Plasma Transport Modelling at the Outer Planets - Model Numerics & Validation

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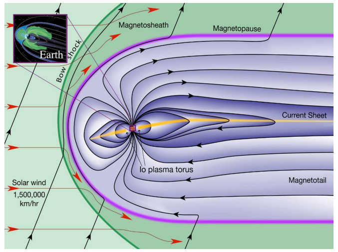
1. Why Model Magnetospheres?

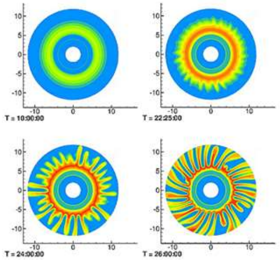
It is important to understand how magnetospheres function and how they respond to external forces. Obtaining an exact solution to the governing equations is very difficult, this means it is necessary to construct a simplified model[1].

Jupiter's magnetosphere differs significantly from the Earth's. The main physical factors for this are:

- Jupiter's magnetic field is ~14 times greater in magnitude
- The planetary spin rate is much greater at ~10 hours
- The volcanic moon Io ejects 1000 kgs^{-1} of plasma into the magnetosphere loading it and creating the plasma torus



Credit: F. Bagenal & S. Bartlett



Liu et al, 2010

We are particularly interested in the simulation of plasma convection from Jupiter's plasma torus radially outwards. This convecting plasma is theorised to undergo the radial interchange instability. Interchange motions occur between magnetic flux tubes and are responsible for the bulk transport of plasma from Io into the inner & middle magnetosphere[3,4]. It is therefore necessary to examine the plasma at the ion-inertial scale in order capture the motion of particles between flux tubes whilst maintaining the computational capacity to resolve length scales on the order of the planetary radii.

Our aim is to produce a hybrid plasma model capable of reproducing radial outflows from Io's torus into the middle magnetosphere over multiple planetary rotations. The 2D magnetosphere will be coupled to the Ionosphere and will provide insight into interchange ion motions.

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2. X. Liu, T. W. Hill, R. A. Wolf, et al. 2010. J. Geophys. Res., 115, A12254
3. Southwood, D. J., & Kivelson, M. G. 1987, J. Geophys. Res., 92, 109
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5. Winske, D., Yin, L., Omidi, N., et al. 2003. In Space Plasma Simulation, ed. J. Büchner, C. T. Dum, & M. Scholer (Springer, Berlin), 136
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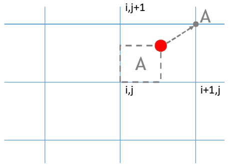
2. How to Model the Jovian Magnetosphere

We have been developing a 2.5D hybrid kinetic-ion, fluid-electron model. The ions are modelled using a Particle-In-Cell (PIC) description and the electrons are a neutralising magnetohydrodynamic (MHD) fluid[5,6]. A Cartesian grid is overlaid across the simulation region on the vertex's of which the electromagnetic (EM) fields are calculated.



The model is advanced through time numerically, with the magnetic field being obtained with a modified MacCormack Predictor-Corrector scheme in order to minimise numerical instabilities allowing larger time steps.

Initial & boundary conditions

Update particle positions & velocities

Ions are pushed numerically considering the Electromagnetic, Coriolis and Centrifugal forces

$$\frac{d\underline{v}}{dt} = \frac{q}{m}\left(\underline{E} + \underline{v} \times \underline{B}\right) - 2\underline{\Omega} \times \underline{v} - \underline{\Omega} \times \left(\underline{\Omega} \times \underline{r}\right) \qquad \frac{d\underline{r}}{dt} = \underline{v}$$

Interpolate particle parameters

$$\rho_c = \sum_p W\left(\underline{x}_p, q_p\right)$$

Parameters are obtained from ion distributions using first-order interpolation onto the EM field grid vertices

Δt

Update magnetic field

$$\frac{\partial \underline{B}}{\partial t} = -\left(\nabla \times \underline{E}\right)$$

The magnetic field is updated using Faraday's Law and the electric field using the MHD momentum equation for massless electrons

Calculate electric field

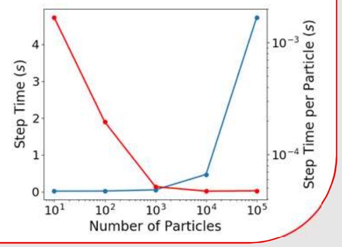
$$\underline{E} = -\frac{1}{\rho_c}\nabla \cdot \underline{\underline{p_e}} - \left[\underline{U_i} \times \underline{B} - \frac{1}{\mu_0 \rho_c}\left(\nabla \times \underline{B}\right) \times \underline{B}\right]$$

3. Model Performance

A series of performance tests on the current version of the hybrid model were carried out. A 10x10m surface was constructed with a 51x51 grid. It was determined as the number of particles increased:

- The time taken to complete one time step increases linearly
- The time taken to computed each particle's motion decreases

Once particle operations dominate the run time the time per particle becomes constant at 47μs. Compared to the particle operation time of a highly optimised PIC model[7] it is approximately 2 orders greater, emphasising the need for optimisation.

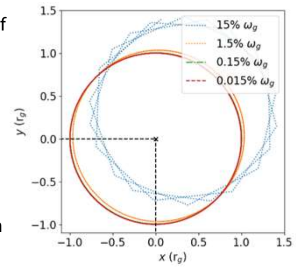


Test System Specs:
CPU: Intel® Xeon® Processor E3-1271 v3 (@ 3.60GHz)
Memory: 32Gb Samsung DDR3 (@ 1600 MHz)
Software: Python 3.7.3 / Numpy 1.17.0

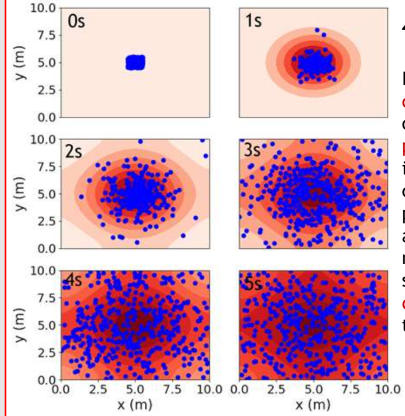
4. Benchmarking

4.1 Ion Gyro-Motions

A 240s ray-trace of an ion's path is shown. The region through which the particle travels contains a uniform magnetic field of 1nT. Comparing theoretical values to the results finds close agreement between those calculated and those observed in the model. There are 4 separate ray traces visible, each is for a separate simulation with the size of the temporal step equal to a proportion of the particles' gyro-frequency. This shows that the temporal resolution of the model must be at least an order of magnitude below the gyro-frequency to obtain accurate results.



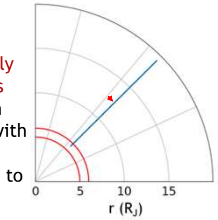
4.2 Diffusion



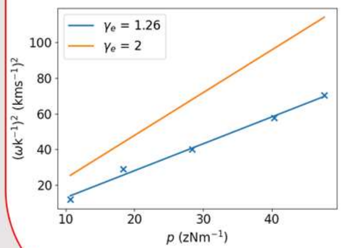
Ions diffuse from an initially compressed distribution to occupy all space available. 400 particles (in blue) were initialised in a 1x1m area at the centre of the model. The particle positions on each second are plotted over a diffusive fluid model of the same region. It is seen that the particle distribution matches well with the contours of the fluid.

4.3 Rotational Motions

By turning off the EM fields it is possible to directly observe the effects of the Centrifugal and Coriolis pseudo-forces. Examining the path of a single ion over 3 hours reveals it moving radially outwards with a small deflection in the azimuthal direction. It is initialised with a position that would be expected to be within Io's plasma tours.



4.4 Ion-Acoustic Waves



By perturbing the velocity of the ions in a weakly magnetised domain a ion-acoustic wave is launched. The accuracy of complex plasma dynamics is ensured by comparing the observed wave speed (in blue) in the model to that obtained analytically for an ideal fluid (in orange). Using multiple simulation runs it is possible to obtain the wave speed as a function of plasma pressure, which is used to calculate the adiabatic index of modelled electron fluid.

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