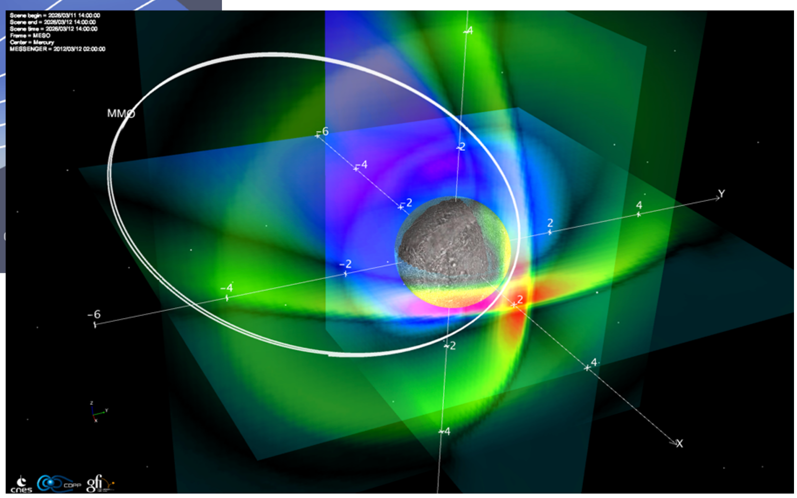
Color : Plasma density

Common visualization tools

ParaView
Parallel Visualization Application



3DView



General conclusions

1. Simulated magnetospheres are **extremely sensitive to the boundary conditions** at the planet's surface. The reason is the weak planetary field which allows for the magnetopause to approach the surface to within less than one planetary radius (not the case for the Earth or giant planets).

2. Comparison of codes allows to observe how a given physical model (hybrid or MHD), boundary condition or integration scheme participates in shaping the magnetosphere. Confrontation with the expected detailed in situ measurements from BepiColombo (including plasma density and temperature measurements!) will much more easily allow to identify the relevant physical mechanisms at work.

3. Simulation of planetary magnetospheres rest on a large number of assumptions and approximation and should always be considered with caution. Rigorous confrontation with real data is the only means to validate/invalidate the adopted assumptions and approximations.