Global Simulations of Mercury's Magnetospheric Interaction under Extreme Solar Wind Conditions

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Introduction

❖ At Mercury, the shielding effect arising from the induction currents in the planetary core and erosion of the dayside magnetosphere by magnetopause reconnection compete against each other for dominance in controlling the global structure of the magnetosphere.

❖ We have developed a global MHD model for Mercury that electromagnetically couples the planet's interior to the surrounding space environment, allowing us to self-consistently characterize Mercury's dynamical response to time-varying external conditions (*Jia et al.*, 2015, 2019).

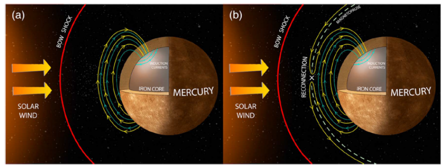

Figure 1*. Schematic illustration from Slavin et al. (2014) showing (a) the induction effect arising from the Mercury's conducting core and (b) erosion of the dayside magnetosphere due to reconnection.*

❖ **In this work, we combine analysis of MESSENGER observations during extreme solar wind events with global MHD simulations to assess the relative importance of the two processes.**

MESSENGER Observations

❖ We have examined all MESSENGER crossings of Mercury's dayside magnetopause and identified events in which Mercury's magnetosphere was impacted by extreme solar wind forcing, *i.e.*, high speed streams or CMEs. These events are categorized into two groups and analyzed in detail in two companion studies:

- ➢ **Highly Compressed Magnetosphere (HCM) events** – ***Jia et al.* (2019)**
- ➢ **Disappearing Dayside Magnetosphere (DDM) events** – ***Slavin et al.* (2019)**

❖ Crossing of the dayside magnetopause allows determination of the location of the magnetopause and measurements of the plasma and field conditions adjacent to the boundary.

❖ Magnetopause reconnection rate is estimated based on the magnetic field component normal to the magnetopause determined from minimum variance analysis.

❖ **Magnetopause location *vs.* solar wind pressure for all HCM events investigated is shown in Figure 6.**

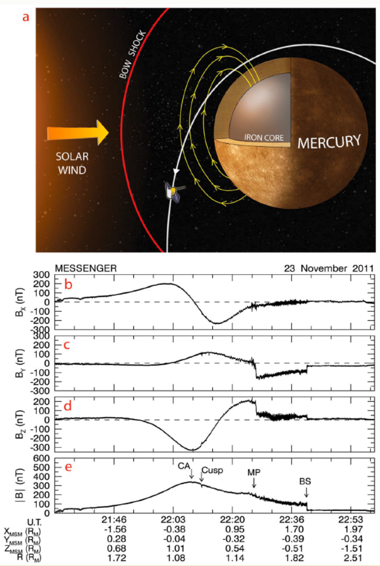

Figure 2*. (a) MESSENGER orbit superimposed onto a schematic view of Mercury's interior and magnetosphere shown in the noon-midnight meridional plane. (b-e) Magnetic field data taken by MESSENGER during the extreme event caused by the passage of a CME on November 23, 2011. Figure from Slavin et al. (2014).*

References

- Jia, X., et al. (2015), Global MHD simulations of Mercury's magnetosphere with coupled planetary interior: Induction effect of the planetary conducting core on the global interaction, *Journal of Geophysical Research – Space Physics*, doi: 10.1002/2015JA021143.
- Jia, X., et al. (2019), MESSENGER observations and global simulations of highly compressed magnetosphere events at Mercury, *Journal of Geophysical Research – Space Physics*, doi:10.1029/2018JA026166
- Slavin, J. A., et al. (2014), MESSENGER observations of Mercury's dayside magnetosphere under extreme solar wind conditions, *Journal of Geophysical Research – Space Physics*, doi: 10.1002/2014JA020319.
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Time-dependent Simulations of Extreme Events

(1) Global MHD Model with Coupled Planetary Interior

❖ Developed a global MHD model that couples the magnetosphere with the planetary interior, allowing us to **self-consistently model the induction effect of the planet's conducting core (*Jia et al.*, 2015).**

- ➢ Use the resistive-MHD version of BATSRUS and extend the simulation domain into the planetary interior following the approach developed for Jupiter's moons, Io and Ganymede (*Jia et al.*, 2008, 2009 & 2010).
- ➢ Electrical conductivities of the different interior layers are specified based on geophysical measurements.

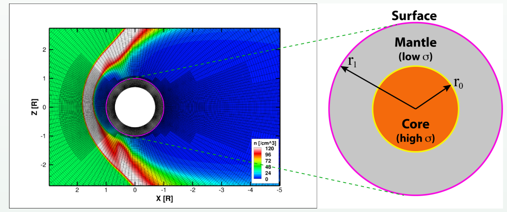

Figure 3*. (Left) High-res, non-uniform spherical mesh used in the Mercury simulations (viewed in the noon-midnight meridian). (Right) A schematic showing the interior model consisting of two layers: insulating mantle + conducting core*

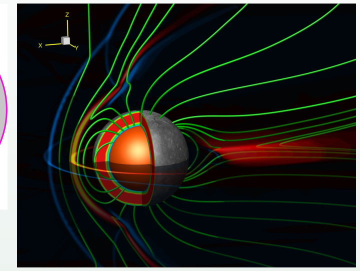

Figure 4*. 3D view of modeled Mercury's interaction system including the magnetosphere and the planetary interior that contains a highly conducting core. Colors in the equatorial and meridional magnetosphere show the current density (Jy), while colors in the interior show the distribution of resistivity used in the model. Figure from Jia et al. (2015).*

(2) Simulation of the Nov. 23, 2011 Event

❖ Simulate Mercury's time-dependent response to the CME impact with induction included using MESSENGER observations as input (*Jia et al.*, 2019).

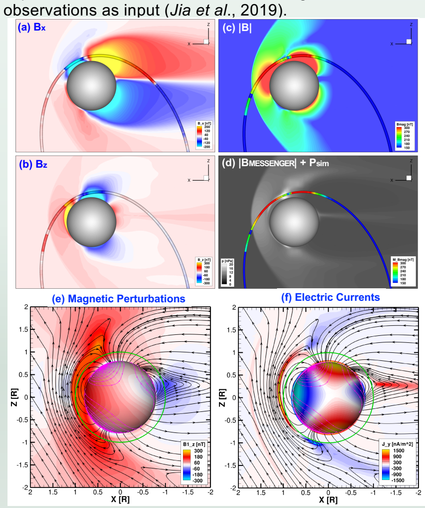

Figure 5*. (a-d) Comparison of simulation with MESSENGER magnetic field data. Colors along the s/c trajectory show measurements, while the colors in the XZ plane show model results. (e-f) Close-up views of the magnetospheric current systems including the induction currents at the core and resultant magnetic perturbations.*

(3) Controlled Simulations of Different Pressure Conditions

❖ Conduct a series of simulations for different solar wind pressure conditions representative of those observed by MESSENGER during extreme events. For each pressure condition, we simulate four different scenarios: **1) High-shear IMF, 2) Low-shear IMF, 3) No IMF, and 4) High-shear IMF without induction.**

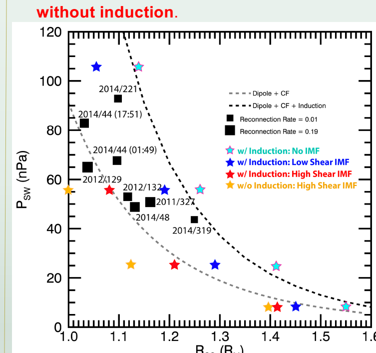

Figure 6*. Subsolar magnetopause distance vs. solar wind pressure. Black squares are from MESSENGER observations of HCM events. The size of the squares indicates the inferred reconnection rate. Color stars are results from our controlled simulations. The grey dashed curve shows the expected dependence when only the internal dipole and the magnetopause currents are considered. The black dashed curve shows a theoretical prediction when induction is included. From Jia et al. (2019).*

❖ The observed MP location during events with high reconnection rate varies roughly as $P_{dyn}^{-1/6}$.

❖ Events with low reconnection rate follow a power-law relationship with steeper slope, more aligned with the prediction that includes induction but no reconnection.

❖ Similar behavior is found in our simulations, demonstrating that during extreme pressure events, the erosion effect due to intense reconnection tends to negate the shielding effect from induction.

Summary

❖ **The 8 highly compressed magnetosphere (HCM) events identified from MESSENGER data represent the highest solar wind dynamic pressures for which MESSENGER's orbit still passed below the magnetopause and provided measurements of the dayside magnetosphere.**

❖ **For solar wind pressures of ~ 40 - 90 nPa, the shielding effects of induction in Mercury's core in standing-off the solar wind typically exceed the erosion of the dayside magnetosphere due to reconnection.**

❖ **For high magnetic shear across the magnetopause our simulation predicts that reconnection would dominate, which is consistent with the observations obtained during the DDM events reported by *Slavin et al.* (2019).**