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Tribocharging and charged interaction in same-material, microscopic grains

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Abstract

We experimentally address the causes and consequences of charging between same-material, microscopic grains. We confirm quantitatively that differences in grain size alone drive charging. By comparing our data to independent thermoluminescence measurements, we show that trapped electrons are not the charged species being transferred. We observe and quantify a zoology of interactions between grains, including attractive orbits and repulsive slingshot events, cluster growth and annihilation via collisions, and granular molecule formation. Our results highlight the important role played by grain polarizability in aggregation and have implications for the dynamics of dust particles in protoplanetary disks.

1. Introduction

The triboelectrification of microscopic grains is thought to be important in settings ranging from volcanic ash clouds [1] to protoplanetary disks [2, 3]. Perhaps the most perplexing aspect of this phenomenon is that it occurs between grains of the *same material*, a fact that violates our intuition that tribocharging should only occur between *different* materials. While this has been known for quite some time [4], and indeed models have been put forth to explain it [5], our understanding of how it works remains foggy at best owing to a lack of experimental data.

We have devised an experimental technique that addresses this gap. By observing a dilute stream of microscopic grains as they fall freely from an orifice in vacuum, we remove gravity and are able to access the otherwise hidden electrostatic forces. Subjecting the grains to a uniform horizontal electric field, we are able to extract the granular charge distribution and for the first time quantify the scale of charge transfer in same material grains. We compare this to independent thermoluminescence measurements and rule out trapped electrons as the species being transferred. Finally, removing the field we are able to watch the grains as they interact amongst themselves. This allows us to witness attractive orbits and repulsive slingshot events, cluster growth and annihilation and granular molecule formation—processes of immediate relevance to planet formation.

2. Charge Measurements

We use an experimental technique similar to Millikan to measure the charges of individual grains [6], but with an adaptation to work with much larger grains and much smaller charge-to-mass ratios. Full details can be found in our previous work [7, 8]. In brief, we subject the grains to a uniform horizontal electric field as they fall vertically in high vacuum. Capturing their motion with a co-falling high speed camera (Phantom v9.1) allows us to track their motion. By fitting the horizontal position of each grain to a parabola, we extract its acceleration. With knowledge of the average grain mass (measured independently by microscopy) we translate the acceleration measurement into a charge measurement. This technique offers a charge-to-mass resolution of $\sim 5 \times 10^5$ elementary charges and a force resolution of ~ 500 pN (comparable to an atomic force microscope).

We work with highly spherical samples of fused zirconium dioxide-silicate grains (ZrO_2:SiO_2 with mass fraction $\sim 65{:}35$) because they are readily available, known to charge well, and known for being capable of holding trapped electrons. (This last point is important because trapped electrons have been considered the leading candidate for the charge species being transferred in same material tribocharging [9].) For monodisperse samples (average diameter $\bar{d} = 300 \pm 9\ \mu$m) we typically find a mean charge close to zero ($\sim 10^4$ elementary charges per grain) and a much larger width ($\sim 10^6$ elementary charges). The scale of the charge distribution width indicates that charging is *not* driven by thermal fluctuations, which would be commensurate with a much smaller width [7].

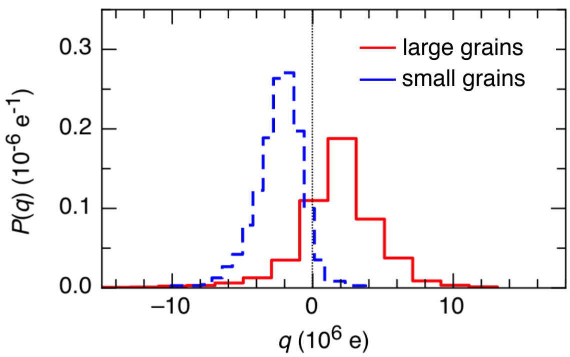

Figure 1: (a) Example still from a high speed video of a monodisperse sample. (b) Charge distributions for binary-sized sample comprised of 50:50 (by number) of large (average diameter $\bar{d}_l = 326 \pm 10$ μm) and small ($\bar{d}_s = 251 \pm 10$ μm) grains.

When we mix two well-separated sizes of grains together, we find that the grains exchange electrical charge with the larger ones becoming positive and the smaller ones negative [8]. Typical data is shown in Fig. 1. This confirms qualitative measurements made previously [10], but here we are able to measure that the amount of charge being transferred is, on average, $\sim 10^6$ elementary charges. By independently measuring the density of trapped electrons with thermoluminescence, we find that there far too few to account for the observed charge transfer [8].

3. Charged Interactions

In the absence of any external field, the grains are free to interact with each other as they fall. Again using the high speed camera, we can observe, quantify, and categorize these interactions. The behaviors we see are qualitatively different for monodisperse and bidisperse samples. This difference arises from the different charge distributions in the two cases.

For monodisperse grains, we see a variety of long range charged interactions. These are explained in detail in our forthcoming manuscript [11] and include attractive elliptical orbits with bounces and attractive and repulsive hyperbolic orbits. By measuring the sizes of grains in the video and fitting segments of these orbits, we are able to extract the charges of pairs of particles on a case by case basis (see Fig. 2a for an example orbital path with bounces). Typically we find that the grains exhibiting such behavior are drawn from the tails of the monodisperse charge distribution, with absolute charges on the order of 10^6 e. We also observe cluster growth and annihilation events where groups of particles grow or are disrupted after colliding with an incoming particle.

Perhaps surprisingly, for bidisperse grains we see *less* long range charged interactions. Instead, we see stable *granular molecules*—groups of large and small particles stuck together with conspicuously characteristic geometries. This is presumably because the larger amount of charge exchange leads to stronger interactions that more quickly damp out any initial motion. An example molecule consisting of five large particles and one small one is shown in Fig. 2b. Given that the binary samples charge systematically, we can assume the small grains have charge $-q$ and the large grains charge $+q$ with high likelihood (where q represents the average amount of charge transferred between the large and small grains—see [11]). Using this knowledge in combination with the full interaction potential (including the Coulomb interaction, polarization effects and steric repulsion), we are able to predict the shapes of such molecules.

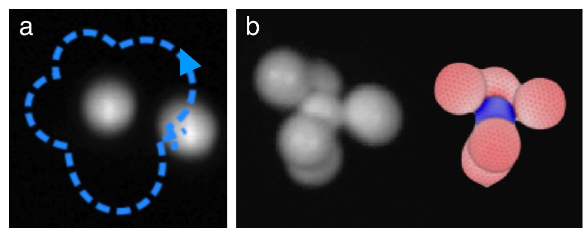

Figure 2: (a) Bouncing orbital path of an oppositely charged pair of grains from a monodisperse sample. (b) Example granular molecule from bidisperse experiments (left) and simulated counterpart (right) that form when one negatively-charged small particle is surrounded by five positively-charged large particles.

4. Summary and Conclusions

We have shown that same material grains transfer electrical charges between each other and that the driving mechanism is related to grain size. Our measurements of the amount of charge transfered reveal that it is too large to be accounted for by trapped electrons. Finally, we are able to observe the interactions of these charged grains in detail, which may play an important part in the aggregation dynamics of protoplanetary disks.

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