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CubeSat Electrostatic Dust Analyzer (CEDA) for Measuring Regolith Dust Transport on Airless Bodies

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ABSTRACT
The CubeSat Electrostatic Dust Analyzer (CEDA) is developed by the Dust BUSTER student team at the University of Colorado for exploring electrostatic dust transport processes on the surfaces of airless bodies such as asteroids and the Moon. CEDA is a 6U cubesat that consists of a 2U dust analyzer module and an autonomous repositioning system (ARS). This instrument measures the charge, velocity, and mass of lofted dust particles, and provides the lofting rate in order to estimate the efficiency of electrostatic dust transport in surface processes. The dust analyzer module consists of two Dust Trajectory Sensor (DTS) units with a Deflection Field Electrodes (DFE) unit in between them. A dust particle can enter from either end of the analyzer and its charge and velocity are measured using the wire-electrodes on which the charge is induced as the particle passes through. The charged particle is deflected in the DFE where its mass is determined from the deflection trajectory. The ARS, consisting of the sun sensors, cover doors and tilting mechanisms, repositions the instrument for optimized dust measurement on the surface. The communication needs to be provided by the mother spacecraft.

INTRODUCTION
Dust charging and transport on airless planetary bodies, due to the exposure to the solar wind plasma and solar ultraviolet (UV) radiation, has been a long-standing problem. This process has been hypothesized to explain a number of unusual space observations[1]. The first evidence was the so-called 'lunar horizon glow', which was suggested to be caused by lofted/levitated dust particles scattering off the sunlight. Since then, many other observations, such as the radial 'spokes' in Saturn's rings and the 'dust ponds' on asteroid Eros as well as on comet 67P, have been also suggested as a result of electrostatic dust transport processes.

However, the exact charging and transport mechanisms remained unsolved for decades. Recent laboratory studies have greatly advanced our understanding of this problem[1,2]. A new "patched charge model" (Fig. 1, top) is developed and validated with laboratory experiments. It explains that emitted photoelectrons and/or secondary electrons can be re-absorbed inside microcavities between dust particles, accumulating surprisingly large negative charges on these particles. The resulting repulsive forces between them cause their lofting and mobilization.

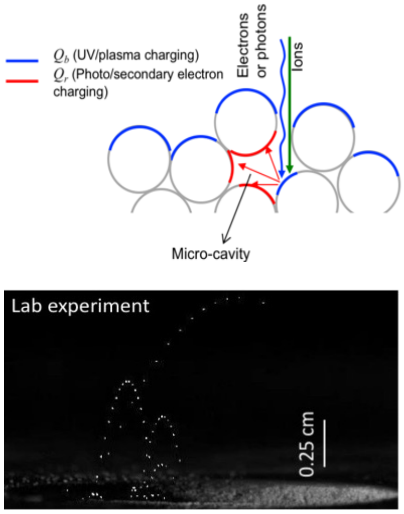

Fig. 1 Top: Schematic of "patched charge model"; Bottom: Trajectories of lofted dust particles with exposure to UV and plasma.

By exposure them to UV and/or plasma in the laboratory experiments, dust particles (a few tens of microns in diameter) were observed to loft to several centimeters high with a launch speed up to ~ 1 m/s with smaller particles moving even faster (Fig. 1, bottom). Lofted dust particles are charged negatively even under UV radiation alone[2]. The transient lofting rate can be as high as a few particles cm^{-2} s^{-1} and last for more than an hour[3], approximately in agreement with the 'lunar horizon glow' observations.

A new dust instrument, the CubeSat Electrostatic Dust Analyzer (CEDA), has been developed by the Dust BUSTER student team at the University of Colorado. In-situ measurements enabled by CEDA will advance our understanding of electrostatic dust transport contributing to the evolution of regolith surfaces of airless bodies, and gain knowledge of potential hazards posed by electrostatically lofted dust in order to develop mitigation strategies for future robotic and human exploration.

INSTRUMENT DEVELOPMENT

CEDA is a 6U cubesat that consists of a 2U dust analyzer module and an autonomous repositioning system (ARS), Fig. 2. The instrument placed on the surfaces of airless bodies measures the charge, velocity, mass of lofted dust particles, as well as their lofting rate that estimates the efficiency of the dust transport process. The ARS, consisting of the sun sensors, cover doors and tilting mechanisms, repositions the instrument for optimized dust measurements on the surface. Power can be provided by solar panels configured on the instrument (for missions to asteroid, comet or small moons) or a lander tethered to the instrument (for landed missions such as on the lunar surface).

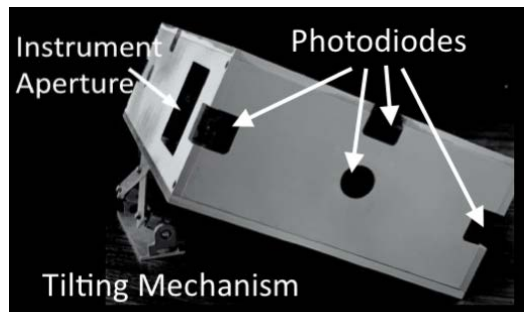

Fig. 2 Photo of the CEDA instrument

Dust Analyzer Module

The dust analyzer module is a miniaturized version of a prototype of the Electrostatic Lunar Dust Analyzer (ELDA)[4]. The analyzer module consists of two Dust Trajectory Sensor (DTS) units with a Deflection Field Electrodes (DFE) unit lying in between the two DTS units (Fig. 3).

DTS consists of two wire-electrode planes, each consisting of 6 wires (0.5 mm in diameter, 7 cm long, 1 cm spacing) aligned in the y direction (Fig. 3, top). The wire-electrodes are electrically shielded using high-open-area grids on both ends. As a charged dust particle passes through the DTS, the induced charge on each of the wires is measured. The total dust charge is close to the sum of charges detected on all wire electrodes when the particle is in between the two planes.

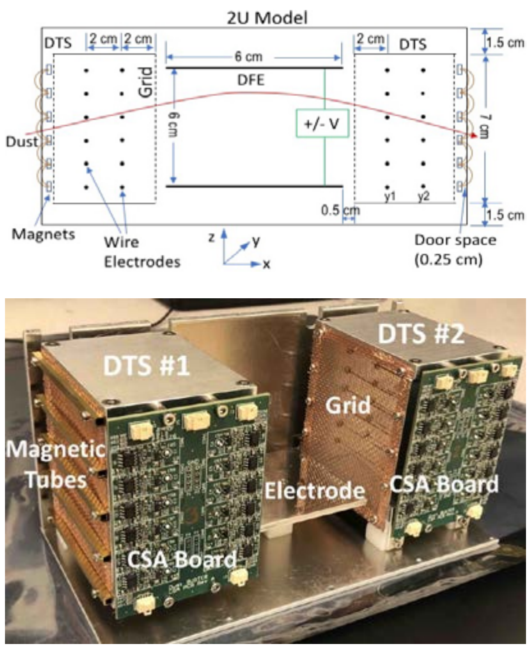

Fig. 3 Top: Schematic of the dust analyzer module; Bottom: Photo of the dust analyzer module.

The magnitude of the induced charge is inversely proportional to the distance between the dust particle and wire. The location of the dust particle is therefore determined from the ratio of the signal magnitudes on the two neighboring wires. The dust trajectory on the x-z plane is reconstructed from the charge signals of two wire-electrode planes separated by 2 cm. The velocity will be then determined from the timing shift between them. CEDA only measures a 2D velocity vector in contrast to the ELDA's 3D velocity measurement due to the additional wire-electrode planes in the z direction. However, this will only lead to a 10% underestimation in the true velocity magnitude while increases the space usage efficiency and field-of-view (FOV), and reduces the data acquisition channels and data sizes.

The charged particle will be deflected in the DFE region and exit through the second DTS on the other end. The mass is then derived from the deflected trajectory. The charge signals are measured using the Charge Sensitive Amplifiers (CSA).

One important issue for in situ measurements is to prevent solar wind plasma and solar UV radiation from entering the instrument, which may produce sufficiently large currents to the wire-electrodes. These currents may cause the saturation of CSA's output voltage and consequently the failure of the measurement. Solar wind ions and solar UV will be blocked by one of the cover doors facing the sun in the AOS components. To prevent ambient electrons (i.e., solar wind electrons and photoelectrons from the surface with the temperature of 3 – 10 eV), two mechanisms are designed: magnetic deflection and electrostatic repelling.

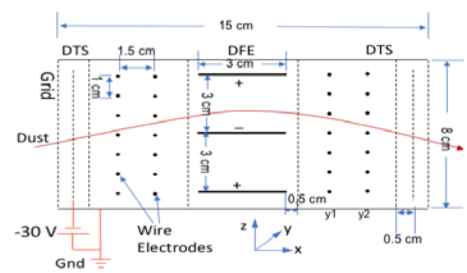

Fig. 4 Alternative design of the dust analyzer module.

In the current model, the magnetic deflection mechanism is employed (Fig. 3). The rectangular tubes filled with small permanent magnets (~ 0.5 Tesla) alternate in polarity to create multi-dipole fields (Fig. 3, top). The electrons will be deflected while the charged dust particles are not affected due to their large masses. This mechanism is appropriate for measuring dust particles with the weak ferromagnetism and a speed lower than 0.1 m/s.

For dust particles with a speed larger than 0.1 m/s, the electrostatic repelling mechanism is a better approach. A grid set consists of two grounded grids sandwiching a negatively biased repelling grid (Fig. 4). The bias voltage is large enough to stop most of the electrons while allow charged dust particles to pass through. As shown in the laboratory experiments[2], lofted dust particles are negatively charged. Dust particles will go through the slow down and re-acceleration without energy loss. For dust particles with a speed lower than 0.1 m/s, the repelling grid may return the dust particles before they become re-accelerated through the grids. In this case, the magnetic deflection mechanism is a better approach.

Dust Measurement Testing Results

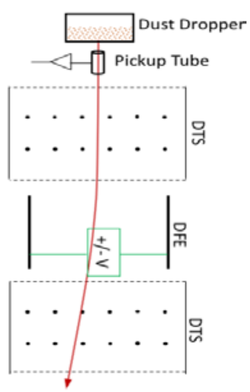

Fig. 5 Setup for dust detection tests

Dust measurement was tested in the atmosphere with a setup shown in Fig. 5. Individual dust particles (lunar simulant) with sizes between 150 – 180 μm in diameter were dropped from a reservoir through a tiny hole 0.5 mm in diameter. A single particle or two was often dropped at a time. The particles are charged due to the tribocharging effect. A particle fell through a pickup tube detector where its charge was measured for calibration. Subsequently, the particle passed through the analyzer and its charge, velocity and mass were determined.

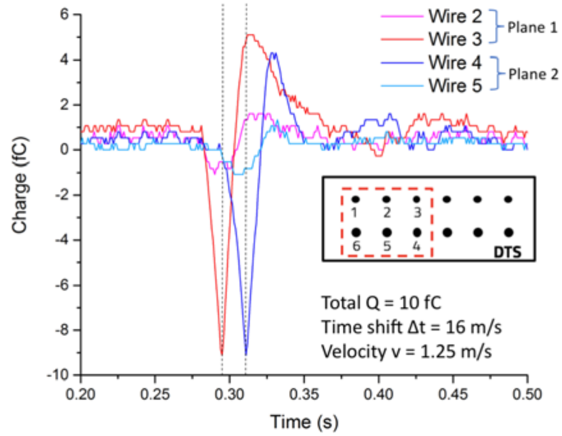

Fig. 6 Charge signals on the wires of two electrode planes in a DTS unit.

Figure 6 shows an example of the charge signals measured on the wires of two electrode planes in a DTS unit. The first wire-electrode plane was 18 cm below the dust dropper. The dust particles passed between wires 2 & 3 and 4 & 5 and closer to 3 & 4 indicated by the larger magnitudes. The total charge on each plane is ~ 10 fC. As expected, it is smaller than the charge measured by the pickup tube ~ 17 fC because a fraction of charge is induced on the grids and walls of the DTS. The root-mean-square (rms) noise level is ~ 0.25 fC. The timing shift is 16 ms, corresponding to a velocity of 1.25 m/s. This is smaller than 1.86 m/s calculated for a free fall motion because of the air drag effect.

AOS Components

The instrument needs to operate in the sun because photoelectrons are expected to be the major charging source for dust particles to loft[1,2]. In order to minimize the interferences of solar wind plasma and solar UV radiation as well as to improve the FOV, the instrument needs to point away from the sun by tilting the anti-solar side for an optimized FOV and opening the same side door for dust collection. The door facing the sun will remain closed to block solar wind ions and solar UV radiation. Because the solar wind ions are supersonic (i.e., their drift speed is larger than their thermal speed), they are not expected to enter the opening aperture that is in its wake.

The sun position is determined with the sun sensors (13 photodiodes) that are configured around the instrument to cover the entire sky (Fig. 7, top). The housings of the photodiodes are manufactured using a 3D printing technology. The sun sensing was tested with ± 15 degree accuracy, lower than the required ± 2 degree accuracy. The errors were mainly attributed to the resolution of the photodiodes. For a landed mission, the determination of the sun position can be provided by lander.

The door mechanism is a sliding door operated by a stepper motor (Fig. 7, middle). The sliding is implemented by a gear which one end is attached to the door and another end is attached to a rack. When the rack is rotated by the motor, it moves the gear to open the door. The functionality of the sliding door was successfully tested. One weakness of this mechanism is that it takes more space for the doors to slide.

The tilting mechanism is a scissor lift system driven by a stepper motor (Fig. 7, bottom). The scissor lift is attached to a shoe pad for a larger contacting surface area that prevents the instrument from sinking into the regolith. An accelerometer is used to measure the actual angle with respect to horizon at a real time, generating a feedback to command the motor until the desired angle is achieved. The scissor lift mechanism was successfully tested with ± 1 degree accuracy. The weaknesses of the current design are: 1) This mechanism requires significant initial torque to move the lift from its fully folded position. It works on the surface of a small asteroid or comet due to their small gravity. However, this operation may be difficult on the surfaces of large bodies such as the lunar surface; and 2) Redundant mechanical joints increase the risk of operation failure.

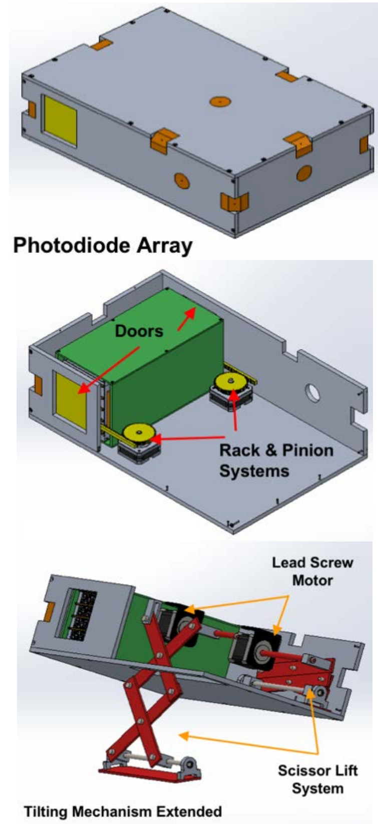

Fig. 7 Top: Photodiode arrays; Middle: Door mechanism; Bottom: Tilting mechanism.

CEDA can be deployed from a mother spacecraft to hard land on a small body (e.g., an asteroid, a comet or a small moon) or deployed on a large body (e.g., the Moon) by landed missions. The mother spacecraft or lander also provides the data/commands communication.

SUMMARY

A prototype of the CEDA instrument has been developed for exploring electrostatic dust transport processes on the surfaces of airless bodies such as asteroids and the Moon. CEDA is a 6U cubesat that consists of a 2U dust analyzer module and an ARS subsystem. The dust analyzer module consists of two DTS units with the DFE unit in between them. The charge and velocity are measured by the induced image charges on the wire-electrodes in the DTS. The mass is determined from the deflection in the DFE region. The dust lofting rate on the surface can be derived from the dust collection rate by the instrument. The ARS, consisting of the sun sensors, cover doors and tilting mechanisms, repositions the instrument for optimized FOV and for preventing solar wind plasma and solar UV radiation from entering the dust analyzer. The critical functionality of the prototype was successfully tested. The communication needs to be provided by the mother spacecraft.

In-situ measurements enabled by CEDA will advance our understanding of the effect of electrostatic dust transport on the surface processes on airless bodies as well as potential hazards posed by electrostatically lofted dust in order to develop mitigation strategies for future robotic and human exploration.

Acknowledgments

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