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SECONDARY ELECTRON EMISSION AND SPACECRAFT CHARGING

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Abstract

Spacecraft charging due to the natural plasma environment found in all orbits is known to produce many of the observed spacecraft anomalies and failures. A primary factor in adverse spacecraft charging is the secondary electron emission of differing materials on the spacecraft. Precipitating electrons and ions from the plasma to spacecraft surfaces can result in varying amounts of charge being released, depending on the secondary electron yield of the materials; this can lead to arcing between surfaces. NASA's Space and Environments Effects (SEE) program has recognized the need to improve their current materials database for modeling spacecraft charging and have chosen the surface science group at Utah State University to carry out electron emission studies on spacecraft materials as well as other research related to spacecraft charging. The instruments being used at USU are specifically designed to study the problem of spacecraft charging and the contributions of the group will continue after my research on secondary electron emission funded by the Rocky Mountain Space Grant Consortium is completed. In addition to improving NASA's ability to model spacecraft charging, my secondary electron research has the potential to benefit numerous other fields, such as scanning electron microscopy.

Spacecraft charging

All spacecraft reside in a plasma of electrons and ions and collect charge as a natural response to their plasma environment. The surfaces of the spacecraft collect charge and adopt varying potentials in an attempt to stop the flow of charge between the plasma and the spacecraft.

Spacecraft charging takes on several forms, all of which affect the operation of the spacecraft. The overall charge on the spacecraft, as referenced by a central electrical ground, can vary from the ambient plasma by up to several thousand volts[1]. Unless the spacecraft comes near another object (e.g. satellite maintenance by the shuttle) this "absolute" charging does not result in severe damage; however, such an overall charge can effect measurements by changing the electrostatic fields around observational instruments on the spacecraft[1].

The various conducting or insulating surface materials on a spacecraft can also acquire different charges, relative to the absolute potential. This "differential" charging can lead to arc discharges between surface materials, through layers of the solar arrays, or into the interior of the spacecraft[1]. Documented spacecraft anomalies resulting from differential charging range from temporary loss of control to the failure of whole satellites[2,3,4]. In addition to arcing, different potentials on spacecraft surfaces can also interfere with charged particle measurements, enhance particle deposition and impact damage, and leak power from solar arrays[1].

Sources of spacecraft charging

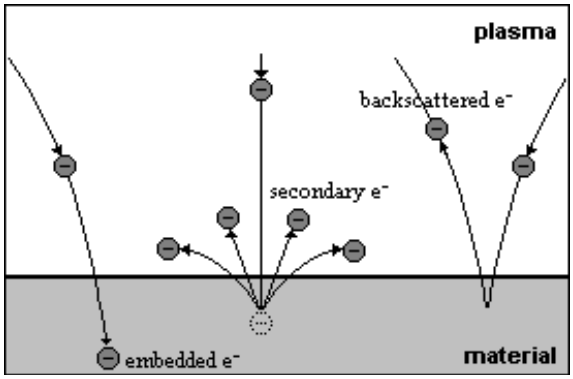
The characteristics and behavior of the plasma environment are important factors in spacecraft charging. For example, the lower thermal velocity of ions in low-earth orbit (LEO) causes the rear of a spacecraft to charge negatively[5]. The low density of the plasma in a geosynchronous orbit (GEO) means that the ambient plasma has less effect on spacecraft, but influxes of high energy electrons and ions from the magnetosphere's tail during a geomagnetic storm can differentially charge a spacecraft beyond arc discharge thresholds. In a polar orbit (PEO), spacecraft are subjected to the same high energy charged particles responsible for the aurora. The later two examples are responsible for the most severe charging events observed on spacecraft.

Another main factor in spacecraft charging is the response of the spacecraft materials incident electrons and ions from the plasma environment. Differential charging is caused by the differing material properties of surfaces on the spacecraft. The physical processes involved have to do with electron scattering and will now be discussed in more detail.

Secondary electron emission

As mentioned, the reaction of spacecraft materials to incident electron and ion bombardment is a driving force in spacecraft charging. Since ion currents during severe charging events are typically much lower than electron currents, we will only consider incident electrons here.

The interaction of an incident electron with a material is a quantum mechanical, multiple scattering problem; however, the reaction can be generalized into three categories (see below).



The incident or “primary” electron can,

1. Embed in the material, creating negative charge
2. Ionize atoms in the material and liberate "secondary" electrons, creating positive charge.
3. Reflect or scatter without losing much energy ("backscattered" electrons), creating no net charge.

Backscattered electrons are considered those close to the primary electron energy, while secondaries have characteristically low energies (< 50 eV). While the adsorption and backscattering of primary electrons are important, the liberation of electrons originally in the material or "secondary electron emission" (SEE) is typically the most significant factor in spacecraft charging. Secondary emission is very material dependent (since secondary electrons originate from the material) and therefore is the focus here. The experiments to be discussed with secondary electrons are closely related to those for the other two processes.

By convention, one refers to the number of secondary electrons produced per primary electron as the "secondary electron yield δ". Secondary electron yields $\delta > 1$ mean that the material is charging positively by emitting more secondary electrons than the incident electron current. The implication for differential spacecraft charging is immediate: If two surface materials have vastly differing secondary electron yields (e.g. $\delta_{carbon} \sim 0.5$ and $\delta_{gold} \sim 1.4$)[5,6], then they can acquire large charge differences even in the same plasma environment. The other electrical properties of materials must be taken into account (e.g. conductivity and photoemission), but the phenomenon of secondary electron emission is central to the issue of spacecraft charging.

NASA's approach to spacecraft charging: Past and Future

In the 1970s, NASA made a concerted effort to understand spacecraft charging and mitigate its effects on future missions. The main result was the creation of the NASA Charging and Analysis Program (NASCAP), designed to model spacecraft charging. Spacecraft designs could then be tested in the most severe charging events expected for their orbit and hardened to resist failures. Research eventually lead to the launch of the Spacecraft Charging at High Altitudes (SCATHA) satellite for research specifically on spacecraft charging. As a result of these efforts, the spacecraft charging problem was thought to be well understood and NASA had protocol to mitigate its effects.

Using the NASCAP code requires accurate information about the properties of the spacecraft's materials in response to the most severe plasma environments. Although the physical process of secondary electron emission due to electron and ion bombardment is reasonably well understood, the experimental materials database is entirely inadequate. In fact, current versions of NASCAP only have secondary and backscattered electron yields on nine materials. Literature in the spacecraft charging community[2,3,4] has referred to this lack of material information since the late 1970s.

In addition to the lack of experimental data, most of the materials research on which NASCAP is based was done before scientists had the ability to attain pressures of 10^{-10} torr in vacuum chambers. This "ultra-high vacuum" (UHV) is necessary to keep surfaces clean on relevant atomic scales. Secondary electrons have characteristically low energies, so if they originate from depths larger than atomic distances (several monolayers of material or 5-50 Å) they undergoes collisional loses and never leave the material. Since secondary electrons are emitted from the near surface of materials, they are "surface sensitive", meaning that adsorbed contaminants (e.g. carbon or oxygen) can dramatically effect the secondary electron yield[6]. Making sure that materials are clean and well characterized at this level is essential for reliable data on secondary electron emission.

Along with the past inadequacies of the NASCAP material database, new spacecraft designs have also increased the need for further research. Modern high-density, low-voltage, low-current electronics are much more sensitive to charging events. New materials for spacecraft design have been or are being developed and will also need to be characterized. The future of spacecraft design will be influenced by NASA’s understanding of materials and spacecraft charging.

In response to these needs, the Spacecraft Environments and Effects (SEE) program at NASA has recently proposed an upgrade to their modeling tools (NASCAP/PLUS). In conjunction with the new computer code, the SEE program wants to improve their material properties database and understand secondary and backscattered emission in more detail. For example, experimental data on the angular dependence of secondary electron emission is almost nonexistent and NASCAP/PLUS needs that information to accurately model the recapture of secondary electrons in the modeled electrostatic and magnetic fields around spacecraft. The surface science group at Utah State University has recently been enlisted to carry out these two tasks for the SEE program.

Secondary emission studies of spacecraft materials

The connection between surface science studies and the charging of spacecraft in orbit is now more understandable. Ground-based research is much less expensive than the experience gained from spacecraft mission disruptions or failures. The facilities at Utah State University for surface science research, and the implications for spacecraft charging, are now considered in more detail.

As mentioned before, experiments in secondary electron emission must be done in a vacuum chamber at "ultra-high vacuum" (UHV), pressures lower than 10^{-10} torr. The design, fabrication and maintenance of UHV chambers is expensive, but the USU surface science group has two operating UHV chambers. There are three benefits of carrying out secondary electron studies in UHV:

1. Electron and ion beams can only be operated in high vacuums ($<10^{-6}$ torr).
2. The surface sensitivity of secondary electron emission, described earlier, makes the knowledge and control of the material's atomic surface extremely important[6]. Unwanted contaminants can change a study of aluminum, for example, into the study of aluminum oxide. The formation of a single atomic layer of contaminants in a UHV chamber takes much longer than a series of secondary electron studies.
3. The natural environment of a spacecraft can be approximated in a UHV chamber.

The spinoffs of research on secondary electron emission go further than the understanding of spacecraft charging. The theory of electron scattering and emission have progressed since the 1970s, but experimental data has not kept the pace. Comparing our data with current theoretical models will advance the fundamental understanding of electron interactions in materials. On the more practical side, images from scanning electron microscopy (SEM) are based directly on an understanding of the material and angle dependence of secondary and backscattered electron emission. In addition, the development of flat panel displays, and the design of vacuum electronics devices can benefit from studies of secondary and backscattered electrons.

Again, the ability to control and characterize the surface cleanliness of a material sample is the main reason for UHV chambers. The vacuum chamber at Utah State that will be used for secondary electron emission can clean surfaces with ion sputtering and electron bombardment heating, map the surface morphology with scanning electron microscopy (SEM), and detail the chemicals adsorbed on the surface with Auger electron spectroscopy (AES).

While cleanliness is vital for reliable scientific data on secondary electron emission, the ability to simulate the spacecraft environment is a coincidental benefit. The environment of a spacecraft is modified due to firing thrusters and chemical interactions with spacecraft surfaces. Contamination studies can be carried out in a UHV chamber by carefully introducing gases during a secondary electron study. The affect of these material and environment interactions on secondary electron yields represent the fine details in the problem of spacecraft charging.

The information that is most important to SEE in the immediate future are the secondary electron yields as a function of incident electron energy for materials that have been used on existing spacecraft. Examples include the dielectric Kapton that is used as a substrate in solar arrays, any form of carbon, copper, silicon, aluminum alloys, and a host of coating materials for conduction and thermal control. Measuring secondary (and backscattered) yields for these materials composes the bulk of my dissertation research and would make a significant contribution to improving the predictions of the NASCAP models.

In addition to secondary electron yields for spacecraft materials, the surface science group at USU is in a position to study other material aspects that contribute to spacecraft charging. Examples include measuring electrical properties, arc discharge thresholds, photoelectron emission, and resolving the angular dependence of secondary electron emission for incorporation into the new NASCAP/PLUS code. My research on secondary electron emission will serve to refine a UHV chamber that will continue to be used for materials research that contribute to the understanding of spacecraft charging.

Technology transfer

Summary

Secondary electron emission is an important material property in the problem of spacecraft charging. The NASCAP program is NASA's standard for the evaluation of all spacecraft designs in severe charging events. The SEE branch at NASA has recognized that NASCAP's database of secondary electron yields for spacecraft materials is inadequate. My secondary electron studies of spacecraft materials at USU will dramatically improve the materials database used in NASCAP predictions, which will influence the design of future NASA spacecraft.

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