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On the charge of nanograins in cold environments and Enceladus dust

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ABSTRACT

In very-low energy plasmas, the size of nanograins is comparable to the distance (the so-called Landau length) at which the interaction energy of two electrons equals their thermal energy. In that case, the grain's polarization induced by approaching charged particles increases their fluxes and reduces the charging time scales. Furthermore, for grains of radius smaller than the Landau length, the electric charge no longer decreases linearly with size, but has a most probable equilibrium value close to one electron charge. We give analytical results that can be used for nanograins in cold dense planetary environments of the outer Solar System. Application to the nanodust observed in the plume of Saturn's moon Enceladus shows that most grains of radius about 1 nm should carry one electron, whereas an appreciable fraction of them are positively charged by ion impacts. The corresponding electrostatic stresses should destroy smaller grains, which anyway may not exist as crystals since their number of molecules is close to the minimum required for crystallization.

1. Introduction

Dust particles of nanometric size have been detected in situ in various parts of the Solar System, e.g. near comets (Utterback and Kissel, 1990), in the Earth low ionosphere (e.g. Friedrich and Rapp, 2009 and references therein), in the solar wind near 1 AU (Meyer-Vernet et al., 2009), in streams ejected by Jupiter (Zook, 1996) and Saturn (Kempf et al., 2005), in the atmosphere of Saturn's moon Titan (Coates et al., 2007), and in the plume ejected by the icy moon Enceladus (Jones et al., 2009). Nanograins, which make the transition between molecules and bulk materials, can be produced by condensation of gases and aggregation of molecules (Kimura, 2012), and/or by fragmentation of larger dust (e.g. Mann and Czechowski, 2012). The large surface-to-volume ratio of nanoparticles makes the proportion of surface atoms significant, so that their characteristic properties often differ from those of bulk materials and they are major agents for interactions with particles and fields.

Nanograins play an important role in magnetized environments because their interaction with electromagnetic fields varies in proportion of their electric charge, which varies more slowly with size than do the friction forces (proportional to surface) and the gravitational forces (proportional to volume). Hence nanograins are generally driven by electromagnetic forces as are plasma particles, so that their electric charge governs their dynamics (e.g. Burns et al., 2001; Horanyi, 1996; Mann and Czechowski, 2012; Mann et al., 2013). The electric charge can also determine the grain's minimum size via the electrostatic stresses producing fracture, and it also affects the grains' growth and coalescence. At larger scales, it determines the Larmor frequency and thus the time scale of grains' pick-up.

At nanometric sizes, several effects make the charging processes different from the classical charging of larger objects. First, it is well known that the particle sticking coefficients and photoelectric and secondary emission yields can change (Watson, 1972; Chow et al., 1993; Weingartner and Draine, 2001; Abbas et al., 2010; Mann et al., 2011), essentially because the electron free path in matter is of the order of (or larger than) 1 nm below ~10 eV (Fitting et al., 2001).

Two further effects appear when the grain radius becomes comparable to

$$r_L = e^2/(4\pi\epsilon_0 k_B T) \tag{1}$$

in a plasma of temperature T. Since $r_{L(\mathrm{nm})} \simeq 1.44/T_{\mathrm{eV}}$, this concerns nanograins in plasmas of temperature $\simeq$1 eV. This scale, often called the Landau radius, is the distance below which the mutual electrostatic energy of two approaching charged particles exceeds the kinetic energy of their relative motion, so that they significantly perturb each other's trajectories. This fundamental scale, which determines the plasma particle cross-sections for Coulomb collisions producing large perturbations, is also of major importance for dust grains. Indeed, the particles approaching a grain of radius $\sim r_L$ or smaller induce polarization charges whose Coulomb attraction increases the collected fluxes, thereby decreasing the charging time scales. Furthermore, since at this scale the charging becomes discretized, the equilibrium charge on a grain no longer varies in

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proportion of its size, but becomes comparable to one electron charge in a wide range of sizes, because the probability that an uncharged grain collects an electron exceeds the probability that a neutral or negatively charged grain collects an ion.

The latter phenomena have been studied in the contexts of the Earth's ionosphere (e.g. Jensen and Thomas, 1991; Rapp and Lübken, 2001 and references therein) and of the interstellar medium (e.g. Draine and Sutin, 1987; Weingartner and Draine, 2001). In this paper, we consider these effects for cold dense planetary environments in the outer Solar System, which are subjected to different constraints. We derive analytical results that can be used in these contexts, and apply them to the nanograins detected in Enceladus plume (Jones et al., 2009; Hill et al., 2012), where the electrons are cold enough (Shafiq et al., 2011) to put the Landau radius in the nano range, the plasma is dense enough (Morooka et al., 2011) for the photoelectron emission to be negligible, and the (larger) dust concentration is high enough to deplete the electrons by a large amount.

These calculations will enable us to estimate the grains' size limit set by electrostatic disruption and to compare it with other physical processes.

Units are SI, unless otherwise indicated explicitly.

2. Basic impact charging

Before considering nanograins, let us briefly summarize the classical electric charging by collection and emission of particles for a dust grain of radius $a \gg r_L$ in a plasma whose electron and ion densities may be different because of the possible presence of dust.

2.1. Impacts of charged particles

The charging of a grain changes its electric potential, which changes the particle fluxes until an equilibrium is reached when the different charge fluxes balance each other. The electron flux tends to exceed that of ions because of the faster electron speeds (except in the case of strong electron depletion discussed in Section 2.3); hence, when the charging is mainly due to electron and ion impacts, the body charges negatively until it repels sufficiently the electrons for their flux to balance that of positive ions. For this to be so, the electron potential energy at the body's surface $e\Phi$ must exceed sufficiently (but not too much) the particle thermal energy $\sim k_BT$. Thus the equilibrium grains' potential with respect to the ambient plasma is $\Phi \simeq -\eta k_BT/e$, with η of order of magnitude unity. For a sphere of radius a much smaller than both the Debye length L_D and the grains' separation, the electric charge is $Q = 4\pi\epsilon_0 a\Phi$. Substituting the above value of Φ yields the number of charge units Q/e at equilibrium

$$Z = -\eta a/r_L \tag{2}$$

with $\eta \sim 1$ in order of magnitude. The mean number of a grain's charges thus exceeds unity when $a/r_L \gg 1$.

The parameter η is easily calculated since in that case the particles are subjected to the Coulomb potential of the grain without intervening barriers of potential (the so-called orbit-limited condition (Laframboise and Parker, 1973; Whipple, 1981)). When the plasma particles are singly charged and have isotropic Maxwellian velocity distributions, the classical fluxes of each particle species can then be expressed straightforwardly as

$$N = N_0 e^{-|\eta|} = N_0 e^{-|Z| r_L/a} \quad \text{repelled particles} \tag{3}$$

$$N = N_0(1 + |\eta|) = N_0(1 + |Z| r_L/a) \quad \text{attracted particles} \tag{4}$$

per unit grain's surface, where r_L is the Landau radius corresponding to the temperature of the species considered and N_0 is the flux of that species on an uncharged grain

$$N_0 = sn\langle v\rangle/4 = sn(k_BT/2\pi m)^{1/2} \tag{5}$$

Here s, n, T, m, and $\langle v\rangle$ are the sticking probability, number density, temperature, mass, and mean speed of the species concerned in the unperturbed plasma. For ions of mass m_i and same temperature T as electrons of mass m_e, we have

$$N_{0e}/N_{0i} = \mu(n_e/n_i) \quad \text{with } \mu = (s_e/s_i)(m_i/m_e)^{1/2} \tag{6}$$

At equilibrium, the electron and ion fluxes balance, and η is the solution of the equation

$$\eta = \ln[\mu(n_e/n_i)/(1+\eta)] \tag{7}$$

This confirms that η is of order of magnitude unity, except if $\mu(n_e/n_i) \simeq 1$ – a case that we will discuss later. Note that we have not assumed $n_e = n_i$, in order for the results to be applicable in dusty environments. Therefore, although $\mu \gg 1$ because of the large ion-to-electron mass ratio, we have not necessarily $\mu(n_e/n_i \gg 1$, but only the weaker inequality $\mu(n_e/n_i) > 1$ (as will be shown in Section 2.3).

For nanograins in a low-energy plasma, the sticking probability of ions $s_i \simeq 1$, but the sticking probability of electrons may be smaller because the free path of electrons in solids (which decreases as energy decreases at energies exceeding a few 100 eV) reaches a minimum generally smaller than 1 nm in the vicinity of tens eV, and increases as energy decreases again to values comparable to or greater than 1 nm around 1 eV, taking into account elastic and inelastic scattering (Fitting et al., 2001). A conservative assumption is $s_e \simeq 0.3$–1 (Jurac et al., 1995; Vostrikov and Dubov, 2006; Megner and Gumbel, 2009) for nanograins, keeping in mind that s_e may be much smaller as the number of atoms decreases (Michaud and Sanche, 1987), essentially because the limited number of degrees of freedom precludes the conservation of energy and momentum in the collision.

For water-group incident ions $\mu \simeq 180 \times s_e$, so that Eq. (7) yields $\eta \simeq 0.31$, 1.85, or 3.65 for respectively $s_e n_e/n_i = 0.01$, 0.1, or 1.

2.2. Other charging processes

The above estimates assume that photoemission (including photodetachment) and secondary emission are negligible. The photoelectron emission on uncharged grains at heliospheric distance r_{AU} (in astronomical units) can be approximated by (Grard, 1973)

$$N_{ph0} \simeq 0.5 \times 10^{14}\chi/r_{AU}^2 \quad \chi \sim 0.1\text{–}1 \tag{8}$$

per unit of the total grain's surface area $4\pi a^2$ – to facilitate comparison with other fluxes (we have taken into account that the projected sunlit area is one-quarter of the grain's surface area). The smaller value of χ corresponds for example to materials such as graphite or ice, the larger to silicates.

For nanograins χ may be different for two main reasons which act in opposite senses. First, since the photon attenuation length generally exceeds the photoelectron escape length by a large amount, a small grain size limits the distance from the excitation region to the surface, which tends to increase the yield compared to that of bulk materials (Watson, 1972; Weingartner and Draine, 2001). Second, the photon absorption cross-section (normalized to the cross-sectional area) at the relevant wave lengths $\lambda \sim 0.1$ µm varies roughly as $2\pi a/\lambda \simeq 6 \times 10^{-2} a_{nm}$ when this size parameter is much smaller than unity; this is expected to decrease χ significantly. Because of the large uncertainties in these properties, we will use the conservative assumption $\chi \leqslant 0.1$ for silicate and water ice nanograins. From (8), we deduce the ratio between photoelectron emission and ion (of mass Am_p) collection for uncharged grains at 10 AU heliocentric distance ($\simeq$Saturn's orbit),