Some Space Hazards of Surface Charging and Bulk Charging

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Abstract Surface charging and deep dielectric charging are hazardous to the electronics onboard spacecraft. Surface charging in concert with deep dielectric charging have not been discussed before. Hypervelocity impact can also play a role together with the charging mechanisms. Using a fictitious spacecraft failure scenario, we discuss various space hazards. Even low level current flow between differentially charged surfaces may cause current leakage and degradation of power systems. Townsend's criterion is a necessary condition for an avalanche ionization discharge to occur. To be sufficient, one needs to include the loss mechanisms such as electron escape, excitation, recombination, etc. In deep dielectric charging, the high electric field built up inside the dielectrics may cause breakdown. The high charge density deposited inside may also cause a sudden change of conductivity. There exists a critical charge density at which the Mott (insulator to conductor) transition occurs. It has been overlooked heretofore that the combination of high electric fields and high charge density can lower the threshold for Mott transition. We then discuss a combination of deep dielectric charging followed by surface charging. During high energy (MeV and higher) electron radiation on dielectric surfaces, electrons are deposited deep inside and an electric field is built up. Afterwards, low energy high density plasma ions are attracted to and deposited on the surface, thus building up a double layer inside the dielectric. An "anodized discharge" may follow. This mechanism is more hazardous to spacecraft after, but not during, a high energy radiation episode. Finally, hypervelocity impacts by meteorites and debris, with or without deep dielectric charging, are hazardous.

1. Introduction

Consider a fictitious scenario: "A geosynchronous satellite, AFLAC, was moved westward from a longitude over Kwajalein to a longitude over Baghdad. A plasma ion thruster on the satellite propelled the satellite. The move started at 02:00 local time in darkness, November 18. During the move, the satellite suddenly lost most of its power. What could be the causes of the satellite's failure?"

"The space weather had been severe. Indeed, an energetic solar coronal mass ejection cloud arrived a week ago. The geomagnetic activity had been exceptionally high all week until the day of the failure. In the week, a few other spacecraft reported some anomalies, and both the plasma temperature and the flux of MeV electrons were exceptionally high. However, the geomagnetic activity was relaxing in the hours preceding the failure. On the other hand, a Leonids meteor storm was intensifying after midnight".

Using the fictitious event above as background, this paper discusses space hazards, including spacecraft surface charging and deep dielectric charging.

2. Spacecraft Surface Charging

It is well known that negative level spacecraft charging occurs often in the midnight to early morning local hours during substorms or storms [Hastings and Garrett, 1996]. For spacecraft charging to onset, it is necessary to have high electron temperature [Lai, 1991; 2000a]. At geosynchronous orbits, the ambient ion current is often two orders of magnitude smaller than the ambient electron current. In darkness, photo-electrons are absent. The critical temperature for charging onset is given by the current balance between the incoming electron current and the outgoing secondary and backscattered electron currents:

$$\int_0^\infty dE E f(E) = \int_0^\infty dE E f(E) [\delta(E) + \eta(E)] \quad \mathbf{(1)}$$

where δ is the secondary electron yield and η the backscattered electron yield. In the Maxwellian space plasma, eq(1) is independent of the plasma density and depends on the temperature only.

The values of the critical temperatures for various spacecraft surface materials are typically 1 to 3 keV. The recent LANL spacecraft charging data have provided abundant evidence confirming the existence of the critical temperature for charging onset (Figure 1) [Lai, 2001b].

Once high level charging onsets, the charging level is determined by the current balance including the ion currents attracted. More refined calculations would include contributions from the geometry of the spacecraft surfaces and the anisotropy of the ambient magnetic fields and the ambient currents. If the surface properties are different, differential charging may occur. The interactions between the surfaces have to be included especially with high voltages. For a good approximation, one resorts to the Maxwellian model for an estimate of the charging level. The model yields a linear dependence of the charging level on the ambient electron temperature approximately.

Thus, if the ambient electron temperature is exceptionally high, not only spacecraft charging would occur but also high voltage charging. Differential charging and interaction between surfaces would also occur, depending on the surface properties.

In the fictitious AFLAC failure case, the electron temperature had been exceptionally high. Therefore, AFLAC surface charging was highly likely. With many surfaces on a complex satellite, differential charging was also likely.

3. Spacecraft Surface Discharging

Why is high voltage surface charging undesira-ble.? Uniform spacecraft surface charging is generally not hazardous although it may disturb scientific measurements and affect electromagnetic wave communications in the sheath. High voltage differential charging is hazardous because discharging between surfaces may occur.

Low level current leakage may persist and cause system degradation. However, an avalanche discharge with ionizing neutral gas is rapid and carries high current. Large capacitances between surfaces can also provide large currents. Discharges with large currents may burn out part of the instruments, spread to the neighboring surfaces, short circuits, and generate electromagnetic disturbances and are therefore hazardous.

3.1 Townsend's Criterion.

Laboratory experiments have repeatedly shown that out-gassing is an important factor for avalanche ionization discharge. Townsend's criterion determines whether a discharge is sustained.

Let there be μ ionizations in the neutral gas by an electron transit between a cathode and an anode. The electrons are accelerated towards the anode, and the μ ions towards the cathode. If an ion impact produces γ electrons, then μ ion impacts would produce $\mu\gamma$ electrons from the cathode. A necessary condition to sustain the discharge is the Townsend's criterion:

$$\mu\gamma \geq 1 \qquad \textbf{(2)}$$

To calculate the quantity μ, let α ionizations be generated by an electron traveling through a distance dx. For n electrons at x, the number of ionizations at x+dx is given by

$$dn = n\alpha dx \qquad \textbf{(3)}$$

The total number of ionizations from the cathode (x=0) to an anode (x=d) is given by

$$n(d) = n(0)\exp(\alpha d) \qquad \textbf{(4)}$$

where $n(0)$ is the initial number of electrons starting the journey at x=0. Thus, $\mu = \exp(\alpha d)$.

To calculate α, one needs to know the cross-section $\sigma(E)$ of impact ionization:

$$\alpha \propto N\int dE E^{1/2} f(E)\sigma(E) \qquad \textbf{(5)}$$

where $f(E)$ is the plasma electron distribution function, $\sigma(E)$ is the impact ionization cross-section, N is neutral density, and E the electron energy. Thus,

$$\mu = \mathbf{exp}\left[Nd\int dE E^{1/2} f(E)\sigma(E)\right] \qquad \textbf{(6)}$$

Thus, both the neutral gas density and the plasma electron distribution function play important roles in mediating a discharge.

The Townsend criterion is necessary but not sufficient [Lai, 2001a]. One needs to include the loss mechanisms such as line excitation of the gas molecules, molecular dissociative recombination, and electron escape from the interaction region. When the ambient magnetic field lines subtend finite angles with the path of discharge, new Townsend's criteria have been formulated to account for electron escape time and electron residence time in competition with ionization time. The roles of these mechanisms in quenching discharges have been studied in a related field called critical ionization velocity.

3.2 Capacitance Discharge

The discharge current contributed by the surface capacitances can be large. The capacitance between a typical spacecraft surface and the vacuum space is usually small, depending on the area of the surface. However, the capacitance between a thin dielectric layer and its conducting substrate can be tremendous. Thin layers, such as thermal blankets, are often used on spacecraft. The thin layer's capacitance is proportional to the inverse of its thickness d:

$$C \propto A / d \qquad \textbf{(7)}$$

where A is the surface area. If d is extremely small in eq(7), the capacitance C becomes extremely large . No wonder thin thermal blankets are often the hot spots involved in spacecraft anomalies [Stassinopoulos, et al., 1996]. Since the charge stored is directly proportional to the capacitance, the discharge current can be extremely large; it can be much larger than that the typical currents in deep dielectric charging and discharging. In view of the high discharge current possibility, spacecraft surface charging and discharging as a prime space hazard deserves full attention.

In view of the space weather conditions in the

AFLAC case, high voltage differential charging and discharging could happen. Details of the spacecraft surfaces condition including geometry are needed for estimates of the Townsend avalanche ionization discharge criteria and the magnitudes of the discharge currents from the large capacitances.

4. Deep Dielectric Charging

High energy (MeV or higher) electrons and ions penetrate deep into dielectrics. Since the conductivity of dielectrics is low, the electrons and ions stay there for a long time with little probability of migration or recombination [Vampola, 1987].

4.1 High Field Breakdown.

The ambient ion flux at geosynchronous orbits is typically two orders of magnitude smaller than that of electrons. Besides, electrons and ions penetrate to different depths [Hastings and Garrett, 1996]. Thus, deep inside dielectrics, the charges are predominantly of the negative sign. There, the electrons deposited can build up high electric field.

$$\varepsilon \frac{dE}{dt} + \sigma E = J \qquad \textbf{(8)}$$

where E is the electric field, t is time, σ the conductivity, and J the incident particle flux. After days of high flux of high energy electrons, the field built up can be so high that it may cause dielectric breakdown, the typical field for breakdown is about 10^7V/m.

Solar coronal mass ejections and coronal hole ejections are typically of MeV energy or higher. They may hit our spacecraft at high altitudes and thereby may cause spacecraft anomalies. In recent years, the four most important satellite failures, viz., ANIK-1, ANIK-2, AT&T Telstar, and Motorola Galaxy-4, all happened after days of Solar high energy (MeV or higher) cloud passage [Baker, 2000].

4.2 Mott Transition.

Since the conductivity of dielectrics is low, the electrons and ions deposited inside stay there for many days. Depending on the conductivity and the fluence, the charge density accumulated may be very high. The high charge density may cause Mott transition, meaning a sudden change from an insulator to a conductor [Mott, 1961; 1977]. The critical density is that which rendering the Debye length equal to the effective Bohr radius.

$$\frac{1}{\lambda^2} = 4\left(\frac{3}{\pi}\right)^{1/3} \frac{n^{1/3}}{R} \qquad \textbf{(9)}$$

where λ is the Debye length and R the effective Bohr radius.

$$n_c^{1/3} R = 0.3 \qquad \textbf{(10)}$$

where n_c is the critical charge density and R the effective Bohr radius of an atom in the the material. Typical critical densities are 10^{15} to 10^{18} e^-/cm^3 depending on the dielectric material.

Recently, it has been suggested that the high electric field built up in the deep region may affect the Mott transition in the dense charge region which is less deep. The result is that both the critical Mott transition density and the high field for breakdown down are not as high as previously thought (Figure 2) [Lai, 2000b].

4.3 Sequential Deep and Surface Charging

The effects of deep dielectric charging and surface charging can happen in concert. Consider a thin dielectric slab on top of the spacecraft ground. During a high energy electron cloud passage, both the slab and the ground charge negatively. Due to its poor conductivity, the slab builds up its electric field over time. After the passage, the slab maintains its high electric field because of its poor conductivity, whereas the spacecraft ground responds to the ambient plasma almost immediately. Suppose the ground potential becomes zero or a few Volts positive while the dielectric remains negatively charged, the large difference in potentials may be hazardous.

To confirm these mechanisms, one needs measurements of the electric fields and charge densities built up as functions of depth and time in the dielectric. Such measurements in the laboratory and in space are feasible. For example, the design by Balmain [1996] may be useful for such measurements.

On AFLAC, it is plausible that deep dielectric charging, Mott-transition, high field breakdown, and their combinations might have occurred.

5. Layer Formation in Dielectrics

High energy (MeV) electrons and ions penetrate to different depths in dielectrics. They form double layers as described below. During the passage of a high energy cloud, mostly electrons are deposited because the ion flux is much smaller. Thus an electron layer is formed deep inside the dielectric. As a consequence, a strong electric field is built up by the electron layer. Since an one-dimensional electric field extends far, it extends beyond the dielectric surface.

5.1 Double Layer

After the high energy cloud passage, the ambient plasma returns to its normal, lower energy, higher density condition. The low energy ambient ions are attracted by the electric field towards the surface, because nature prefers neutrality. However, no matter how the low energy ions are coming in, they can never reach the deeply deposited electrons. Therefore, they can never neutralize the electrons. Eventually, a double layer is formed inside the dielectric. In between the double layers, the electric field is high. Outside the surface, a detector would detect near zero electric field. Demonstration of the double layer formation in the laboratory is feasible.

5.2 Anodized Discharge

Since the electric field between the double layers is higher than in the single layer case and, furthermore, the distance between the layers is very short, the situation is unstable and is therefore potentially hazardous. Any defective path, weakness, or local maximum electric field along impurity cites, allowing the electrons to breakthrough, would likely result in a discharge. Since the double layer is formed in a sequential cathode-anode formation, the discharge may be termed an "anodized discharge" (Figure 3). It is feasible to demonstrate the formation process of a double layer and a subsequent discharge in the laboratory.

In the AFLAC case, the geomagnetic activity had been relaxing in the several hours before the failure. The condition is right for a double layer followed by an "anodized discharge" to occur.

6. Hypervelocity Impacts

6.1 Impact by Meteorites

A Leonids meteorite has a velocity of about 72 km/s. At such a high velocity, each atom of the meteorite has a kinetic energy around 1 keV. Depending on the size of the meteorite (typically 0.1 to 0.001 gm), it can puncture through aluminum walls of a few mm thick (Figure 4). The neutral gas generated by heating and evaporation and the plasma generated by impact ionization can short circuits, inside or outside the wall.

If the hypervelocity impact in on a double layer in a dielectric, an "anodized discharge" may be initiated. This is because the meteorite has punctured an ionization path between the layers for the discharge to occur. The puncture shorts the circuit of the layers inside the dielectric.

It is difficult to diagnose a hypervelocity impact, because the angular momentum imparted to the spacecraft is small unless the spacecraft is small or unless the impact is on a light solar panel.

In the AFLAC case, a Leonids storm was intensifying at the time of the failure. A hypervelocity impact, with or without a double layer, could have occurred.

6.2 Debris Impact

Debris are generated from spacecraft. Since geosynchronous spacecraft are rotating at the same angular velocity as the Earth, they are also rotating in the same direction, viz., eastward. The relative velocity between the geosynchronous objects is nearly zero. If a satellite is orbiting westward, a head-on collision with another object, such as a debris, would have a relative velocity equal to twice its orbital velocity. Depending on the westward travel speed and the mass of the debris, the collision may cause a satellite failure.

In the AFLAC case, the satellite was moving westward, the wrong traffic direction. The chance of debris collision was higher than in an eastward move.

7. Plasma Propulsion

So far, every character in the fictitious AFLAC scenario has played a role. There is one more character left, viz., the plasma ion thruster.

The plasma ion thruster also has a role to play. In plasma thrusters today, a plasma is generated in an ionization chamber and is extracted by means of electrodes. The efficiency of ionization, however, is typically a few percent. The neutral gas molecules can wander out at their thermal energies because the electrodes do not interact with them. As a result, the neutral molecules form a slow gas cloud around the exit point of the thruster. They may collide with the fast plasma ions, thus forming slow ions by charge exchange.

$$A_{slow} + A^{+}_{fast} \rightarrow A^{+}_{slow} + A_{fast} \qquad \textbf{(11)}$$

where A is a thruster gas molecules.

If the nearby surfaces are charged negatively, the slow ions are attracted and return to the surfaces. (Figure 5) This mechanism, in concert with deep dielectric charging, can form a double layer, followed by a high probability of an "anodized discharge", as discussed in Sec.5. Thus, a plasma thruster operation after a prolonged high energy (MeV or higher) electron deposition in dielectrics is a potential hazard.

In th AFLAC case, a plasma thruster was used to move the satellite after days of high energy electron flux. The slow ions returned to the surface. An "anodized discharge" possibly occurred.

8. Summary and Conclusion

We have discuss some space hazards, concerning spacecraft surface charging, deep dielectric charging, hypervelocity impact, and plasma thrusters. Surface charging occurs when the ambient electron temperature exceeds a critical or threshold temperature. The charging level increases linearly with the electron temperature approximately. The magnitude of the surface discharge current depends on the capacitances and on the multiplicative ionization of out-gassing.

Deep dielectric charging can build up high electric fields which may lead to dielectric breakdowns. One-dimensional electric fields extend much farther than that from a point charge. Heretofore, Mott transition has not been applied to space physics, and high electric field effects on Mott transition has not been studied in any field. The electric fields can affect the high density deposited in another part of the dielectric, rendering a high field Mott-transition to occur.

After the passage of a high energy electron cloud, a double layer may form inside dielectrics. While the electric field outside the double layer may be nearly zero, that inside is high. Heretofore, double layers in dielectric charging has never been studied. This configuration is potentially hazardous. Any ionization path through cracks, weakness paths, or localized impurities may initiate an "anodized discharge". Again, this terminology is new in space physics.

As another example, a hypervelocity impact by a meteorite can also initiate a discharge. A wrong direction satellite traffic can also collide with a debris.

Finally, the plasma ion thruster, heretofore unsuspected, may also play a role by generating slow charge exchange ions which return to the negatively charged spacecraft surface. The surface ion deposit fostered the double layer formation, followed by a possible "anodized discharge".

The AFLAC satellite failure scenario in the introduction serves as kind of detective story. It provides clues for the readers to follow and think. In this manner, it helps illustrate the above "space hazards" mechanisms. They may lead to satellite anomalies or failures. The mechanisms may act singly or in concert with some others.

9. Acknowledgment

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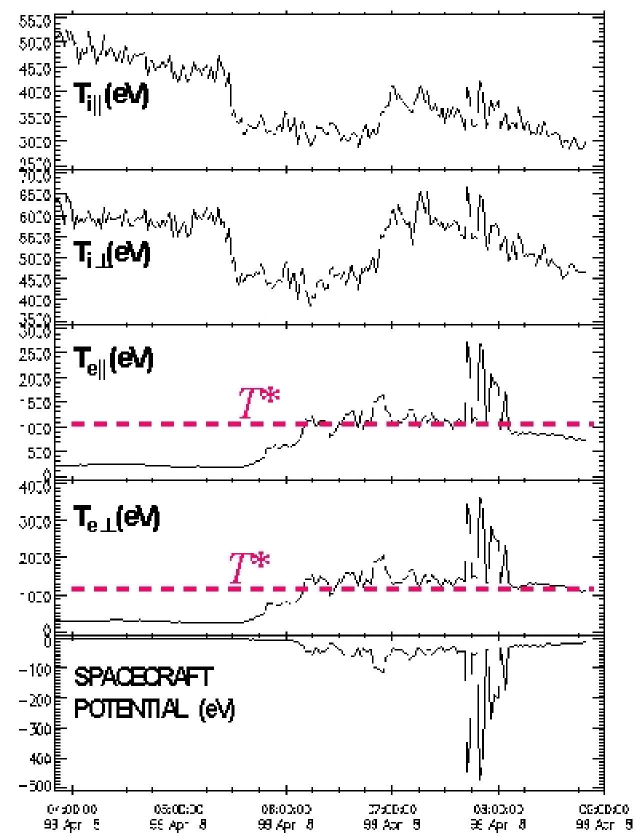

Figure 1. Existence of critical temperature for the onset of spacecraft charging. The ion temperature has no effect.

(Data courtesy D. McComas)

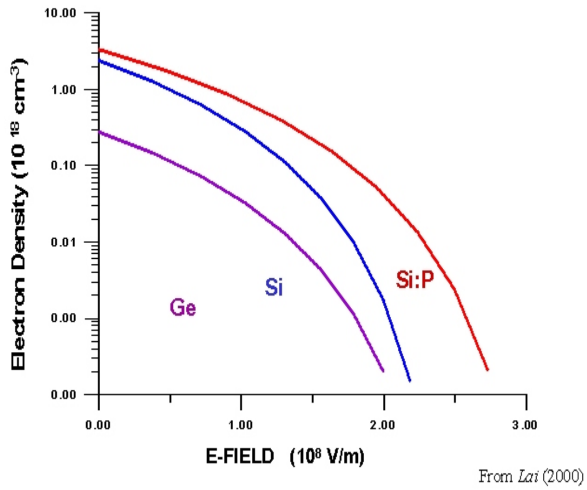

Figure 2. Critical Electron Density and Critical E-Field in the High Electric Field Mott Transition

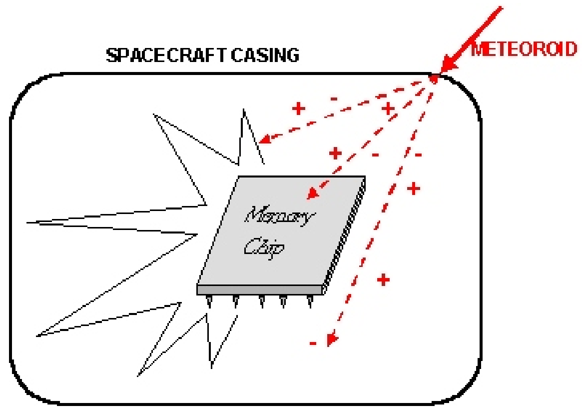

Figure 4

. Meteoroid penetrating through the spacecraft casing. Plasma and vapor generated inside can cause discharge inside and damage the electronics.

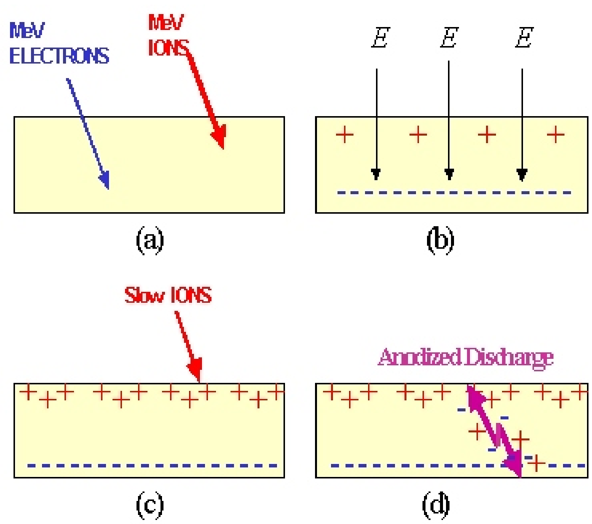

Figure 3. A sequence of double layer formation in a dielectric material. (a) During high energy (MeV or higher) events in space, electrons and ions bombard on and penetrate into different depths in dielectrics. (b) After days of bombardment, a deep electron layer is built up. Ion fluxes in space are lower than those of electrons. Electric fields form, attracting ambient ions. The ions, however, are too fast to turn; they fly by and leave. (c) When the high energy flux decreases, the space plasma is returning towards normal. Slow ions are attracted. Although nature tends to favor eventual charge neutrality, the positive and negative charge layers remain separated because of the poor conductivity of the dielectric material. A double layer inside the dielectrics is therefore formed. (d) Anodized Discharge.

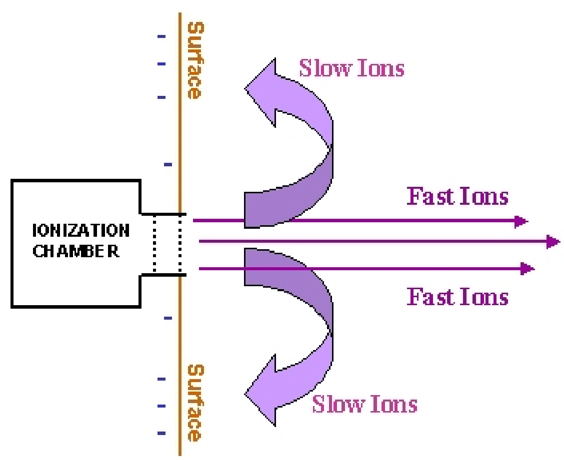

Figure 5. Plasma Ion Thruster. Slow ions generated by charge exchange are attracted back to the negatively charged spacecraft surfaces.