1-D Hybrid Kinetic/Fluid Modelling of the Jovian Magnetosphere


Introduction & Model Overview

Open questions
- What is the quasi-static potential structure along auroral field lines in Jupiter’s middle magnetosphere, ~30R_J?
- How is plasma distributed along field?
- What is the energy deposited in the atmosphere by precipitating field-aligned currents?

Finding answers?
- \[\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial s} + \frac{1}{m}(qE - \mu B) \frac{\partial f}{\partial s} + m a \mu \frac{\partial f}{\partial \omega} = 0\]
  - Solve time-dependent, 1-D, spatial, 2-D velocity Vlasov equation along field.
  - Couples ionosphere and middle magnetosphere.
  - Fully kinetic, time-varying description.
  - Non-uniform grid allows fine resolution in acceleration region.
  - No collisions considered.
  - Examine limited region of L=30 flux tube.

Previous work
- Confined to Io flux tube (Su+ 2003, Ray+ 2009, Mastuda+ 2010).
- No time-variation considered.
- Quasi-static acceleration region identified ~1-3 R_J.

Challenges
- Computationally intensive – HPC required.
- Choice of boundary conditions non-trivial.
- Large scale sizes and mirror ratios.
- Centrifugal forces.

Boundary & Initial Conditions

- Heavier species confined to equator.
- Bulk flux tube temperature, 0.01 eV.
- Bulk densities two orders less than BC.
- Maxwellian distribution function for all species.
- Positive velocities planetward; negative velocities equatorward.

Model Results

- Load fields/densities/etc.
- Initial/boundary conditions
- Solve Poisson equation
- Advection in velocity space
- Model flow diagram.
- Update densities

Fig. 2 – Model flow diagram.

Fig. 1 – Field aligned currents in the Jupiter-Io system [Ray+ 2009].

Fig. 6 – Plasma densities, potential structure & current flow, t=0.09 s.

Future Improvements

- Fluid treatment of species
- No centrifugal forces, only 4 species.
- Improves computational times.
- Tested on low-resolution Terrestrial case.
- No centripetal forces, only 4 species.

Fluid treatment of species

<table>
<thead>
<tr>
<th>Species</th>
<th>Density (m^3)</th>
<th>Temp. (eV)</th>
<th>Density (m^3)</th>
<th>Temp. (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^-</td>
<td>2.89x10^11</td>
<td>100</td>
<td>2x10^11</td>
<td>0.31</td>
</tr>
<tr>
<td>H^-</td>
<td>2.88x10^10</td>
<td>100</td>
<td>2x10^11</td>
<td>0.31</td>
</tr>
<tr>
<td>e^+ (hot)</td>
<td>1.44x10^4</td>
<td>25,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O^+</td>
<td>1.02x10^9</td>
<td>550</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S^+</td>
<td>4.3x10^4</td>
<td>550</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5 – Boundary condition of hot electron population.

Fig. 3 – Relevant dipole field lines in the Jovian system.

Fig. 4 – Centrifugal and gravitational forces in model, L=30 flux tube.

Fig. 7 – Distribution func. for ionospheric sources, t=0.09 s.

Fig. 8 – Distribution func. for magnetospheric sources, t=0.09 s.

Fig. 9 – Density & ambipolar potential profiles from diffusive equilibrium model.

Realistic densities/temperatures in flux tube

- Filling flux tube takes significant computational time.
- Option 1: data from Juno/JADE [Huschler+ 2019].
- Option 2: diffusive equilibrium model [Bagenal & Sullivan 1981; Dougherty+ 2017].

<table>
<thead>
<tr>
<th>All kinetic</th>
<th>Kinetic elec. &amp; fluid ions.</th>
<th>%age Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advection in vel. space (seconds)</td>
<td>13,220</td>
<td>14,473</td>
</tr>
<tr>
<td>Advection in space (seconds)</td>
<td>31,421</td>
<td>20,103</td>
</tr>
<tr>
<td>Update densities (seconds)</td>
<td>194</td>
<td>33</td>
</tr>
<tr>
<td>Poisson eq. (seconds)</td>
<td>0.30</td>
<td>0.27</td>
</tr>
<tr>
<td>Advection fluids (seconds)</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Total run-time (seconds)</td>
<td>71,735</td>
<td>54,730</td>
</tr>
</tbody>
</table>

Fig. 10 – Distribution func. for magnetospheric sources, t=0.09 s.