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

Chuanfei (/tʃuæn'feɪ/) Dong¹, Liang Wang¹, Ammar Hakim¹, Amitava Bhattacharjee¹, James A Slavin², Kai Geramaschewski³

¹Princeton University/PPPL
²University of Michigan, Ann Arbor
³University of New Hampshire

2019 AGU Fall Meeting
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

<table>
<thead>
<tr>
<th>Desirable non-ideal physics</th>
<th>Solutions/progresses</th>
</tr>
</thead>
<tbody>
<tr>
<td>kinetic physics, particularly pressure tensor</td>
<td>full PIC/Vlasov, Hybrid (ion kinetics), MHD-EPIC</td>
</tr>
<tr>
<td>efficient Hall term</td>
<td>implicit Hall term</td>
</tr>
<tr>
<td>multi-ions</td>
<td>multi-fluid MHD</td>
</tr>
</tbody>
</table>
Our Approach: Multi-Moment Multifluid Model

- Solve identical moment equations for both electron and ion

\[
\frac{\partial (m_s n_s)}{\partial t} + \frac{\partial (m_s n_s u_{i,s})}{\partial x_i} = 0,
\]
\[
\frac{\partial (m_s n_s u_{i,s})}{\partial t} + \frac{\partial P_{ij,s}}{\partial x_j} = n_s q_s \left( E_i + \epsilon_{ijk} u_{j,s} B_k \right),
\]

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., 2\textsuperscript{nd} order moment, the pressure.
- No need to directly compute Ohm’s law for \( E \).
- \( \Delta t \) restrained by CFL condition from speed of light, usually not a severe constraint.
Evolution equation for full pressure tensor

\[
\frac{\partial P_{ij,s}}{\partial t} + \frac{\partial Q_{ijk,s}}{\partial x_k} = n_s q_s u_{[i,s} E_{j]} + \frac{q_s}{m_s} \epsilon_{[ikl} P_{kj,s]} B_l
\]

where

\[
P_{ij} = m \int f v_i v_j dv = m \int f (v_i - u_i) (v_j - u_j) dv + nm u_i = P_{ij} + nm u_i u_j.
\]

\[
Q_{ijk} = m \int f v_i v_j v_k dv = m \int f (v_i - u_i) (v_j - u_j) (v_k - u_k) dv + u_{[i} P_{jk]} - 2nm u_i u_j u_k = Q_{ijk} + u_{[i} P_{jk]} - 2nm u_i u_j u_k.
\]

“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?

\[ E_z = -\left( \partial_x P_{xz,e} + \partial_y P_{yz,e} \right) / n_e |e| \]

Magnetic field, B

Current density, J

Plasma flow

Generalized Ohm’s Law

Non-ideal Electric Field

\[ E + v \times B = \sqrt{\frac{n}{n_e}} + \frac{J \times B}{n|e|} - \frac{\nabla \cdot P_e}{n|e|} + \frac{m_e}{n|e|^2} \left[ \frac{\partial J}{\partial t} + \nabla \cdot \left( vJ + Jv - \frac{JJ}{n|e|} \right) \right] \]
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
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

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 highly tilted magnetosphere!
Ten-Moment Multifluid Simulation of Uranus’ Magnetosphere
Ten-Moment Multifluid Simulation of Ganymede’s Magnetosphere

Asymmetric Drifts (equatorial view)

Alfven Wings

Please stop by Liang Wang’s poster SM33E-3258 on Wednesday for more details!
Latitudes of Brightest “Emission” at Ganymede

Wang et al., 2018

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