Vlasov Simulation of Nonlinear Wave Structures in Space Plasmas

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There are two primary approaches to kinetic simulations of space plasmas: particle-in-cell (PIC) methods and Vlasov methods. Both of these complementary approaches have advantages and disadvantages relative to one another. In the PIC method, a large number of particles from a given plasma species is represented by a single *macroparticle* with the charge-to-mass ratio characteristic of that species. The relatively small number of macroparticles (compared to the number of *physical* particles in the plasma being modeled) makes the evolution of their individual positions and velocities numerically tractable. By contrast, the Vlasov method takes the opposite approach in which the discrete particles are represented by a continuous phase-space fluid, while again maintaining the original charge-to-mass ratio. The Vlasov partial differential equations for each species are then numerically integrated on a phase-space grid. In both methods the evolution is governed by applied and self-consistent fields, with the latter found by solving the Maxwell (electromagnetic) or Poisson (electrostatic) equations.

As a result of the absence of discrete particles, Vlasov simulations are inherently quieter than corresponding PIC simulations. Consequently, simulation diagnostics (especially phase-space diagnostics) are easier to analyze. Implementing non-periodic boundary conditions is also simpler in Vlasov simulations. However, PIC simulations enjoy a major computational advantage when scaling to higher spatial dimensions because the simulation grid is only of dimension D of the physical space whereas the corresponding Vlasov phase space dimension is (in general) $2D$. Thus, for example, a Vlasov simulation of a 3-D plasma in 6-D phase space is numerically impractical—even on today's massively-parallel computers—for physically useful grid dimensions.

The focus of this talk will be an exploration of methods that can be employed to extend Vlasov simulations into higher dimensions without "breaking the computational bank." A primary example will be the extension of 1-D Vlasov simulations of current-driven double layers and associated electron holes (D. L. Newman et al., *Phys. Rev. Lett.*, **87**, 255001, 2001) into a second spatial dimension by restricting consideration to highly-magnetized species. Under this approximation, which is valid for electrons (but not ions) in regions of the auroral ionosphere where double layers and electron holes have been observed (R. E. Ergun, et al., *Phys. Rev. Lett.*, **87**, 045003, 2001), phase space is reduced from 4-D to 3-D because of restricted particle motion perpendicular to **B**. Proposed modifications to the Vlasov algorithm that will accommodate unmagnetized or weakly magnetized ions while keeping the computational demands well within the capabilities of today's computers will also be discussed.