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STUDIES OF THE CHARGING OF A THIN DUST LAYER IN A PLASMA

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INTRODUCTION

When an infinite plane layer of dust having a number-density profile normal to the plane is exposed to an ambient e^-, p^+ plasma, one can imagine the features of the charging process near the layer boundary. If the e^-, p^+ temperatures are equal, and the B field is normal to the dust layer, the controlling factor is the large electron relative to proton speeds. Since the collision rate between plasma particles of number density n and speed v and an uncharged dust grain of radius a is estimated as the product $n\, v\, \pi a^2$, electrons dominate the charging process. The outer edge of the layer charges negatively, setting up an electrical potential that inhibits penetration of electrons into the layer and at the same time accelerates protons inward. Interior to the outer negative region then, one would expect many energetic protons compared to a reduced number of electrons from the ambient plasma. Charge imbalances are bound to arise, but the details are not so easy to deduce from simple arguments. These details are the subject of the present study.

DISCUSSION

Studies of dust charging have been carried out by a number of authors under a variety of assumptions. An important effect pointed out first by Goertz and Ip (1984) is that for interparticle grain separations much smaller than the plasma Debye length, the amount of charge on single grains is much smaller than the value expected when other dust grains are absent. Refinements to the charging model were made by Whipple, et al. (1985) and by Houpis and Whipple (1987). These efforts all involved a linearized form of the Poisson equation. The study by Houpis and Whipple also included a power-law grain-size distribution.

For many problems involving plasmas, neither a fluid approach nor an analytical kinetic approach is practical at present. For this reason, Wilson (1987, 1988) constructed a simulation code to determine the charge and field structure of an optically thin layer of dust in a plasma. Parameters chosen were within the ranges that describe the A and B rings of Saturn. The dust layer was described as a plane sheet of grains with fixed radius, having either Gaussian or square number-density profile and fed by a pool of Maxwellian plasma particles. In addition to the charge structure and the E fields in the layer, the results also gave the phase space distribution of plasma particles in the layer. Photoionization of dust grains was included. Along with collisions between plasma particles and dust grains, p-p collisions were assumed, e-p and e-e collisions were neglected. The primary factor controlling particle trajectories within the dust layer are local E fields.

The present work has been a three-phase process to extend Wilson,s code. In phase I, the code was modified to move particles more accurately through the simulation cells so that larger cells and longer time steps can be used. This has resulted in a faster code that still gives reasonable convergence and consistent results, although more testing is needed to further reduce run time. The movement of particles is done by starting with the initial position Z_1 and Z-component of velocity V_1 in a given simulation cell. The particle is then moved to its new position Z_2 with new velocity V_2 by assuming there is an average acceleration and an average velocity that we can deduce by successive approximations. For example, as long as no cell boundary is crossed, then a resonable starting point is

$$V_2 = V_1 + (e/m)\,(E_{AVE})\,dt \tag{1}$$

and

$$Z_2 = Z_1 + (V_1 + V_2)\,dt/2. \tag{2}$$

Knowing the fields at the lattice points allows one to write Eq. 1 to first order in a Taylor expansion of the E-field,

$$V_2 = V_1 + (e/m)E_1\,dt + (e/m)(\text{Grad } E)(V_{AVE}/2)\,dt^2 \tag{3}$$

Approximately, one can set $V_{AVE} = V_1$ in Eq. (3) to get V_2, which is used back in Eq. (2) to get a final value of Z_2. If a boundary is crossed by a particle during a time step, or if a particle changes direction in a cell, one must of course use special techniques.

Phase II has been to introduce a size distribution by defining a discrete starting distribution of Gaussian form for each dust particle radius a_i

$$n(z,a_i) = c\,a_i^{-P} \exp-[z/z_0(a_i)]^2 \tag{4}$$

where the central density is described by a power P that normally is expected to lie between 3 and 4. The width of the Gaussian is controlled for each size by making the parameter z_0 a function of particle radius. The optical depth for each particle size is then defined by the integral

$$T_i = \int_{-\infty}^{\infty} n(z,a_i)\,\pi a_i^2\,dz \tag{5}$$

giving

$$T_i = c\,a_i^{-P}\,\pi^{3/2}\,a_i^2\,z_0(a_i) \tag{6}$$

By specifying the total optical depth, the constant c is determined for the given parameters P and $z_0(a_i)$.

RESULTS

A single long computer run was made to test code improvements and to track the charging process. Parameters are for a dust layer of total optical depth 1.0 in a 1 eV plasma. Seven grain radii, between 1×10^{-5} to 1×10^{-2} m are included, with P = 3.5 in Eq. (4). Grains are assumed as Gaussians with 1/e widths of 10.0 m for the smallest grains to 5.0 m for largest grains. The resulting E field after 56,000 iterations, is shown in Fig. 1. In the outer region of the layer, as expected, the negative E field indeed is a barrier for incident electrons. By z = 23 m, the integration of the E field leads to a potential of about -2.7 volts, thus boosting proton energies but allowing only those electrons having energy above 2.7 eV to penetrate to the interior of the layer. For z near 23 m, protons outnumber electrons by almost 2 orders of magnitude. Thus, interior to the outer negative layer, a positive E field develops. The process then repeats itself. Figure 2 shows the variations of electrical potential with position. Of particular interest are the consistent oscillations of the potential between zero and almost -3.0 volts. It appears that the well known result for isolated grains, where equilibrium is achieved when the grain potential has the value 2.51 kT/e (which equals 2.51 for a 1 eV plasma), has its counterpart for the dust layer.

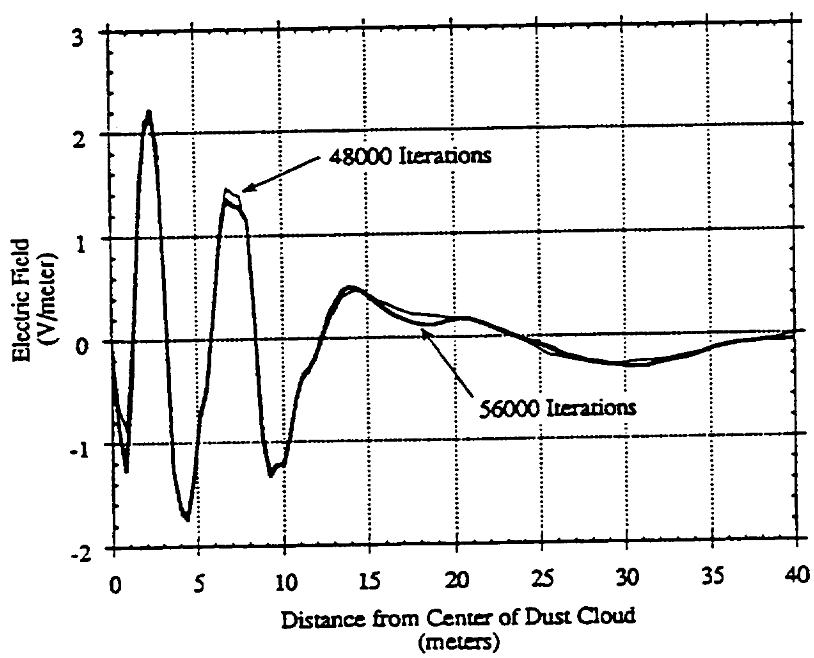

Figure 1. Electric field versus position for 48,000 iterations (light line) and for 56,000 iterations (heavy line)

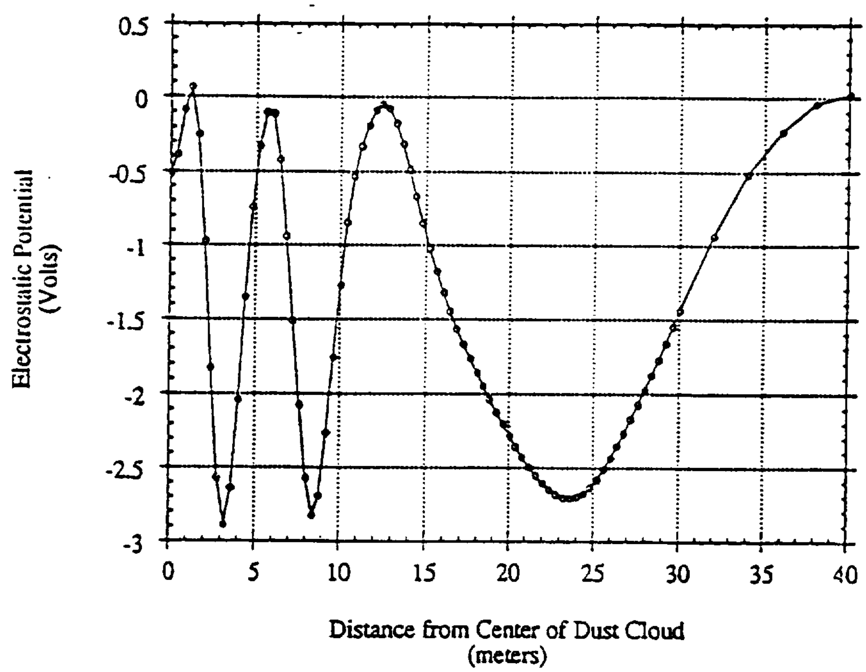

Figure 2. The electrostatic potential versus position in the layer

The result of looking at the average charge on individual grains also suggests the consequence of allowing the dust grains to move in response to the E field. The smallest grains near the layer edge will have relatively large negative e/m values and will be forced outward. Equilibrium will be reached ultimately when the outward electrical force is balanced by the restoring gravitational force. These issues will be explored in the near future.

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