Ten-Moment Multifluid Modeling of the Dynamic Magnetospheres of Mercury, Earth, Uranus and Ganymede

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Outline

- Motivation
- Model Description
- Magnetized Plasma Flow Interaction with Mercury, Earth, Uranus and Ganymede
- Conclusions and Future Work

Motivation: Improving Kinetic (e.g., Reconnection) Physics in Global Magnetosphere Codes

Desirable non-ideal physics	Solutions/progresses
kinetic physics, particularly pressure tensor	full PIC/Vlasov, Hybrid (ion kinetics), MHD-EPIC
efficient Hall term	implicit Hall term
multi-ions	multi-fluid MHD

Our Approach: Multi-Moment Multifluid Model

- Solve identical moment equations for ***both*** electron and ion

$$\frac{\partial (m_s n_s)}{\partial t} + \frac{\partial (m_s n_s u_{i,s})}{\partial x_i} = 0,$$

$$\frac{\partial (m_s n_s u_{i,s})}{\partial t} + \frac{\partial \mathcal{P}_{ij,s}}{\partial x_j} = n_s q_s \left(E_i + \epsilon_{ijk} u_{j,s} B_k\right),$$

plus ***full*** Maxwell equations

$$\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{J}, \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},$$

- Conceptually like a fluid version of Particle-in-Cell, truncated at a certain order of moment, e.g., 2nd order moment, the pressure.
- No need to directly compute Ohm's law for E.
- Δt restrained by CFL condition from *speed of light*, usually not a severe constraint.

Truncation at 2nd Order Moment: A 10-Moment Model

- Evolution equation for full pressure tensor

$$\frac{\partial \mathcal{P}_{ij,s}}{\partial t} + \frac{\partial \mathcal{Q}_{ijk,s}}{\partial x_k} = n_s q_s u_{[i,s} E_{j]} + \frac{q_s}{m_s} \epsilon_{[ikl} \mathcal{P}_{kj,s]} B_l$$

where

$$\begin{aligned} \mathcal{P}_{ij} &= m \int f v_i v_j d\mathbf{v} \\ &= m \int f (v_i - u_i)(v_j - u_j) d\mathbf{v} + n m u_i \\ &= P_{ij} + n m u_i u_j . \end{aligned}$$

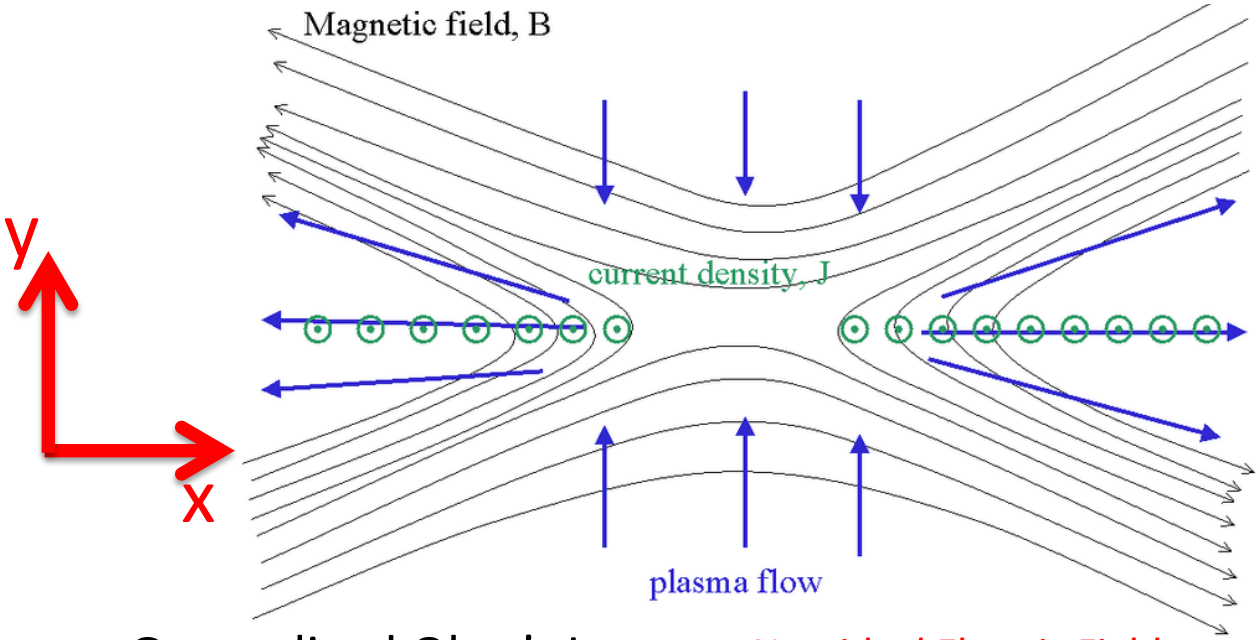
$$\begin{aligned} \mathcal{Q}_{ijk} &= m \int f v_i v_j v_k d\mathbf{v} \\ &= m \int f (v_i - u_i)(v_j - u_j)(v_k - u_k) d\mathbf{v} + u_{[i} \mathcal{P}_{jk]} - 2 n m u_i u_j u_k \\ &= Q_{ijk} + u_{[i} \mathcal{P}_{jk]} - 2 n m u_i u_j u_k \end{aligned}$$

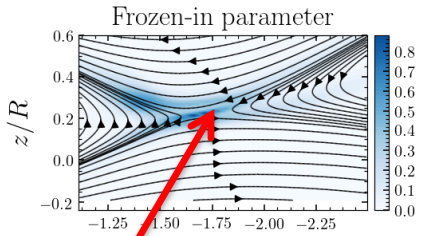
- "10-moment" refers to 10 moment equations for each species.
- Simplified fluid closure (Wang et al., 2015) to approximate the Landau-fluid closure by Hammett and Perkins (1990):

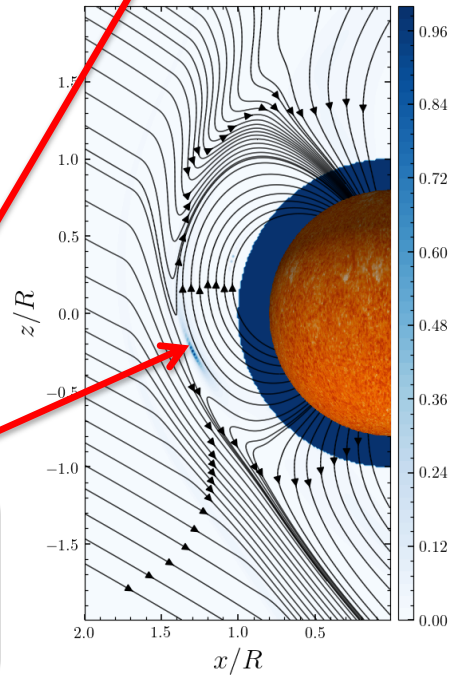
$$\partial_m Q_{ijm} \approx v_t |k| (P_{ij} - p \delta_{ij})$$

Why need the electron pressure tensor?

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







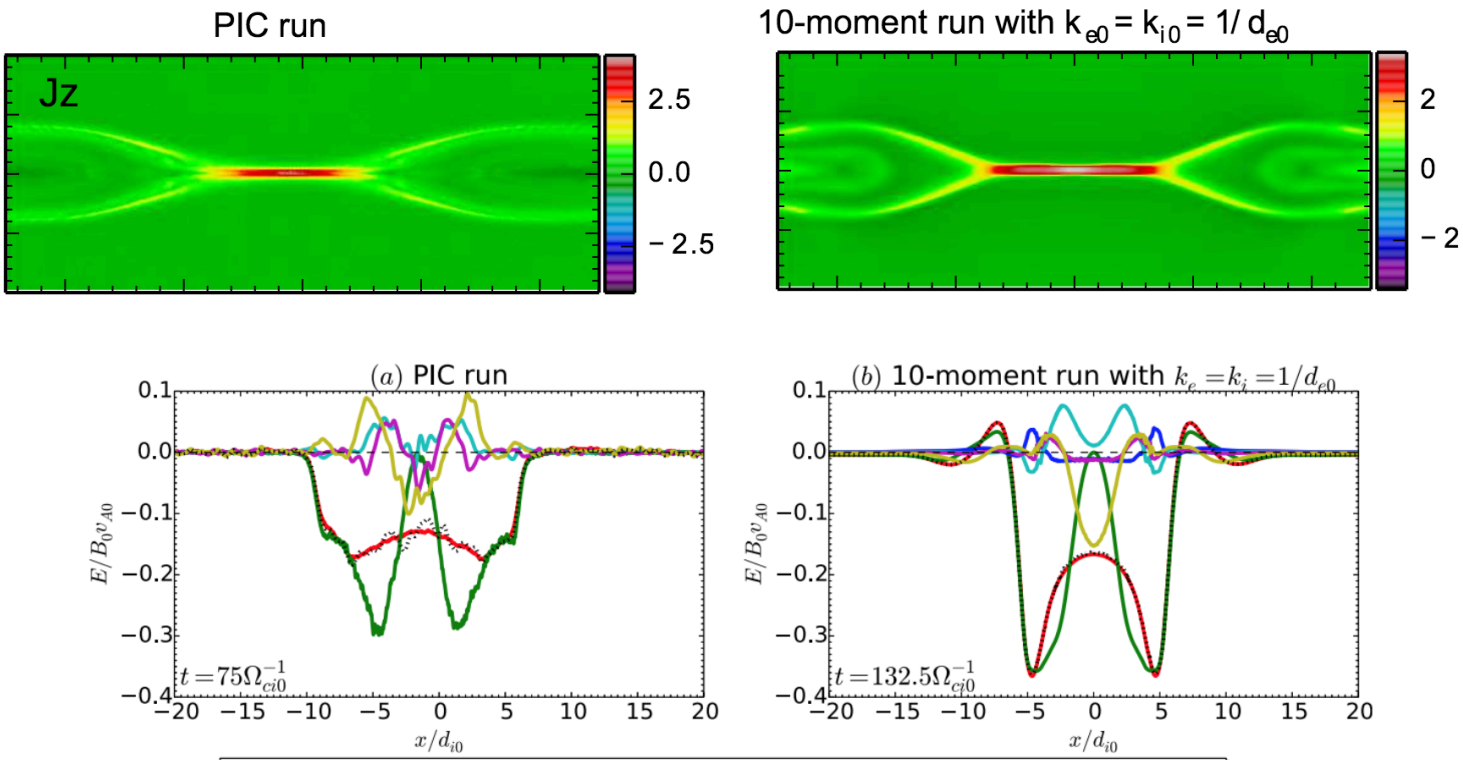
Generalized Ohm's Law

Non-ideal Electric Field

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

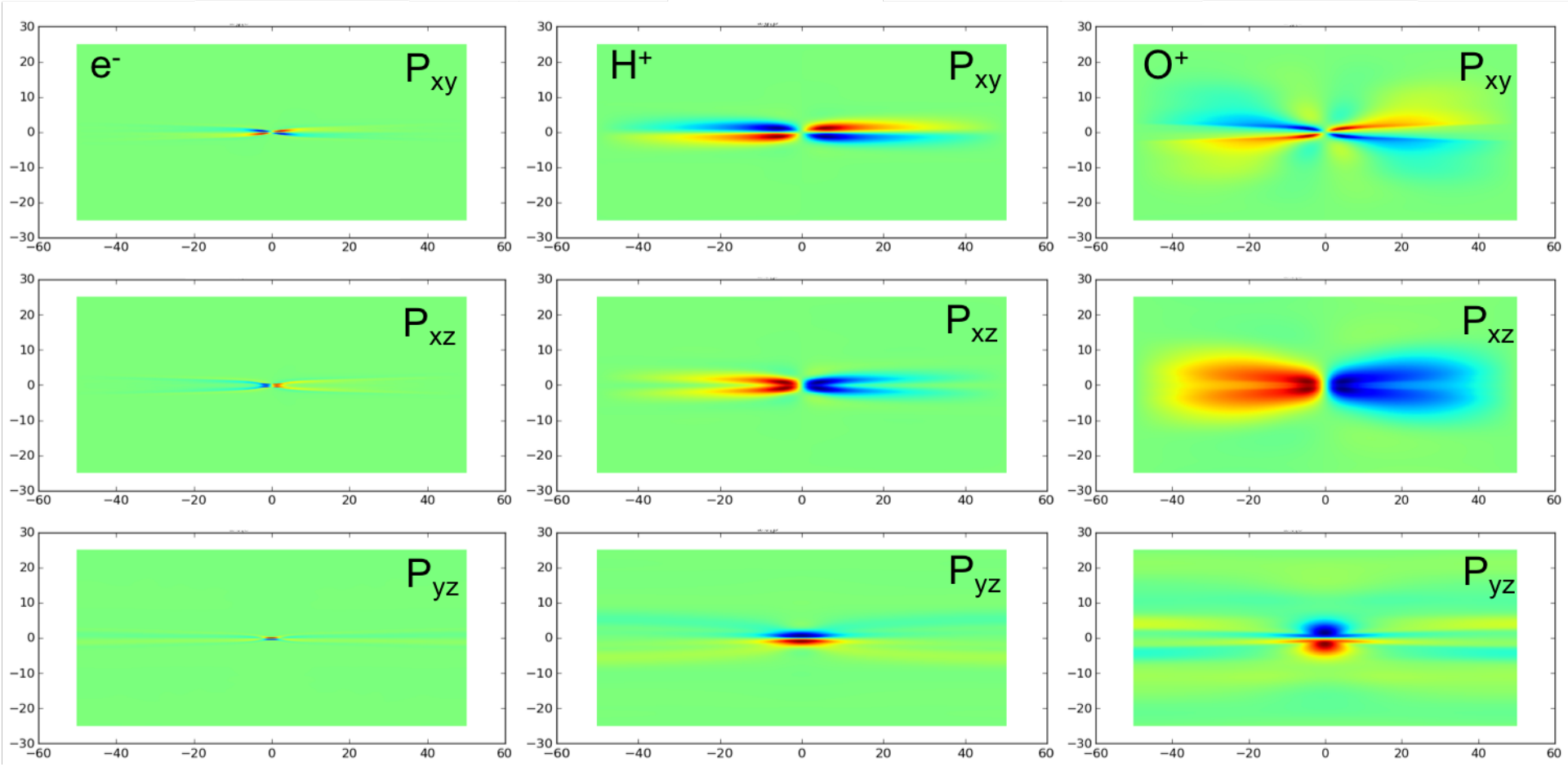
2D Anti-Parallel Reconnection Comparisons

10-moment two-fluid simulation captures key features in PIC simulation

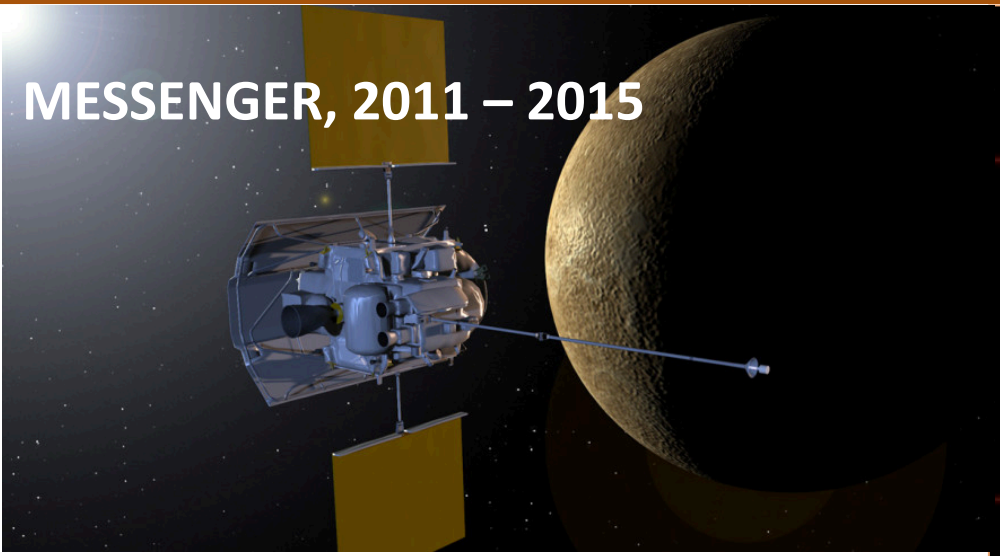


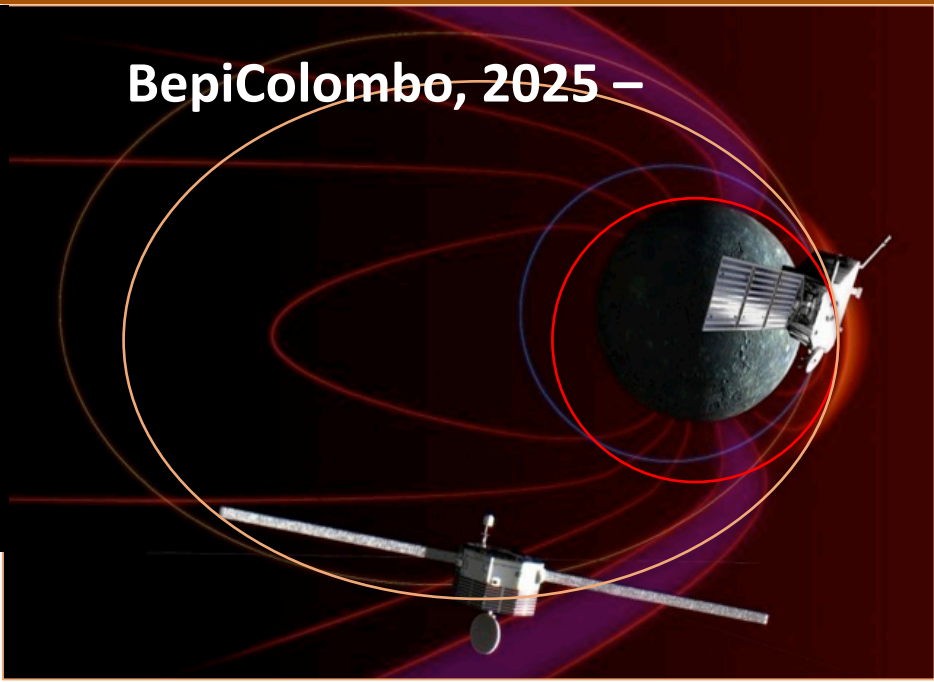
Wang et al., 2015

2D Reconnection with O^+ by Ten-Moment Multifluid Model



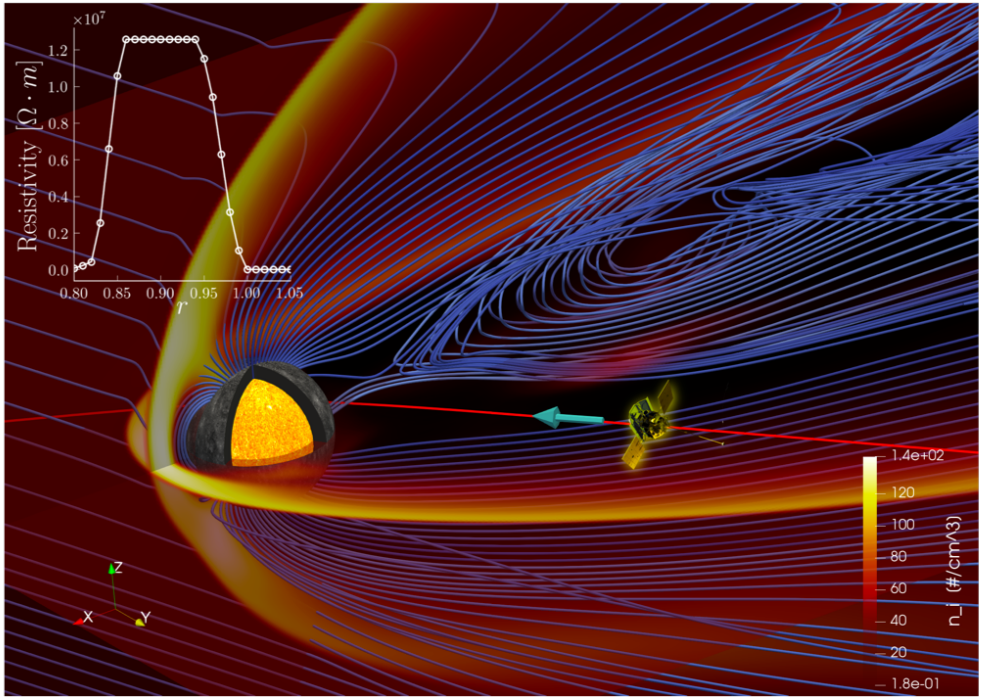
MESSENGER and BepiColombo at Mercury!

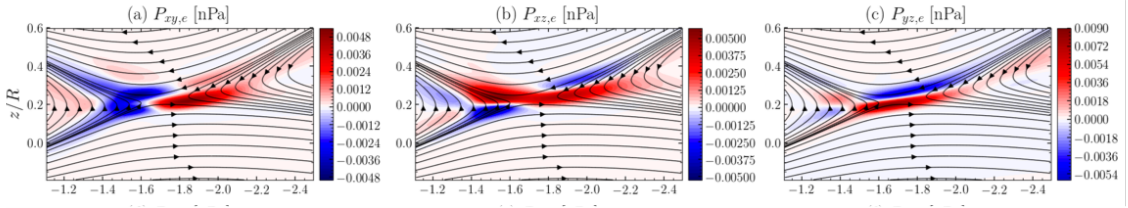


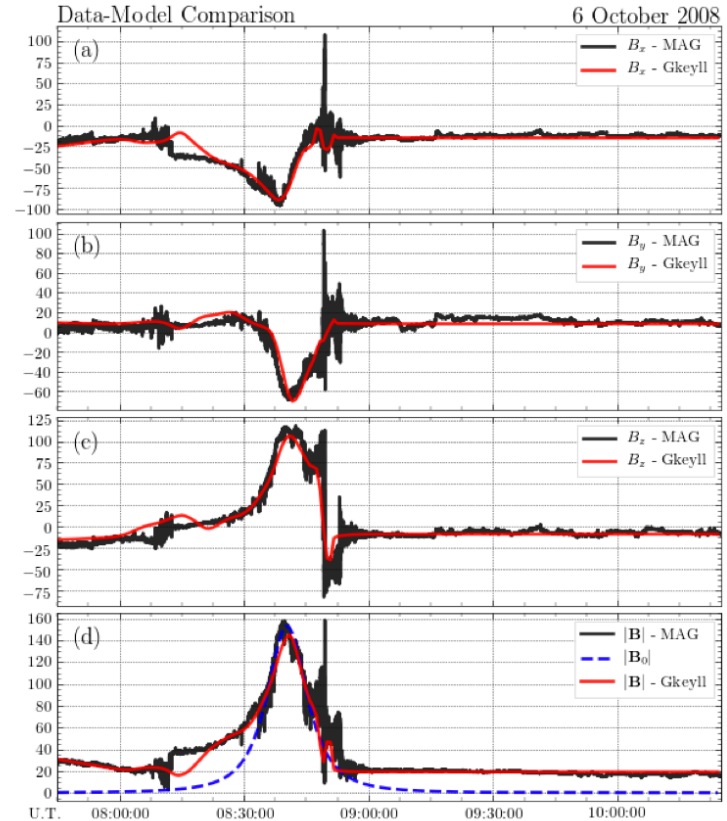


BepiColombo: A joint mission between ESA and JAXA. It was launched on 20 October 2018 and will arrive at Mercury in late 2025.

Ten-Moment Multifluid Simulation of Mercury's Magnetosphere



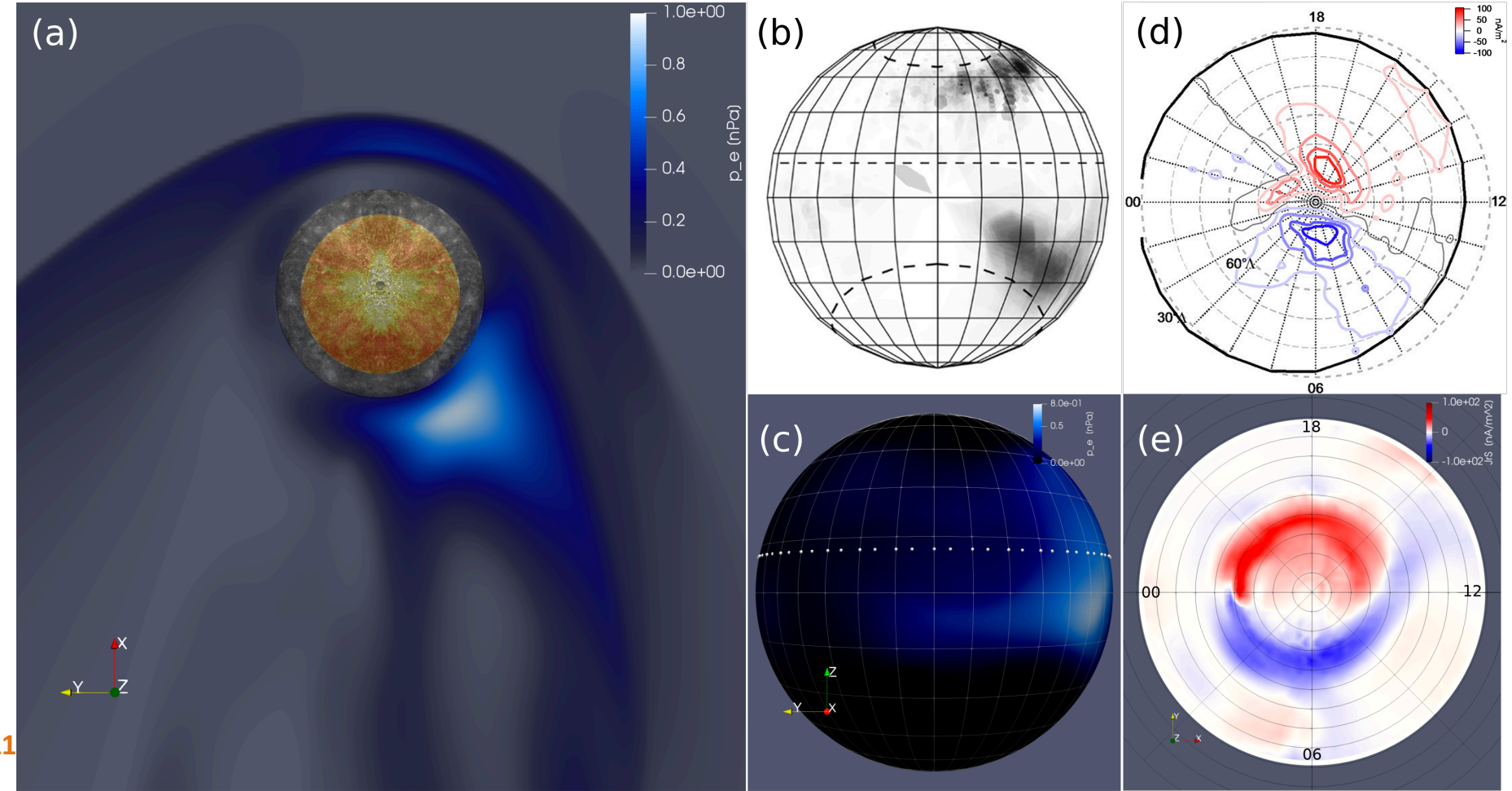




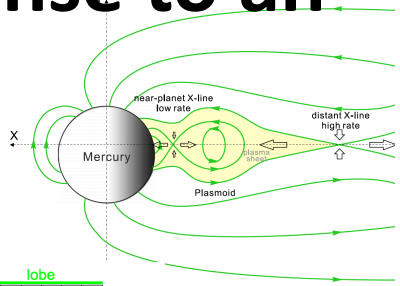
U.T.	08:00:00	08:30:00	09:00:00	09:30:00	10:00:00
$X_{MSM}(R_M)$	-4.10	-1.78	1.66	5.17	8.57
$Y_{MSM}(R_M)$	3.97	0.47	-2.49	-4.62	-6.68
$Z_{MSM}(R_M)$	0.08	-0.03	-0.08	-0.08	-0.09
$R_{MSM}(R_M)$	5.71	1.85	3.00	6.93	10.87

Dong et al., 2019, GRL

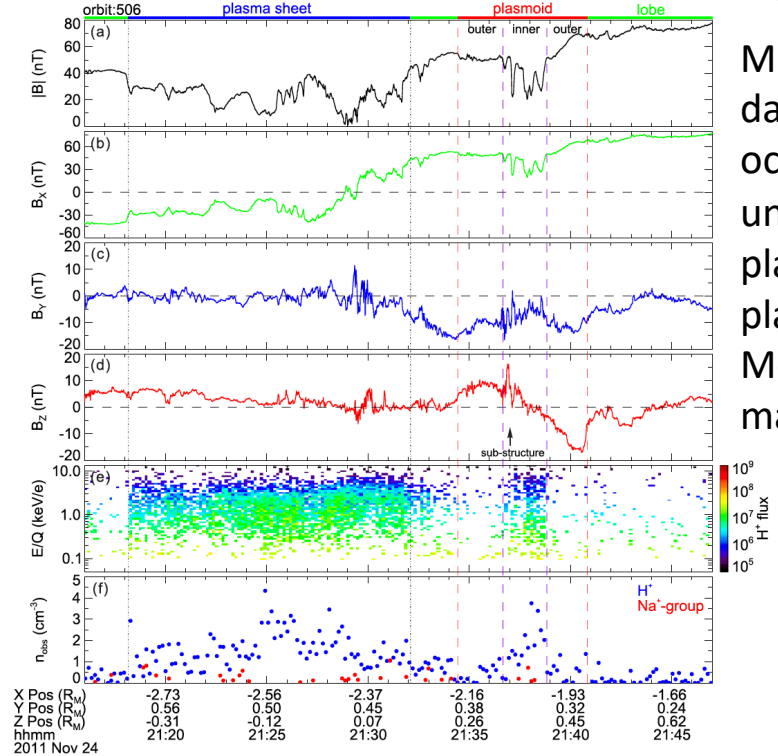
Asymmetry in Mercury's Magnetotail and FACs



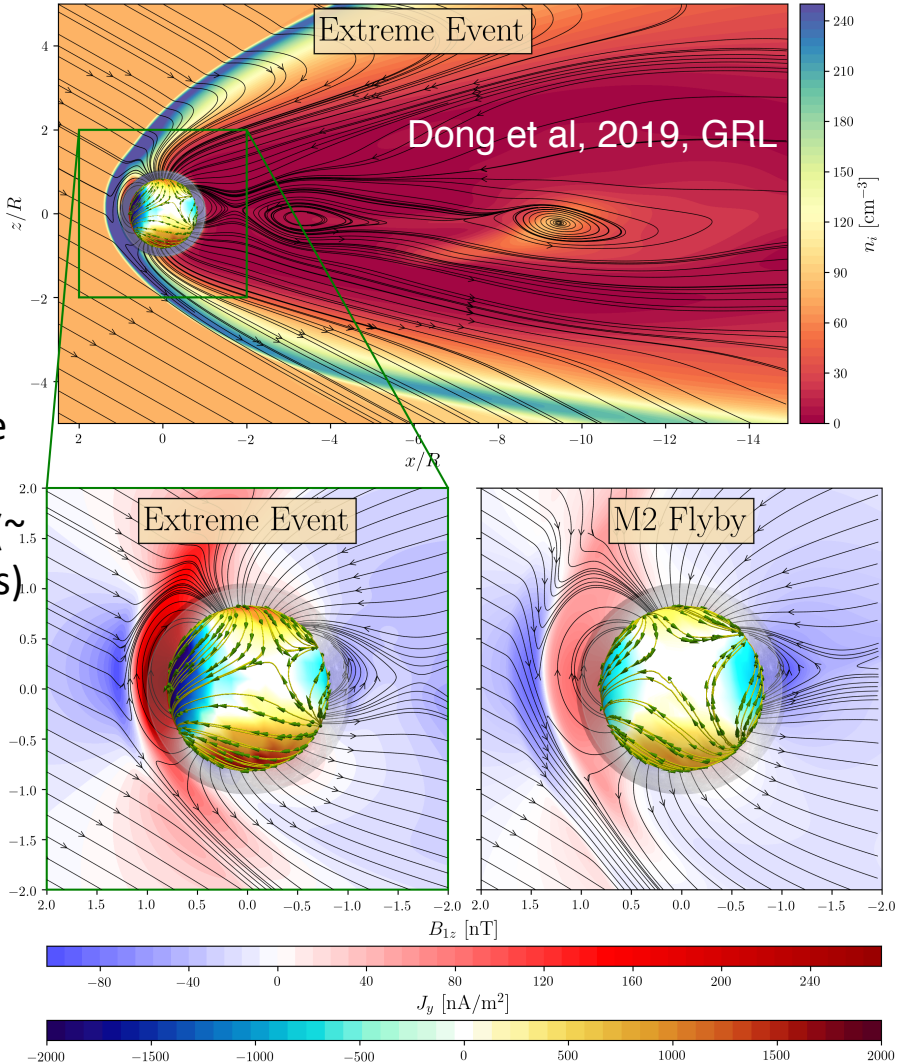
Mercury's Response to an Extreme Event

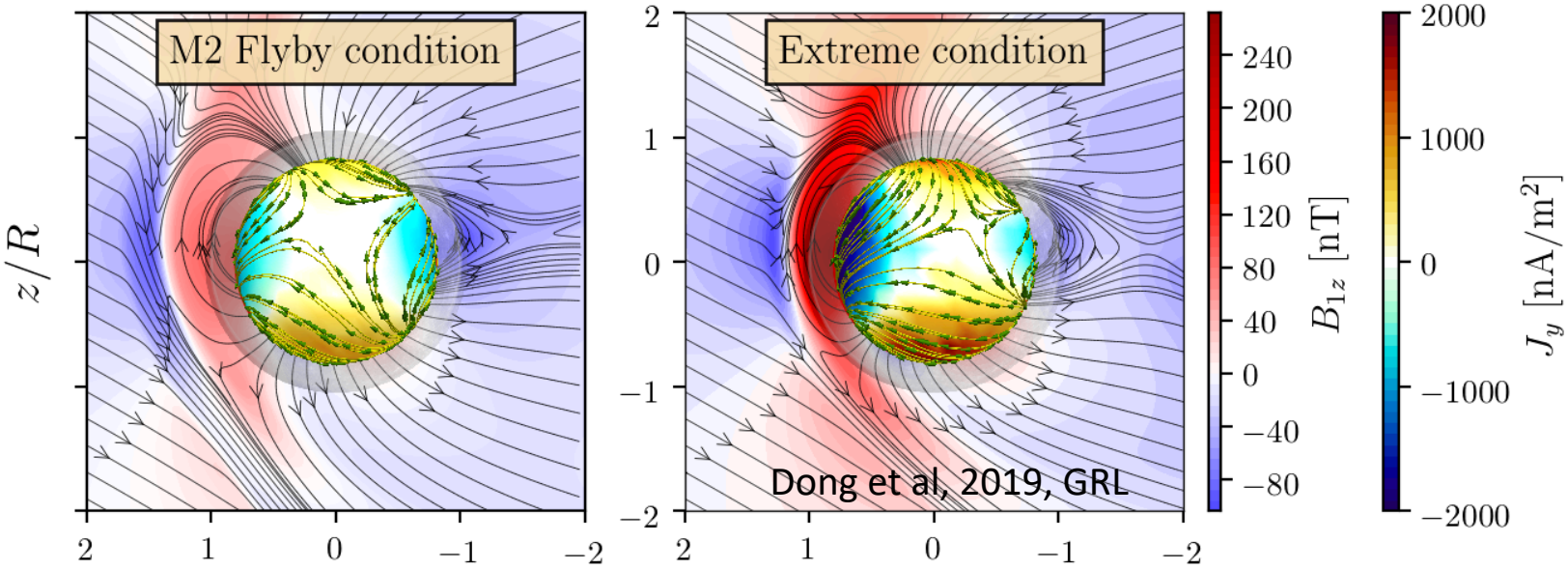


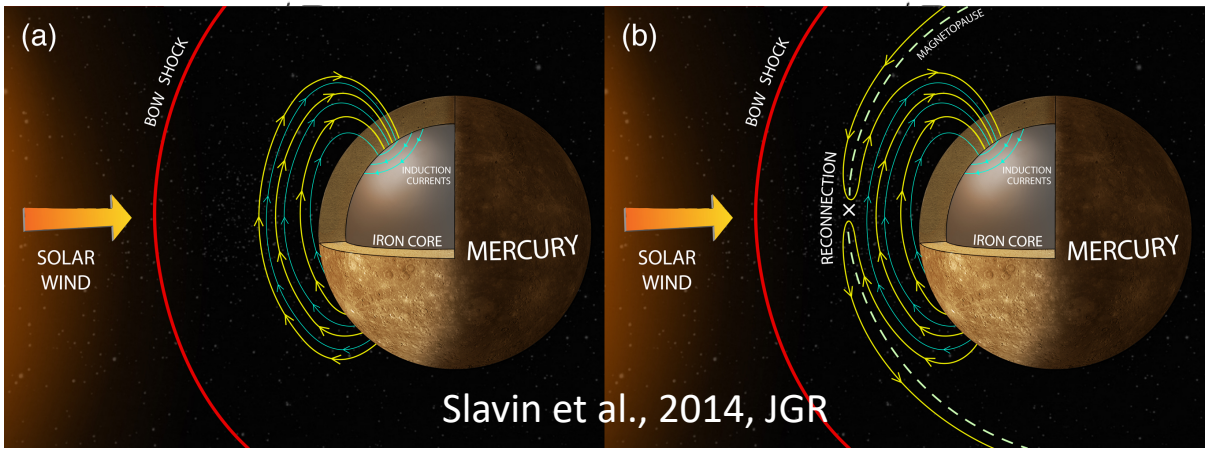
Zhong et al, 2019



MESSENGER data reveals the occurrence of unusually large(~ planetary radius) plasmoids in Mercury' s magnetotail.

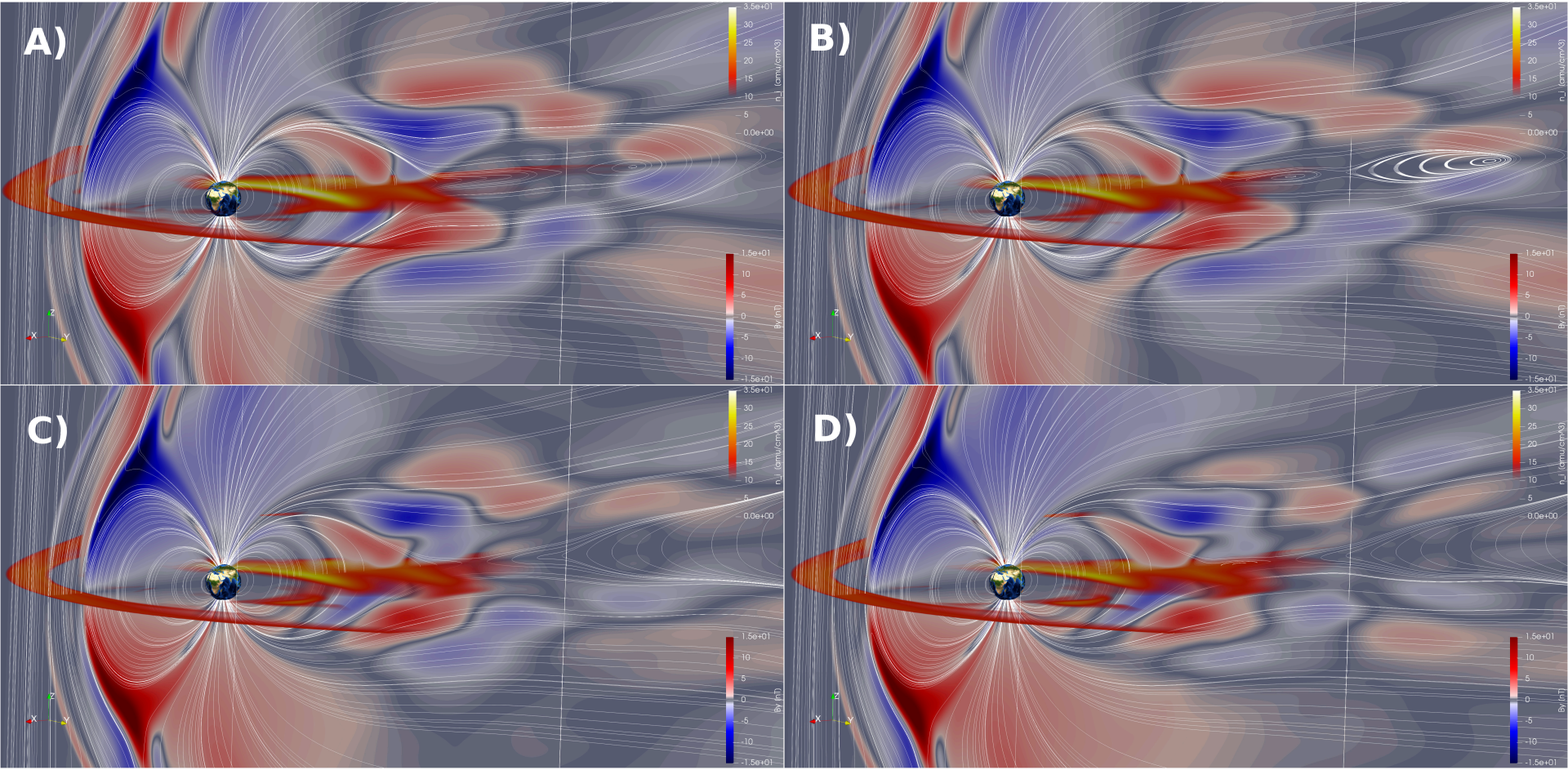




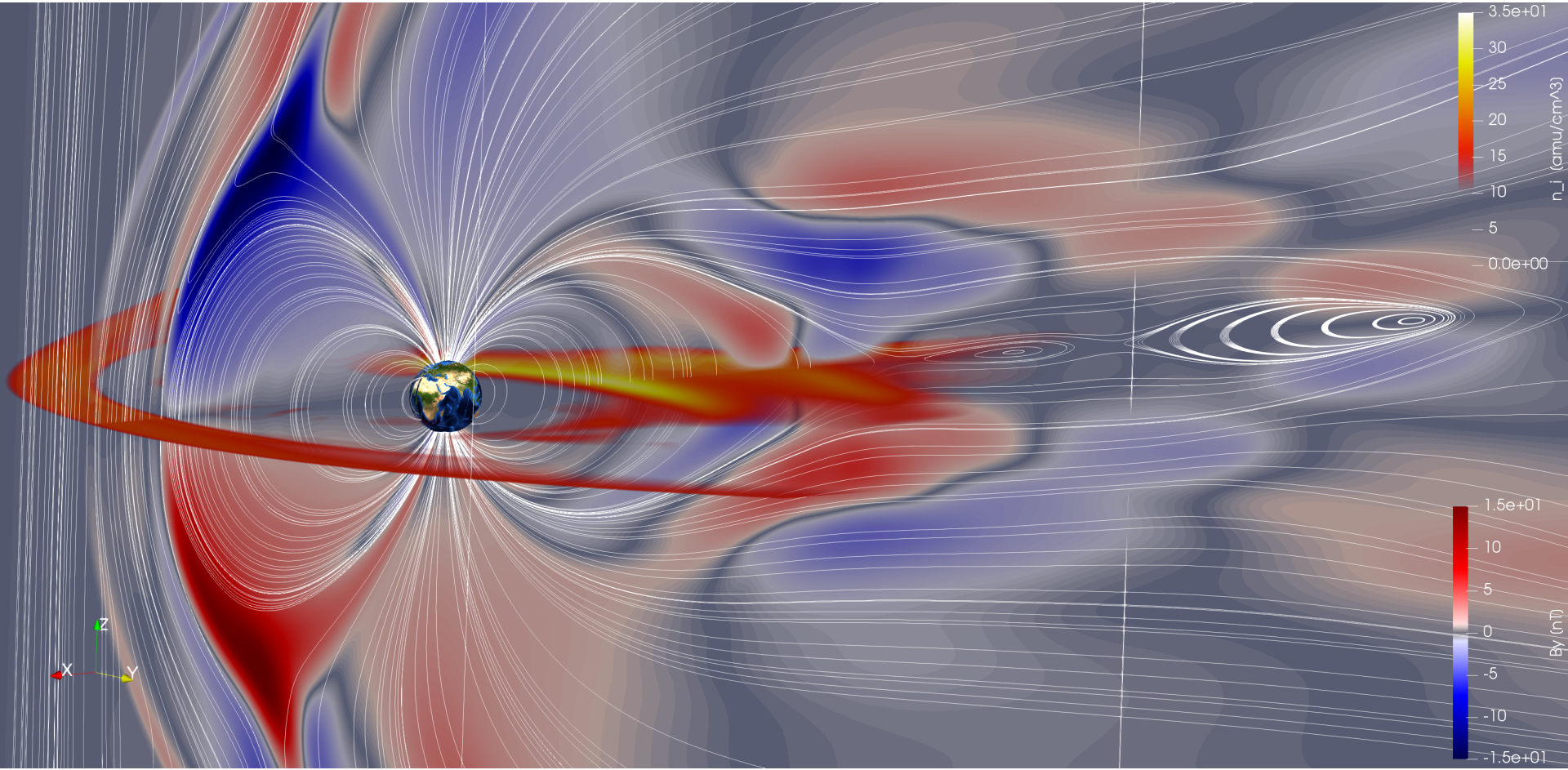


The induction response arising from the electromagnetically-coupled interior plays an important role in solar wind-Mercury interaction.

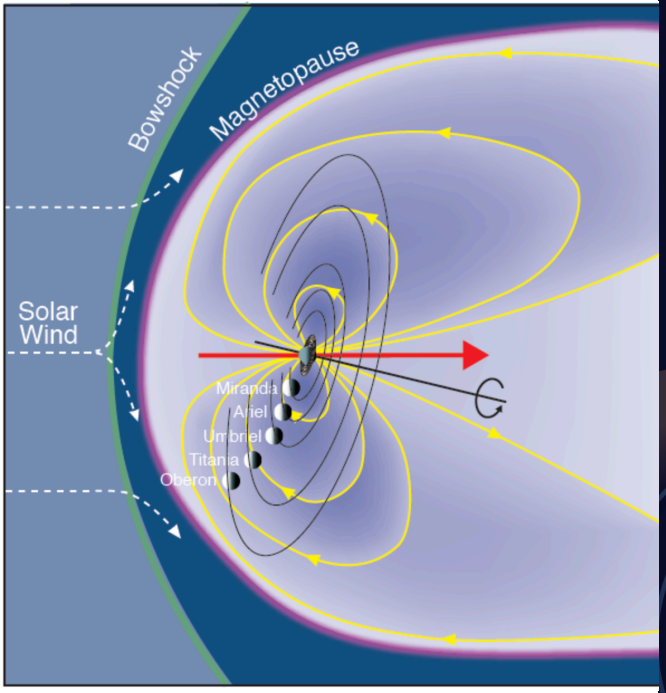
Ten-Moment Multifluid Simulation of Earth's Magnetosphere



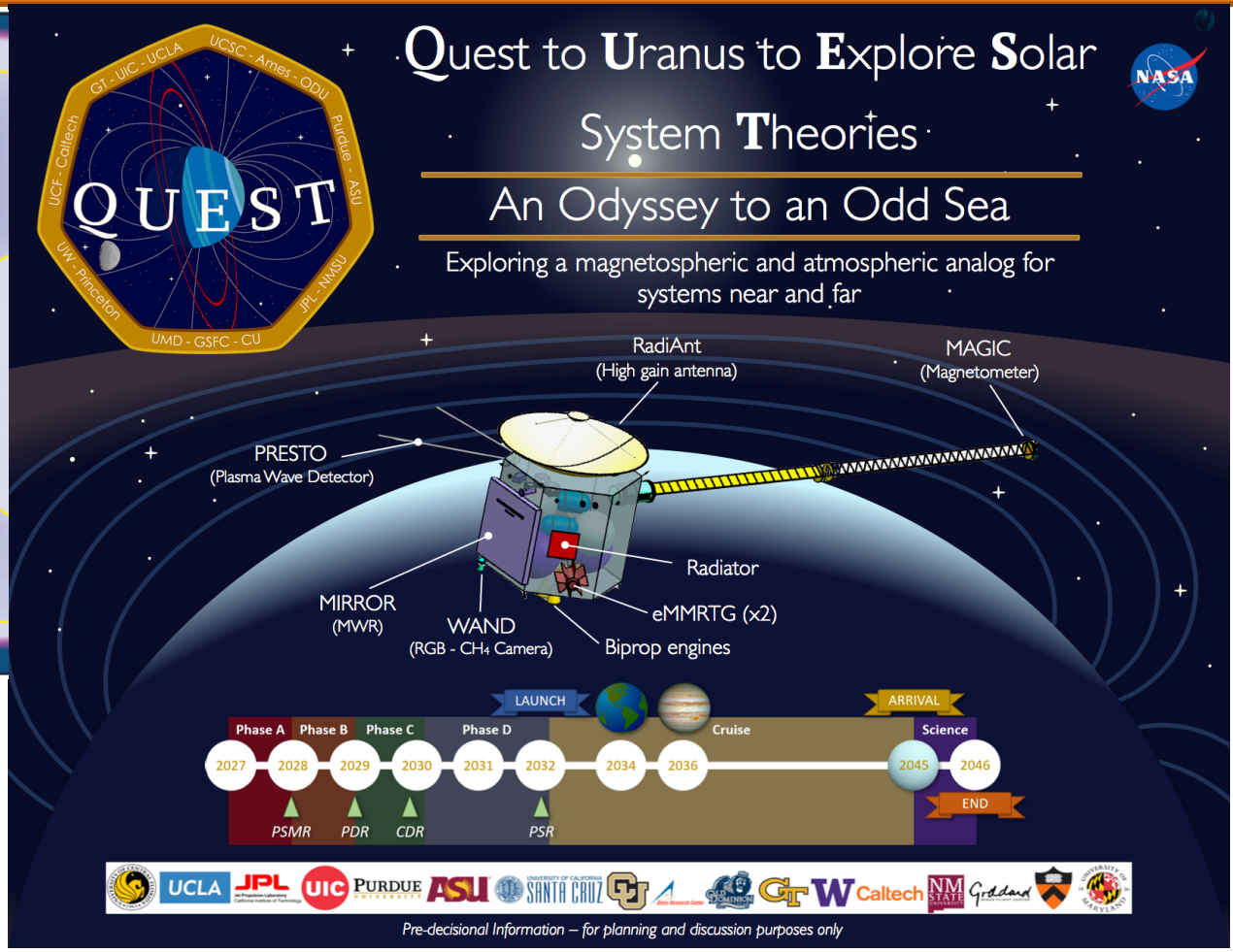
Ten-Moment Multifluid Simulation of Earth's Magnetosphere



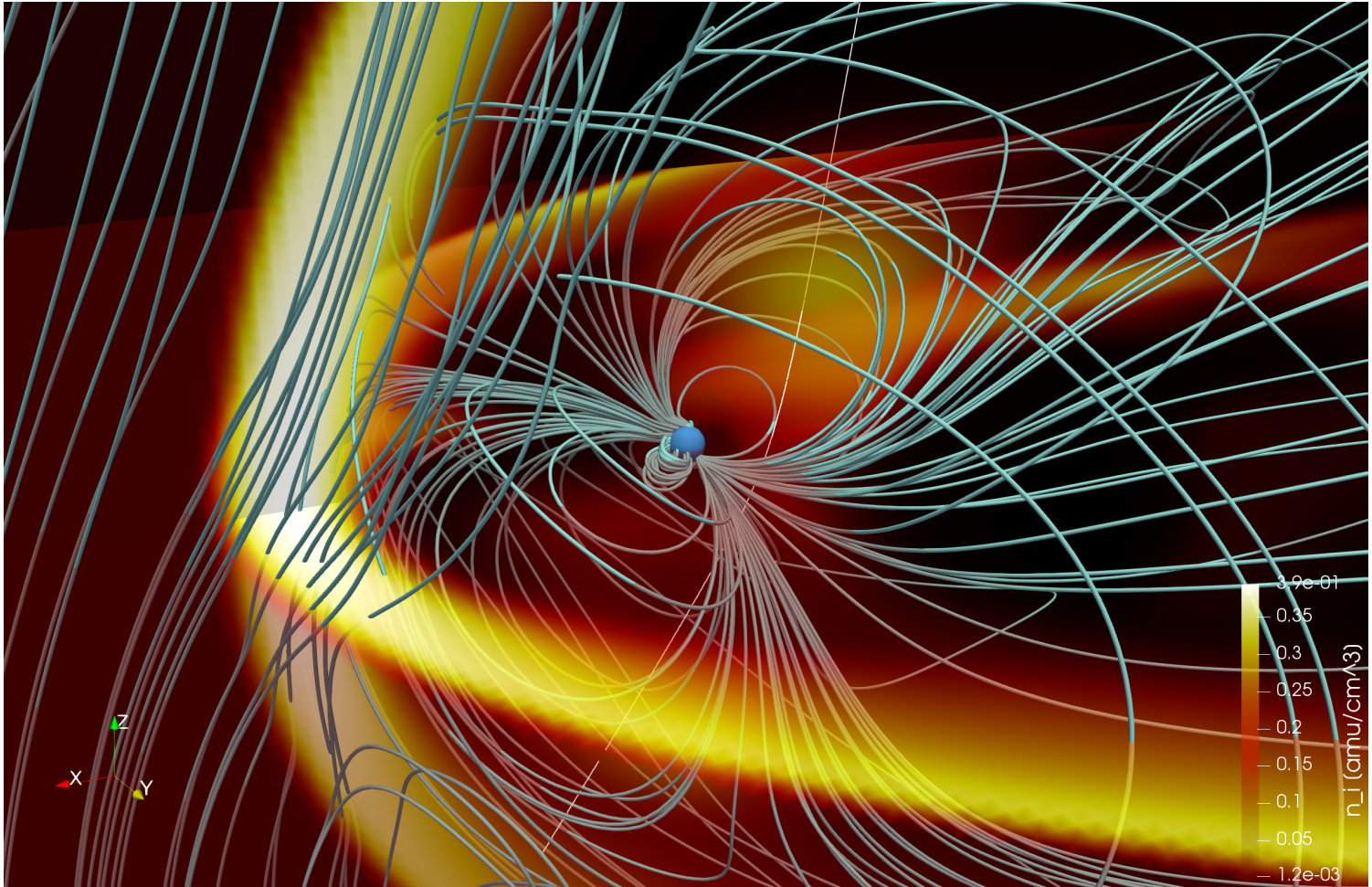
A New Frontier Mission Concept Study to Uranus



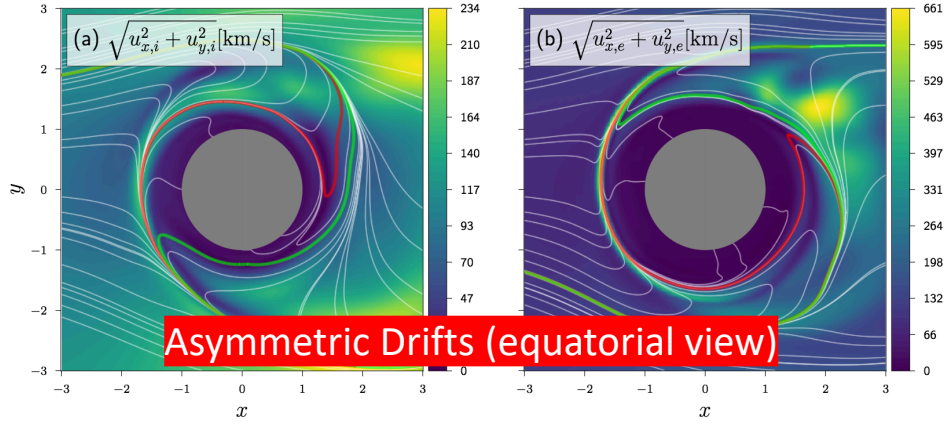
A highly tilted magnetosphere!

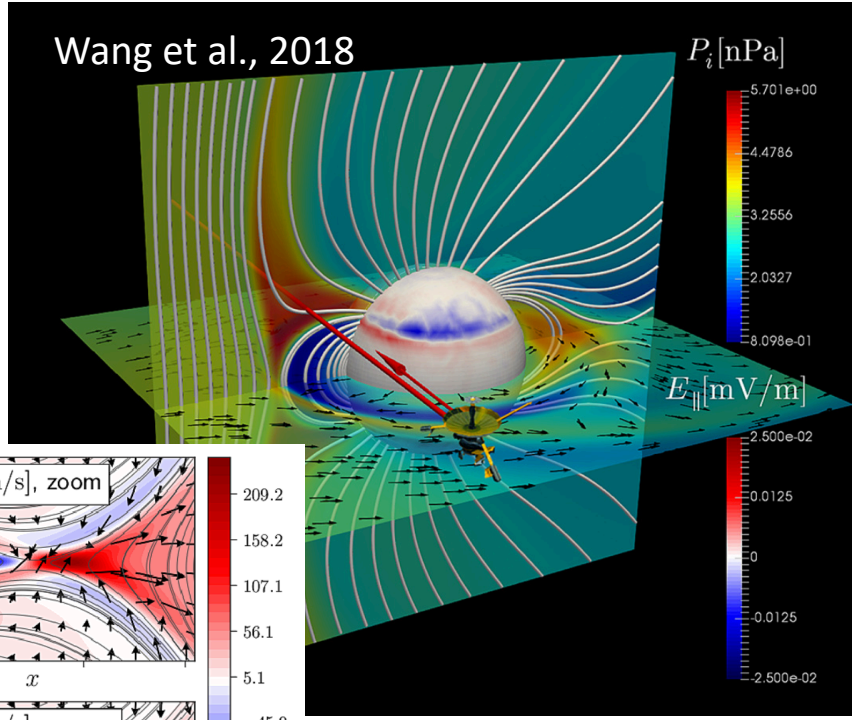


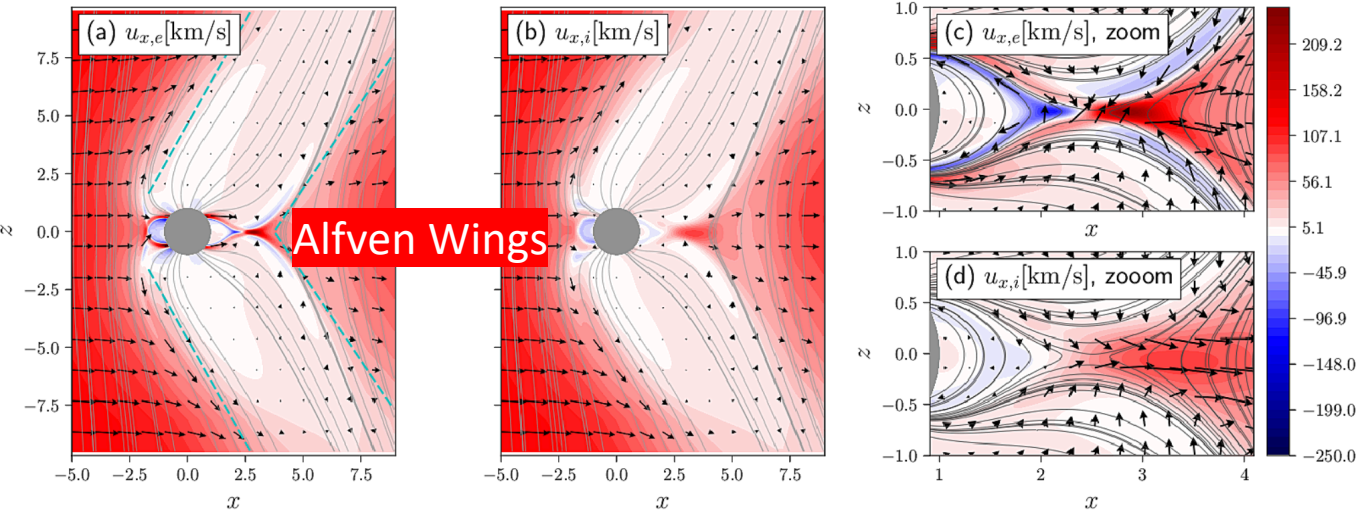
Ten-Moment Multifluid Simulation of Uranus' Magnetosphere



Ten-Moment Multifluid Simulation of Ganymede's Magnetosphere

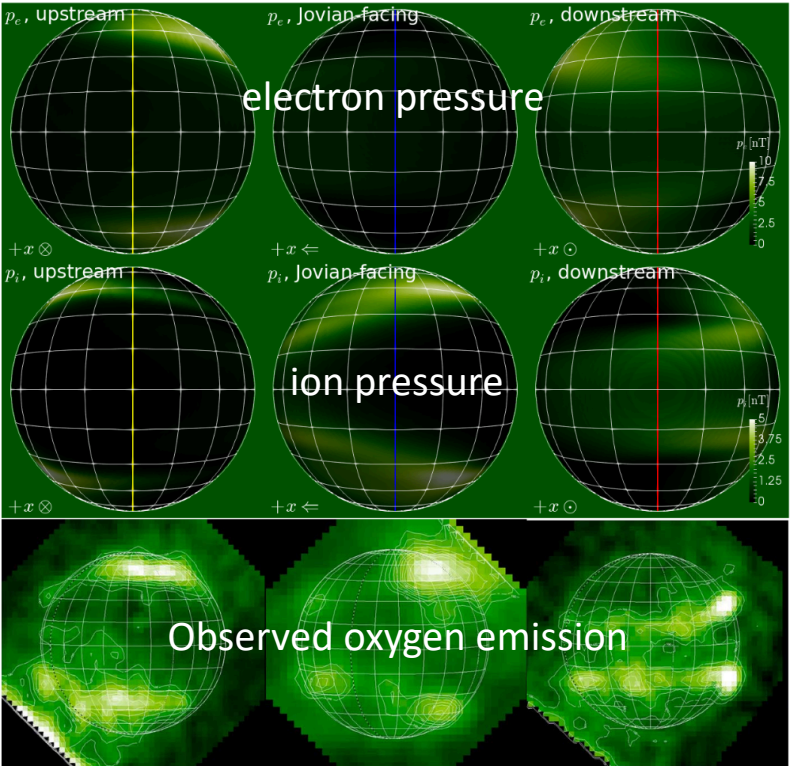




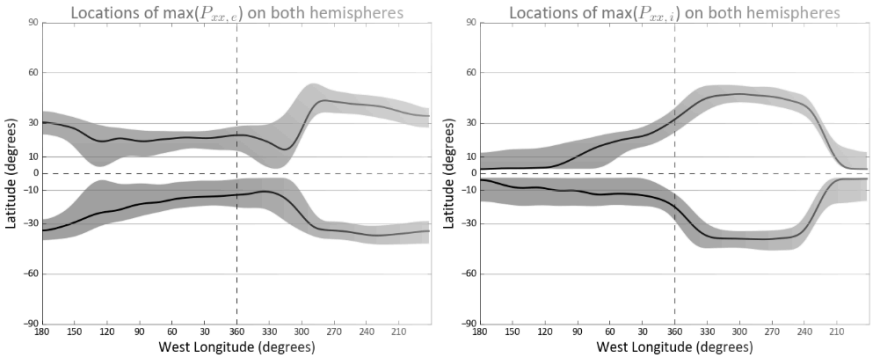


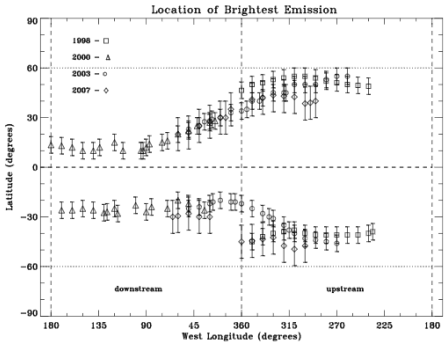
Please stop by Liang Wang's poster SM33E-3258 on Wednesday for more details!

Latitudes of Brightest "Emission" at Ganymede



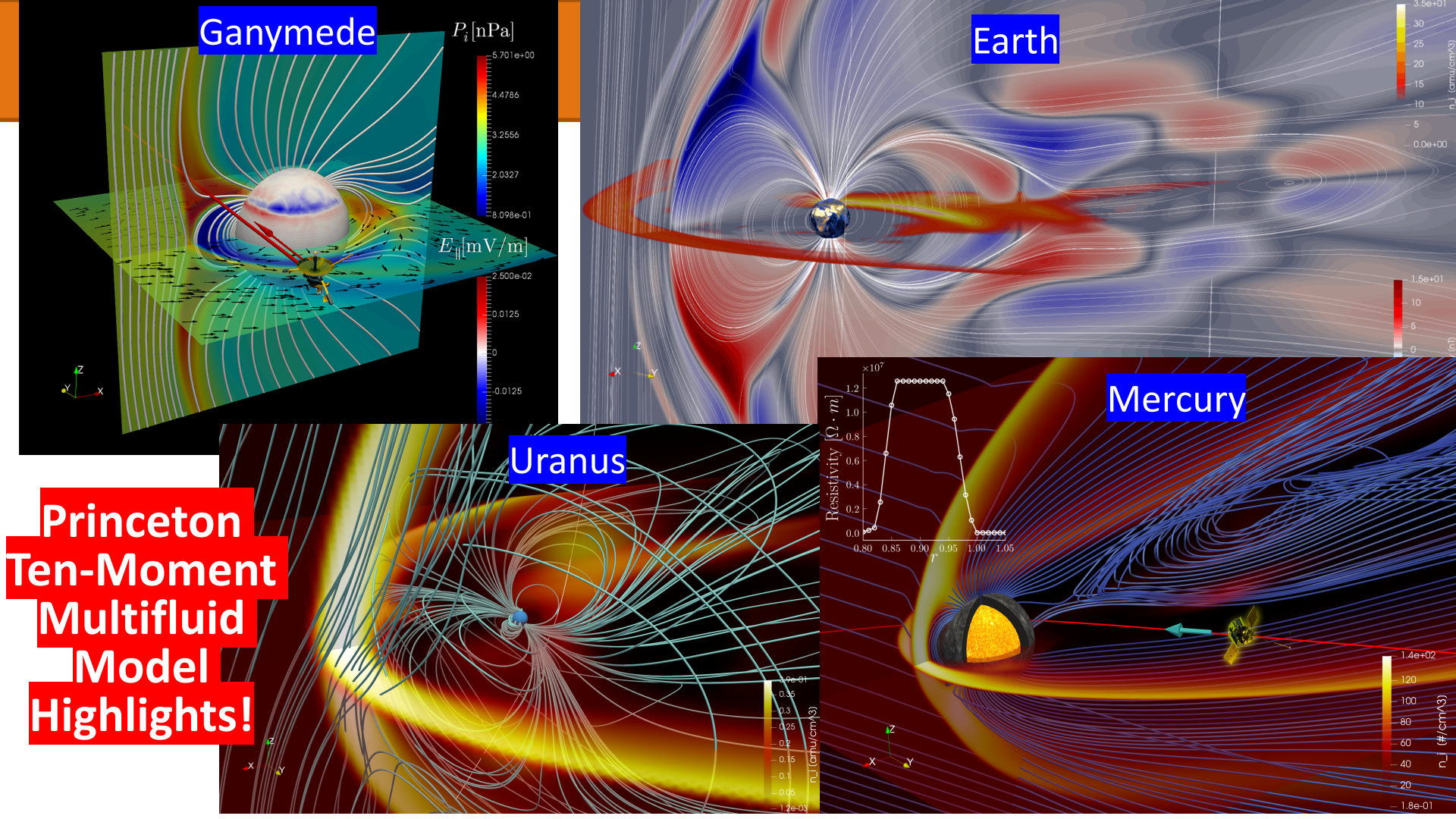
upstream Jovian-facing downstream





Wang et al., 2018

- **Gkeyll reproduces more brightness observations.**
- Top row: Simulation vs. Bottom: Observation
- Locations of $p_{i,\max}$ agree well with observation; Locations of $p_{e,\max}$ show sharper transitions


Ganymede
P_i[nPa]
5.701e+00
4.4786
3.2556
2.0327
8.098e-01
$E_{\parallel}$[mV/m]
2.500e-02
0.0125
0
-0.0125
Earth
3.5e+01
30
25
20
15
10
5
0.0e+00
n_i (amu/cm^3)
1.5e+01
10
5
0
Uranus
n_i (amu/cm^3)
Mercury
Resistivity $[\Omega \cdot m]$
$\times 10^7$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.80
0.85
0.90
0.95
1.00
1.05
r
1.4e+02
120
100
80
60
40
20
1.8e-01
n_i (#/cm^3)
Princeton Ten-Moment Multifluid Model Highlights!

Conclusions and Future Work

- For the first time, we utilize a three-dimensional ten-moment multifluid model to study solar wind interaction with Mercury, Earth, Uranus, and Ganymede.
- This novel fluid approach incorporates the non-ideal effects including the Hall effect, inertia, and tensorial pressures that are critical for collisionless magnetic reconnection.
- The simulation results are in good agreement with spacecraft observations.
- The induction response arising from the electromagnetically-coupled interior plays an important role in solar wind-Mercury interaction.
- We plan to study the impact of space weather events at Mercury, Earth and Uranus. We also plan to include ionospheres, thermospheres, and exospheres in the models.