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Global Hybrid Simulations of the Earth's Magnetosphere

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Abstract. The interaction of solar wind with the Earth's magnetosphere has turned out to be much more complex than originally thought. A major reason for this complexity and richness in the type of underlying processes is that the interaction occurs in a regime where kinetic effects dominate the physics and affect the large-scale dynamics of the magnetosphere. Spacecraft observations have established the fact that most critical plasma processes regulating mass and energy transfer in the magnetosphere take place at relatively thin boundaries/discontinuities between major regions of geospace. The traditional tool for global studies of the magnetosphere has been MHD simulations. Recent advances in technology and simulations are, however, making global kinetic simulations possible. In this paper we present an overview of the specialized multi-scale techniques that we are developing and show examples of our global simulations.

1. Introduction

Numerical simulations are primary tools for theoretical investigation of solar wind-magnetosphere interaction. The wide disparity in the temporal (fractions of seconds to tens of hours) and spatial scales (centimeter to over 100 R_E) involved in the underlying physical processes have necessitated the use of different types of simulation codes, differing in physics that they include and questions that they can address. MHD simulations have been used to address the global dynamics of the magnetosphere with the goal of predicting eminent features of substorms and other global events [e.g., Lyon et al., 1998; Kabin et al., 2000; Raeder et al., 2001 and references therein]. MHD simulations, which can be run for many hours in real time, do not provide information about the structure of boundaries but are helpful in developing a global morphology of the magnetosphere. Kinetic simulations, on the other hand, demand more computational resources and have traditionally been used to study local description of boundaries within more idealized geometries. However, a host of important problems that fell between these simulation limits went unanswered. These are the type of problems that require a kinetic treatment but could not be addressed due to computational limitations. For instance, the effect of the ion foreshock on the motion of the magnetopause is purely a kinetic effect that requires a simulation box that is sufficiently large to include both the bow shock and the magnetopause. Similarly, formation of low latitude boundary layer during northward

IMF requires inclusion of the cusp, ionosphere, magnetosheath and the magnetopause in the simulation box.

Continued advances in technology and development of faster computers with larger memories, however, have made it possible in recent years to tackle these very important problems. We have taken full advantage of these gains in computational power to extend our kinetic simulations from local studies of boundaries to 2-D and 3-D global kinetic studies of the magnetosphere. Although full particle simulations of the magnetosphere are expected to remain out of reach in the foreseeable future, global hybrid simulations which treat electrons as fluid but retain full ion kinetic effects are becoming possible. A number of groups are working on development and refinement of global hybrid codes and there are considerable variations in the algorithms and approaches. Description and critical assessment of these works are beyond the scope of this paper and will be discussed elsewhere. In this paper, we limit our discussion to several specialized techniques we are developing and show examples of our global simulations.

2. Approach

Magnetosphere processes span a wide range in temporal and spatial scales. Accordingly, we are pursuing a three-pronged approach involving distinct multi-scale techniques: (i) multi-zone, (ii) discrete event simulations, and (iii) reverse engineering of collisionless magnetic reconnection.

2.1. Multi-Zone Simulations

The traditional plasma simulations are based on time-stepped methodology where the state of the system is updated at regular time intervals. We are working on two approaches. One uses a non-uniform stretched mesh. In this case additional computational savings can be achieved by dividing the simulation domain into a number of zones and then updating each zone based on its Courant condition. Figure 1 shows a typical mesh structure as well as the different zones. As the solar wind interacts with the dipole field, a magnetosphere starts to form and increases in size. During this process, a large region upstream of the forming bow shock is unaffected and consists of the pristine solar wind. The boundary of this region is marked as the expanding front in Fig. 1. Since the solar wind is simply convecting inward in the region between the left simulation boundary and the expanding front, we advance the particles in this region using their analytical orbits. This affords particle updates at very large time steps, leading to considerable CPU savings. Figure 2 shows the intensity plot of log of density from a 2D global hybrid simulation. The left panel shows that without proper care, disturbances can develop at the boundaries between different temporal zones whereas the right panel shows that with our technique the boundaries are almost entirely free of any numerically induced disturbances. Our second approach is based on the adaptive mesh refinement (AMR) technique [Berger and Olinger, 1984] for block-structured meshes. In this technique, refined meshes overlap regions covered by the coarser mesh so that the global mesh is made of a hierarchy of nested levels of logically rectangular patches. AMR has the advantage that the mesh structure is more flexible than the stretched mesh scheme and the mesh can be dynamically adapted. Each

patch in AMR is also updated based on its own Courant condition, enabling asynchronous explicit time-stepping. Although AMR techniques have been used in computational fluid dynamics and MHD, they are as yet to be applied to particle-in-cell (PIC) simulations. The presence of particles leads to additional complications at the coarse-fine patch boundaries (such as particle self-force) that need to be addressed. There are also issues related to spurious wave reflection at the patch boundaries. We have made progress in overcoming these issues and results will be reported elsewhere.

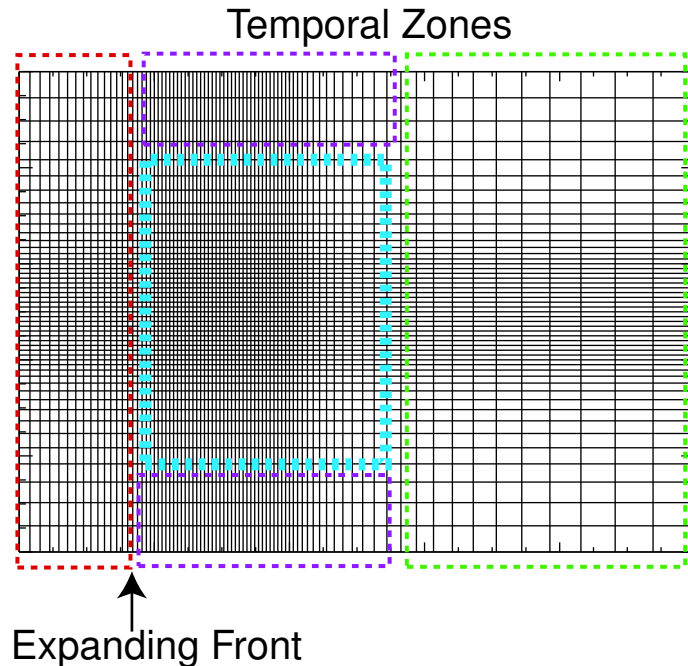


Figure 1. Stretched mesh along with introduction of temporal zones that enable asynchronous update of simulation state.

2.2. Multi-Zone Simulations

We have recently proposed an alternative paradigm to time stepping [Karimabadi et al., 2005a, b; Omelchenko and Karimabadi, 2006a, b]. This new approach is based on explicit discrete-event simulation technology. It offers distinct advantages over synchronous time-stepping: (i) updates of individual macro-particles and field elements are performed asynchronously, (ii) local time increments are determined and self-adaptively adjusted in time through scheduling and execution of physically meaningful local updates (“events”). The event-driven time advance is accurate, free of the global Courant condition, stable, and parallelizable. We have successfully applied this technique to electrostatic PIC simulations [Karimabadi et al., 2005a], advection-diffusion-reaction equations [Omelchenko and Karimabadi, 2006b], hybrid simulations [Karimabadi et al., 2005b, Omelchenko and Karimabadi, 2006a], and computational fluid dynamics

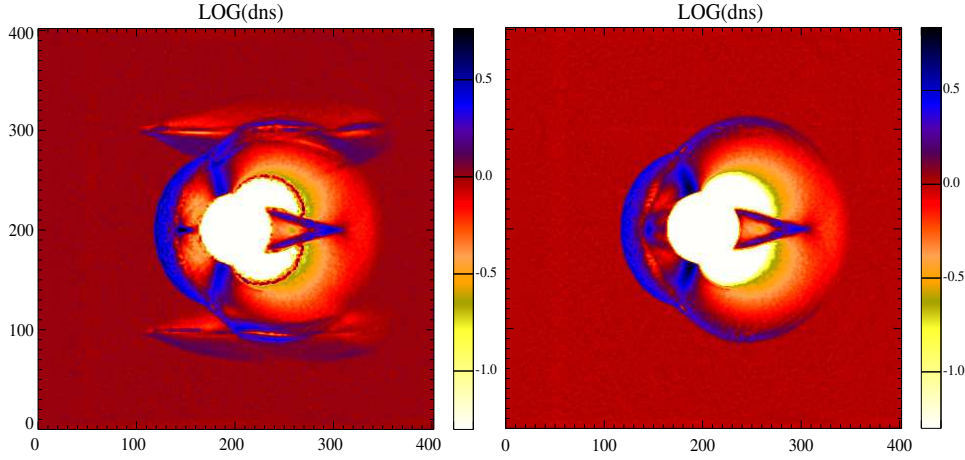


Figure 2. Intensity plot of log of density for (a) improper and (b) proper matching of temporal zones.

[in preparation]. Figure 3 shows the discrete event simulation of strong fast shock turbulence at two different times. Note that the region ahead of the shock (the pristine region) is not updated. As the turbulence expands to the left, the algorithm automatically moves the window for the no-update region. The two bottom panels also demonstrate that both the field and particle update time steps are spatially varying from cell to cell. This is because the algorithm self-adaptively determines the proper time step based on the required accuracy. We are currently extending our algorithm to 3D.

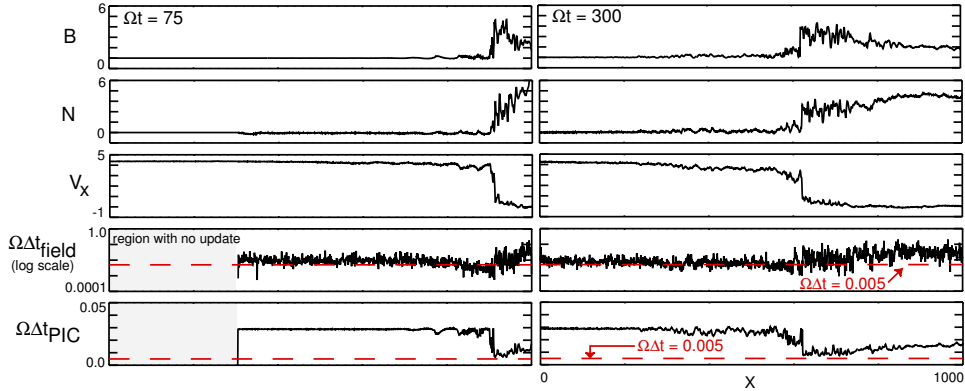


Figure 3. Discrete event simulation of a high Mach number fast magnetosonic shock.

2.3. Reverse Engineering of Electron Microphysics

Details of the magnetic reconnection require full electron kinetic treatment. It can be easily shown that full particle simulation of the magnetosphere would take over million years even on the fastest computers available today. Thus other

techniques have to be developed to extract the electron physics and embed it in global simulations. We present one such technique that we think is the most promising with the highest probability of success. Let us consider the generalized Ohm's law:

$$E' \equiv E + v_e \times B = -\frac{1}{en_e} \nabla \cdot \mathbf{P}_e - \frac{m_e}{e} \frac{dv_e}{dt} + \eta J \quad (1)$$

Within the diffusion region, the right hand side of this equation becomes finite and leads to the reconnection electric field. Here J is the total current density, \mathbf{P}_e is the electron pressure tensor, v_i is the ion fluid velocity, v_e is the electron fluid velocity, η is the resistivity, n_e is the electron density, m_e is the electron mass, and e is the electron charge. The goal is to have a general expression for the reconnection electric field, which correctly captures the microphysics of the reconnection as a function of local variables to be used to model reconnection in the global codes. We are working on a unique approach to this difficult problem that relies on two innovations:

Empirical approach: Perform full particle simulations under a variety of geometries and generate a large data set describing the time evolution of the reconnection electric field as a function of local variables. The training of the algorithm also requires examples of non-reconnection phenomena and we plan a series of such simulations (e.g., fast magnetosonic shock).

Reverse Engineering: Apply our reverse engineering techniques [Karimabadi et al., 2006] that enable derivation of *analytical* expression from data in order to develop an expression for the reconnection electric field based on the local variables:

$$E' = F(x_1, x_2, \dots, x_n) \quad (2)$$

where x_i 's are local variables on the edges of each cell in a global simulation and can consist of moments, field quantities, their gradients, and nonlinear combinations of such quantities. The goal is then to derive an analytical expression for F that provides the proper description of the electric field for reconnection.

3. Simulation Results

Our multi-zone code is fully operational and we are using it to study the magnetosphere. Figure 4 shows the 3D hybrid simulation of magnetosphere for a purely southward IMF. Visually this figure looks similar to global MHD simulations. However, these simulations include the full ion kinetic effects. Thus, the physics of boundaries, generation of turbulence, ion foreshock and associated waves, are all captured. The ion foreshock region, a kinetic effect, is evident in the top left part of Figure 4. The presence of waves generated due to the ion populations in the foreshock region are also evident in the magnetic field lines. Figure 5 shows the comparison of a 2D and 3D hybrid simulation of southward IMF. There are clearly some similarities in the resulting magnetosphere, pointing to the fact that 2D simulations are of value for studies of the magnetosphere. However, one has to be aware of limitations of 2D simulations. For example, it is not possible to achieve a steady state magnetosphere in 2D and distances of

bow shock and magnetopause would not be the same as in 3D. The diversion of flow of plasma and fields around the magnetosphere are also not possible in 2D.

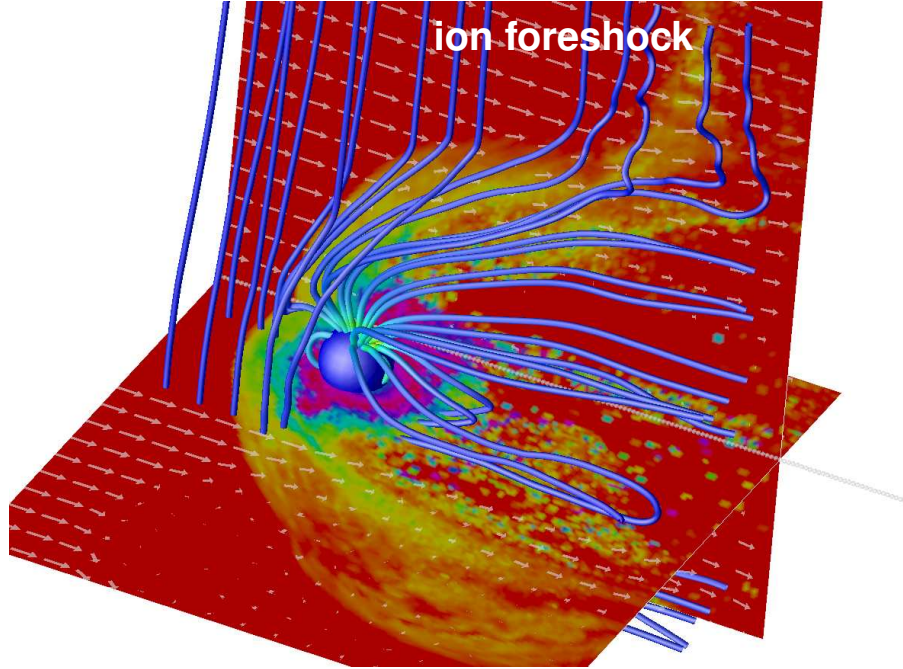


Figure 4. Global 3D hybrid simulations of the magnetosphere.

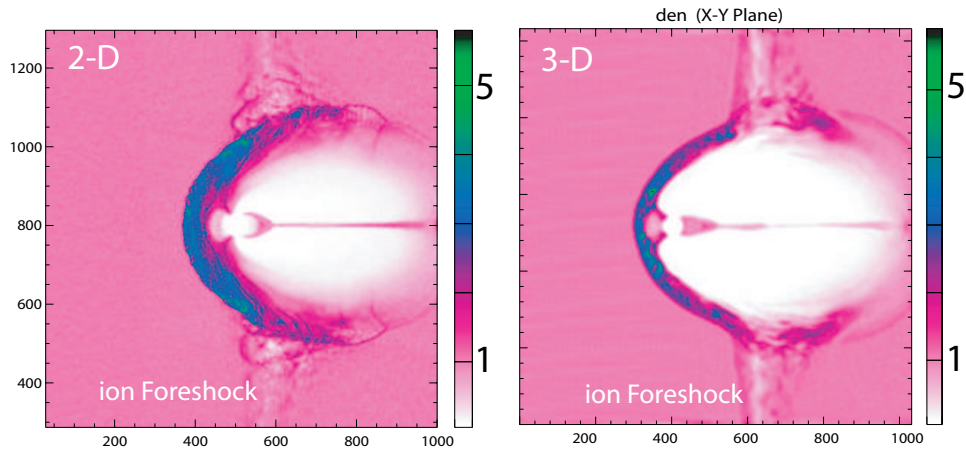


Figure 5. Comparison of 2D and 3D hybrid simulations during southward IMF.

Our final example shows the formation of flux transfer events (FTE) in Figure 6. Hybrid simulations provide detailed information about ion distribution function. Here we show the distribution function as one crosses a FTE from the magnetosheath to the magnetosphere. This figure clearly demonstrates the mixing of the two plasmas within the FTE.

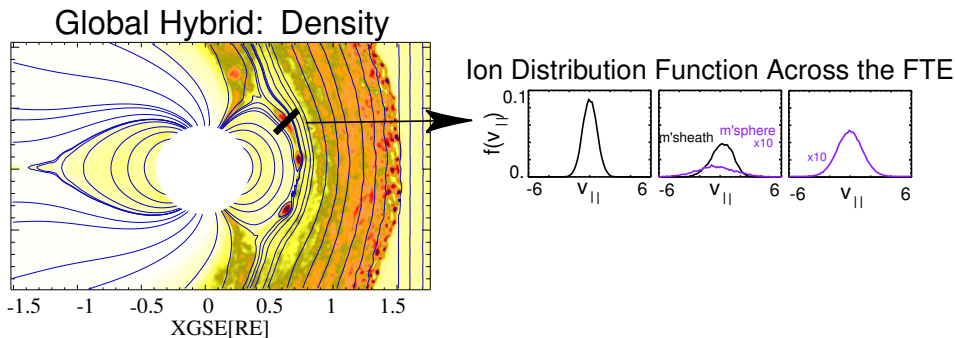


Figure 6. Formation of flux transfer events and the resulting particle distribution functions.

4. Conclusion

We are pursuing three different multi-scale techniques to achieve performance gains in 3D global hybrid simulations of the magnetosphere. Our multi-zone code is fully operational and we are using it to investigate various kinetic aspects of the magnetosphere. Our discrete event methodology is fully tested and has been benchmarked. We are in the process of extending it to 3D. The work on applying the reverse engineering algorithms to magnetic reconnection is just starting but it appears as a promising way to embed microphysics of magnetic reconnection in global simulations.

5. Acknowledgments

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