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Field Emissions from Dust Grains

Abstract of Doctoral Thesis

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Preface

Almost one percent of our galaxy consists of dust grains—objects of different shapes with a size distribution from micro to nanometers. In the space, a number of processes leads to their charging. Among them, the photoemission and electron and ion attachments are dominant. On the other hand, processes like electron or ion field emissions can limit the total grain charge (or the surface grain potential). Our laboratory simulations of dust grain charging are performed inside a quadrupole trap where we can hold a single dust grain for several days and expose it to electron and/or ion beams and thus this experimental approach allows us to separate individual charging process. The doctoral thesis presents a survey of our experimental results with a special attention to electron and ion field emissions from dielectric and gold grains.

Introduction

Dust grains are now considered to be a standard component of various laboratory and space plasmas [Mendis and Rosenberg, 1994]. In the space, they can work as a carrier of mass and charge and also as a catalyst for a variety of chemical reactions.

Since dust grains are important elements in the solar system and in the interstellar medium, there are many missions detecting dust (e.g., Galileo, Ulysses, Cassini, Stardust, LDEF[1]) and exploring in detail the possible dust grain size, mass, and charge, as well as dust dynamics. Investigations of a space dust and its properties is rather complicated, and thus a number of "near space" and laboratory experiments simulates the space environment and studies different processes. Robertson et al. [2004] measured the mass density and charge of dust grains and aerosols in the Earth's mesosphere using a rocket facility. Sternovsky et al. [2002] studied the triboelectric charging of dust grains staying on the surface with respect to the Moon's observations where levitating dust was detected. Sickafoose et al. [2002] observed levitation of a dust cloud above the conducting surface in the plasma sheath while irradiating by UV. Barkan et al. [1994] and Robertson et al. [1998] studied charging of dust grains falling through the plasma column under varying conditions. Spann et al. [2001] dealt with secondary electron emission of dust grains trapped in the Paul trap[2], unfortunately in a very narrow range of attainable charges (due to the experimental technique of charge measurement). Abbas et al. [2002] charged dust grains in the same experiment by the UV radiation and observed the red light scattering by these objects [Abbas et al., 2003]. Švestka et al. [1993] measured the secondary electron emission profile of dust grains in a similar experiment using an electron beam up to 20 keV. They achieved a positive charge even at high-energy electron charging and this effect was attributed to an emission from the opposite side of the grain. On the other hand, Čermák et al. [1995] observed a field ion emission

[1] http://www2.jpl.nasa.gov/galileo/, http://www2.jpl.nasa.gov/ulysses/, http://saturn.jpl.nasa.gov/, http://stardust.jpl.nasa.gov/, http://setas-www.larc.nasa.gov/LDEF/

[2] Paul and Steinwedel [1956] invented a 3D quadrupole trap for ions storing (the Nobel prize in Physics 1989 [Paul, 1990] "for the development of the ion trap technique").

from dust grains charged by energetic ions (grains were stored in the Paul trap). They shown that field ion emission can occur at much lower electric field than was expected, nevertheless, they attributed the emission to the field evaporation.

The charge acquired by dust grains in the plasma is principal for the understanding of the physics of dusty plasmas. The most important processes that provide the dust grains with a charge are the collection of electrons and ions, secondary electron emission, and photoemission [Whipple, 1981]. Due to the higher random flux of electrons, dust grains typically charge negatively in the plasma [Walch et al., 1995]. However, positive dust charges may be achieved when photoemission or the emission of secondary electrons are dominant. In plasmas with a strong UV radiation content (e.g., space plasmas), photoelectrons can be released from the surface of the dust. Leaving photoelectrons represent a positive charging current to the dust grain and if strong enough, then can result in positive net charge on the dust [Arnold and Hessel, 1985]. Secondary electron emission is another process that may lead to positive dust charge when surrounding plasma is hot. The composition of dust grains in plasmas can be diverse and many materials have secondary emission yields larger than unity [Horanyi, 1996]. In the space, combination of all charging processes takes place and resulting grain charge depends on many factors that determine what process would dominate. We describe several of them in detail in following subsections.

Secondary electron emission

The secondary emission of electrons is a process where primary electrons affect the surface of a sample and excite the electrons of the material, which can in some cases leave the sample. Then, the yield of "true secondary emission" is defined as the ratio of emitted secondary electrons to primary electrons δ.

This process leads to either positive or negative charge of the dust grain; the polarity depends on the energy of incident electrons. If we define σ as the total yield of the secondary electron-electron emission, then the grain is charged positively when $\sigma > 1$. If we denote the yield of backscattered electrons as η, a simple relation can be written:

$$\sigma = \delta + \eta. \tag{1}$$

When the grain is positively charged, it attracts by its surface charge a portion of secondary electrons with energies lower than $e\phi$, where ϕ is the grain's surface potential. Thus, another quantity playing a role in establishing the charge is the energy distribution of secondary electrons.

Last but not least, properties which affect the total yield of secondary emission is the shape and size of the particular grain. At first, one should take into account the incidence angle of primary electrons, and at second, the finite grain size that plays an important role when primary electrons are energetic enough to penetrate through the grain.

This process can lead to an enhancement of the grain charge for high energies of primary electrons, E_e, as found by Švestka et al. [1993]. Chow et al. [1994] treated this effect theoretically but a satisfactory explanation was given by a Monte-Carlo model of secondary emission by Richterová et al. [2004, 2005].

Field electron emission

Because of a small size of dust grains, even a relatively small dust charge may induce a large electric field on its surface. Thus, also the high-field processes of electron or ion field emissions have to be considered [Draine and Salpeter, 1979]. These processes may establish a limit to the attainable surface potential. Mendis and Axford [1974] and others [e.g., Northrop, 1992] set the negative limit potential due to a field electron emission to about

$$(\phi/\mathrm{V}) < -900(a/\mu\mathrm{m}), \tag{2}$$

where a is the dust radius[3]. These calculations are based on the Fowler-Nordheim relation [e.g., Fowler and Nordheim, 1928; Good and Müller, 1956; Gomer, 1961], which describes well the field-emitted current density:

$$i \sim \frac{F^2}{\varphi \; t^2 \left(F, \varphi\right)} \cdot \exp\left(\frac{\varphi^{\frac{3}{2}}}{F} v\left(F, \varphi\right)\right), \tag{3}$$

where F is the electric field strength, φ is the work function, and v and t are weak functions of F and φ whose values are tabulated. In a semi-logarithmic plot of $\log((i/\mathrm{A})/[F/(\mathrm{V/m})]^2)$ vs. $1/F \cdot (\mathrm{cm/V})$, the curve is nearly linear with a slope proportional to $(\varphi/\mathrm{eV})^{3/2}$:

$$\text{slope} \sim \varphi^{\frac{3}{2}} s\left(F, \varphi\right), \tag{4}$$

where the function s varies from 0.83 to 1.

Field ion emission

Not only negative charges are limited, but also the field ion emission will play a role when a high positive charge is reached. Emission of positive ions in a high electric field is caused by three main processes: (1) field desorption, (2) field ionization, and (3) field evaporation [Good and Müller, 1956; Gomer, 1961]. Field desorption means that the atoms or molecules of an adsorbed gas are ionized in the strong electric field at the surface and desorbed by a repulsive electric force. Field ionization is a process where the atoms of a surrounding gas get ionized close to the surface by the strong electric field and then are as ions repulsed. Field evaporation is similar to the field desorption but the emitted ions originate from the bulk material. Which of aforementioned processes will play a leading role in the field ion emission depends on the combination of the surrounding gas, the surface material of the sample, and of the adsorbed layer. From earlier experiments [e.g., Good and Müller, 1956], one should expect the ion emission at an electric field of about 10^{10} V/m.

Čermák et al. [1995] observed an anomalous discharging current from spherical glass grains appearing at high positive surface potential. The authors attributed this effect to field emission of ions from the grains surface, although the electric field intensity was only 5×10^8 V/m, i.e., nearly two orders of magnitude less than can be expected from theoretical predictions or earlier experiments.

[3] In other words, the field strength of the order of 10^9 V/m is sufficient for field electron emission.

Sternovsky et al. [2001] repeated the experiment of Čermák et al. [1995] on glass grains of different diameters. The authors observed a limitation of the surface potential due to ion field emission for the surface field strength of 3×10^8 V/m. The discharging current density was as high as 10^{-5} A/m^2 and increased exponentially with increasing electric field strength.

Velyhan et al. [2004] performed a series of field ion emission measurements from melamine formaldehyde resin (MF) grains of various sizes (diameters 2.35, 4.97, and 9.78 µm). They found that discharging due to field emission does not depend on the pressure of the surrounding gas within a range from 10^{-8} to 10^{-6} Pa. Furthermore, the aspect of the charging history was found to be of a crucial importance.

Experimental set-up

We take advantage of our laboratory facilities [detail description in Pavlů et al., 2004b] which allow us to catch a single electrically charged grain in an electrodynamic trap and to affect it by electron/ion beams with a tunable energy. The experiment is conducted under ultra-high vacuum conditions (typically 10^{-7} Pa, i.e., 10^{-9} mbar). The grain is illuminated by a red laser light and the charge to mass ratio of the grain, Q/m, is calculated from the frequency of the grain oscillations detected by an optical system [Čermák et al., 1995]:

$$\frac{|Q|}{m} \cong \pi^2 r_0^2 \cdot \frac{f_{AC} f_z}{V_{AC}^{eff}} \cdot \frac{1}{\sqrt{1 + (1.8 f_z / f_{AC})^2}}, \tag{5}$$

where r_0 is the inner radius of the ring quadrupole electrode, V_{AC}^{eff} and f_{AC} are the amplitude and the frequency of the power supply respectively, and f_z is the grain oscillation (secular) frequency. The ratio $f_z : f_{AC}$ is kept about $1 : 10$ during experimental procedure because of keeping the stability of the grain motion within the trap. Further parameters of the grain (surface potential, radius, total charge, mass, etc.) can be determined from a simple experimental procedure [Čermák et al., 1995; Pavlů et al., 2004b].

The aim of thesis

As it was shown, the investigation of dust grains (their composition and properties) become more important recently together with exploration of the Saturn–Titan system. Therefore, laboratory simulations of charging processes plays a leading role due to an ability to separate individual processes and to study single one of them. Our task was to further enlarge current knowledge, optionally to proof some of the theories describing dust grains charging.

Čermák [1994] built an experiment for such kind of measurements. He verified basic principals of operation and obtained preliminary results — mainly connected with volt-ampere characteristics and field ion emission [Čermák et al., 1995]. Žilavý et al. [1998] performed series of measurements dealing with the study of "background currents", compiled a simple model and on its basis improved technical aspect of the

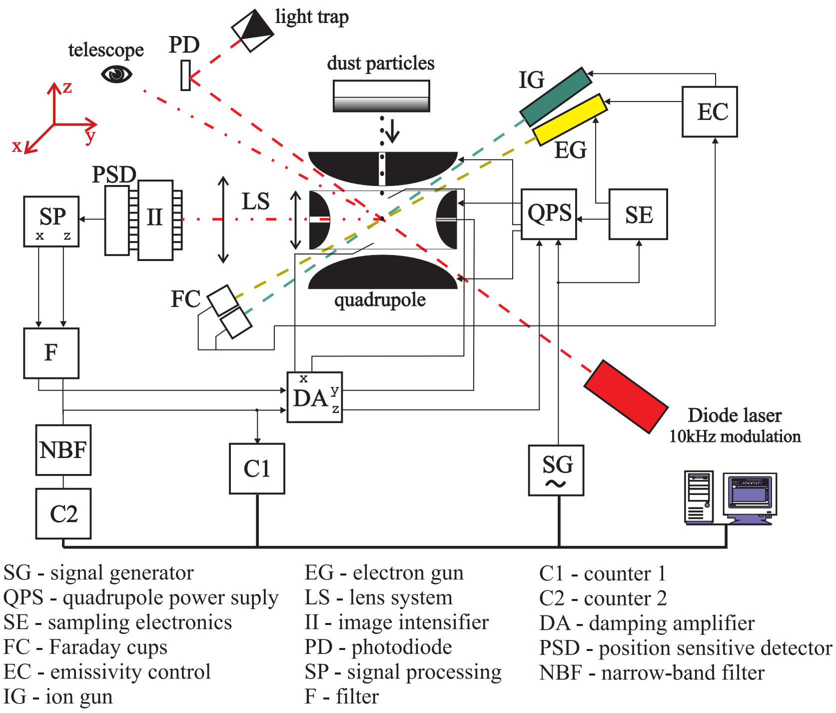


Figure 1: Simplified scheme of the experimental set-up.

experiment by sampling the quadrupole power supply that reduced these background currents significantly. Sternovsky et al. [2001] studied field ion emission from glass and zinc grains. They proved preliminary results [Čermák, 1994] that the influence of this emission becomes important from electric fields of 5×10^8 V/m which is nearly two times lower than was expected.

My study was focused on negative charging of dust grains with motivation to deeply understand field electron and ion emissions. This complex topic could be divided into following tasks:

1) To perform a detail study of MF grains, mainly their properties, and to make a recommendation for their further application in laboratory simulations of space dust charging.

2) To determine the conditions suitable for negative charging of dust grains and to prepare the methodology of this process.

3) To study field electron emission of dielectric grains by attaining large electric field strengths which was not possible up to now.

4) To contribute to clarification of the processes connected with field ion emission and to apply this knowledge on a variety of materials ranging from dielectric grains (glass, MF) to metals (MF/Ni, Au) and for charging by different kinds of ions as well as for different charging histories.

Used dust simulants

The most relevant materials for the simulation of dust processes are silicates of different composition. Thus, glass seems to be an appropriate material and it has been already used by several previous authors[4]. However, the parameters (composition, mass density, dimensions, and shape) of such samples are usually not well defined. For this reason, many experiments apply the melamine formaldehyde resin (hereafter MF) particles as a dust simulant [e.g., Cabarrocas et al., 2002; Morfill et al., 2002; Paeva et al., 2002; Samarian and Vaulina, 2002, and many other papers in that issue]. The MF resin is known to be hydrophilic. Advantages of this simulant are a spherical shape with a guaranteed diameter and a well defined mass density. However, we have found that some parameters of these particles change during the experiments.

As an example, the time evolution of MF grain parameters is shown in Figure 2. We have found that 2.35 µm grains placed into a vacuum vessel gradually evaporate with a rate of $\approx 1.2 \times 10^{-18}$ kg/day. Such rate can be explained in terms of drying that was observed on ≈ 10 µm grains as well. The total mass loss during the time interval in Figure 2 was $\approx 5 \times 10^{-18}$ kg (i.e. about one per mile). Since the grains were exposed to air, we can expect at least a monolayer of water adsorbed on the surface. In this case, the drying seems to be a reasonable explanation for this behavior.

A baking of the MF grains in vacuum at $\approx 240\,^\circ$C causes a relative decrease of the grain mass by $\approx 10\%$. We think that the rate of the mass losses of a non-heated dust simulant is probably negligible for most laboratory experiments because the mass decrease cannot reach the limits given by the uncertainty of the grain diameter in a reasonable time. However, this change can be of a considerable interest in experiments where grains can be heated (or stored in vacuum for a very long time).

It's now obvious that observations made on MF grains would be done with kind of uncertainty of the structure and of some physical properties. In order to check how the results of measurements depends on the grain structure, we have also used the MF grains covered with a thin nickel layer (hereafter MF/Ni), and gold grains as well.

Secondary electron emission of dust grains and clusters

One of the basic measurements is to obtain the charge-to-mass ratio (or surface potential) as a function of the energy of primary electrons (hereafter, we will call this "equilibrium characteristics"). When the electron energy is larger than about 100 eV, the dust charge will be positive due to secondary electron emission. Each equilibrium point (i.e., the equilibrium surface potential) is defined by the secondary electron emission yield ($\sigma(E_e) = \delta(E_e) + \eta(E_e)$) and by the energy spectrum of true secondary electrons. An important role plays the size of the grains. When it is small enough, an increase of the surface potential for higher electron energies can occur due to the penetration of primary electrons through the grain that enhance the backscattered yield, η. This increase was previously attributed to the rise of the

[4]Silicates represent a significant part of the composition of cosmic grains.

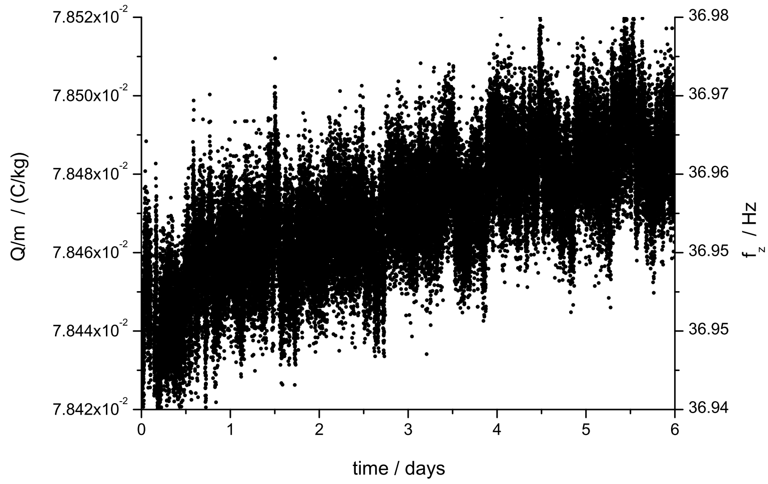


Figure 2: Time evolution of the charge-to-mass ratio ($Q/m(t)$) of MF grain of the radius $R \approx 1.17\,\mu$m without any external acting. On the vertical axis, the secular frequency is depicted, which is proportional to Q/m. Adopted from Pavlů et al. [2004b].

number of true secondary electrons from the opposite side of the grain [Chow et al., 1993]. Nevertheless, the model of Richterová et al. [2004] has shown qualitatively and quantitatively that this effect is due to an enlargement of the yield of backscattered electrons, $\eta(E_e)$, with respect to planar samples.

The effect is demonstrated in Figure 3 where the equilibrium specific charge of a grain is plotted as a function of the electron beam energy. Shapes of these curves are discussed in Richterová et al. [2004] and we just point out here that the MF/Ni grain was charged positively for all investigated energies, whereas the pure MF grain can be charged negatively for primary electron energies in the range of 5 to 8 keV. That is due to a low yield of secondary emission in this range. The grains are generally charged negatively, when using electron beam of the energy E_e corresponding to $\sigma(E_e) < 1$.

The electrons leaving the grain (true secondary electrons as well as scattered primaries) can be captured by another grain in the case of grain clusters. This effect is shown in Figure 4 where the equilibrium characteristics are plotted for several clusters from glass grains of 1.2 µm of diameter. Note that the characteristics for all clusters exhibit a clear local minimum at ≈ 5 keV. The following rise of the grain potential is steeper for small clusters. Large clusters behave like a planar sample due to the aforementioned shielding effect. However, the local minimum remains at ≈ 5 keV. It indicates a characteristics dimension of the grains in the cluster[5].

High negative potentials: Field electron emission

Since secondary emission tends to charge grains positively, negative potentials can be reached only if the total yield of secondary emission, σ, is lower then unity. As can be seen from Figure 5 that schematically shows the energy dependence of the

[5]The minimum should shift toward higher energies with growing radius of the grain.

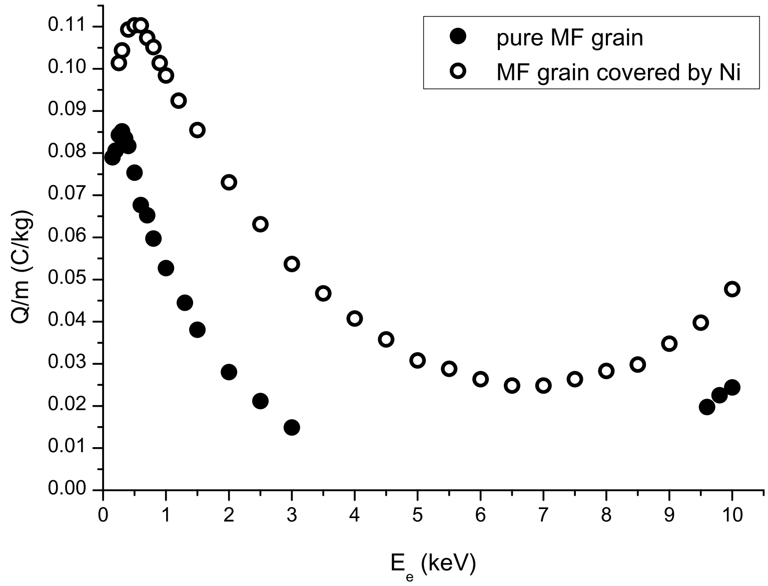


Figure 3: Comparison of the equilibrium characteristics for MF (full circles) and MF/Ni (open circles) grains with the radius $R \approx 1.17\,\mu$m [Pavlů et al., 2005a]. The charge of the grains is in both cases positive due to secondary electron emission.

secondary emission yield, this situation occurs at low as well as high energies of the impinging electron beam. It should be pointed out that in a consideration of effects of secondary emission, the acceleration or deceleration of primary electrons by the grain potential, ϕ, must be taken into account and thus the impact energy, $E^{eff} = E_e - e\phi$, is plotted on the horizontal axis in Figure 5. As it can be seen from the figure, there are two regions allowing to reach negative potentials by the electron bombardment. Providing that the impact energy is very low, $E^{eff} < E_1$, an negatively charged grain is charged by a negative current up to the point where $E^{eff} = 0$. Then the energy of the primary electrons can be increased slightly (again keeping $E^{eff} < E_1$) and the process repeats. The step by step increase continues until the field emission process limits the further increase of the surface potential.

The second possibility of increasing the negative charge of dust grains is to apply a high impact energy, $E^{eff} > E_2$. The negative grain potential increases (i.e., becomes more negative) in order to reach a stable point where $E^{eff} = E_2$.

An example of a measured equilibrium characteristics is given in Figure 6a. The points show the equilibrium potential of one dust grain as a function of the electron beam energy measured for three different pressures in the vacuum chamber. As the currents of secondary and field emissions as well as the ion current are negligible for the lowest energy, we can assume that the surface potential numerically approximately equals to the beam energy[6].

If the electron beam were the only current onto the grain, one would expect a linear dependence, which is plotted in Figure 6a as a thin straight line. The deviations of the measured points from this line are caused by additional currents. At low beam energies, the deviation nearly linearly increases with the energy. This

[6]This procedure was partially proved by an independent measurement of a grain capacitance.

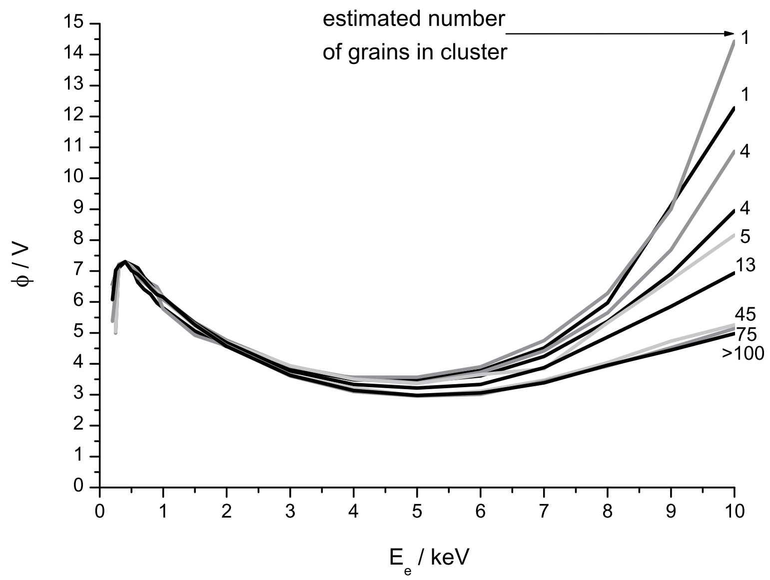


Figure 4: Equilibrium characteristics measured for several clusters of dust grains made out of glass with monodisperse radius of $R \approx 0.6\,\mu$m. [Pavlů et al., 2002b].

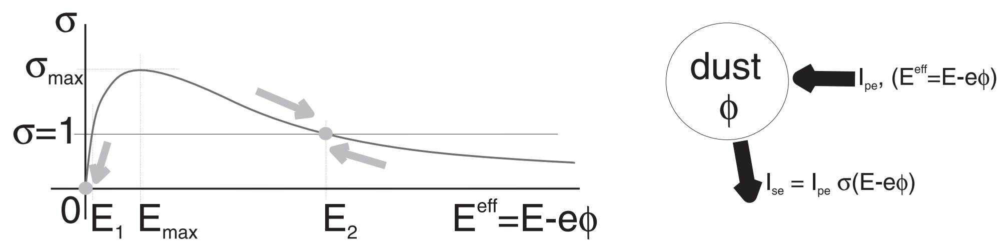


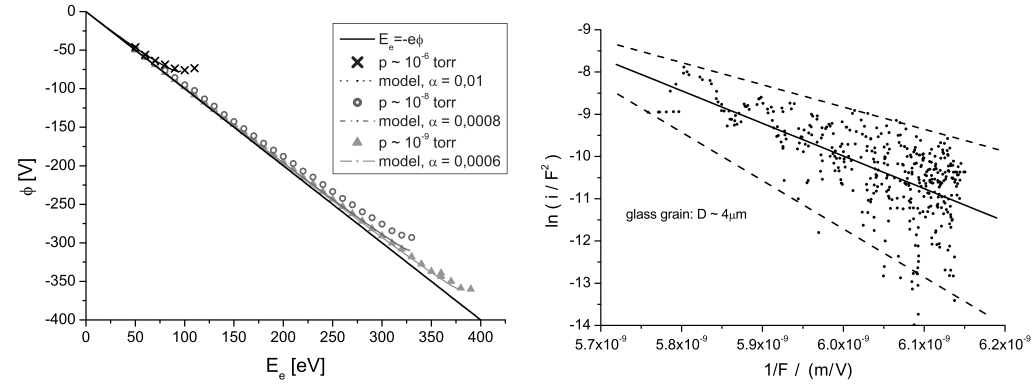
Figure 5: Schematic dependence of the total yield of secondary emission on the primary electron energy. The equilibrium points at the curve ($E^{eff} = 0$ and $E^{eff} = E_2$) are marked by full circles. The equilibrium can be reached only if the grain surface potential is negative.

indicates the ion current as a possible source. However, at a certain beam energy, the measured surface potential tends to saturate. A careful inspection shows that saturation starts at the point where the difference between the grain potential and the beam energy reaches a value of $\approx$ 15 to 20 V. The fast rise of the current from the grain is caused by secondary electron emission. If the difference between the surface potential and the beam energy reaches $\approx$ 30 V, the yield of the secondary emission reaches the unity and the net current becomes positive. This leads to a rapid discharging of the grain, which is then finally getting lost from the trap.

In Pavlů et al. [2004a], we have developed a simple model of the negative grain charging that deals with ionization of the residual gas and secondary emission. The resulting potential can be written as:

$$\phi = \frac{\alpha + \delta - 1}{\frac{1-\delta(E)}{\phi_e} + \frac{\alpha}{\phi_i}} \tag{6}$$

where ϕ stands for the grain potential, α is the proportionality constant between the



(a) (b)

Figure 6: (a) Equilibrium characteristics for three different pressures in the vacuum chamber (we used a grain with a diameter of about 4.4 µm) and a comparison of the equilibrium characteristics with the model (the constant α is proportional to the pressure, the constants ϕ_i, E_{max}, and δ_{max} were set to 10 V, 500 eV, and 3, respectively). (b) The Fowler-Nordheim plot measured on the glass grain (parameters were: slope $\approx -7.7 \times 10^7$, electric field strength $\approx 1.7 \times 10^8$ V/m, calculated work function ≈ 2 eV). Adapted from Pavlů et al. [2004a].

electron beam current and the ion current at zero grain potential (it is proportional to pressure of the residual atmosphere), δ stands for the energy dependent yield of secondary electron emission, ϕ_e is the accelerating potential of the electron beam, and ϕ_i the characteristic potential of the ionization process (i.e. numerically equal to the characteristic ion energy).

The experimental points in Figure 6a can be fitted by the function (6) and the values of the unknown constants can be obtained. Results of such fits are also plotted in Figure 6a, and the used constants are given in the figure caption. We can note that the obtained values of the constants E_{max} and δ_{max} are in a good agreement with the values expected for glass [Gibbson, 1966].

If the pressure in the chamber is low enough, we are able to reach surface potentials of -350 V on ≈ 5 µm glass grains. This corresponds to an electric field at the grain surface of about 2×10^8 V/m. A spontaneous discharging of the grain after switching off the electron gun was observed at such field strengths. We calculated the discharging current and re-plotted it in a $\ln(i/F^2)$ vs. $(1/F)$ plot (Figure 6b) where the best fit of the experimental points is shown as the full line. Using the equation (4), we have estimated the effective work function to be ≈ 2 eV.

In order to check the dependence of the field emission properties on the grain structure, we have carried out a similar experiment with grains from melamine formaldehyde (MF) resin. Figure 7 shows the Fowler-Nordheim plots for the aforementioned grains. However, the effective work function derived in this case was about ≈ 5 eV, i.e., close to the work function expected for insulators. The difference between the low work function determined for glass grains and the much higher work functions for MF grains can be connected either to different material properties or to a different way of charging. In the case of glass grains, the first stability point (see Figure 5) was used for charging, unlike the MF grains where the charging was achieved by the second one.

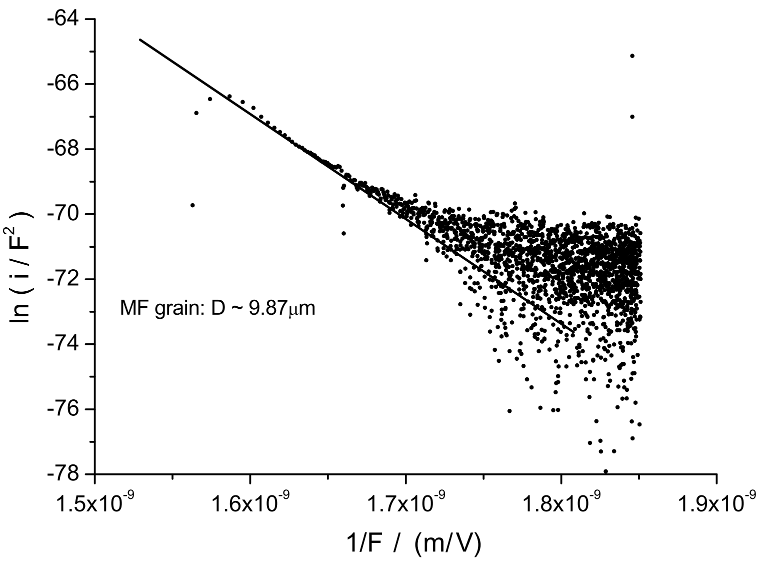


Figure 7: Fowler-Nordheim plots for 10 μm MF grain.
Curve parameters: slope $\approx -3.3 \times 10^8$, electric field strength $\approx 6.3 \times 10^8$ V/m, calculated effective work function ≈ 4.9 eV. Adapted from Pavlů et al. [2004a].

Charging by ion beam: Field ion emission

The paper by Pavlů et al. [2005a] compares field ion emission from MF and MF/Ni grains of the same diameter charged to high positive potentials using a He^+ beam. Although in the case of field evaporation, there should be a strong material dependence, but the process that we probably observe is field ionization of adsorbed atoms and molecules and therefore one would expect only a weak dependence of the emission current on the grain material. Figure 8 shows that it is not the case. The attainable positive potential is by a factor of 2 larger for MF grains. However, the nickel layer covering MF/Ni grains exhibits a certain degree of roughness (checked by the electron microscope), the surface electric field can be locally enhanced and thus the larger discharging currents are not so surprising in this case.

The discharging characteristics describes the changes of the grain charge. It does not allow to decide directly what of suggested processes (field ionization, desorption, or evaporation) is responsible for discharging. Velyhan et al. [2004] carried out a measurement during which the pressure in the chamber was increased by a factor of 10. The measurement is shown in Figure 9 and indicates that field ionization can be only a negligible part of the discharging current under our conditions.

The field evaporation of the grain material is probably again only a minor source because we have reached the measurable currents at field strengths of the order of 10^9 V/m. It means that a most probable source would be the field desorption of adsorbed atoms and their consecutive ionization in the large electric field at the grain surface. Since the important part of the adsorbed layer is created from the beam ions recombining at the grain surface, one would expect that the discharging current would depend on the type of ions used for the grain charging.

This topic was treated in Pavlů et al. [2005b] in a systematic way. We have used

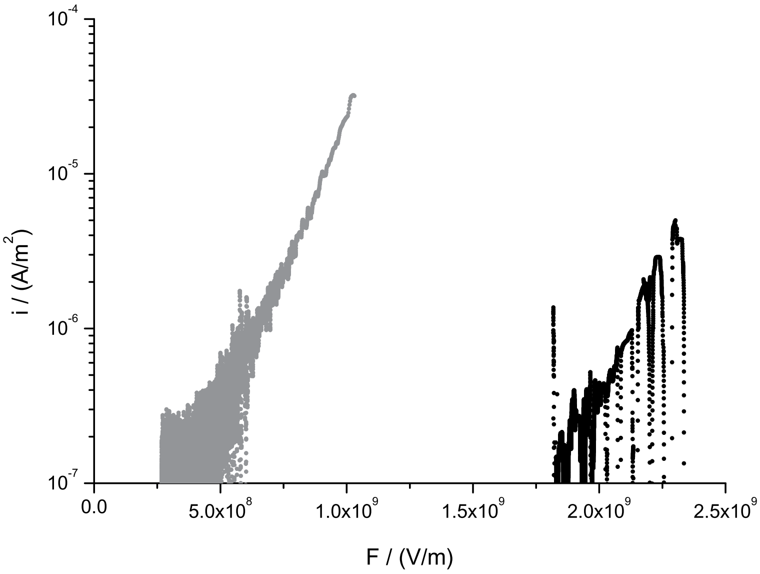


Figure 8: Discharging characteristics for pure MF (black) and MF/Ni (grey) grains with diameters of $\approx 2.35\,\mu$m. The beam current density used was $10^{-5}\,$A/m^2 and the beam energy was 5 keV. The grey and black lines show similar slopes of current decreases for both grains. Adapted from Pavlů et al. [2005a].

dust simulants from gold in order to exclude unknown material constants of MF. Figure 10a shows three discharging characteristics. The dashed curve was measured just after trapping the grain into the quadrupole and the two others after three hours of grain treatment with 5 keV He^+ ions. We conclude that the surface treatment set up a defined (from the point of view of the surface roughness and impurities) surface state. Figure 10b compares the discharging characteristics obtained after charging the grain with 5 keV He^+ and Ar^+ ions. The discharging current at the same surface potential is smaller if the grain is charged with Ar^+ that probably corresponds to a higher bonding energy of Ar atoms at the surface.

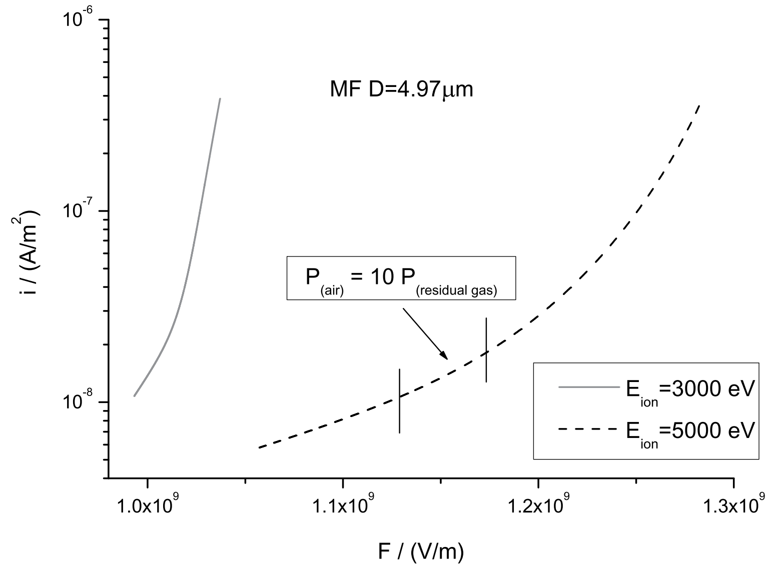
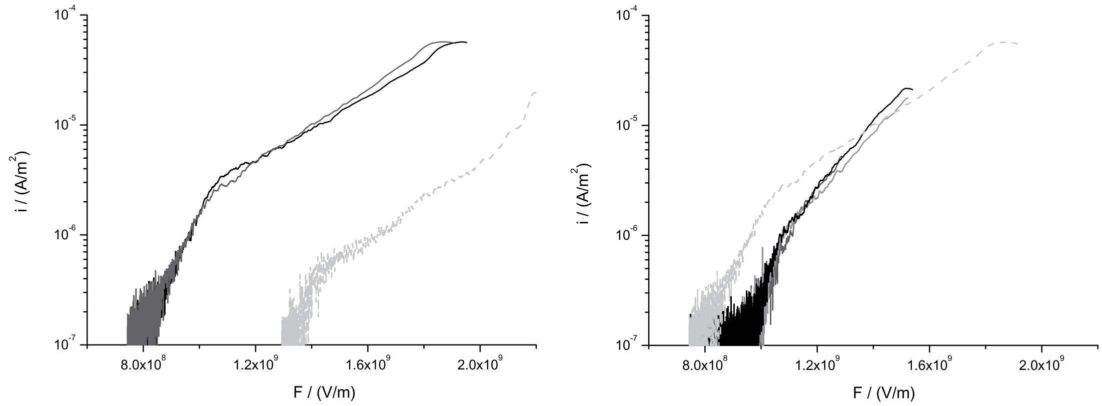


Figure 9: Discharging currents from a MF grain (of diameter $\approx 5\,\mu$m) charged by different ion energies. The arrow points to the part of the discharging curve measured under the increased pressure (residual pressure is of the order of 10^{-8} Pa. Adapted from Velyhan et al. [2004].



(a) (b)

Figure 10: Discharging characteristics of an Au grain with a diameter of $\approx 1.5\,\mu$m:(a) after two-times three-hour bombardment by 5 keV He^+ ions. The dotted curve is the discharging characteristics before the treatment; (b) charged by 2, 3, and 5 keV Ar^+ ions (all curves are nearly identical)—for a better comparison, we added the grey curve from Figure a (here grey, dotted). Adapted from Pavlů et al. [2005b].

Conclusion

Dust grains may become charged by various processes in different environments. Immersed in a plasma, grains are subjected to collisions with electrons and ions, thus acquiring generally a non-zero electric charge. Processes leading to dust charging range from electron and ion attachments to different kinds of emissions. The most important are emissions induced by UV radiation, particle impact, and presence of strong electric fields. Dust grains may be charged negatively or positively and both components can coexist in laboratory and space plasmas. Usually, a combination of several charging processes takes place and the resulting grain charge depends on many factors (the properties of surrounding environment, the grain material, or the grain charging history) that determines which process dominates.

In the thesis, processes leading to ion and electron field emissions from various spherical samples have been demonstrated. The experiments were performed on our unique apparatus using an electrodynamic quadrupole trap [Čermák, 1994; Žilavý et al., 1998; Čermák et al., 2004]. A few modifications and improvements were implemented into the experimental facilities [Pavlů et al., 2002a].

The most important scientific results can be summarized as follows:

1) The comparison of the secondary emission from MF and MF/Ni grains indicates that the increase of the grain potential at higher electron beam energies is caused by enhanced back-scattering yield of primary electrons [Pavlů et al., 2005a]. This conclusion contradicts to the suggestion of Chow et al. [1993] claiming that this increase is due to enhanced current of true secondary electrons.
2) We have shown that the attainable surface potential of a dust cluster is a decreasing function of the number of grains in the cluster [Pavlů et al., 2001]. This effect was attributed to the capture of electrons leaving a particular grain by other grains in the cluster.
3) The techniques developed for negative charging allow us to charge dust grains to several hundreds volts and observe spontaneous discharging by field electron emission. Application of Fowler-Nordheim theory on discharging currents provided the effective work functions[7] of different grains and materials $\varphi_{\mathrm{SiO_2}} \approx 2\,\mathrm{eV}$, $\varphi_{\mathrm{MF}} \approx 4,9\,\mathrm{eV}$, $\varphi_{\mathrm{MF/Ni}} \approx 2,4\,\mathrm{eV}$, $\varphi_{\mathrm{Au}} \approx 5,2\,\mathrm{eV}$, [Pavlů et al., 2003, 2004a, 2005a]. The surprisingly low work function obtained for SiO_2 grains was attributed to the emission of the electrons from surface states [Pavlů et al., 2003]. The comparison of results obtained for SiO_2 and MF suggests that the energy of primary beam can influence the subsequent discharging current [Pavlů et al., 2004a].
4) The grains charged by an ion beam to high positive potentials spontaneously release their charge at field intensities of $\approx 10^9\,\mathrm{V/m}$. Čermák et al. [1995] at-

[7] One should realize here that the work function of dielectrics is partially uncertain, especially when it is charged externally. In this case, surplus electrons are located within surface states and even in conduction band. Moreover, due to an electric field penetration inside the bulk material, the energy bands are bent down and therefore surface part of the conduction band can be located under a Fermi level. For this reason, we are talking about "effective work functions" of a certain grain.

tributed this discharging to field evaporation of the grain material. This idea was further developed by Sternovsky et al. [2001]. The authors calculated the evaporation rate of very small dust grains charged with photoemission. Because they expected the emission rates similar to the ion beam experiment, they have expected the evaporation at much lower field strengths. As was shown, the emission process in ion beam experiment, unlike charging by photoemission, is not evaporation in the electric field.

Our measurements lead us to suggestion that the field ion emission mechanism is dominantly caused by the desorption (and following field ionization) of the atoms of the primary ion beam [Pavlů et al., 2005b]. Nevertheless, the discharging of non-metallic grains can be influenced by other factors that should be further investigated [see e.g., Velyhan et al., 2004].

Our series of ion and electron emission studies contributed to understanding of dust charging processes. Nevertheless, many questions still remain open and further investigations dealing with particular charging/discharging processes are desirable.

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