

# LABORATORY STUDIES OF CHARGING PROPERTIES OF DUST GRAINS IN ASTROPHYSICAL/PLANETARY ENVIRONMENTS

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**Abstract.** Dust grains in various astrophysical environments are generally charged electrostatically by photoelectric emissions with UV/X-ray radiation, as well as by electron/ion impact. Knowledge of physical and optical properties of individual dust grains is required for understanding of the physical and dynamical processes in space environments and the role of dust in formation of stellar and planetary systems.

In this paper we focus on charging of individual micron/submicron dust grains by processes that include: (a) UV photoelectric emissions involving incident photon energies higher than the work function of the material and b) electron impact, where low energy electrons are scattered or stick to the dust grains, thereby charging the dust grains negatively, and at sufficiently high energies the incident electrons penetrate the grain leading to excitation and emission of electrons referred to as secondary electron emission (SEE).

It is well accepted that the charging properties of individual micron/submicron size dust grains are expected to be substantially different from the bulk materials. However, no viable models for calculation of the charging properties of individual micron size dust grains are available at the present time. Therefore, the photoelectric yields, and secondary electron emission yields of micron-size dust grains have to be obtained by experimental methods. Currently, very limited experimental data are available for charging of individual micron-size dust grains. Our experimental results, obtained on individual, micron-size dust grains levitated in an electrodynamic balance facility (at NASA-MSFC), show that: (1) The measured photoelectric yields are substantially higher than the bulk values given in the literature and indicate a particle size dependence with larger particles having order-of-magnitude higher values than for submicron-size grains; (2) dust charging by low energy electron impact is a complex process. Also, our measurements indicate that the electron impact may lead to charging or discharging of dust grains depending upon the grain size, surface potential, electron energy, electron flux, grain composition, and configuration (e.g. Abbas et al, 2010).

Laboratory measurements on charging of analogs of the interstellar dust as well as Apollo 11 dust grains conducted at the NASA-MSFC Dusty Plasma Lab. are presented here.

# Laboratory Studies of Charging Properties of Dust Grains in Astrophysical/Planetary Environments

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**Abstract.** Dust grains immersed in ambient plasmas and radiation, are charged and coupled to the plasma through electric and magnetic fields. Dust grains in various astrophysical/planetary environments are generally charged by: (a) photoelectric emissions with incident radiation at photon energies higher than the work function of the material and (b) sticking of low energy electrons and ions of the surrounding plasma or by secondary electron emissions induced by incident electrons/ions at sufficiently high energies. Consequently, the particle charge is an important parameter that influences physical and dynamical processes in the interplanetary and interstellar medium, planetary rings, interstellar dust clouds, comets and the outer atmospheres of planets. The charging properties of individual micron-size dust grains are expected to be substantially different from the bulk materials. However, no viable models for calculation of the charging properties of individual micron size dust grains are available at the present time. Currently, very limited experimental data are available for charging of individual micron-size dust grains. In this paper we give a review of the results of the measurements on charging of analogs of the interstellar as well as Apollo 11 and 17 lunar dust grains carried out on the Electrodynamic Balance Facility at the NASA-MSFC.

## 1. Introduction

Dust grains in various astrophysical environments are generally charged electrostatically by photoelectric emissions with UV/X-ray radiation, as well as by electron/ion impact. Knowledge of physical and optical properties of individual dust grains is required for understanding of the physical and dynamical processes in space environments and the role of dust in formation of stellar and planetary systems.

In this paper we focus on charging properties of individual micron/submicron dust grains by processes that include:

- (a) UV photoelectric emissions involving incident photon energies higher than the work function of the material,
- (b) Electron impact at low energies with the incident electrons sticking to the dust grains, charging the dust grains negatively; and

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(c) Electron impact at sufficiently high energies with the incident electrons penetrating the dust grain and leading to excitation and emission of electrons referred to as secondary electron emission (SEE).

It is well accepted that the charging properties of individual micron/submicron size dust grains are expected to be substantially different from the bulk materials (e.g. [1-2]). However, no viable models for calculation of the charging properties of individual micron size dust grains are available at the present time. Therefore, the photoelectric yields, and secondary electron emission yields of micron-size dust grains have to be obtained by experimental methods. Currently, very limited experimental data are available for charging of individual micron-size dust grains (e.g. [3]). Our experimental results, obtained on individual, micron-size dust grains levitated in an EDB facility (at NASA-MSFC), indicate that the following significant features:

(1) The measured photoelectric yields are substantially higher than the bulk values given in the literature [e.g. 3-7], and indicate a particle size dependence with larger particles having order-of-magnitude higher values than for submicron-size grains [e.g. 4-5];

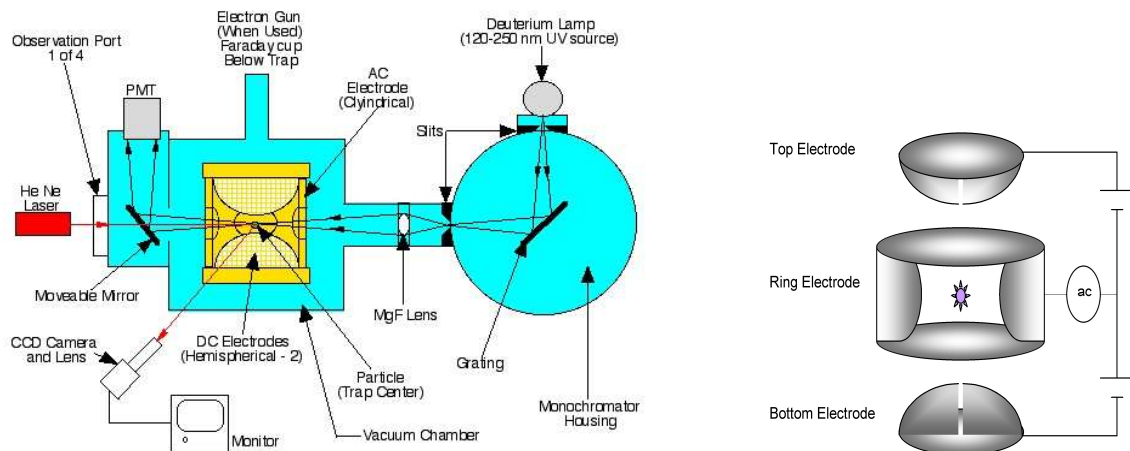
(2) Dust charging by low energy electron impact is a complex process. Also, our measurements indicate that the electron impact may lead to charging or discharging of dust grains depending upon the grain size, surface potential, electron energy, electron flux, grain composition, and configuration (e.g. [6-7]).

A review of the laboratory measurements on charging of analogs of the interstellar dust as well as Apollo 11 and 17 dust grains conducted at the NASA-MSFC Dusty Plasma Laboratory is presented in the following.

## 2. Experimental set-up for the dust charging experiments

The research work presented here is based on the experimental investigations conducted on a facility referred to as EDB that provides a unique capability to conduct a wide range of experiments on micron size dust grains in simulated space environments.

The experimental apparatus consists of: particle generator, EDB (with the top and bottom DC electrode and the AC ring electrode), DC and AC voltage power supplies, vacuum system, electron gun, the monitoring equipment, the UV source and monochromator and the electron gun. The experimental setup is shown in Fig. 1 (a).



**Fig.1. (a) Experimental Setup; (b) Electrodynamic Balance**

The particle injector employing a pressure impulse technique is used to charge the particles [e.g. 8]. The balance itself consists of spherically shaped DC top and bottom electrode and a ring AC electrode with apertures made to allow optical access to the trapped particle as shown in Fig.1(b). Such an electric field configuration creates a null potential at the geometric centre of the electrodes. A charged micron-size dust grain can be levitated against the gravity by adjusting the dc potential ( $V_{dc}$ ) applied between the two cap end electrodes. The trap is placed in a vacuum chamber. A 5 mW-HeNe laser and a CCTV camera with a zoom microscope lens are used to observe the particle by projecting the scattered light from the dust grain onto a TV monitor.

The above experimental facility has been used to conduct the measurements presented in the following sections.

### 3. Laboratory measurements on dust charging by photoelectric emissions

The photoelectric emission process is considered to be the dominant process in many astrophysical environments with radiation from nearby sources. Photoelectric emission occurs at the incident photon energies higher than the work function of the material. The photoelectric efficiencies and yields have to be determined experimentally. In Section 3.1 we describe the experimental technique employed in the Dusty Plasma Laboratory at NASA/MSFC, while in Section 3.2 we present and discuss some of the results of the measurements on dust charging by photoelectric emissions.

#### 3.1 Experimental technique for measurements on dust charging by photoelectric emissions

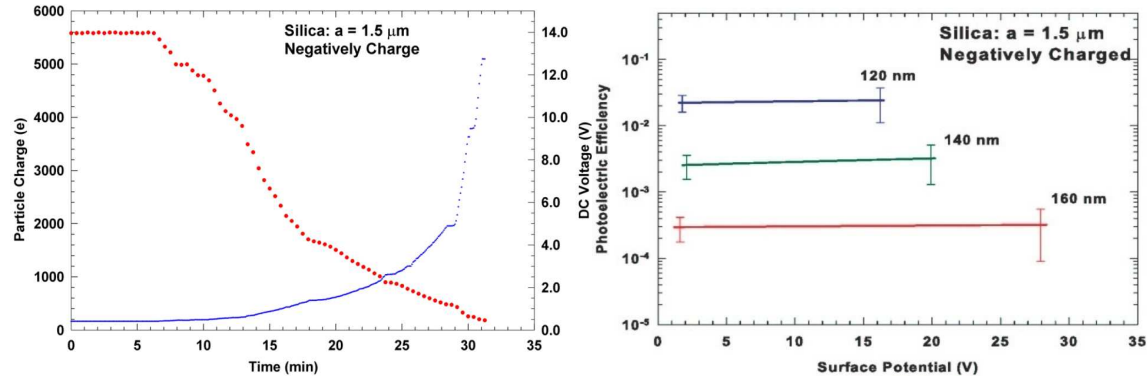
Dust grains of desired composition and size are injected into the balance at atmospheric pressure. Once the particle is stably trapped and the particle generator is removed, the chamber is closed and the system is evacuated to pressures of  $\sim 1$ -5 torr at which the effective diameter is determined by measurements based on marginal stability conditions (“spring point” measurements) [e.g. 8]. The particle diameter has to be determined separately since the direct measurements on the EDB provide the charge to mass ratio only. This technique is based on slowly varying the electrical parameters of the EDB to a point near an unstable regime when the particle begins to oscillate. The system is then evacuated to pressures of  $\sim 10^{-5}$  torr at which the photoelectric emission measurements on the levitated particles are carried out. The particle is then exposed to UV radiation in the range of 120-160 nm. As the particle charge changes, its position in the trap is balanced against gravity by adjusting  $V_{DC}$ . The change in particle charge is then determined as a function of time in accordance with equation:

$$q(t) = \frac{gz_o m}{C_o} \frac{1}{V_{DC}(t)} \quad (1)$$

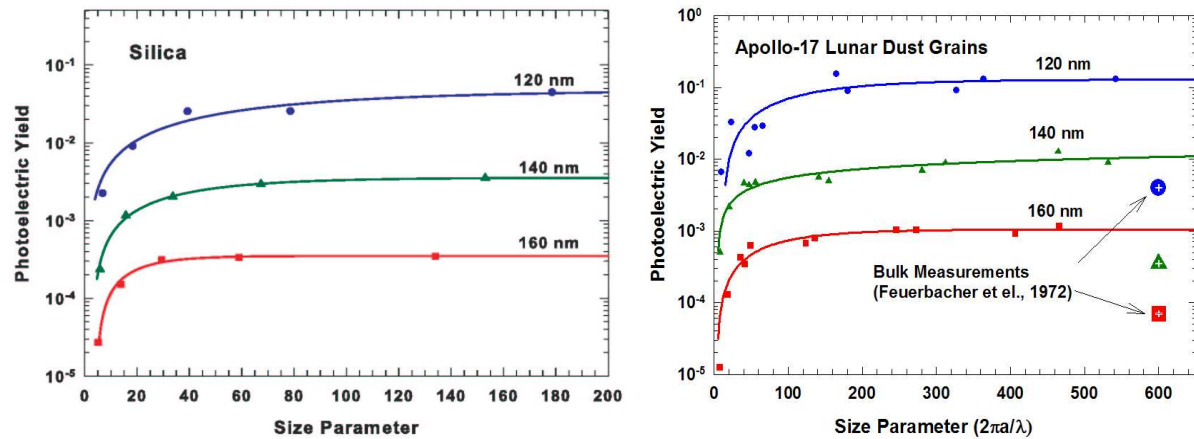
With the value of  $V_{DC}$  needed to balance the gravity and the mass  $m$  that is calculated by using the effective particle diameter determined by the “spring point” technique and the known particle mass density ( $\rho$ ), the particle charge  $q(t)$  is calculated from equation (1) as a function of time. With this measurement technique change in particle charge by one electron can be detected in certain regimes.

### 3.2. Experimental results and discussion on dust charging by photoelectric emissions

The above measurements were conducted on a number of SiO<sub>2</sub> spherical particles in the size range of 0.2-6.62 μm that represent the analogs of the interstellar dust grains as well as a number of selected lunar dust grains collected during Apollo 11 and 17 missions that were obtained from NASA-JSC. In the following figures we present some of the results from the measurements dust charging by UV photoelectric emissions that are published in [4-5]



**Fig.3 (a)** Discharging of a 1.5 μm SiO<sub>2</sub> particle exposed to UV radiation of λ=120 nm (red dots) and the corresponding change of V<sub>dc</sub> during the experiment (blue curve); **(b)** The average photoelectric efficiencies as a function of the particle surface potential for silica particles illuminated with UV radiation at λ=120, 140, and 160 nm.



**Fig4.** Composite plot of the photoelectric yields Y measured at UV wavelengths of 120, 140, and 160 nm as a function of the size-parameter  $x = (2\pi a / \lambda)$  for **(a)** SiO<sub>2</sub> particles and **(b)** Apollo 17 lunar dust grains.

Fig.3.(a) shows discharging of a 1.5 μm SiO<sub>2</sub> particle when exposed to UV radiation of λ=120 nm (red dots) and the corresponding change of V<sub>dc</sub> during the course of the experiment (blue curve). Fig.3(b) represents the average photoelectric efficiencies as a function of the particle surface potential based on measurements on silica particles illuminated with UV radiation at 120, 140, and 160 nm wavelength. The error bars indicate the 1-σ standard deviation due to variability of the particles size as well as the measurements errors. Fig. 4 shows the composite plot of the photoelectric yields Y measured at UV wavelengths of 120,

140, and 160 nm (10.3, 8.9, and 7.9 eV) as a function of the size-parameter  $x = (2\pi a / \lambda)$  for (a) SiO<sub>2</sub> particles and (b) Apollo 17 lunar dust grains. In Fig.4(b) the corresponding data for the bulk materials [9] are shown for comparison. The details of the calculations of photoelectric efficiencies and yields are given in [4-5].

### 3.3. Conclusions from measurements of dust charging by photoelectric emissions

Some of the most important conclusions from the above presented experiments on dust charging by photoelectric emissions are:

- (1) Measurements on individual 0.1 to 11.8  $\mu\text{m}$  silica, carbonaceous, olivine, and lunar dust grains exposed to 120-160 nm UV radiation indicate size dependence of the photoelectric yields, with yields of submicron size particles being lower than for large size particles.
- (2) Measured photoelectric yields for carbonaceous particles and lunar dust grains are found to be larger by ~an order of magnitude compared to bulk measurements.
- (3) This is in contrast with the existing models that indicate higher values for smaller particles.
- (4) However, surprisingly size dependence of the yields is found to be in qualitative agreement with the size dependence predicted by classical electrostatic models applied to the atomic clusters.

## 4. Laboratory measurements on dust charging by electron impact

The dust charging by electron impact is an important dust charging process in planetary and astrophysical environments. Low energy electrons are reflected or stick to the grains charging the dust grains negatively. At sufficiently high energies, electrons penetrate the grain leading to excitation and emission of electrons referred to as secondary electron emission (SEE). Available theoretical models for the calculation of the SEE yield applicable for neutral, planar, bulk surfaces, are generally based on Sternglass Equation [10]:

$$\delta_{\text{sec}}(E) = 7.4\delta_M(E/E_M)\exp[-2(E/E_M)^2] \quad (2)$$

where  $\delta_M$  is the yield at maximum energy  $E_M$ .

However, laboratory experiments on micron-size dust grains carried out on our facility indicate that the SEE by electron impact is a very complex process. Incident electrons may lead to positive or negative charging of dust grains depending upon the grain size, surface potential, electron energy, electron flux, grain composition, and configuration. In Section 4.1 we give a brief description of the experimental technique employed at Dusty Plasma Laboratory at NASA/MSFC, and in Section 4.2 we present and discuss some of the results of the measurements on dust charging by low energy electron impact with the conclusions given in Section 4.3.

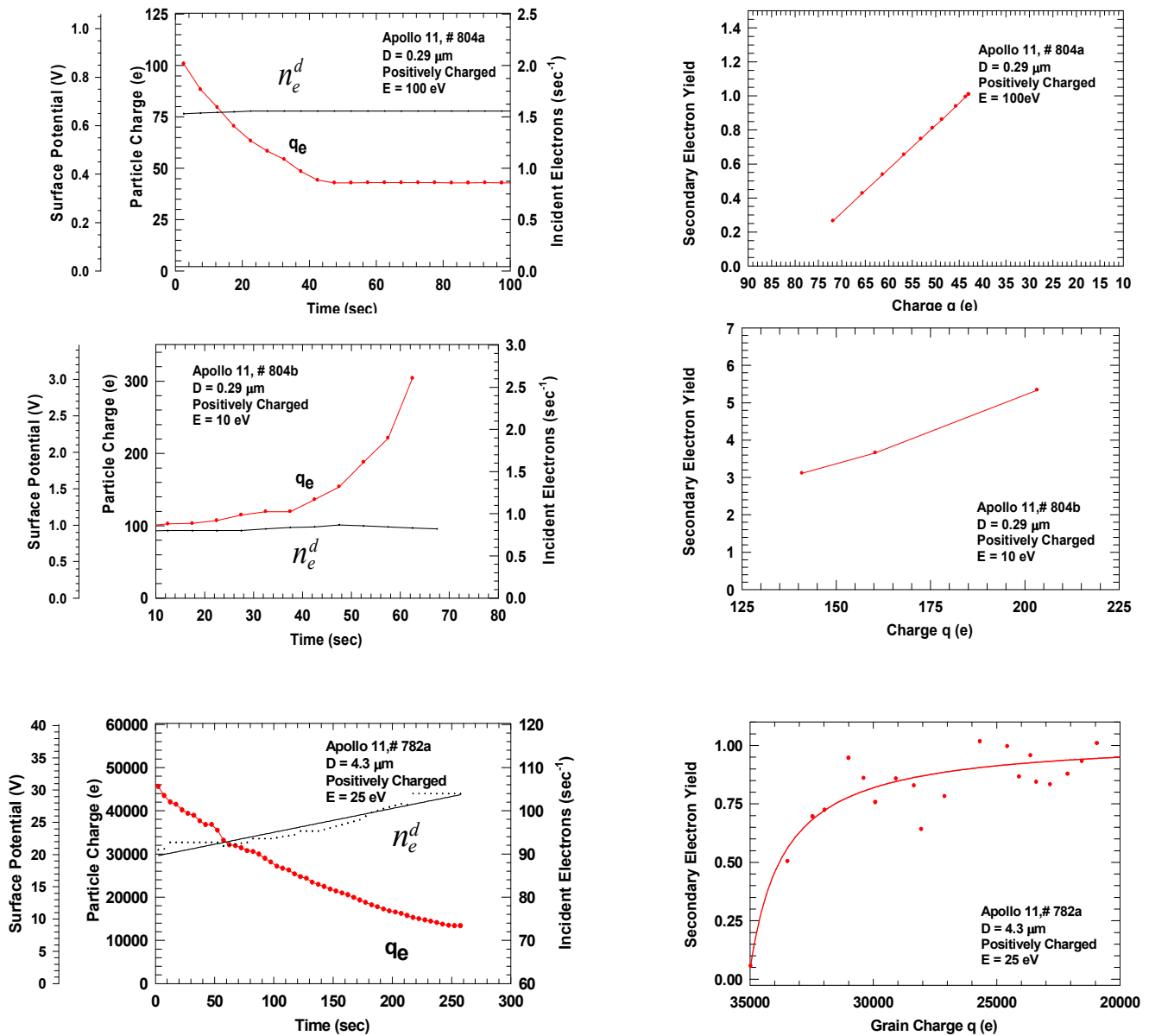
### 4.1 Experimental technique for measurements of dust charging by electron impact

The experimental setup for dust charging by the electron impact is essentially same as for the measurements discussed in the previous section. Once the particle is stably trapped and the particle generator is removed, the electron gun (Kimball Physics ELG-5/EGPS-5A) is installed on the top of the chamber. After the determination of the grain effective diameter, the system is evacuated to pressures of  $\sim 10^{-5}$  torr, and the levitated lunar dust grain is exposed to 25 or 100 eV electron beam. The electron beam current is measured by a Faraday

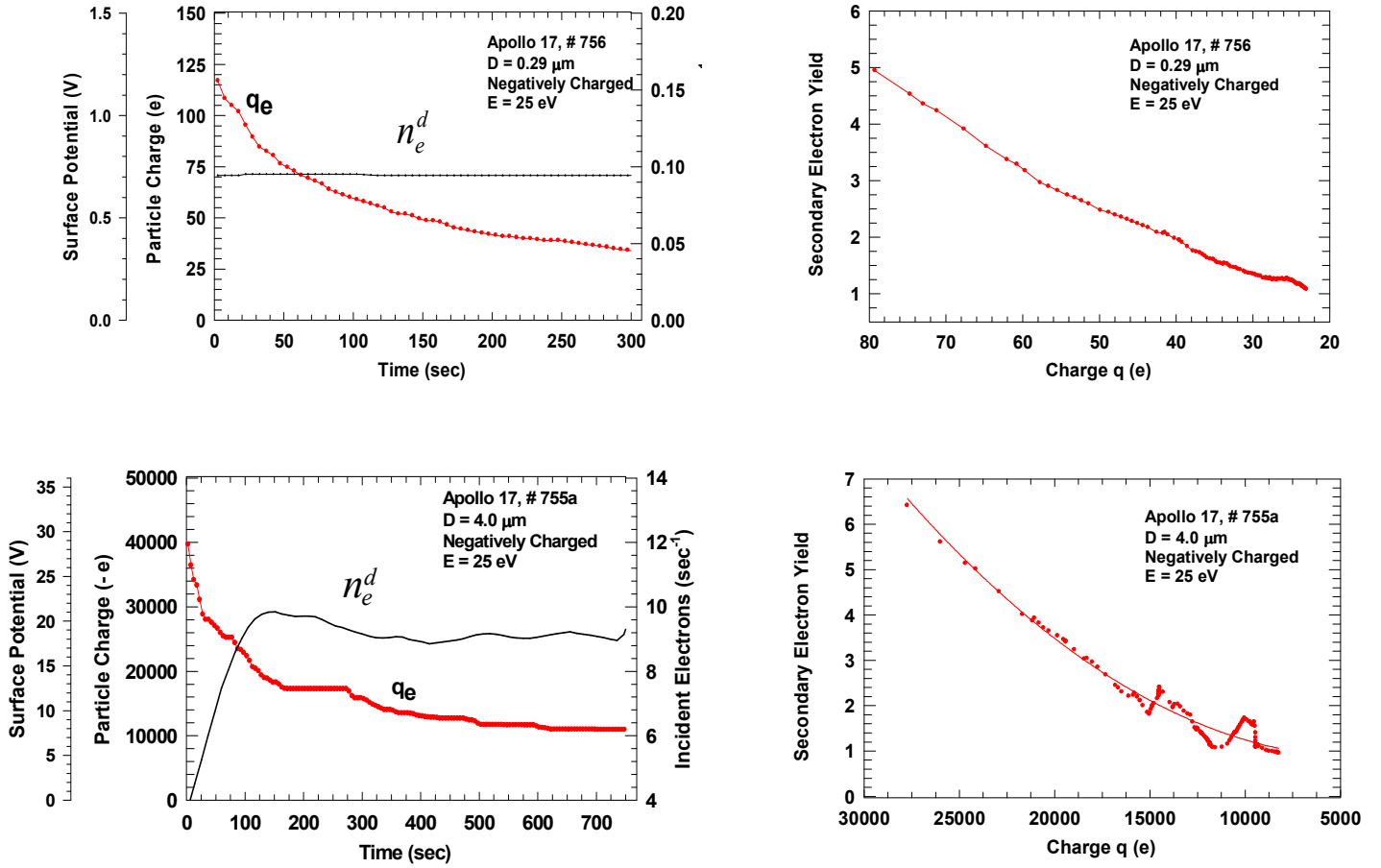
cup located below the bottom electrode of the trap. The change in the particle charge is determined by manually adjusting  $V_{dc}$  to position the particle at the trap center by balancing gravity as described in Section 3.1.

#### 4.2. Experimental results and discussion on dust charging by electron impact

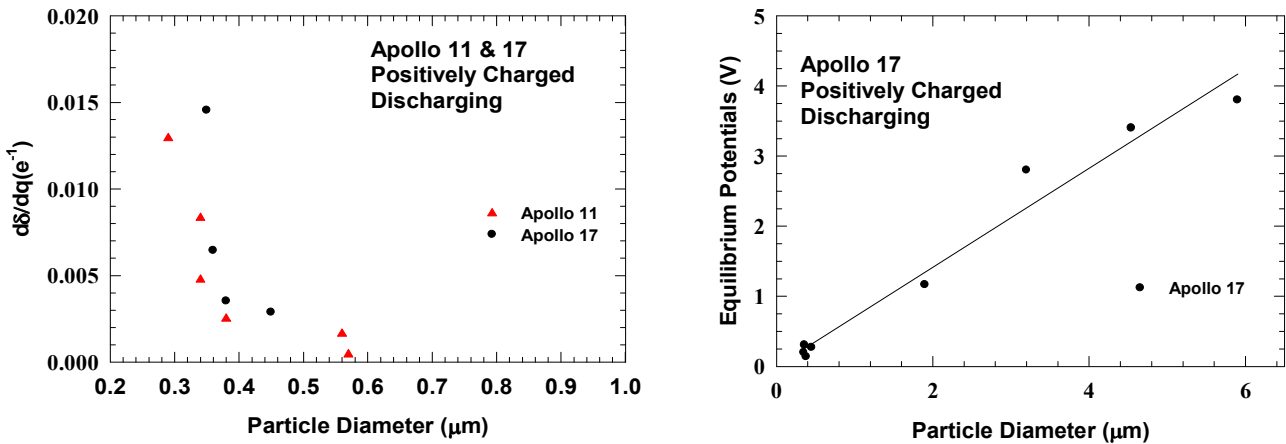
The above measurements were conducted on a number of selected lunar dust grains collected during Apollo 11 and 17 missions that were obtained from NASA-JSC and some  $\text{SiO}_2$  particles. The results of this research were presented in [6-7]



**Fig.5 (a,b)** Discharging of Apollo 11 positively charged dust grain of  $D = 0.29 \mu\text{m}$ , exposed to an electron beam of  $E = 100 \text{ eV}$  with a corresponding calculated SEE yield; **(c,d)** Charging of the same particle when exposed to a beam of electrons of energy  $E = 10 \text{ eV}$  and the corresponding calculated SEE yield; Discharging of Apollo 11 positively charged dust grain of  $D = 4.3 \mu\text{m}$ , exposed to an electron beam  $E = 25 \text{ eV}$  with the corresponding calculated SEE yield.



**Fig.6 (a,b)** Discharging of Apollo 17 negatively charged dust grain of  $D = 0.29 \mu\text{m}$ , exposed to a 25 eV electron beam with the corresponding calculated SEE yield; (c,d) Discharging of Apollo 17 negatively charged dust grain of  $D = 4.0 \mu\text{m}$  when exposed to a  $E = 25 \text{ eV}$  electron beam with the corresponding calculated SEE yield.



**Fig.7 (a)** Time averaged change in the SEE yield normalized to the change in the particle charge over the course of the experiment vs the grain diameter for discharging of positively charged lunar dust grains; **(b)** Equilibrium potentials for small size dust grains vs dust grain diameter.

Fig.5 (a,b) shows discharging of Apollo 11 positively charged dust grain of diameter  $D = 0.29 \mu\text{m}$ , exposed to a beam of electrons of energy  $E = 100 \text{ eV}$  with the corresponding calculated secondary electron yield (SEE) while Fig.5 (c,d) represents charging of the same



particle when exposed to a beam of electrons of energy  $E = 10$  eV and the corresponding calculated SEE yields. Discharging of Apollo 11 positively charged particle of diameter  $D = 4.3\mu\text{m}$ , exposed to a beam of electrons of energy  $E = 25$  eV with the corresponding calculated SEE is shown in Fig. 5 (e,f).

In Fig. 6 we present some of the results for Apollo 17 negatively charged particles. Fig.6 (a,b) shows discharging of Apollo 17 negatively charged dust grain of diameter  $D = 0.29\mu\text{m}$ , exposed to a beam of electrons of energy  $E = 25$  eV with the corresponding calculated secondary electron yield (SEE) while Fig.6 (c,d) represents discharging of Apollo 17 negatively charged dust grain of diameter  $D = 4.0\mu\text{m}$  when exposed to a beam of electrons of energy  $E = 25$  eV and the corresponding calculated SEE yield.

Fig.7 (a) shows the size dependence of the time averaged change in the SEE yield normalized to the change in the particle charge over the course of the experiment for discharging of positively charged lunar dust grains. The equilibrium potentials for small size dust grains vs dust grain diameter presented in Fig. 7(b) indicate a general linear dependence. The details of the calculations of SEE yields are given in [e.g. 6].

#### 4.3. Conclusions from measurements of dust charging by the electron impact

Following are some important conclusions based on the measurements on dust charging by SEE presented here:

- (1) The current models & measurements of SEE by low energy electron impact on planar/bulk/neutral materials are not valid for individual micron/submicron size dust grains. Rigorous theoretical models applicable for individual micron-size particles are not available yet.
- (2) Charging/Discharging processes and equilibrium potentials of small size dust grains are complex and depend on the conditions of: Particle size, Polarity, surface potential, and electron flux density.
- (3) Our results are validated with the model calculations of Chow et al [11], as well as the independent experimental measurements by Ziemann et al. [e.g. 3], that indicate strong size dependence and higher SEE yields for submicron-size particles.

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