Acta Astronautica 69 (2011) 1082–1088

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Active dust control and mitigation technology for lunar and Martian exploration ☆

C.I. Calle [a,*], C.R. Buhler [b], M.R. Johansen [a], M.D. Hogue [a], S.J. Snyder [b]

[a] NASA Kennedy Space Center, FL 32899, USA
[b] ASRC Aerospace, Kennedy Space Center, FL 32899, USA

ARTICLE INFO

Article history:
Received 28 January 2011
Received in revised form
8 June 2011
Accepted 9 June 2011
Available online 1 July 2011

Keywords:
Lunar exploration
Mars exploration
Planetary exploration
Exploration missions
Dust mitigation
Dust control
Dust removal

ABSTRACT

Mars is covered with a layer of dust that has been homogenized by global dust storms. Dust, levitated by these storms as well as by the frequent dust devils, is the dominant weather phenomenon on Mars. NASA's Mars exploration rovers have shown that atmospheric dust falling on solar panels can decrease their efficiency to the point of rendering the rover unusable. Dust covering the surface of the moon is expected to be electrostatically charged due to the solar wind, cosmic rays, and the solar radiation itself through the photoelectric effect. Electrostatically charged dust has a large tendency to adhere to surfaces. The Apollo missions to the moon showed that lunar dust adhesion can hinder manned and unmanned exploration activities. In this paper, we report on our efforts to develop an electrodynamic dust shield to prevent the accumulation of dust on surfaces and to remove dust already adhering to those surfaces. The technology uses electrostatic and dielectrophoretic forces to carry dust particles off surfaces and to generate an electrodynamic shield that prevents further accumulation of dust. The concept of the electrodynamic dust shield was introduced by NASA in the late 1960s and later reduced to practice during the 1970s for terrestrial applications. In 2003, our laboratory, in collaboration with several universities, applied this technology to space applications, specifically to remove dust from solar panels on Mars. We show how, with an appropriate design, we can prevent the electrostatic breakdown at the low Martian atmospheric pressures. We are also able to show that uncharged dust can be lifted and removed from surfaces under simulated Martian environmental conditions. We have also been able to develop a version of the electrodynamic dust shield working under hard vacuum conditions that simulate the lunar environment. We have implemented the electrodynamic dust shield on solar arrays, optical systems, spectrometers, viewports, thermal radiators, batteries, and power systems, as well as on fabrics for spacesuits. We present data on the design and optimization of the electrodynamic dust shields and provide data on the performance of the different implementations of the technology for lunar and Martian exploration activities.

Published by Elsevier Ltd.

1. Introduction

The surfaces of Mars and the moon are covered with a layer of dust. In the case of Mars, the material on the surface has been homogenized by the dust transport mechanism caused by global dust storms and dust devils. Except for the individual dust clearing events experienced by NASA's Spirit and Opportunity rovers – believed to have been produced by a passing dust devil – the accumulation of dust on the rover's solar panels decreases their efficiency. In the case of the moon, the entire surface is covered with a layer of dust with sizes in the micrometer and sub-micrometer range. This layer of dust is

☆ This paper was presented during the 61st IAC in Prague.
* Corresponding author.
E-mail address: carlos.i.calle@nasa.gov (C.I. Calle).

0094-5765/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.actaastro.2011.06.010

expected to be electrostatically charged for three main reasons. First, the moon has practically no atmosphere (it has a tenuous atmosphere with an atmospheric pressure in the 10^{-13} kPa range) and no magnetic field so that the high energy electrons and protons in the solar wind reach the surface completely unimpeded. Second, due to the relatively high surface and volume resistance of the lunar regolith and the complete lack of liquid water in the regolith, the charge decay of the lunar dust should approach infinity. Third, due to the lack of an atmosphere, the full spectrum of the sun's electromagnetic radiation reaches the surface, charging the dust via the photoelectric effect and also affecting its current charge state.

It is believed that both Martian and lunar dust may be harmful. Lunar dust is a threat to humans because it can produce a respiratory disease (pneumoconiosis) if it is inhaled [1]. Martian dust could also be highly toxic. Data from the Pathfinder craft showed that chromium is present in Martian dust [2]. In the highly oxidizing Martian environment, this element could have formed toxic chromates.

The development of efficient dust mitigation solutions is critical for the success of any mission to the moon and for future human missions to Mars. The Electrodynamic Dust Shield technology developed by our group is perhaps the first active method of *automated* dust removal from surfaces. Prototypes of the dust shield have been tested under Martian and lunar simulated environments.

2. The electrodynamic dust shield

The dust removal technology described in this paper is based on the electric curtain concept developed by F.B. Tatom and collaborators at NASA in 1967 [3] and further developed by Masuda at the University of Tokyo in the 1970s [4–8]. This technique has been shown to lift and transport charged and uncharged particles using electrostatic and dielectrophoretic forces [9,10]. The technology has never been applied for space applications on the moon or Mars.

The Electrodynamic Dust Shield consists of a series of parallel electrodes connected to an ac source that generate a traveling wave acting as a contactless conveyor (Fig. 1).

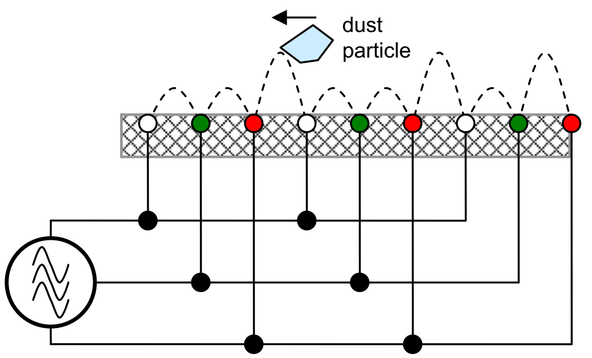

Fig. 1. Schematic diagram of a multiphase electrodynamic dust shield.

The Electrodynamic Dust Shield has been described in detail elsewhere [11–13].

3. Dust mitigation for solar panels

Experiments at simulated Martian and lunar conditions were performed in our laboratory. The dust simulant used for the testing at Martian conditions was JSC Mars-1 simulant [14]. For the lunar experiments, we used JSC-1A and JSC-1AF, which includes only the under 70 μm fraction of the simulant. The JSC-1A simulant was sieved into different size fractions.

3.1. Experiments under simulated Martian conditions

Tests were performed with several dust shields with 0.5 mm trace spacing. The JSC Mars-1 simulant was kept in a vacuum oven at temperatures above 120 °C and atmospheric pressures of about 1 kPa for several days to obtain a relatively high degree of dryness in the simulant.

In an effort to neutralize any possible charge accumulation on their insulating coatings, the dust shields were exposed to an ionizer prior to dust loading. All experiments were performed in an atmosphere composed of 95.5% carbon dioxide, 2.7% nitrogen, 1.6% argon, 0.13% oxygen, and 0.07% carbon monoxide at a pressure of 0.9 kPa. These conditions reproduce fairly well the composition and pressure of the Martian atmosphere. A Moesner and Higuschi waveform at 10 Hz with an amplitude of 400 V was applied to the dust shields. The shields were activated prior to dust deposition and were then operated continuously for 90 min. After dust clearing, additional dust was delivered every 15 min with the dust shields energized. Six cycles of dust deposition with the dust shields activated were performed. The dust removal efficiency was 97% under these conditions.

3.2. Experiments under simulated lunar conditions

Experiments with JSC-1A simulant were performed in a vacuum chamber at 10^{-6} kPa. The lunar simulant was kept in a vacuum for several days. Aerosolized simulant dust (<20 μm) was deposited on the shields under very low relative humidity conditions. The shields were rapidly transferred to the chamber for testing. Although the simulant-covered shield was briefly exposed to ambient air at 50% relative humidity, we believe that the small amount of water absorbed was quickly removed when the chamber was promptly evacuated.

Four dust shields were placed inside a stainless-steel high vacuum chamber in order to perform tests under simulated lunar vacuum conditions. The chamber pressure is monitored using two MKS Series PR 4000 vacuum gauges for pressures above 6 kPa and a Varian Ion Gage for high vacuum ranges. The high vacuum was supplied using a Varian Model 300HT Turbo molecular pump, and the roughing vacuum is accomplished using a Varian 600 series scroll pump. Together the system is capable of reaching 10^{-7} kPa with tests typically performed at $5.0 \pm 2.0 \times 10^{-6}$ kPa.