Photoelectric Charging of Dust Particles in Vacuum

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Photoelectric charging measurements are presented of dust grains in vacuum for isolated grains and for grains near a photoemissive surface. Isolated grains reach a positive-equilibrium floating potential, dependent upon the work function of the particle, which causes the emitted electrons to be returned. Grains dropped past a photoemitting surface reach a negative floating potential for which the sum of the emitted and collected currents is zero. The particles tested are 90–106 μm in diameter and are composed of Zn, Cu, graphite, and glass.

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Natural and man-made objects in space charge to a floating potential determined by the balance between charging currents in the local plasma environment [1,2]. The dominant currents are the flux of electrons and ions from ambient plasma, electrons created by secondary emission, and photoelectrons. Charging proceeds until the sum of the charging currents is zero and the object has reached an equilibrium floating potential. The charging of objects in interplanetary space is typically dominated by photoelectric emission. In this situation, the object obtains a positive equilibrium floating potential at which nearly all of the photoelectrons are returned to the surface. This potential is altered only slightly by the small flux of solar wind electrons.

For objects approaching centimeter scale and larger, the local plasma environment is dominated by photoelectrons which create a sheath at the surface. Electron energy analyzers have observed low energy photoelectrons which originate at spacecraft and are returned to the surface by the sheath potential [3]. These analyzers also see ambient plasma particles accelerated toward spacecraft by this potential [4]. For smaller objects such as dust grains, the particle size is small with respect to the Debye length and a potential [4]. For smaller objects such as dust grains, the potential is altered only slightly by the small flux of solar wind electrons.

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Photoelectric emission of ~20 μm is induced by a 1 kW Hg-Xe arc lamp. The light is collimated by a lens.
and directed through a quartz window into the vacuum system. The photocathode is a 12.5-cm diameter zirconium foil plate. Zirconium has nearly the lowest work function (4.05 eV) of elements that do not react with air [11]. There is also an anode, composed of a highly transparent, 15-cm square, nickel wire grid which may be electrically biased.

The electron sheath above the cathode of a vacuum tube has received extensive analysis [12]. The emitted electrons have a single-sided Maxwell-Boltzmann distribution with a mean energy of order 0.1 eV determined by the cathode temperature. For a laboratory generated photoelectron sheath, however, the energy distribution has a width of several eV and has a well-defined high energy cutoff determined by the work function of the material and the short-wavelength cutoff of the spectrum. The sheath potential profile can be found by simultaneously solving Poisson’s equation and the Vlasov equation. Solutions have been given for several model electron velocity distribution functions [5,13].

In our experiment, the photoelectron energy distribution perpendicular to the photocathode is determined by retarding potential analysis. The photocathode is swept in voltage and the emitted current is measured. The anode mesh is spaced 2.5 cm from, and parallel to, the photocathode and is held at −4.5 V to prevent collection of electrons emitted from the walls of the chamber (see Fig. 1). The Zr plate is illuminated in a central region ∼10 cm in diameter to minimize electron losses from the edge. Figure 2(a) shows the photocathode current as a function of bias potential and Fig. 2(b) shows the derivative of this curve which gives the electron energy distribution perpendicular to the plate. For these data, the photocurrent was decreased to 2 μA to reduce space charge effects that perturb the applied potential. The absence of a reverse current in Fig. 2(a) indicates negligible emission by surfaces other than the photocathode. The small “wings” on the distribution are probably due to small patches of material having a different work function than zirconium.

A modified kappa function [14] fit to the energy distribution has intercepts that are separated in energy by 1.96 eV (excluding the wings). This is approximately the difference between the maximum photon energy (6.03 eV) and the tabulated work function of Zr (4.05 eV). The peak of the energy distribution indicates a mean energy of emission of ∼1.3 eV, which corresponds to a mean emission velocity of $6.8 \times 10^4$ m/s. For an average photoemission of 20 μA, the density of photoelectrons immediately above the surface is $2.3 \times 10^4$ cm$^{-3}$. This density is doubled when the photocathode is at the floating potential and the emitted electrons are returned to the surface. The Debye length in this case is approximately 4 cm.

The charge due to photoemission on grains of Zn, Cu, and graphite was measured by exposing the particles to ultraviolet illumination. For these experiments, the photocathode and anode are removed from the chamber. In the absence of illumination, there are no trigger events, indicating that the initial charge is less than the threshold of $± 2 \times 10^4$ e. Data were taken for 100 particles and plotted as a histogram in Figs. 3(a)–3(c). The mean measured charge is positive with a value of $5.3 (±1.6) \times 10^4$ e for zinc grains, $5.0 (±1.0) \times 10^4$ e for copper grains, and $4.1 (±1.0) \times 10^4$ e for graphite grains. The capacitance for spherical grains with a mean radius of 49 μm (the middle of our size range) is 5.4 pF which indicates that the charge should be $± 3.4 \times 10^4$ e per volt of charging potential. The expected particle potential is given by $V = (hc/\lambda - W)/e$, where the maximum photon energy from the light source $hc/\lambda = 6.03$ eV. The tabulated work functions are $W = 4.33$ eV for zinc, $W = 4.65$ eV for copper, and $W = 5.0$ eV for graphite [11]. A plot of

![Image](http://example.com/figure2.png)
FIG. 3. Charge distributions for 100 grains of (a) zinc, (b) copper, and (c) graphite dropped through the UV beam. The bin size is $0.8 \times 10^4$ e with zero labeled for reference.

measured charge as a function of $V$, Fig. 4 shows that the charge is approximately the value obtained from Eq. (1). The short wavelength cutoff and the work function could not be varied over a sufficiently wide range to verify that the experimental line has the proper slope. In addition, there is a systematic error in the mean arising from rejecting data below the threshold. This error results in overestimation of charge for materials having charge near the threshold.

In the second set of experiments, the charge on grains dropped through the photoelectron sheath was measured for grains of zinc, copper, and graphite. The grains fell less than 2 cm from the surface of the photoemitter. The grain charging time is of the order of 0.1 ms and is much shorter than the sheath transit time of 100 ms. The grains are expected to charge to the negative potential determined by collection of electrons from the sheath, and the charging does not depend on particle composition. The mean charge measured on zinc (Fig. 5) is $-4.3 \pm 0.9 \times 10^4$ e. Data for copper and graphite are not significantly different. This charge corresponds to a potential of $-1.26 \pm 0.3$ V.

For a monoenergetic electron distribution of energy $E$, the electron current collected by a grain with a potential $V$ is $I = J_0 A [1 + eV/E]$ for $eV > -E$, where $J_0$ is the current density to a surface at zero potential and $A$ is the surface area of the grain. For a distribution of electrons, $F(E)$, the collected current is

$$I(V) = J_0 A \int_{-eV}^{-E} F(E) \left[1 + \frac{eV}{E}\right] dE, \quad eV > -E$$

(2)

for a maximum electron energy $K$. The current collected by the grain as a function of its potential, using the measured energy distribution function plotted in Fig. 2(b), is shown in Fig. 2(c). For the spectrum of illumination in our experiment, the photoelectron yield from a photocathode of Zn was determined to be 0.12 that of Zr. Since

FIG. 4. The mean measured charge for zinc, copper, and graphite particles exposed to UV illumination as a function of the particle potential, $V = (hc/\lambda - W)$. The slope of the solid line is the capacitance of an isolated spherical grain, $C = Q/V$, for $r = 49 \mu m$. The dashed lines represent the capacitance for the upper and lower limits of the particle size range, $r = 45 \mu m$ and $r = 53 \mu m$. The error bars are the standard deviation of the mean.

FIG. 5. Measured charge distribution for 100 particles of zinc dust dropped through the photoelectron sheath. The bin size is $0.8 \times 10^4$ e, and zero is labeled for reference.
FIG. 6. Measured charge distributions for (a) 100 particles of glass dropped through the chamber with no illumination, (b) 100 particles of glass dropped through the UV beam, and (c) 100 particles of glass dropped through the photoelectron sheath. The bin size is $8.0 \times 10^4$ e, an order of magnitude larger than in the previous charge plots.

the current density immediately above the photocathode is doubled by the return of the electrons to the surface, the grains should charge to the potential at which 0.06 of the current from the surface is collected. This occurs at a charging potential of $1.17$ V, which compares favorably with the potential of $1.26$ (±0.3) V calculated from the measured charge.

The data for glass, a nonconductor, showed different behavior from that of the conducting materials. A charge histogram for glass obtained with no illumination, Fig. 6(a), show that most grains leave the dust dropper with an initial charge above the threshold for detection. There is a broad charge distribution centered at $4.0 \times 10^4$ e with an rms value $10.8 \times 10^4$ e corresponding to an rms charging voltage of $3.2$ V. This charge occurs in the dust dropper and is apparently triboelectric. The charge distribution for glass obtained with UV illumination is shown in Fig. 6(b). This distribution is more positive, with an average charge of $7.0 \times 10^4$ e and a standard deviation of $10.8 \times 10^4$ e. The relatively small shift in the center of the distribution results from photoelectron emission with a yield that is too low for an equilibrium charge to be obtained. The data for glass particles dropped through the photoelectron sheath are shown in Fig. 6(c). This distribution has an average of $-5.9 \times 10^4$ e with a standard deviation of $4.1 \times 10^4$ e. Positively charged particles are absent from this distribution because they are neutralized by electrons collected from the sheath. The average charge is more negative than that of the conducting grains because many particles have a negative initial triboelectric charge that is retained because of the low photoelectric yield of glass.

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