A DUSTY PLASMA PRIMER

What is a dusty plasma, where are dusty plasmas, and why do we study them

Robert L. Merlino
Department of Physics and Astronomy
The University of Iowa, Iowa City IA, 52242
email: robert-merlino@uiowa.edu

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I. WHAT IS A DUSTY PLASMA

Dusty plasmas (also known as complex plasmas) are ordinary plasmas (ionized gas) with embedded solid microparticles. The particles can be made of either dielectric or conducting materials, and can have any shape. The typical size range is anywhere from 100 nm up to about 100 μm. Dust particles that are dispersed into plasmas for experimental studies, tend to be glass or plastic particles (melamine formaldehyde is a commonly used particle) and are spherical with a very narrow distribution of diameters. For example, a typically used particle may have a diameter of 3.50 ± 0.05 μm and a mass $\sim 3\times10^{-11}$ kg. Such narrowly sized particles are termed monodisperse. Some experiments use fine powders, such as aluminum silicate (kaolin) with a broad size distribution ranging from the sub-micron to tens of microns, and contain particles having laminar shapes with jagged edges.

II. WHERE ARE DUSTY PLASMAS

Dusty plasmas are ubiquitous in the universe; examples are proto-planetary and solar nebulae, molecular clouds, supernova explosions, interplanetary medium, circumsolar rings, and asteroids. Within the solar system there are the planetary rings, cometary tails and comae, and dust clouds on the moon. Closer to earth, are the noctilucent clouds composed of small ice particles that form in the summer polar mesosphere at an altitude of about 85 km where the temperature can dip as low as 100 K. Dust also turns out to be common in laboratory plasmas, such as tokamaks, plasmas used in the processing of semiconductors, and even in electron storage rings. In plasmas used to manufacture semiconductor chips, dust particles are actually formed in the discharge from the reactive gases used to form the plasmas. These particles can then grow by agglomeration and accretion and eventually fall onto the semiconductor chips contaminating them, resulting in an overall significant reduction in yield. The increased interest in dusty plasmas was due to two major discoveries in very different areas: (1) the discovery by the Voyager 2 spacecraft in 1980 of the radial spokes in Saturn's B ring, and (2) the discovery in the early 80's of the dust contamination problem in semiconductor plasma processing devices. More recently, the realization of the presence of dust particles in magnetic fusion plasmas, has led to expanded efforts to understand how these particles interact with plasmas. This is of particular concern for the design of the ITER device.

III. CHARGING OF THE DUST

Dust is important in plasmas because it becomes charged. This can occur due to the collection of electrons and ions from the plasma, secondary emission, or photoelectron emission from UV radiation, which is often the predominant mechanism for charging of dust in space and astrophysical plasmas. The dust in typical laboratory dusty plasmas is negatively charged, due to the fact that the electrons move about more swiftly than the ions. A 1 micron radius dust particle in a plasma with an electron temperature of a few eV, will have a charge corresponding to a few thousand electrons, with a resulting charge to mass ratio, $Q/m < 1$.

What makes dusty plasmas interesting other than $Q/m < 1$? There are several reasons. First, in the naturally occurring dusty plasmas there is typically have a range of sizes. The mass of the dust scales as the size cubed and the charge scales directly with the size. Thus, unlike ordinary plasmas, there will be a distribution of Q/m values. Secondly, the charge on a dust particle is not fixed, but fluctuates. For example, in the presence of plasma potential fluctuations, Q will vary. Also since Q depends on the electron temperature, it will vary if the dust moves through regions of varying T_e. The fact that Q is variable leads to phenomena, such as new collisionless wave damping mechanisms that are unique to dusty plasmas.

IV. SEEING THE DUST

Perhaps the most intriguing aspect of dusty plasmas is that the particles can be directly imaged and their dynamical behavior recorded and studied visually. This is accomplished using laser light scattering and fast digital video cameras. This allows for the unprecedented ability to study the dynamics of the dusty plasma at the kinetic level. In it relatively routine that the position and velocity of several thousand dust particles can be followed in real time.

V. DUST CRYSTALS

One of the novel properties of a dusty plasma is related to the relatively large value of the charge on the particles. Since Q/e can be ~ thousands, the interaction between dust grains can be very strong. As a result, dusty plasmas are often in the strongly coupled state, i. e., the ratio of Coulomb potential energy to thermal kinetic energy can be much greater than one. In this state, the dust particles form ordered solid-like structures, called Coulomb solids or crystals in one, two and three dimensions.

VI. RECENT WORK AND FUTURE DIRECTIONS

To prevent the dust particles from falling out of the plasma, it is necessary to provide a levitation force to balance the weight of the dust particles. One typical way in which this is done is to use a parallel plate RF plasma discharge with the lower plate as the cathode. Dust particles can then be levitated in the downward sheath electric field of the lower electrode. For example, a spherical dust particle of radius 1 μm composed of a material of mass density 2 g/cm^3 has a mass ~ 10^{-14} kg, requiring a levitation electric field E = mg/Q ~ 300

V/m. Such electric fields are typical in plasma sheaths. The downside of this approach is that the particles accumulate in two dimensional layers just above the lower electrode. To circumvent this problem, researchers have taken advantage of the microgravity environment provided onboard the International Space Station.

An important next step in the study of dusty plasmas is to study the effects of an applied magnetic field. This requires the development of a relatively large and extended dusty plasma in which the dust particles themselves are magnetized, i.e., the gyroradius of the dust particles is considerably less that the transverse dimension of the plasma. This is a difficult endeavor. For example, a 1 μm, cold (T_{dust} = 0.025 eV) dust particle, with a charge number Z = 2000, has a gyroradius ~ 2 cm/Tesla.

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