A Particle Charge Spectrometer for Determining the Charge and Size of Individual Dust Grains on Mars

Stephen Fuerstenau* and Gregory Wilson

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena CA 91109

Airborne dust is a primary factor influencing climate on Mars. Electrostatic charge carried by dust particles can play a role in their suspension, settling, and adhesion to spacecraft surfaces. Furthermore, the possibility for atmospheric discharges on Mars and the likelihood of associated hazards to robotic exploration remains an open and important question. In order to understand these aspects of the Martian surface environment, NASA is developing a portable instrument capable of measuring the charge and size of airborne particles. In the Particle Charge Spectrometer (PCS) the measurement of charge is based on direct capacitive coupling to a charge sensitive pre-amplifier. Aerodynamic particle diameter in the range from 2 to 100 micrometers is determined from the particle velocity in the sample inlet tube. Currently the field-portable device can measure charge on single particles with an error of less than 180 electrons and at a rate of over 200 particles per second. The goal of the research is to provide this measurement capability in an instrument that weighs under a kilogram and will operate in the Martian atmosphere with just a few watts of power. This paper describes the instrument and preliminary data from laboratory and field tests. The measurement approach is presented in the context of earlier particle charge instruments.

1. Introduction and background

1.1 Motivation

As with precipitation particles on Earth, airborne dust grains are theorized to play a dominant role in the as yet undetermined electrification of Mar's atmosphere (Eden and Vonnegut 1973, Farrell et al. 1999). Dust devils, the rotating dust-laden plumes of thermally unstable air that are a frequent phenomenon on Mars (Thomas and Gierasch 1985, Edgett and Malin 2000), have been observed on Earth to induce strong perturbations in local electric fields (Frier 1960, Crozier 1964, Kamra 1969) due to the electrostatic charge carried by the dust. The electrostatic charge can play an important role in the mechanisms of particle suspension, transport, sedimentation, and capture on surfaces, influencing the rates at which dust is injected and removed from the Martian atmosphere. Knowledge of such rates is crucial to understanding the Martian global dust cycle and climate. Moreover, atmospheric lightning, surface charging and discharging, interference with radio communication, and enhanced adhesion to materials, may all pose

significant hazards to future robotic and human exploration missions. In response to these issues NASA has listed the measurement of the charge on dust particles in the size range from 1 to 100 microns as a priority science objective. Initially we sought to simply adapt a previous instrument for use on Mars. However, we quickly arrived at the conclusion that the measurement of charge on suspended particles in this size range is by no means a routine measurement and remains a largely unexplored parameter of dust-laden environments on Earth.

1.2 Particle Charge Measurement

Aerosols generated by mechanical means, for example sprays and dust lifted by wind, are almost invariably highly charged, in contrast to particles that form by condensation such as fogs and smokes which typically carry only a few unit charges at most. Numerous aerosol instruments based on mobility analysis rely on this charge to size particles smaller than one micron. Above this size mobility analysis becomes impractical without the use of high voltage (>1 kV). Despite the importance of the substantial electrical charge carried by larger particles to fields such as atmospheric science and powder technology, very few instruments have been developed for the purpose of surveying charge on individual particles in the sub pico-coulomb range, ie. 10 to 1,000,000 charges (Brown 1997).

Those methods that do look at individual particles tend to sacrifice speed of analysis for sensitivity. A well-known case in point is the famous oil droplet experiment in which Millikan was able to determine the charge on individual particles with the precision of a single electron (Millikan 1910). This approach requires a microscopic inspection of the size and mobility, or velocity, of drifting particles. Kunkel employed strobe photography in a similar set-up to obtain the charge on dust particles in the 5 to 15 μm (Kunkel 1949). The approach required among other constraints, extreme care with reduction of small perturbations in air flow and temperature gradients. The E-SPART instrument monitors the motion of particles in response to oscillating acoustic and electric fields with laser doppler velocimetry (Mazumder 1991). While the instrument is able to measure size and charge on particles at count rates of up to 200 particles per second, the equipment is reported to possess an extreme size and weight, more than 50 Kg. Furthermore, the low pressure atmosphere on Mars would not sustain potentials required by these devices above a few hundred volts without electrical discharge.

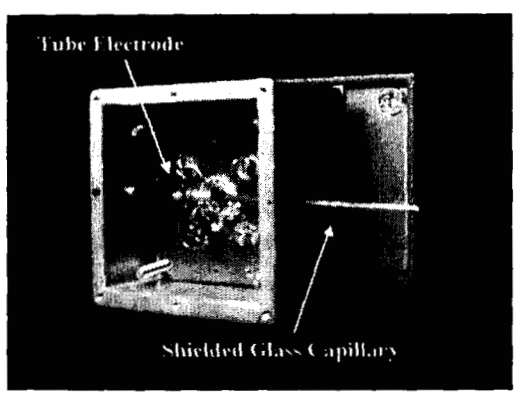
2. Instrument Description and Function

2.1 Measurement Approach

The PCS instrument is based on direct sensing of the charge on particles as they pass through a tube electrode that acts as a Faraday cage. As particles enter and exit the conducting tube they induce a change in potential in the tube, due to image charge forces, that can be detected with a charge sensitive preamplifier connected to the tube electrode.

The magnitude of the induced signal is proportional to the charge carried by the moving particle and has been analyzed in detail (Weinheimer 1988). The small size of the cylindrical electrode (1mm x 7 mm) aids sensitivity by ensuring that the capacitance is low. This strategy for measuring charge has previously been applied for single micro-particles with relatively high amounts of charge ($q > 10^{-14}$ Coulombs) (Vercoulen 1995), and with much lower charge levels ($q < 10^{-17}$ Coulombs) in experiments to 'weigh' individual nano- particles of biological interest (Fuerstenau 1995, 2001). The Faraday cage approach to measuring charge on cloud droplets dates back to at least the 1940's (Gunn 1949) but most of the numerous airborne instruments that employed it have exhibited limits of sensitivity not less than 0.1 to 1 pico-Coulombs.

The PCS instrument has two unique features. Unlike most of the airborne predecessor instruments, the PCS utilizes a small air pump to sample particles with a high-speed flow. The flow is induced in a narrow capillary nozzle and moves with a velocity of about 100 m/s. The rapid acceleration of the flow permits a determination of the aerodynamic diameter of the particles based on the speed with which they transit the tube electrodes, larger particles requiring a longer time to travel the length of the tube. Differential acceleration in high-speed flows at the exit of a nozzle is one technique for sizing particles in a commercially available instrument (Dahneke 1990). In the PCS the imposed flow allows information on both charge and size to be determined from the shape of the amplified pulse. A second feature of the instrument is the use of a glass-wall capillary to de-couple the flow geometry from that of the electrode, obviating the need for careful alignment of the Faraday tube with the gas flow. The approach works because electrostatic charge can be sensed across a dielectric barrier, and can be implemented without introducing noise, even at the extremely sensitive levels displayed in our device. The glass-wall method has been used extensively for sensing charge on powder particles (Gajewski 1975, 1993), but all of these experiments involved clouds of powder and not individual particles.



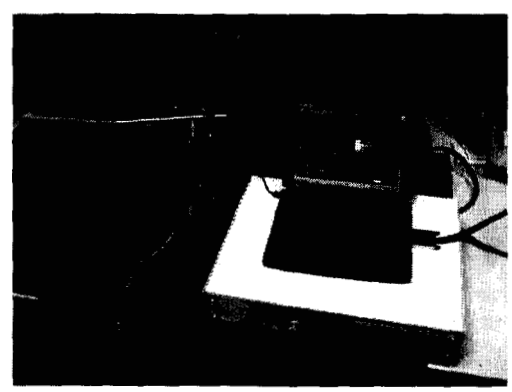


Figure 1. Photograph of the remote front end of the charge sensitive preamplifier. The coated glass capillary (0.5 mm I.D. bore) enters and exits from the side of the box and passes through the 7 mm long tube electrode at the center of the housing. View (right) of bench-top PCS system with Power supply, sensor head, pulse processing electronics enclosure, and computer.

2.2 *Calibration and Performance*

The noise level of the charge sensitive preamplifier is currently less than 200 electrons. The minimum charge detectable is 300-400 electrons and the maximum charge at this sensitivity is +/- 120,000 electrons. The charge equivalent noise is determined by pulsing a known voltage across a calibrated capacitor onto the gate of the FET which is in contact with the tube electrode. The pulsed capacitor introduces a known amount of charge onto the preamplifier input, which in turn induces a measurable voltage pulse at the output inversely proportional to the feedback capacitance of the amplifier. The procedure results in a measure of the system output voltage as a function of input charge. The capacitance of the tube electrode assembly and all feedback elements are kept small in order to reduce noise. It is estimated that cooling the amplifier will reduce the intrinsic noise of the FET by perhaps 30%. The correlation of particle transit time to particle size is currently based on a simple model for particle motion in a one-dimensional flow. The size response of the PCS will be calibrated with charged particles of known size generated with a vibrating orifice droplet generator. Size measurement of particles in the range from 1 to 200 micrometers is theoretically possible with a precision of better than 50% for small sizes but the resolution and effective range remains to be confirmed.

Signals from the preamplifier are fed to a pulse processing board that further amplifies them and reduces the pulse amplitude and duration to two analog signal levels. These are relayed on a single channel to the data acquisition card of a lap-top computer. A 'LabView' (National Instruments) program acquires the information for up to 200 individual particles per second and displays them after processing in a continuously updated graph of charge vs. particle size. The prototype system is shown in figure 1.

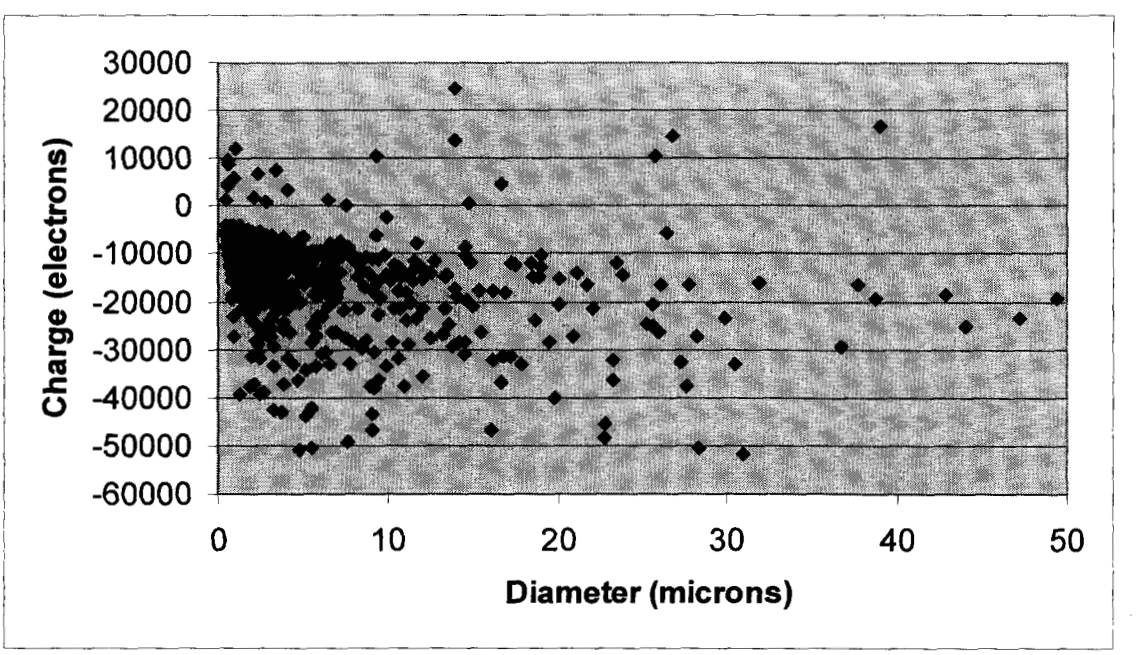


Figure 2. Charged dust particles in the Arizona desert measured with the PCS. Data are consistent with a strong negative electric field observed in the vicinity of dust devils.

2.3 Sample Data

We have used the PCS in the laboratory to investigate charge on particles from various agitated dusts and electrostatic sprays. Figure 2 illustrates a data set collected in the desert during the passage of a nearby dust devil. Noteworthy is the fact that most particles carried a negative charge, as large as 50,000 e- for some particles. A vertical electric field of over 20 kV per meter was observed at ground level when these data were collected.

3. Future Developments and Applications

We are developing an improved sample inlet system based on dilution. It will increase by a factor of 10 to 30 the maximum particle concentration sampled by the 1 liter per minute flow of the PCS. We are also exploring the performance of the system at the 10 mbar pressure of the thin Martian atmosphere to determine any variation in the sizing capability of the instrument. Compact versions of the device are being developed for possible deployment on balloons or aircraft to aid studies of thunderstorm electrification. It is anticipated that the PCS will find application in agricultural investigations aimed at better understanding crop dusting and artificial pollination. The charge carried by industrial powders, such as pharmaceuticals during processing and toners inside working xerography machines, may eventually be observed with the PCS instrument.

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