Global Ten-Moment Multifluid Simulations of the Solar Wind Interaction with Mercury: From the Planetary Conducting Core to the Dynamic Magnetosphere

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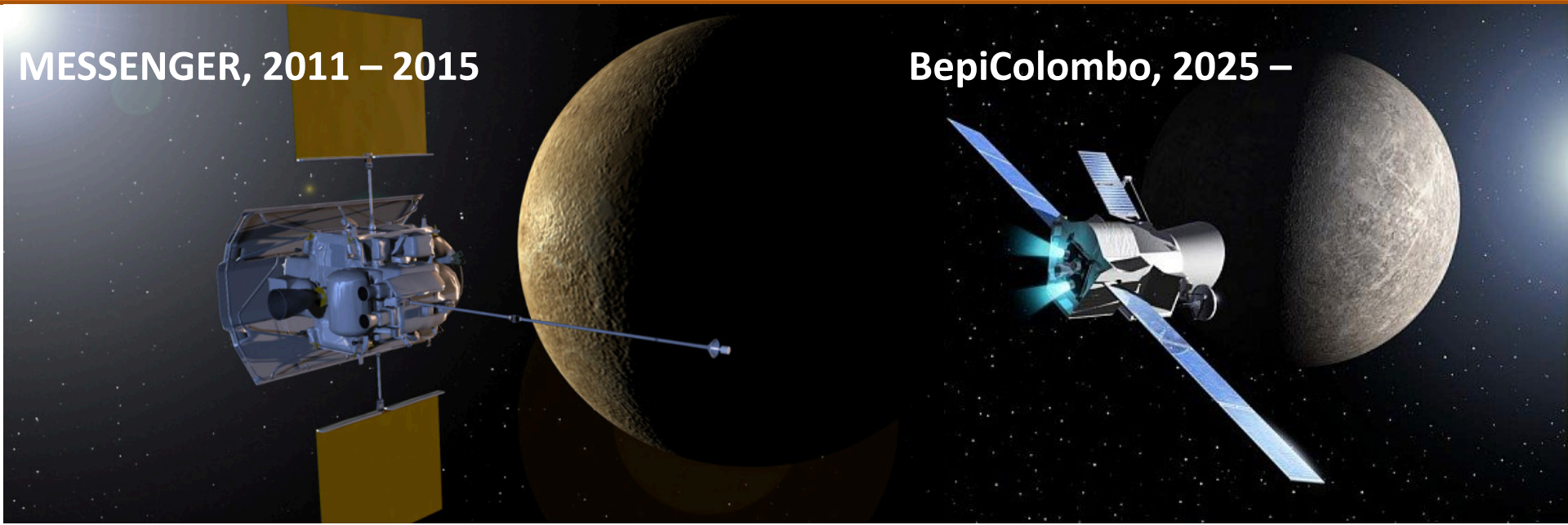
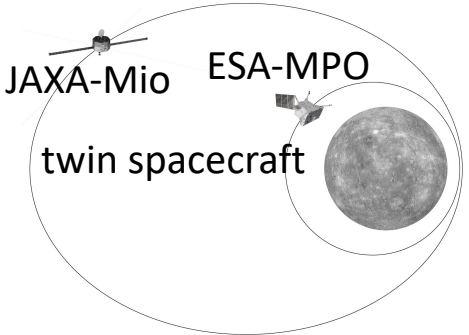
MESSENGER and BepiColombo at Mercury



BepiColombo is a joint mission of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to the planet Mercury. It was launched on 20 October 2018 and will arrive at Mercury in late 2025.

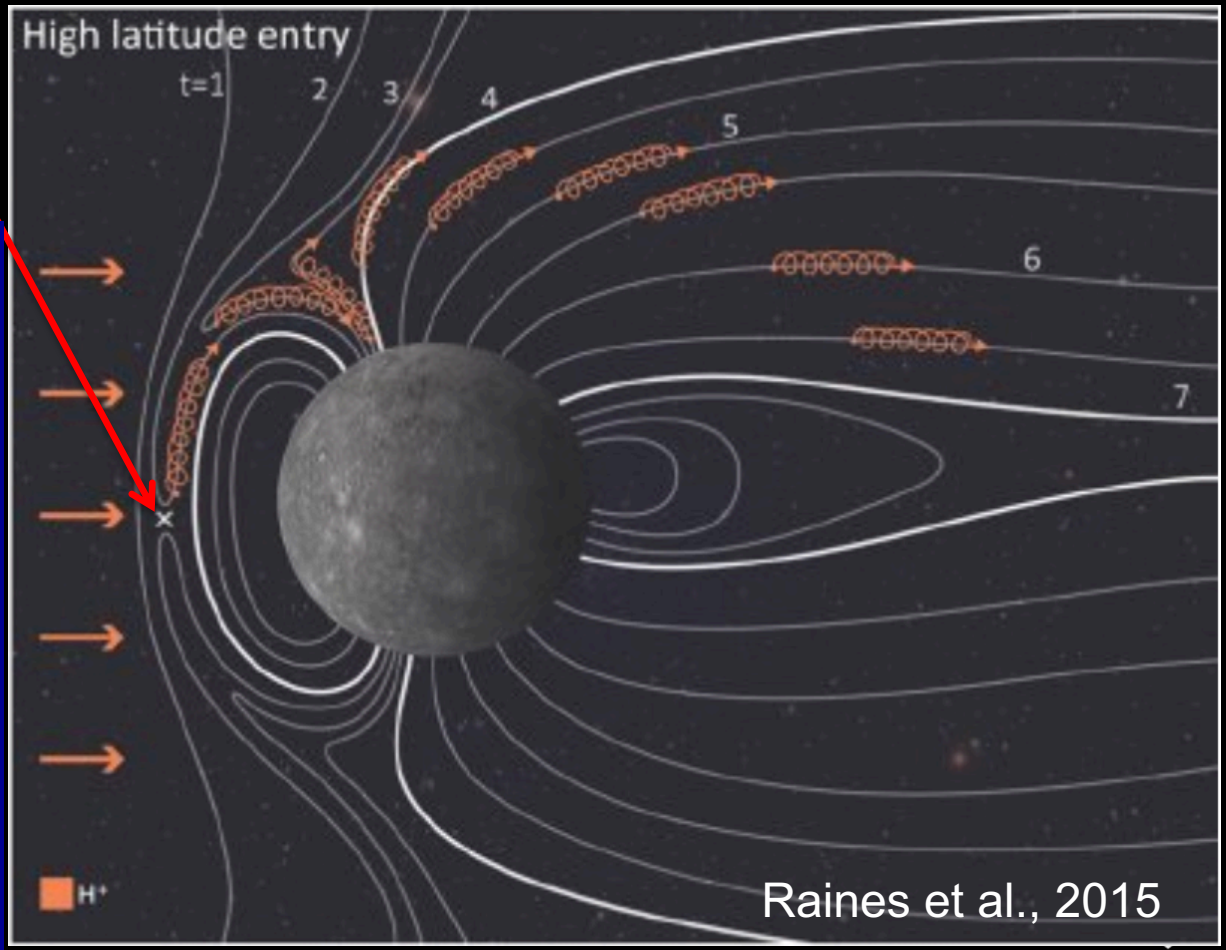


Why Develop a New Model?

Magnetic Reconnection and Solar Wind Plasma Entry in Mercury's Magnetosphere

***Improve kinetic (e.g., collisionless magnetic reconnection) physics in global magnetosphere codes.**

***Note that MHD and hybrid codes cannot capture the collisionless reconnection physics.**



Our Approach to Capture the Collisionless Magnetic Reconnection: Ten-Moment Multifluid Model

- Solve 10-moment equations for *all* electron and ion groups

$$\text{one density eqn: } \frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{v}_s) = 0$$

$$\text{three momentum eqns: } m_s \frac{\partial (n_s \mathbf{v}_s)}{\partial t} + \nabla \cdot \mathcal{P}_s = n_s q_s (\mathbf{E} + \mathbf{v}_s \times \mathbf{B})$$

$$\text{six pressure tensor eqns: } \frac{\partial \mathcal{P}_{ij}}{\partial t} + \frac{\partial \mathcal{Q}_{ijk}}{\partial x_k} = nq v_{[i} E_{j]} + \frac{q}{m} \epsilon_{[ikl} \mathcal{P}_{kj]} B_l$$

plus *full* Maxwell equations $c^2 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J} = \nabla \times \mathbf{B}$, $\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$

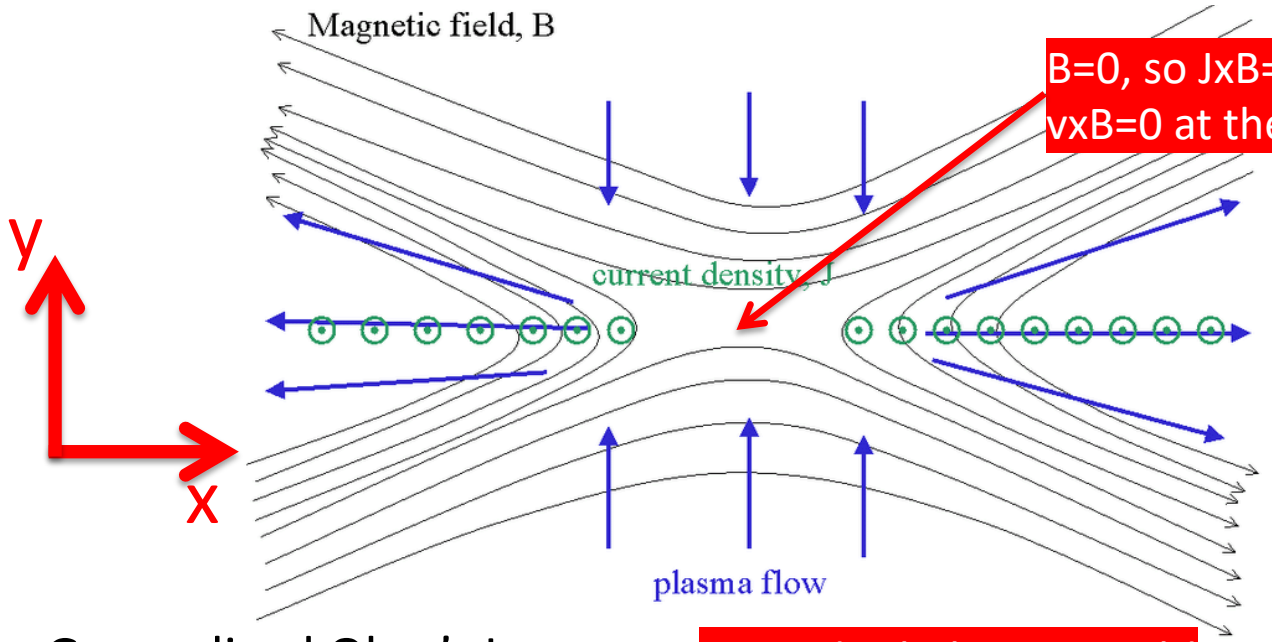
- Closure to approximate heat-flux

$$\partial_m Q_{ijm} = v_t \, |k_0| \, (P_{ij} - p \delta_{ij})$$

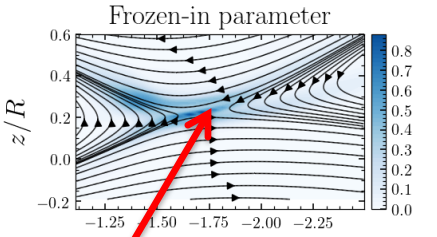
  - For magnetic reconnection, a reasonable choice is $k_{s0} = 1/d_{s0}$

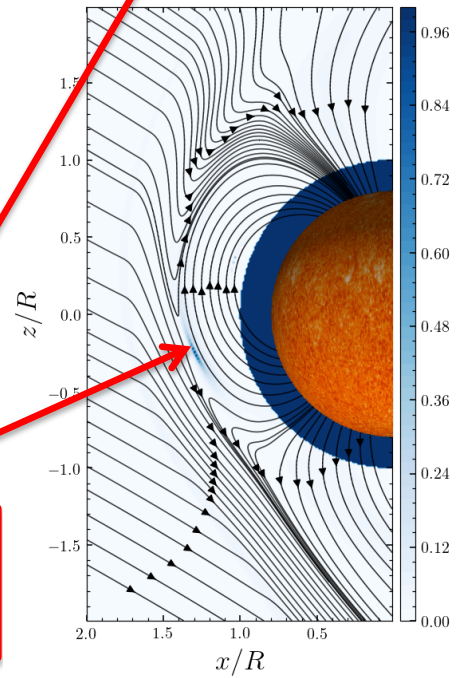
Why Need Electron Pressure Tensor?

$$E_z = -(\partial_x P_{xz,e} + \partial_y P_{yz,e})/n_e|e|$$



B=0, so JxB=0 and vxB=0 at the X-point



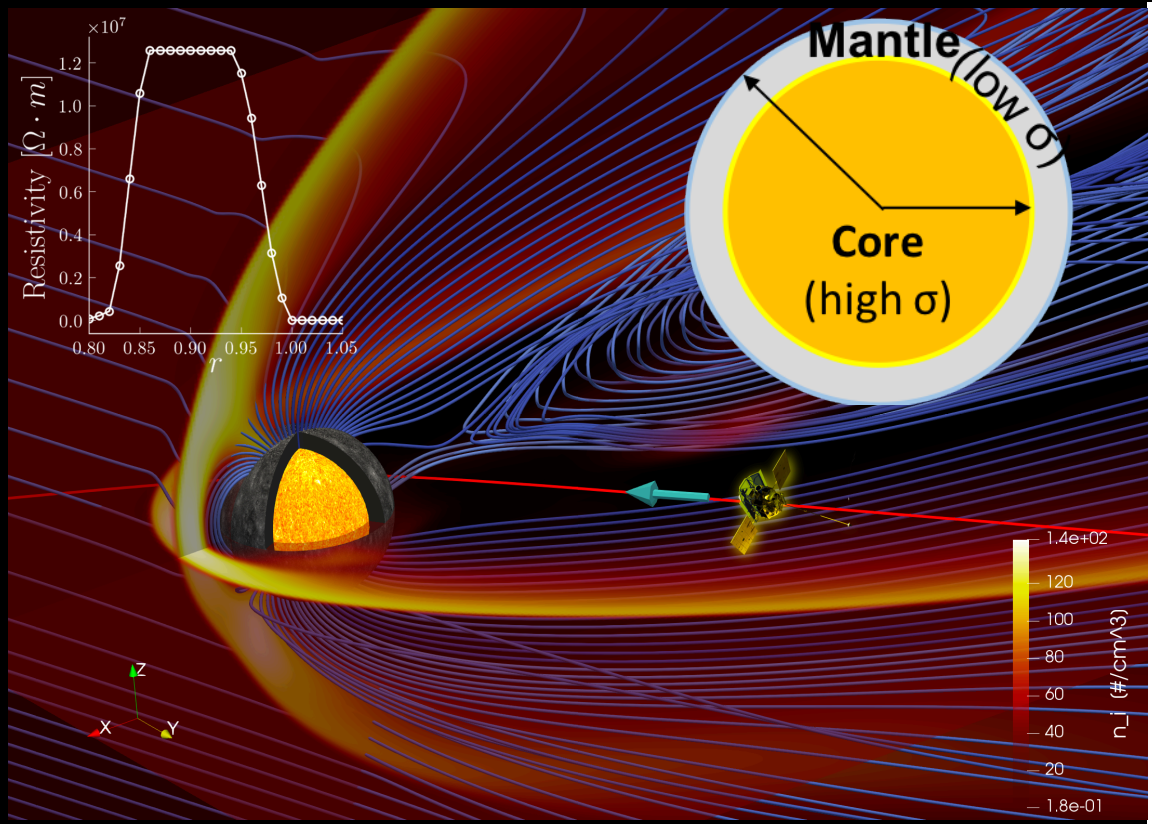


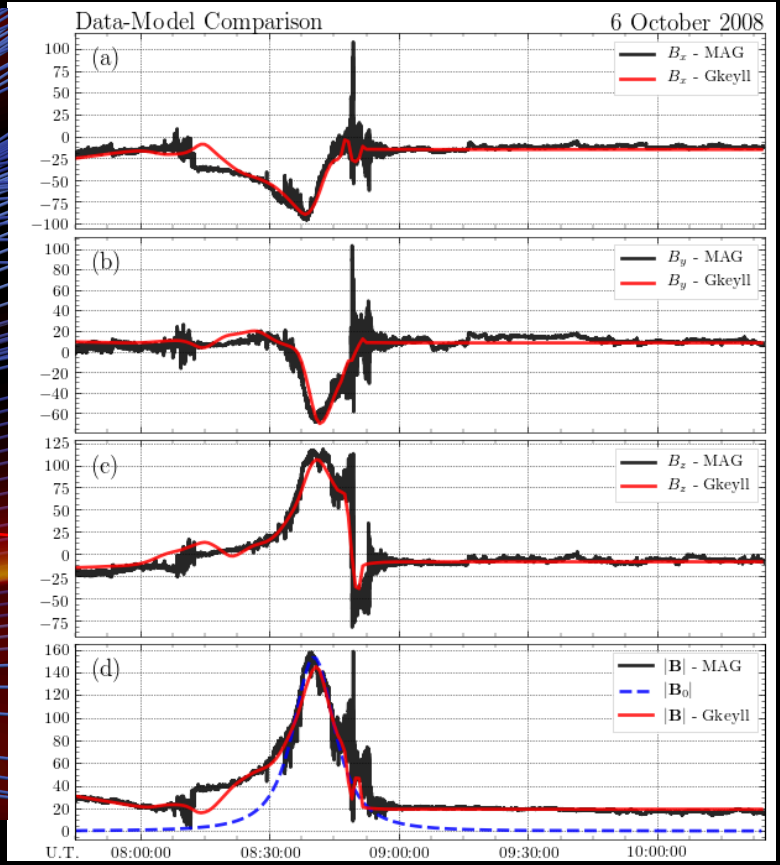
Generalized Ohm's Law

Non-ideal Electric Field

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \underbrace{\eta \mathbf{J}}_{0} + \frac{\mathbf{J} \times \mathbf{B}}{n|e|} - \frac{\nabla \cdot \mathbf{P}_e}{n|e|} + \frac{m_e}{n|e|^2}\left[\frac{\partial \mathbf{J}}{\partial t} + \nabla \cdot \left(\mathbf{vJ} + \mathbf{Jv} - \frac{\mathbf{JJ}}{n|e|}\right)\right]$$

Ten-Moment Multifluid Simulation of Mercury's Magnetosphere

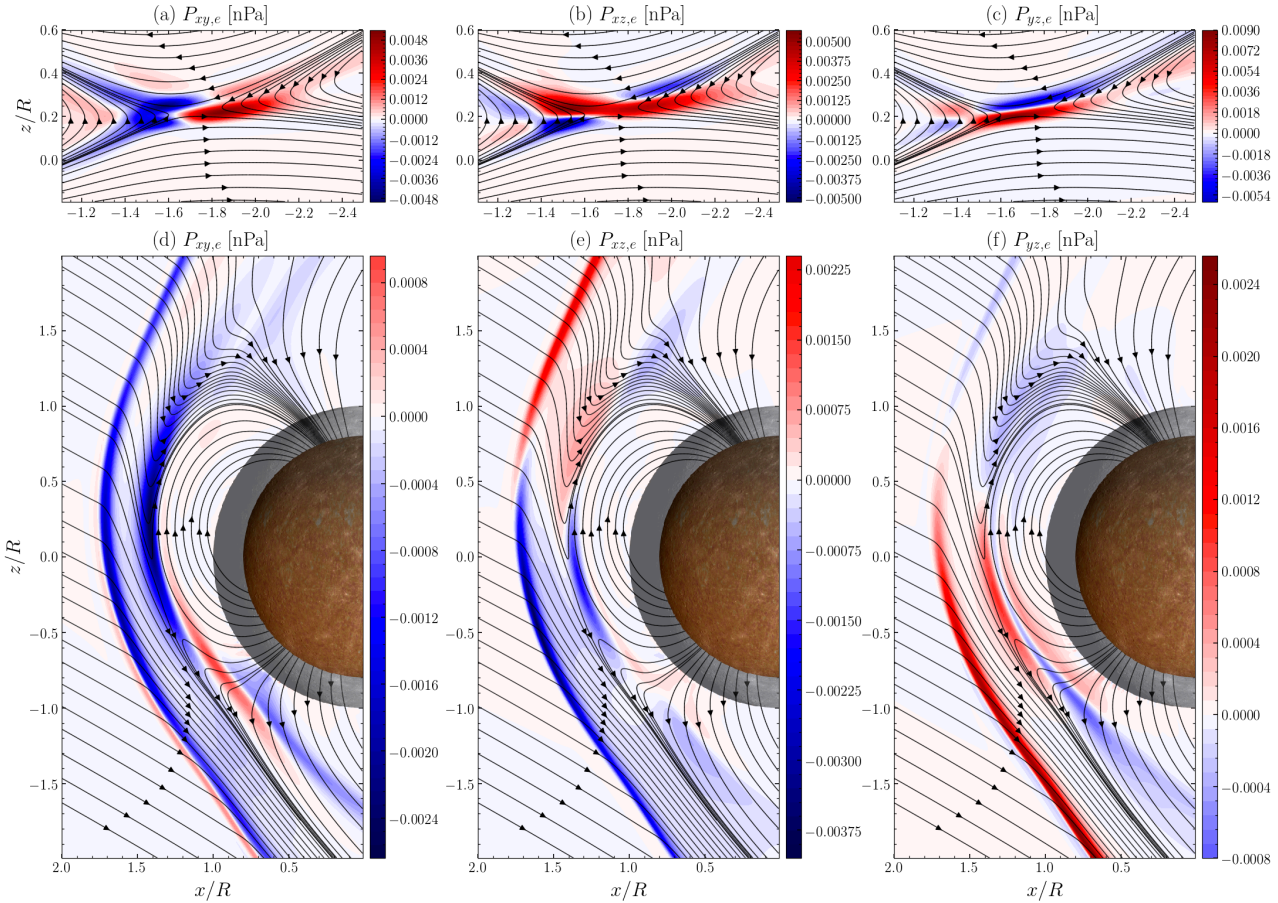




Smallest resolution: dx=dy=dz=0.01R_M!

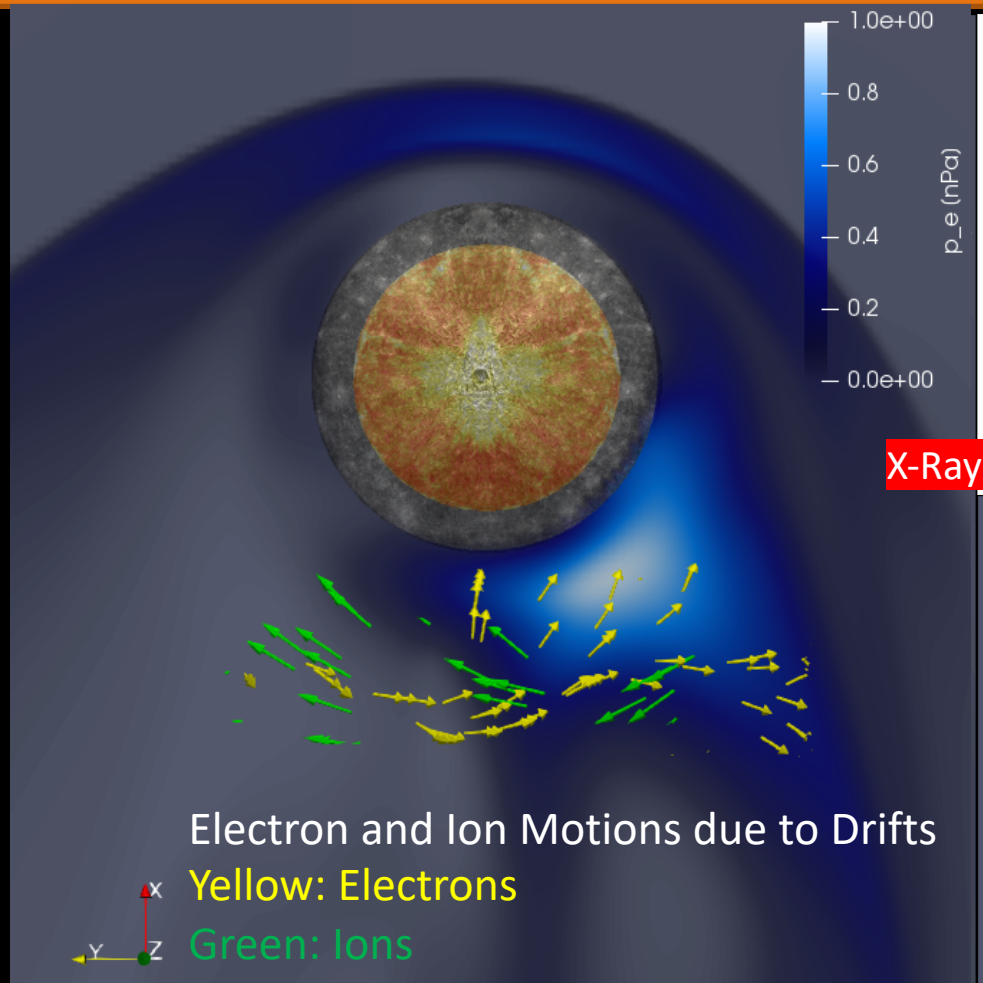
Dong et al., 2019, GRL

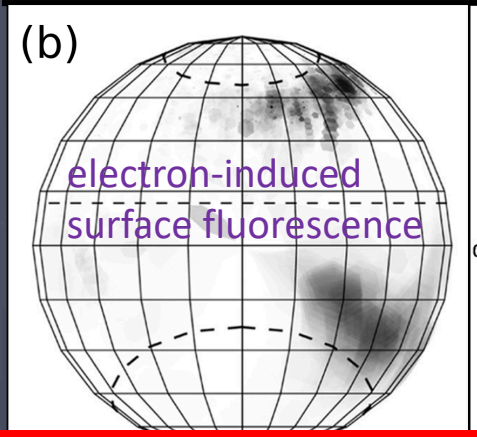
Electron Pressure Tensor at Dayside and Nightside Reconnection Sites



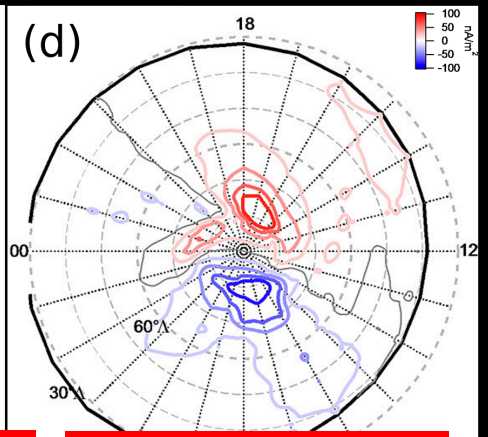
Dong et al., 2019, GRL

Asymmetry in Mercury's Magnetotail

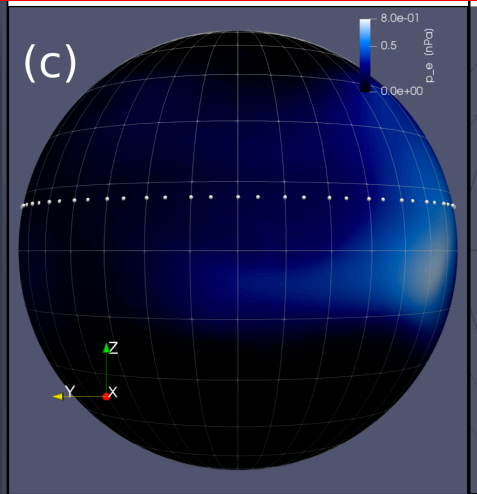


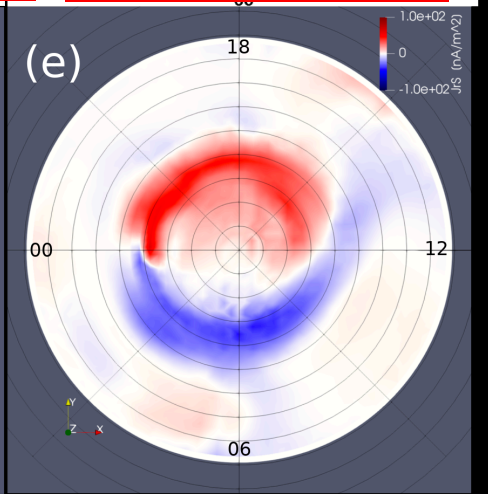


X-Ray Spectrometer Observations

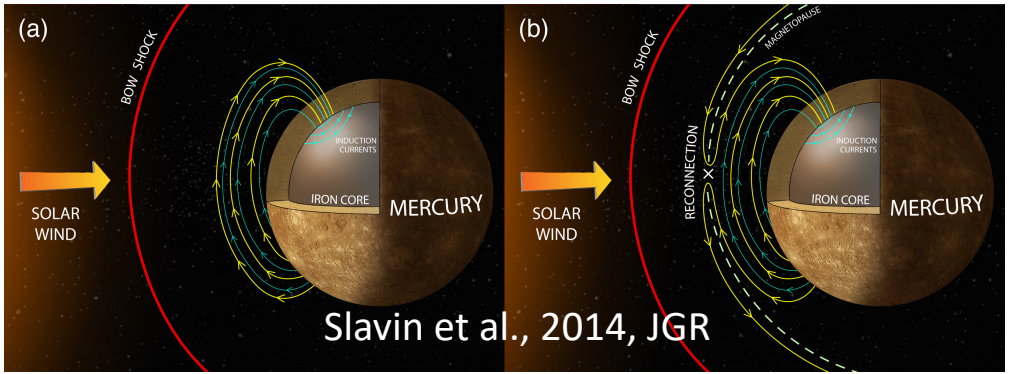


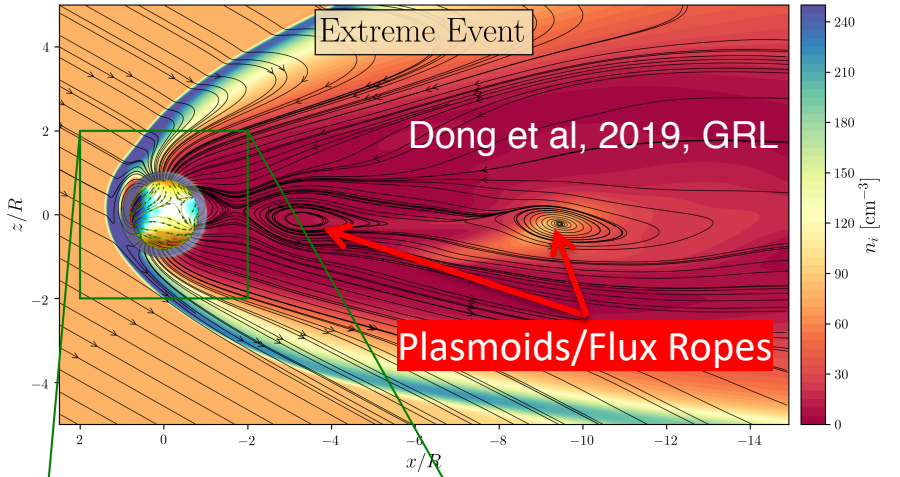
Field-Aligned Currents

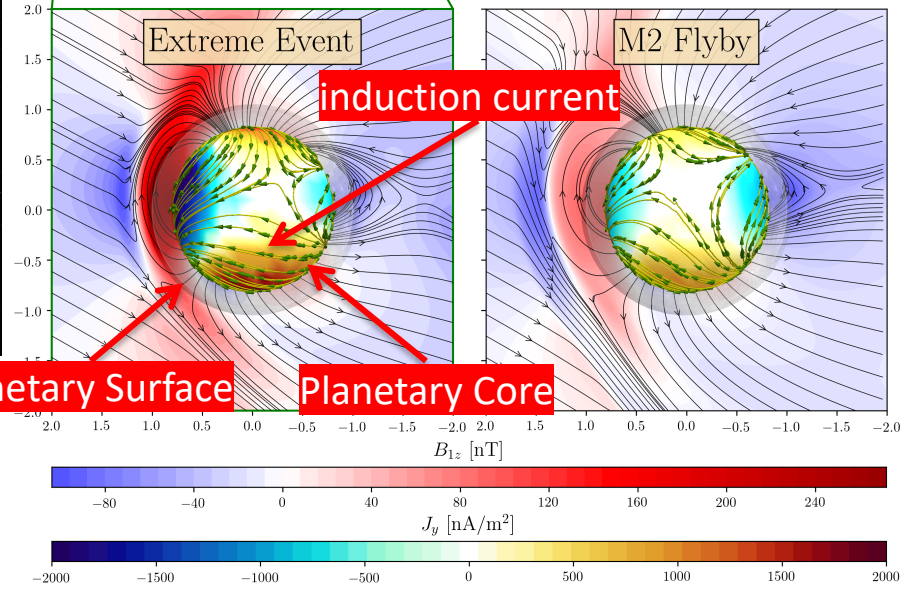




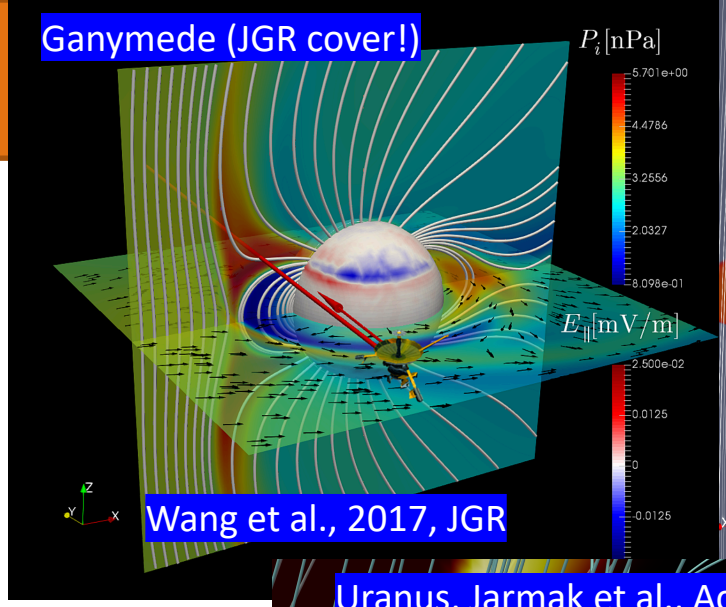
Mercury's Responses to an Extreme Event and Plasmoid Formation in Mercury's Magnetotail

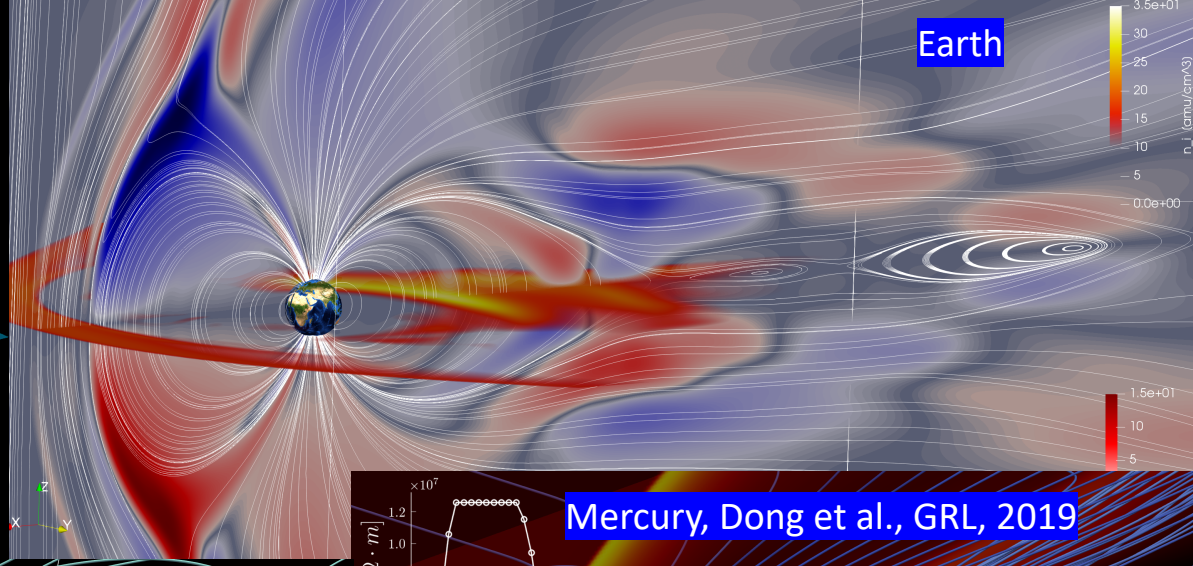


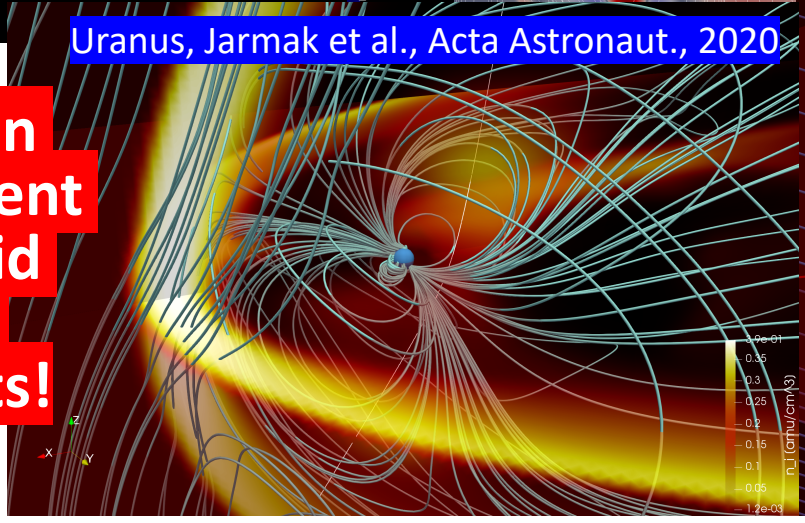


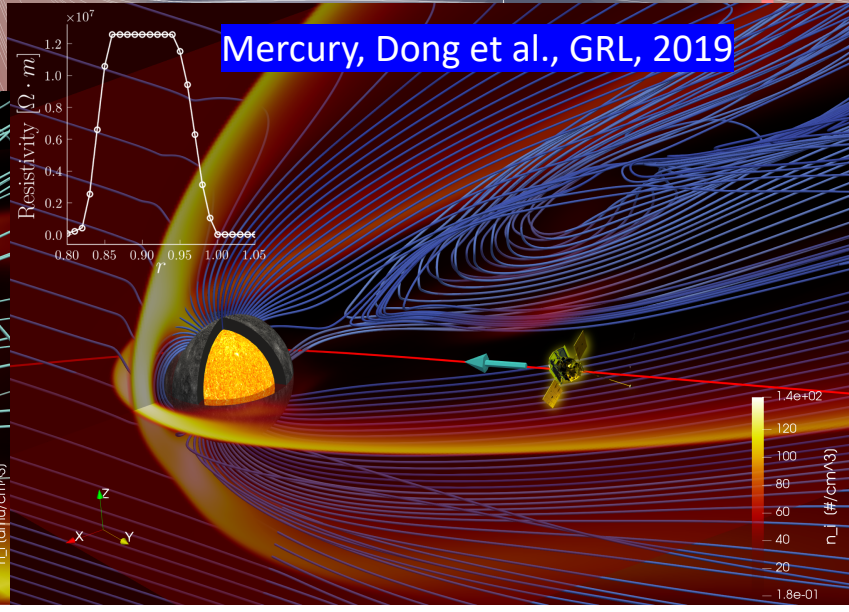


The induction response arising from the electromagnetically-coupled interior plays an important role in solar wind-Mercury interaction.









Princeton Ten-Moment Multifluid Model Highlights!