White Paper for *Frontiers of Plasma Science Panel*

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Title:	Wave-Particle Interaction in the Inner Magnetosphere
Corresponding Author:	Eun-Hwa Kim
• Institution:	Princeton Plasma Physics Laboratory
• email:	ehkim@pppl.gov
Co-Authors:	Jay R Johnson and Peter Porazik

Wave-Particle Interaction in the Inner Magnetosphere

Eun-Hwa Kim, Jay R Johnson, and Peter Porazik
Princeton Plasma Physics Laboratory

A. Scientific challenge

As the solar wind encounters the magnetosphere, it drags magnetic flux tailward leading to the formation of a hot, energetic plasma sheet. The plasma sheet serves as a reservoir of particles that may be injected into the inner magnetosphere during storms and substorms. These populations are transported earthward during periods of strong convection and/or bursty injections associated with reconnection or other non-adiabatic processes. As the plasma transports earthward, it energizes and changes the structure and dynamics of the entire inner magnetosphere. In turn, the altered fields and wave environment control the variability of the ring current and outer radiation belts. The necessity to self-consistently model cross-scale feedback between these global and kinetic-scale processes that govern transport and energization in the inner magnetospheres presents one of the most significant challenges to the space physics community.

Waves provide one of the most effective means of redistributing mass, momentum, and energy in the coupled solar wind-magnetosphere-ionosphere system. In the inner magnetosphere, it is widely accepted that ultra-low frequency waves play an important role in transport processes during the recovery phase of storms. These waves drive radial transport by breaking the third adiabatic invariant (drift motion) [*Jacobs and Westphal*, 1964; *Schulz and Lanzerotti*, 1974]. Diffusion can either populate the radiation belts when there is a plasma sheet source population or deplete the radiation belts for a locally energized population in the inner magnetosphere [*Green et al.*, 2004]. These waves are generated either internally resulting when unstable ring current populations develop following injection, or they may be driven externally by solar wind compressions or velocity shear instabilities [*Claudepierre et al.*, 2008] that leak wave energy into the inner magnetosphere (See Figure 1). Test particle simulations have shown the importance of both internally and externally driven waves for electron transport [*Elkington*, 2006; *Ukhorskiy et al.*, 2009]. A significant improvement in modeling the effect of ULF waves on radial transport during storms can be achieved by employing a self-consistent description of how wave-particle interactions modify the plasma profiles. Because transport depends critically on wave amplitudes, the model should include a nonlinear description of internal instabilities and wave propagation that incorporates the feedback of waves on the plasma distribution and fields.

The grand challenge is to be able to describe the self-consistent evolution of the inner magnetosphere including the effects of external ULF waves (imposed at the outer boundary), plasma injections, and internally generated low-frequency waves resulting from unstable particle distributions.

B. Approach

Global Wave Modeling – In order to address the issue of wave-particle interactions, it is fundamentally important to understand the global structure and distribution of wave amplitudes and polarizations. One approach is to develop a global wave model that can be coupled to a transport

code. A two-dimensional finite element code developed at PPPL [*Johnson et al.*, 2012; *Kim et al.*, 2015a] in collaboration with fusion scientists provides a linear model for waves in general geometries with realistic magnetic field and density models, is a suitable model. This code enables us to study a wide range of fluid waves from MHD waves to Langmuir oscillations in a consistent manner when the system is arbitrarily inhomogeneous, and has been used to examine magnetosonic waves in a magnetospheric geometry [*Johnson et al.*, 2012], the linearly polarized EMIC wave at Earth [*Kim et al.*, 2015b], and ultra-low frequency waves at Mercury [*Kim et al.*, 2015a].

One advantage of using the finite element method is that the local basis functions can be adapted to boundary shapes and can provide higher resolution in regions where solutions may exhibit singular behavior. In addition, any axisymmetric plasma configurations can be analyzed including a more tail like magnetospheric configuration [e.g., *Lu et al.*, 2003]. The global finite element wave model could be coupled to a transport code and provide spatial distribution of waves and properties suitable for quasilinear modeling. Such an approach would be an advance beyond empirical models.

Global Gyrokinetic Modeling – Application of the gyrokinetic approach has led to remarkable advances in understanding astrophysical, space, and laboratory plasmas. For example, gyrokinetic theory and simulations have been used extensively to describe excitation of low frequency pulsation driven by drift-bounce resonance with energetic particles in dipole geometry [e.g., *Porazik and Lin*, 2011] and describe how storm-time Pc5 waves are generated by energetic ions. Gyrokinetics has been used to successfully simulate the effect of instabilities that control anisotropy in the solar wind and magnetosheath, such as the mirror instability [e.g., *Porazik and Johnson*, 2013].

To advance understanding of the self-consistent evolution of the particles, large-scale fields, and waves in the inner magnetosphere, it is necessary to develop a massively parallel global kinetic code to model wave-particle interactions in the inner magnetosphere. The code development should proceed systematically with increasing capability to address waves at progressively higher frequency. Low frequency ULF waves can be addressed with a global gyro-kinetic ion description such as that developed by *Porazik and Lin*, [2011], while higher frequency fast magnetosonic, electromagnetic ion cyclotron, and whistler waves can be addressed by the gyro-gauge approach, which is valid when the frequency is on the order of the cyclotron frequency [*Qin et al.*, 2007]. The gyro-gauge model exploits the gyrosymmetry and has provided significant improvement in efficiency over simulation schemes that follow the full ion orbits for waves in the cyclotron range of frequency. The simulation can be used to investigate the self-consistent evolution of the inner magnetosphere including the effects of external waves (imposed at the outer boundary), plasma injections, and internally generated waves resulting from unstable particle distributions

C. Impact

Because the wave environment are key players in controlling the dramatic variability of the outer electron radiation belts and ring current ions, the better wave modeling will lead to better understanding the wave phenomena and finally to understand fundamental physical processes of the space environment. Furthermore, understanding wave properties and associated wave particle interactions is also a key ingredient in understanding the magnetospheric response to storms including the energization of electrons that can damage sensitive satellite equipment. Thus the wave modeling effort also leads the capability to predict extreme and dynamic conditions in space.

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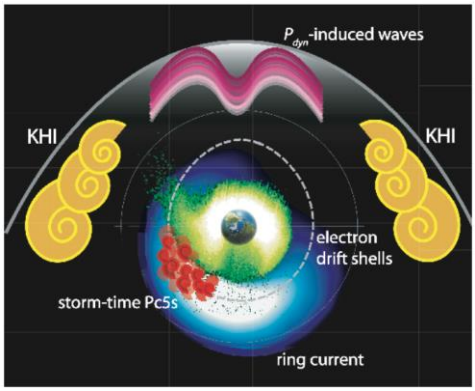

Figure 1. ULF waves in the inner magnetosphere can be classified by their energy sources as illustrated by *Ukhorskiy et al.* [2009]. Internally-driven pulsations, such as stormtime Pc5s, result from instabilities of ring current ions. Externally-driven pulsations can result from solar wind dynamical pressure variations, which produce pulsations localized on the dayside, or Kelvin-Helmholtz instability that generates waves localized on the magnetospheric flanks. How efficiently these waves couple wave power into the inner magnetosphere and their self-consistent coupling with energetic particles remains an outstanding question.