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Dust Contamination of the Spacecraft Environment by Exposure to Plasma

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Introduction

THE presence of dust can dramatically alter how material bodies interact with a plasma environment. These dust-plasma-object interactions are increasingly thought to be important for several areas of research.[1] To date, most studies of dust-plasma interactions have been in magnetospheric physics, where researchers have identified them as a critical factor in various astrophysical plasmas.[2]

The design and operation of spacecraft is another field where dust-plasma-object interactions are important. Yet the literature contains little on the topic. We can mention here only two related observations. First, the release of dust from a spacecraft was recognized in early infrared observations.[3,4] The dust originated from launch-borne contaminants, and then it was shed in Earth orbit. In identifying the cause of the release, however, the effects of plasma were not suspected. Second, dust release due to the spacecraft environment was demonstrated by the Magellan spacecraft mission to Venus. Anomalies of the startrackers on board were attributed to dust contaminants generated in situ in the Venus environment.[5] Solar ultraviolet (uv) exposure and heating were identified as the cause, and this was confirmed in a series of experiments at the UCLA Plasma Physics Laboratory.[6] Those experiments revealed that solar uv exposure is effective in the generation and shedding of dust from astroquartz surfaces.

One might be concerned that uv exposure is not the only environmental factor that leads to dust generation and shedding. Another factor worth evaluating is the plasma in a low-Earth orbit. We show here that plasma exposure does cause dust shedding.

We limit the scope of this paper to the release of dust due to plasma exposure. How the dust behaves once it is free of the spacecraft is a separate problem. For that topic, we refer the reader to the theoretical work by Murphy and Chiu.[1] They assumed a spherical body immersed in a plasma with a low dust density and Maxwellian velocity distributions and performed a dynamic simulation, subject to the boundary conditions imposed by the spacecraft. Murphy and Chiu found that the presence of the dust resulted in a diminished charge on the body. Conversely, the density of the dust cloud was reduced by the presence of the body. Their results were found to be sensitive to the initial dust velocity and the size of the body in comparison with the Debye length.

Dust Sources

Stringent cleanliness requirements for spacecraft have been found to be absolutely necessary to detect weak infrared backgrounds such as zodiacal light.[3,4] Modern infrared astronomy imaging missions have internal safeguards to nullify nonstationary light sources. Nevertheless, there are several trends and factors in the development of future space missions that will force a more careful consideration of dust-spacecraft interactions, since preventive measures cannot be extended without limit.

The first of these factors is that the near-Earth orbit is increasingly polluted by the effluents of spacecraft themselves and by the break-up of old satellites into long-lived "debris belts." The behavior of effluents near the surfaces of satellites and of micrometer-size debris around the core of satellite remnants requires basic understanding. The electrodynamics of dust-surface interactions in a plasma environment are increasingly becoming the science of satellite "ecology" in the near-Earth orbit.

The second factor is that missions are becoming increasingly complicated and sensitive. Mission durations are becoming longer, requiring attention to dust generation by erosion of components. In near-Earth orbit, a major contributor to surface erosion is exposure to atomic oxygen. Oxygen erosion was demonstrated, for example, by the Long Duration Exposure Facility (LDEF).[7] In the LDEF, aluminized mylar thermal blanket backing eroded and produced micrometer-size aluminum flakes. This flaking was so serious that it saturated quartz crystal microbalances while the LDEF was brought into the Shuttle bay.[8] Under such conditions, the function of sensitive optical devices can no longer be trusted, since dust effluents may attach to (or detach from) sensitive surfaces. Thus, spacecraft environment requirements specified at the beginning of a mission may be different from those at its end.

New spacecraft materials are being brought forward, but their performance regarding the dust environment is almost unknown. A good example is the release of dust from the astroquartz blankets on the Magellan spacecraft, as discussed earlier.[5] The Magellan startracker was often saturated due to light scattering from the dust. For an insensitive "housekeeping" instrument, such as the startracker, signal interference by dust is a recoverable spacecraft anomaly. It can be avoided simply by pointing the tracker away from the Sun. Yet, for a much more sensitive "tracker" attempting to obtain signals against a cluttered background, the dust interference signal may result in a complete malfunction.

The aforementioned factors, as well as trends in future space missions, indicate a need for experiments to identify and understand the facts governing dust-spacecraft-plasma interactions. Unfortunately, a controlled experiment in space has not yet been reported. There has been, however, a laboratory experiment that illuminates the physics of dust-spacecraft-plasma interactions. This experiment, reported by Sheridan et al.,[9] simulated a short-duration (< 1 h) exposure of a dusty spacecraft to a plasma. The experimenters proved that plasma exposure causes dust shedding from material bodies. In this paper we will briefly review that experiment and discuss its implications for spacecraft contamination.

Laboratory Experimental Evidence

Here we review the experiment reported by Sheridan et al.[9] A test sphere was coated with micron-size particulates and then placed in a laboratory plasma. To simulate a spacecraft, the sphere rotated at 10 rpm and it was electrically floating. This was done by mounting the sphere on a rotating support rod with an insulating break. The insulating break was a passive feature that assured that the sphere would be at the floating potential.

A nitrogen plasma was formed in a vacuum chamber with a hot tungsten filament electron source. The nitrogen neutral gas pressure was 0.056 Pa (5.6×10^{-7} atm). Typical plasma parameters

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measured with a Langmuir probe, were an electron temperature $T_e \approx$ 4–7 eV and density $n_e \approx 10^{13}$–10^{14} m^{-3}. The plasma had two electron components: a primary component from the filament emission and a colder and denser plasma component created from ionization of the neutral nitrogen by the primary electrons. The floating potential of the sphere ranged from −15 to −20 V. The floating potential is important because it determines in part the sheath electric field surrounding the object, which accounts for the dust shedding, as we will show later.

Some of the laboratory plasma parameters differ from those in the Earth's ionosphere. Nevertheless, the results remain applicable to spacecraft. The electron temperature approximates that of the auroral regions of the ionosphere, and the presence of a fast electron beam component was appropriate because such a tail is generated by instabilities associated with water outgassing from a spacecraft.[10] The biggest difference was in the electron density, which was about three decades larger in the experiment than in the ionosphere. The results of Ref. 9 can be extrapolated at least qualitatively to ionospheric densities because it reports the dependence of dust shedding on plasma density.

The spheres were 4.45 cm in diameter and were made of aluminum. Three different surfaces were tested: bare aluminum, black anodized aluminum, and aluminum wrapped with mylar tape. All three exhibited essentially the same dust-shedding behavior. This suggests that the surface material does not matter much. Of course, the type of surface material may be important in the generation of the dust due to erosion. Yet once the surface has dust on it, whether from erosion or another cause, the surface material is probably not a major factor in its release due to plasma exposure.

The dust that was used was Alcoa tabular alumina, which is a dielectric. It was intended to simulate the dust that might be found on a spacecraft. The powder consisted of particulates of various sizes in the range of 0.25–10 μm. In comparison with the Debye length λ_D in the plasma, the particulates were much smaller than λ_D where the sphere was larger than λ_D. This is the same situation as for a dust-covered spacecraft in the ionospheric plasma.

Before inserting the sphere in the vacuum vessel, 80 mg of dust was applied using an electrostatic method. This amount corresponds to roughly 2×10^8 individual particulates. The test sphere was grounded momentarily to remove any charge. Next it was inserted into the vessel, which was evacuated by vacuum pumps. A continuously operating argon-ion laser beam was pointed beneath the sphere, and scattered light was collected at an angle of 45 deg. This laser light scattering setup detected dust particles when they fell from the spheres.

The experimenters switched the plasma on and off and observed vigorous dust shedding when the plasma was on and almost none when it was off, proving that exposure to plasma can release particulate contamination from an object's surface. The strongest shedding occurred on the top of the sphere, which was exposed directly to the source of fast electrons. The experimenters found that dust particulates were not shed all at once when the sphere was first exposed to the plasma, but gradually, with a certain probability per unit time of a grain jumping off. This was determined by observing that the laser light scattering signal decayed exponentially in time, showing that the amount of dust remaining on the sphere also decayed exponentially vs time. This reveals that the rate of shedding is proportional to the amount N of dust remaining on the surface, $dN/dt = -KN$. The proportionality constant K is the probability per unit time for a grain to be released.

Averaged over the various plasma conditions during the experiment, the rate of shedding was estimated to be 10^6 particulates/s. The rate of shedding K was found to increase with the plasma density. Because of the experimental technique, it is impossible to quantify exactly the density dependence, but one can roughly extrapolate to ionospheric densities by assuming that K scales with some power α of density, $K \propto n_e^{\alpha}$. From the data presented in Ref. 9 it is possible to say that the exponent lies in the range $0 < \alpha \leq 1$, but a more exact value is still unknown.

Dust-Shedding Mechanism

Here we offer an hypothesis, consistent with the dust shedding results of Ref. 9, to explain why the dust is shed. A particulate is held to an object (spacecraft) by strong adhesion forces such as Van der Waal forces. For particulates to be shed there must be an opposing force that overcomes the adhesion. This force is electrostatic, $F = QE$. Here Q is a charge on the grain, and E is the electric field of the sheath surrounding the object. These forces are sketched in Fig. 1.

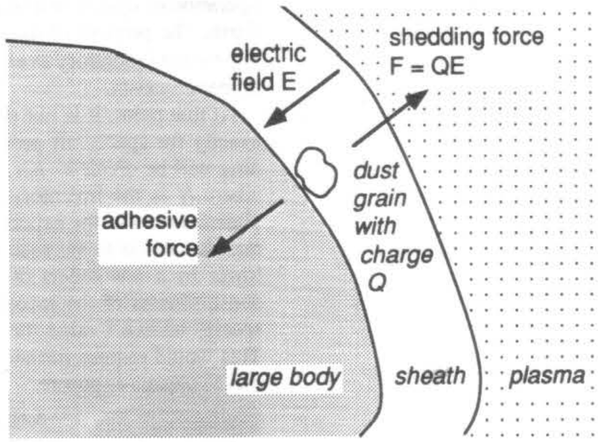

Fig. 1 Sketch of forces acting on a dust particulate attached to a large body (not to scale).

The particulate acquires a charge Q because it collects electrons and ions from the plasma bombardment. Since it is made of a dielectric material, it retains a net charge rather than transferring it to the large body. This charge is negative (in the absence of secondary electron emission processes).[2] The object (spacecraft) is also charged negatively, and so it is surrounded by a plasma sheath.[11] This sheath has an electric field E that points from the plasma toward the surface. The resulting force $F = QE$ on the particulate is in the direction away from the sphere's surface.

In other words, the particulate is electrostatically repelled from the object when it is immersed in the plasma. The electric force will accomplish particle removal when it exceeds the adhesion force. Thus the charge Q must exceed a threshold for the particulate to be shed. Based on their experiment, the authors of Ref. 9 determined that this threshold is typically > 15,000 electron charges for an 8-μm particle (and much less for smaller particles). The threshold is high enough that the removal of particles is inefficient.

We believe that the grain's charge fluctuates in time. This conclusion is based on the result of Ref. 9 that there is a definite probability per unit time for the grains to be shed. Because the charge fluctuates, it will cross the threshold eventually, after a random interval of time. Here we explain why this fluctuation might happen and how it regulates the shedding process. Remember that the grain is small, and the electrons and ions it collects are discrete particles. So the small particulates collect ions and electrons at random intervals of time. They do not necessarily collect one electron immediately after one ion, but sometimes several ions and then several electrons. Thus the charge on a grain fluctuates in time. It may require the collection of millions of electrons and ions, with Q fluctuating up and down about a mean value, until the threshold is crossed. Then the particulate is released from the surface. This accounts for the finite probability per unit time that a particulate is released. In the laboratory experiment, this probability was $\approx 10^{-2}$ s^{-1}, and in an ionospheric plasma it would be lower since the rate of shedding scales with plasma density, as discussed earlier.

Implications for Spacecraft

Particulate contamination of spacecraft is recognized as an important engineering issue. Yet it is probably not widely known that dust on the payload of a rocket can become detached when it is exposed to an ionospheric plasma. This shedding process due to plasma exposure lasts as long as there is any dust remaining on the exposed surfaces. The source of the dust can be contamination on the ground or generation in space by degradation of spacecraft materials. Once the dust has been released, it can remain in the immediate environment of the spacecraft and interfere with the operation of optical instruments by scattering light from the Sun or Earth. The purpose of this paper was to introduce this idea and to review the laboratory evidence that the plasma-dust shedding phenomenon exists.

At this point, it is not possible to quantify the rate of shedding exactly for spacecraft problems. It is likely that the rate of shedding will be $dN/dt = -KN$, as it was in the laboratory experiment, where N is the inventory of dust on the surface. For the dense plasma found in the experiment, $K \approx 10^{-2}\ s^{-1}$. Since the shedding rate was found to increase with plasma density, K would likely be lower by a few orders of magnitude for a spacecraft in the less dense plasma of the ionosphere. It is not possible at this time to specify an exact value for K for various conditions in Earth orbit. This would require further observations of the rate of dust release due to plasma exposure.

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References

[1]Murphy, D. L., and Chiu, Y. T., "Dusty Plasmas in the Vicinity of Large Dielectric Objects in Space," *Journal of Geophysical Research,* Vol. 96, No. A7, 1991, pp. 11291–11305.

[2]Goertz, C. K., "Dusty Plasmas in the Solar System," *Reviews of Geophysics,* Vol. 27, No. 2, 1989, pp. 271–292.

[3]Murdock, T. L., and Price, S. D., "Infrared Measurements of Zodiacal Light," *Astronomical Journal,* Vol. 90, No. 2, 1985, pp. 375–386.

[4]Simpson, J. P., and Witteborn, F. C., "Effect of the Shuttle Contaminant Environment on a Sensitive Infrared Telescope," *Applied Optics,* Vol. 16, No. 8, 1977, pp. 2051–2073.

[5]Robinson, P., private communication, Jet Propulsion Lab./California Inst. of Technology, Pasadena, CA, Sept. 1990.

[6]Wong, A., and Wuerker, R., private communication, Univ. of California, Los Angeles, Dept. of Physics, Los Angeles, CA, March 1988.

[7]Vest, C. E., "The Effects of the Space Environment on Spacecraft Surfaces," *Johns Hopkins APL Technical Digest,* Vol. 12, No. 1, 1991, pp. 46–54.

[8]Magg, C., private communication, Science Applications International Corp., McLean, VA, May 1989.

[9]Sheridan, T. E., Goree, J., Chiu, Y. T., Rairden, R. L., and Kiessing, J. A., "Observation of Dust Shedding from Material Bodies in a Plasma," *Journal of Geophysical Research* (*Space Physics*), Vol. 97, 1993, pp. 2935–2942.

[10]Machida, S., and Goertz, C. K., "A Simulation Study of the Critical Ionization Velocity Phenomenon," *Journal of Geophysical Research,* Vol. 91, No. A11, 1986, pp. 11965–11976.

[11]Al'pert, Y. L., Gurevich, A. V., and Pitaevskii, L. P., *Space Physics with Artificial Satellites,* Consultants Bureau, New York, 1965, pp. 63–105.

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