Implementation of a numerical solver for the Klimontovich kinetic equation in weakly ionized plasmas.

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Abstract. Complex (dusty) plasmas are systems that are seeded with condensed matter particulates of nanometer to micrometer size and are typically engineered in low-temperature low-pressure plasma discharges. These particulates, when embedded in plasmas, get charged by constantly collecting and emitting plasma particles and radiation. The theoretical description of weakly coupled unmagnetized complex plasmas is based on the so-called fluctuation theory. The central objects of fluctuation theory are the exact microscopic phase densities of each plasma species, with each one obeying its own exact Klimontovich equation. A central feature of the many contributions of Klimontovich to the many-body physics is his emphasis on the microscopic phase space density as a fundamental variable in terms of which all other properties, microscopic and macroscopic, could be expressed. In classical mechanics, this density obeys an exact nonlinear Vlasov equation. Remarkably, this constitutes an exact mapping of Hamiltonian particle dynamics onto a simpler field theory.

Objectve. The primary goal is to simulate many types of plasma physics, including multi-component plasma, or dusty plasma, or other, by directly using the Boltzmann Equation, in phase space. There are numerous of benefits, including, the calculation of macroscopic quantities of interest, like, current, density, pressure, without the need of further assumptions, for example, an equation of state, or incompressibility.

Implementation. In this solver, the phase space is discretized into a 2D grid (x,v), therefore, one spatial dimension, and a numerical scheme is used primarily based on Newton's law in order to calculate the trajectories in the phase space. This closely resembles the Klimontovich distribution function for the Boltzmann Equation, except, in a discretized way. This then allows for a smoothing of the exact Klimontovich distribution into a smooth and continuous function from where one can obtain macroscopic plasma quantities of interest. In the implementation, the particle density and the average velocity distribution are taken as the macroscopic quantities of interest. From there, running the code shows a detailed evolution of the phase space with respect to time, from an initial condition in phase space. As an example, the evolution is shown in the figures below for two systems: an 'explosion' type system, where the initial condition consists of all particles at x=0, with a uniform distribution of velocities. As a second example, a 'jet' system is shown, where the particles are initially placed at x=0, but with a velocity distribution mostly positive, instead of evenly distributed around zero, like in the explosion case. Other simulations have been done, but not shown here, such as, random initialization in phase space, and others.

Discussion and Results. The time evolution of the 'explosion' and 'jet' initial conditions are shown right below in the pictures. As expected, each individual grid in phase space as if 'follows' a newtonian evolution, until hitting the wall at x=1 or x=-1, where they are sent to the opposite velocity v → -v. Because this is a 1D spatial system, the speed distribution (the absolute value of velocity) shouldn't change, and in fact, it doesn't. However, as for the velocity distribution, changes may occur as the particle gets reflected by the wall. The particle density starts at a peak in both cases, and then it soon spreads out in the entire space available, with some flutuations which persisted across the analyzed times in the simulation.

Furthermore, the collision has been implemented as well in the code, in both ways: using a newtonian approach two-body collision which is done two-by-two comparing all two different velocities in a given position; and, by actually calculating the Boltzmann Collision integral and making the update in phase space in each time iteration. It has been demonstrated that, a collisionless system, and a collisional system, are identical, and there are no differences, because the collision between two particles of same mass simply swaps their velocities.

The persistance of the flutuations in density, gives a clue that the implemented procedure is somehow limited. Indeed, because this is basically a Klimontovich distribution, the simulation is accurate with few number of particles, or low pressure, and such limitation is given by the number of points in the discretized phase space grid. Because of this, when compared to fluid simulations, there might be some sort of deviation from the results given by the implemented simulation.

Future Work. Many aspects can be explored, given the objective. Example: an extension to a 2D or 3D spatial dimensions (4D and 6D phase space dimensions). Also, the implementation of a fluid approach, Vlasov approach, and others, as to compare the results. And then, implementation of an actual numerical solver of the Boltzmann distribution equation.

Conclusion. A numerical procedure was implemented in a discretized phase space grid in 1D spatial dimensions. From there, a newtonian-like evolution was implemented, mostly described by Klimontovich distribution function. Many type of systems have been able to be simulated, with some initial position in phase space, in a particular, it has been shown here the 'explosion' and 'jet'. The implementation is limited in the sense it gives results for a small number of particles.