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

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INTRODUCTION

Unlike the normal forms of matter (solid, liquid and gas) usually experienced on Earth, the usual form of matter in most of the universe is that of a plasma, or at least that of a partially or fully ionized gas. Often coexisting with the plasma are dust clouds containing grains varying in size from the submicrometer to the centimeter range or larger, grains which are in general charged by collisions with plasma ions and electrons or by photoionization. In most cases, the dust grains are widely enough separated in comparison with plasma particles that these relatively isolated grains follow orbits controlled mainly by external gravitational and electromagnetic fields, including radiation pressure. In other cases, the dust grains are of sufficient density that their presence has a significant effect on the plasma itself, as well as on each other, resulting in collective motions. In a complete calculation, then, the dust particles have a charge state and undergo motion, both of which are dependent on the plasma parameters as well as on the location of other charged grains. The charged particle trajectories themselves create fields that are superimposed on any external fields, and the resulting fields in turn exert partial control over the trajectories that create these same fields. In other words, a complete analysis requires a self-consistent calculation. Two examples of these latter types of cases within the solar system include cometary tails immersed in the solar wind and the dust rings of Saturn, Uranus and Jupiter embedded in each planet's magnetosphere.

DISCUSSION

One of the fundamental properties of any plasma is its Debye length, defined in MKS units by the expression

$$_{D} = \left(\frac{\epsilon_0 K\ T_e}{n\ e^2}\right)^{1/2} \tag{1}$$

Here, T_e is the electron temperature and n is the plasma particle density. The Debye length is a measure of the distance over which a charge embedded in the plasma is effectively shielded by plasma charges of opposite sign. Collective effects are expected whenever a large number of dust grains are present within a sphere of a Debye radius. Otherwise, if grains are widely separated the dust grains are effectively shielded from each other and are able to act independently. One of the important collective effects pointed out first by Goertz and Ip (1984) is that under the condition that interparticle grain separations are small with respect to the Debye length, the amount of charge on single dust grains in a dusty plasma is much reduced from its value expected when other dust grains are not present. The reduction can be as much as two or three orders of magnitude. Additional refinements to the charging model were made by Whipple et al. (1985) and by Houpis and Whipple (1987). These efforts all made use of the solution to a linearized form of the Poisson equation. The study by Houpis and Whipple also included a power-law particle-size distribution. The charge-to-mass ratio for grains is an important determining factor in assessing the significance of electromagnetic forces over other factors, such as gravity. In Saturnian rings, gravitational force on a typical grain is much larger than electromagnetic forces. Yet, even weak electromagnetic forces are capable of causing substantial variations in the normal Kepler orbits expected from gravity alone and must often be included because of their subtle effects.

Analytic solutions are of great value in understanding important aspects of the dust-plasma system but are by nature limited because of the approximations needed to make the problem tractable in practice. In order to overcome some of the limits imposed by an analytic solution, Wilson (1987, 1988) used a particle simulation technique to study the charge structure and electric field in a thin dust layer, one which has a thickness of the order of the plasma Debye length. In addition to the charge structure and the electric fields present as a function of position in the layer, the results also give the phase space distribution of plasma particles within the layer, as discussed in the next paragraph.

The assumptions of Wilson's study are as follows. First, the dust layer is considered a plane sheet of either a Gaussian or a square number-density profile fixed in space and is subjected to an ambient electron and proton plasma that feeds simulation charges from a reservoir outside the boundaries of the dust layer. Secondly, the only source of plasma particles is photoionization, resulting in Maxwellian photo electrons from the dust grains. Thirdly, collisions between plasma particles and dust grains are, of course, included, but plasma-plasma collisions are neglected since they involve mean free paths much larger than the dimensions of the dust layer. Fourthly, the only factor controlling particle trajectories within the dust layer are local electric fields. Finally, the dust grains all have the same radius. The equation set that is effectively satisfied are the Boltzmann equation, Poisson's equation and the dust charging equation,

$$\frac{\partial f_s}{\partial t} + v_z \frac{\partial f_s}{\partial z} + \frac{q_s}{m_s} E_z \frac{\partial f_s}{\partial v_z} = \left(\frac{\delta f_s}{\delta t}\right)_1 + \left(\frac{\delta f_s}{\delta t}\right)_g \qquad (2)$$

$$\frac{\partial E_z}{\partial z} = \frac{1}{\epsilon_0} \left[e(n_i - n_e) + q_d n_d \right] \qquad (3)$$

$$n_d \frac{\partial q_d}{\partial t} = \int_{-\infty}^{\infty} \sum_s q_s \left\{ \left(\frac{\delta f_s}{\delta t}\right)_g - \left(\frac{\delta f_s}{\delta t}\right)_1 \right\} dv_z \qquad (4)$$

In equations (2) through (4), f_s is a one-dimensional distribution function for species s (electrons or protons) in t, z and v_z space and n_e, n_p and n_d are electron, proton and dust grain number densities. Subscripts 1 and g in equations (2) and (4) denote loss terms and gain terms, respectively, for particles of species s. The distribution functions for electrons and protons are found by injecting simulation particles from the bordering plasma into the dust layer, each particle representing a certain number of electrons or protons. The dust density distribution stays constant, but of course becomes charged as time progresses toward some equilibrium state of the system.

WORK IN PROGRESS

Wilson's results indicate the presence of significant and systematic structure in the electric field as a function of location within the dust layer. Since the plasma and dust parameters assumed are in the range of the values that describe the rings of Saturn, this structure, if real, has implications for the dynamical features of the rings. Of prime importance, therefore, is a detailed look at the results to see if any mechanisms exist that can mute the fields.

The present study, in collaboration with C. J. Pollock from MSFC and G. R. Wilson from UAH, is designed to extend Wilson's model to include refinements in the actual operational design of the simulation code itself and to include additional physics in order to assess the resulting electric field structure and grain charges. Most of the initial phases of the work have focussed on the fact that the code, though in principle reliable, suffers from severe time constraints, requiring as much as 10-50 hours of CPU time for typical runs on a VAX computer. It is likely that by staging the code into steps in which early steps are carried out crudely and later steps successively fine tune the results, stage-by-stage, the total CPU time can be cut significantly. Preliminary results indicate the possibility to cut CPU time to as much as 1/3 or 1/5 the former time. The original Wilson code has been carefully examined, tested and documented. Shortcuts and staging systems have been introduced and tested which should make the code produce more accurate results with a finer grid system than would have been feasible heretofor. Continued testing and implementation of these refinements will be carried out at the author's home institution in the near future.

In addition to the effort at reducing CPU time to a manageable amount, work is in progress to include a dust-size distribution instead of assuming all dust grains have the same size. Competition between dust grains of different sizes may well lead to interesting and important differences in charging that lead to differences in small grain versus large grain particle dynamics. For example, one possible effect is for electric repulsion to spread out smaller particles more than larger particles in the dust layer. These differences, as well as the E-field structure are of special interest to research on Saturnian rings with their unusual spoked and beaded appearance, as well as on rings about Uranus and Jupiter.

in the longer term, there are additional processes that may need to be included. One is the possibility of charging by the knocking off of secondary electrons as a result of energetic electron or ion collisions. Another effect may be field emission of electrons by grains of very small radius. Finally, the generation of ion cyclotron or ion acoustic plasma waves may serve as a damping mechanism for thermalizing the plasma distribution and muting the interior electric field variations.

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