Self-similar expansion of a warm dusty plasma—I. Unmagnetized case

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Abstract. The self-similar expansion into vacuum of a warm dusty plasma filling semi-infinite half-space is investigated by including the adiabatic equation of state for the dust fluid. Given the complex nature of the problem, for simplicity the analysis is restricted to a one-dimensional expansion of a collisionless plasma in which the dust particles have constant charge. Exact analytical solutions are obtained for the case of the cold dust fluid for positive as well as negative charging of the dust particles. For the warm case, numerical solutions are obtained by solving the relevant self-similar equations. It is shown that an isothermal negatively charged dust fluid expands over a larger distance than an adiabatic one before the density drops to nearly zero. The effects of several plasma parameters such as the density and the temperature ratios on the expansion profiles are discussed.

1. Introduction

Plasmas consisting, in addition to the usual electrons and ions, of finite-size, charged particulate matter in the micron or sub-micron range have attracted much attention in recent years. These so-called dusty plasmas exist naturally in astrophysical and space environments such as cometary tails, planetary ring systems, interstellar and circumstellar clouds, etc. (Goertz, 1989). Nearer the Earth, the enhanced radar backscatter from the noctilucent clouds often observed in the polar regions during the summer seasons has been attributed to the presence of dust in the Earth's lower ionospheric regions (Havnes et al., 1990). On the other hand, understanding of the trapping as well as the movement of the dust grains is important in the fabrication of semiconductors using plasma-aided processes.

The effect of the dust component on the collective behaviour of plasmas has been extensively studied in the last few years by various authors. In particular, various types of waves and instabilities have been investigated (de Angelis et al., 1988; D'Angelo, 1990, 1993; Shukla et al., 1991; Shukla, 1992; D'Angelo and Song, 1990; Rosenberg, 1993; Rao, 1993a; Rawat and Rao, 1993). Because of the large mass of the dust particles compared to the electron and the ion mass, dusty plasmas support new kinds of waves in the very low-frequency regime. By considering thermal electrons and ions having Boltzmann distributions, Rao et al. (1990) predicted the existence of a novel kind of low-frequency electrostatic mode which they called the dust-acoustic wave. The inertial contribution to this mode comes from the dust fluid. Recently, the electromagnetic generalization of this mode to include compressional magnetic field and plasma density perturbations in a magnetized dusty plasma has been obtained by Rao (1993b).

The expansion of a dusty plasma is a fundamental process which is important in many practical situations. For example, the dusty plasmas found in space environments have typically free boundaries and therefore can expand into vacuum. On the other hand, in laboratory devices the dust particles in the form of impurities are produced in the source regions and can subsequently expand into the central plasma region. In this regard, Lonngren (1990) examined the self-similar one-dimensional expansion of an unmagnetized cold dusty plasma into a vacuum using the model of Rao et al. (1990). The analytical solutions presented by Lonngren (1990) are, however, strictly valid for the case of identically zero electron density. The work of Lonngren has been extended by Yu and Luo (1992) who provide a more detailed analytical study as well as numerical solutions for the density profiles and the flow velocities. A study of the expansion process via kinetic theory (Luo and Yu, 1992a,b) produces results which are in agreement with those from the fluid model. In this

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