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14. ABSTRACT

The geosynchronous environment is the most important region in the magnetosphere for spacecraft charging because the plasma temperature can be very high; the plasma density is sometimes very low, and most communications satellites are there. It is now well understood that, for a given surface material, there exists a critical plasma temperature above which spacecraft charging to negative potentials occurs. High energy (MeVs) electrons and ions penetrate into material to different depth. At energies below 100 MeV, electrons penetrate deeper than ions, and may remain in a deep layer, causing a high electric field. High energy "killer electrons" can cause deep dielectric charging and spacecraft anomalies. Studies of correlations of coronal mass Ejections, and exo-events, when a satellite gets outside of the magnetosphere are needed. Spacecraft used for planetary studies can also be affected. More study is also needed to determine whether surface charging or deep dielectric charging is more damaging to satellites.

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Spacecraft Charging - Present Situation and Some Problems

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This overview discusses some aspects of the present situation of spacecraft charging related to space weather and suggests some simple research problems.

I. Introduction

With the launch of the geosynchronous SCATHA satellite some three decades ago, full-fledged research in spacecraft charging started. The main reasons for studying spacecraft charging [1,2] are (1) effects on scientific measurements onboard, and (2) damage to the scientific instruments [Figure 1]. Significantly, spacecraft charging can have impact on mission. Many advances have been made in the past decades. A historical development can be reflected by the series of Spacecraft Charging Technology Conferences, which started some 30 years ago at the Air Force Academy, Colorado Springs. Spacecraft surface charging now stands up as a field in science and engineering. There are many new research opportunities to be opened up for future research in surface charging.

In recent years, much attention has been paid to space weather, which is becoming an important field. Much satellite data on space weather are becoming available. A main purpose of studying space weather is for eventual applications to space systems. With the availability of the space weather data and spacecraft charging data, it is now beginning to be ready for venturing into their overlapped area, viz., coordinated data studies on the effects of space weather on space systems.

This talk will present an overview on some aspects of spacecraft charging related to space weather and suggest some simple problems. Advances in laboratory measurements, computer modeling, spacecraft instrumentation, and future space systems, are important but will be outside the scope here.

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This talk will present an overview on some aspects of spacecraft charging related to space weather and suggest some simple problems. Advances in laboratory measurements, computer modeling, spacecraft instrumentation, and future space systems, are important but will be outside the scope here.

II. Space Weather Effects on Spacecraft Surface Charging

The geosynchronous environment is the most important region in the magnetosphere for spacecraft charging to occur. The reason is because (1) the plasma temperature is sometimes very high (multiple keV) and the plasma density is sometimes very low (few electrons per cc.) in that region, and (2) most communication satellites are there. It is now well understood that the onset of spacecraft charging depends very much on the plasma temperature. For a given surface material, there exists a critical temperature above which spacecraft charging to negative potentials occurs [Figure 2]. Below it, charging to negative potentials does not occur. The theory of critical temperature was

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obtained by considering Maxwellian space plasmas. It is surprising that the theory agrees very well with the observed data on the Los Alamos National Laboratory (LANL) satellites [Figure 3].

It is not surprising that the Maxwellian model is correct; it is surprising why the space plasma should be Maxwellian so often, rendering the better-than expected agreement between theory and observations. Indeed, the space plasma should be sometimes in a double Maxwellian distribution [3], especially when fresh energetic plasmas arrive at a region where less energetic plasmas are already present. In a double Maxwellian plasma environment, triple-root jump in spacecraft potential can occur. A study [4, 5] has shown that, even in a double-Maxwellian environment, the critical temperature still plays an important role in delineating the parametric domains of the charging behavior.

However, the space plasma is sometimes non-Maxwellian. For example, the distribution sometimes resembles a kappa distribution [6-9], in which the high-energy tail is more prominent than in a Maxwellian distribution. A study [10] on spacecraft charging in a kappa distribution of space plasma has shown that the onset of spacecraft charging is determined by a critical value very close to the critical temperature of the Maxwellian plasma theory. A thorough statistical study, using the LANL satellite charging data, on the problem of spacecraft charging in an ambient environment with kappa distribution of electrons has to be done and may be worthy to be thesis material.

The advent of critical temperature enables forecast of spacecraft charging at geosynchronous altitudes to be carried out. Although there are many parameters in space weather, it is useful to single out the most direct parameter, or parameters, for spacecraft charging forecasts. As an analogy, although there are many parameters in our daily weather, sometimes we only hope to know whether it will rain at a Saturday evening. Whatever the barometric pressure distribution is at 7500 feet altitude within 10 miles may not be our concern.

In space weather, the main driving force is the large eruptions on the Sun. The solar plasma propagates to the Earth's magnetosphere and disturbs the Earth's space weather. The space weather parameters are many, including the electron density, electron temperature, ion temperature, ion density, magnetic field vector, ion group velocity, ratio of the magnetic to particle pressures, etc. However, if one can forecast just the plasma electron temperature at or near the geosynchronous region, one can predict whether spacecraft charging is likely to occur. It is amazing that only one parameter is practically sufficient for the prediction of the onset of spacecraft charging. See, however, the following remark.

This paragraph remarks on the Maxwellian model. The Maxwellian model [11] yields two results, viz., (1) the critical electron temperature for the onset of spacecraft charging and (2) the charging voltage for each given electron temperature exceeding the critical value. A statistical study [12] has shown the existence of critical temperature agreeing reasonably well with the data obtained from the LANL geosynchronous satellites. There are statistical fluctuations and they are tabulated in Ref.11. The study also shows the linear or quadratic trend of charging voltage as a function of electron temperature. With a given temperature, one can therefore predict the charging voltage by using the linear or quadratic trend. The trend deviates from being linear when the voltage reaches about 3 kV (Figure 4). A quadratic trend (dash line in Figure 4) fits better. There are statistical fluctuations. One reason for the fluctuation is because possible deviation of the distribution from being Maxwellian. In the kappa distribution study[10], only a small set of data (the set used in Ref. 11) was used. The results are close to those of the Maxwellian theory as far as onset is concerned. No charging voltage as a function of temperature was studied in the Harris thesis [10]. The reason for the closeness of the onset results is probably because the plasma is not deviating too much from equilibrium at low temperatures, such as 0.1-3.0 keV. This range is approximately that of the critical temperature values for typical surface materials. For highly disturbed plasma, not only the temperature becomes very high but also the distribution often deviates from being Maxwellian. However, as far as prediction of onset of charging is concerned, the low temperature range (up to about 3 keV) enables the Maxwellian theory to be useful.

The space weather[13] parameters allow one to do many interesting spacecraft charging problems. For example, how does the sequence of a severe geomagnetic storm correlate with spacecraft charging? How severely does a coronal mass ejection (CME) affect spacecraft charging [14-16]? How does one compare the effects of a co-rotating interaction region (CIR) with those of a CME on spacecraft charging? How much does an exo-event (when the solar wind compresses the magnetosphere so much that part of the sunward side of the satellite orbit lies outside the magnetosphere) affect spacecraft charging, etc. These are some suggested problems related to space weather. The answers to these problems may contribute towards an ultimate goal of space weather – to apply scientific knowledge of space weather to space systems.

In addition to the space weather of the Earth, one should look towards the moon and the planets. This is a future direction, as mankind's horizon is expanding towards farther outer limits. The moon does not have a magnetosphere and is therefore exposed to the solar winds. It is dusty on the moon. More on charging of lunar dust [17-18] in solar wind plasmas with energy distributions needs to be studied systematically. The small dust size poses problems to secondary electron emission, because the secondary electrons are generated from shallow depths only [19-20].

Furthermore, the primary electron, if energetic enough, can pass through a dust particle and exit from the opposite side. Depending on the size distribution of the dust particles [21-22] and the energy distribution of the plasma electrons, one can formulate charging theories of dusts with further assumptions. Such theories may be worthy to pursue and are possibly thesis materials. This is a futile area for research [23-26].

The planets have their magnetic field orientations and magnetospheres. It is well known that Jupiter has aurorae [Figure 5]. (http://www.jpl.nasa.gov/releases/2001/belts.html) It has been observed that spacecraft surface charging can occur in the magnetospheres of Jupiter and some other planets[27-30]. X-ray observations have yielded evidence of electrons up to 200 MeV in energy on Jupiter. High-energy electrons with energies in MeV or more are well known as 'killer-electrons' for their ability to penetrate, deposit, and accumulate into dielectric materials of spacecraft. Therefore, deep dielectric charging [30-35] is an important subject for spacecraft traveling into highly energetic charged environments such as the magnetospheres of Jupiter and some other planets. In summary, both surface charging and deep dielectric charging are likely to occur in some planetary magnetospheres. More planetary magnetosphere data are needed. This is likely a fruitful area for future spacecraft charging research.

III. Deep Dielectric Charging

High energy (MeVs) electrons and ions penetrate into material to different depths. At energies below 100 MeV, electrons penetrate deeper than ions. For spacecraft dielectric materials, the electrons penetrate inside, stay there for hours, days, or months, depending on the material conductivity, and accumulate as more and more energetic electrons bombard the spacecraft. Without the presence of ions in the deep layer, the electrons are not neutralized and therefore form a high electric field. The electric field may eventually reach a critical value E*. Typically, E* is about 10^6 V/m, depending on the material [2]. Above the critical electric field E*, dielectric breakdown occurs.

The electric field of the deep electron layer may extend outside the surface, thus attracting low energy ambient ions to the surface, forming a double layer of electrons and ions. However, the ions entering the material can not reach the deep layer of electrons because MeV electrons and ions penetrate to different depths [Figures 6,7]. Since the ambient ion flux is typically two orders of magnitude lower than that of ambient electrons, the surface ions deposit relatively slowly. Since nature prefers neutrality, the far field of the double layer is eventually neutral. Inside a double layer, the electric field is higher than that of one electron layer alone. With a double layer, the electric field outside the spacecraft surface becomes nearly zero, because the electric field of the ion layer cancels approximately that of the electrons. This phenomenon suggests that surface charging is not associated with deep dielectric charging [36].

Energetic electrons are present in the Earth's radiation belts, especially during highly active events of the Sun. Indeed, the CRRES satellite experienced anomalies in the radiation belts, especially during solar activities [35]. The anomalies were attributed to deep dielectric charging [30-35]. Interestingly, no surface charging (beyond -30V) occurred during the days of the anomalies. [Figure 8].

Following the CRRES papers [37-39] analyzed the correlations between killer electrons and spacecraft anomalies observed on several satellites and declared the evidences conclusive [Figure 9]. Subsequently, more and more spacecraft anomalies attributed to killer electrons during highly active solar events have been reported [40]. It now well accepted that killer electrons can cause deep dielectric charging and spacecraft anomalies.

Whether deep dielectric charging or surface charging is more important for causing spacecraft anomalies is still in debate. Koons et al [41] have analyzed all spacecraft anomaly events available up to about 1999 and concluded that surface electrostatic discharge is the most likely cause of missions terminated [Figure 10]. Although surface charging provides higher current than deep dielectric charging, the latter probably hurts the electronics more. In view of the near perfect correlations between the anomalies observed on various satellites (such as CRRES, DRA, TC1 and TC2) and the high fluence of high-energy electrons in the radiation belts, deep dielectric charging is emerging as the more important cause of anomalies in the radiation belts following very energetic solar events. If so, the future direction of spacecraft charging research should turn more towards deep dielectric charging. This is not a new field but much more needs to be done.

IV. Summary and Discussion

We have discussed some aspects of spacecraft charging related to space weather and suggested some simple problems for research. There exists a theory of critical temperature for the onset of spacecraft surface charging. Observations have agreed very well with the theory. It is strange why the agreement should be so good in view of the fact that the space plasma may not be always in equilibrium. The future of spacecraft research applications should be broadened towards applications on the planetary magnetospheres. Jupiter has aurorae and high-energy

(MeV) electrons. The latter are called 'killer-electrons' because they can penetrate into and deposit inside dielectrics. Observations of anomalies on satellites in the Earth's radiation belts have shown (1) near perfect correlations with the fluence of 'killer-electrons', and (2) there exists a critical fluence above which the anomalies are likely to occur. Deep dielectric charging may emerge in the future as a very important charging research area. There are many research problems in deep dielectric charging. For example, there is no effective method at the present for mitigation of deep dielectric charging. Shielding of high-energy electrons certainly works, but a satellite needs to have eyes and ears which should not be shielded. Development of tailored conductivity in materials appears as a feasible approach [42, 43]. The problem of mitigation of deep dielectric charging needs to be solved.

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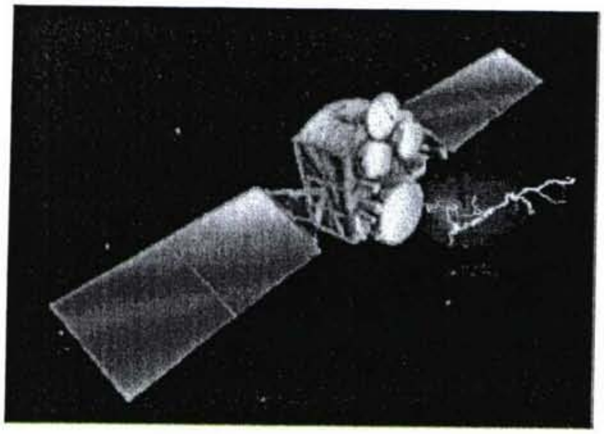

Figure 1. Spacecraft charging and discharging.

MATERIAL	ISOTROPIC	NORMAL
Mg	0.4	---
AL	0.6	---
Kapton	0.8	0.5
Al Oxide	2.0	1.2
Teflon	2.1	1.4
Cu-Be	2.1	1.4
Glass	2.2	1.4
SiO_2	2.6	1.7
Silver	2.7	1.2
Mg Oxide	3.6	2.5
Indium Oxide	3.6	2.0
Gold	4.9	2.9
Cu-Be (Activated)	5.3	3.7
MgF_2	10.9	7.8

Figure 2. Critical temperature (keV) for the onset spacecraft charging.

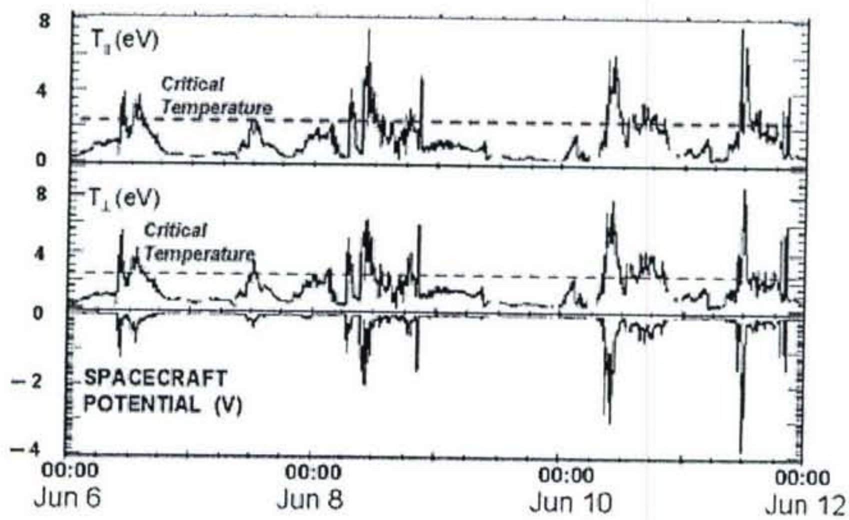

Figure 3. Spacecraft charging on a LANL satellite. The data show existence of critical temperature for the onset of spacecraft charging. [Ref.11]

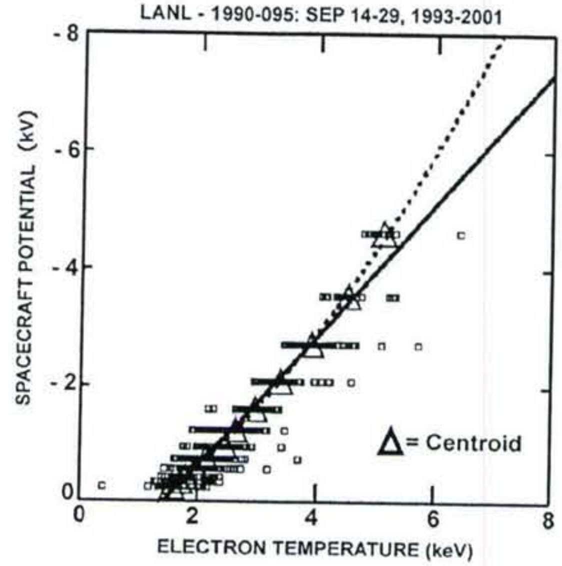

Figure 4. Spacecraft potential and electron temperature measured on Spacecraft LANL-1990-095, during eclipse periods, 14–29 September 1993–2001. [Ref. 12]

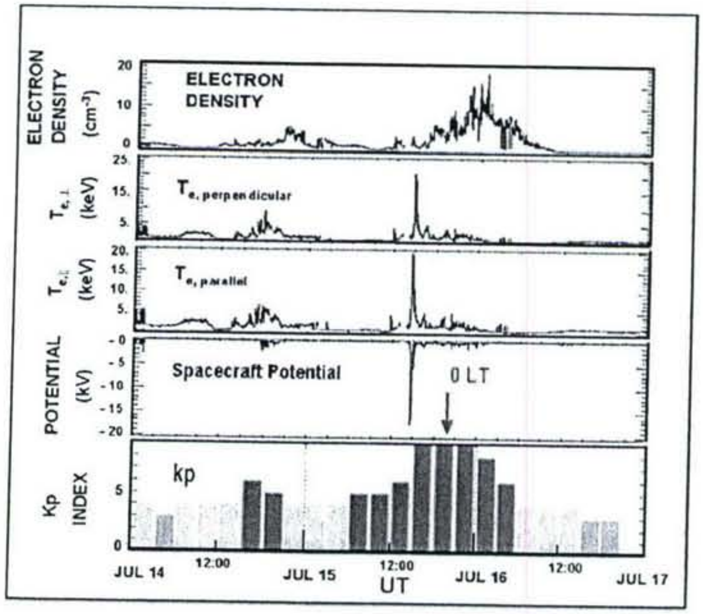

Figure 5. Spacecraft charging on Bastille Day, 2000. Charging occurred during a brief period of high electron temperature. The charging duration was short despite high kp. [Ref.12]

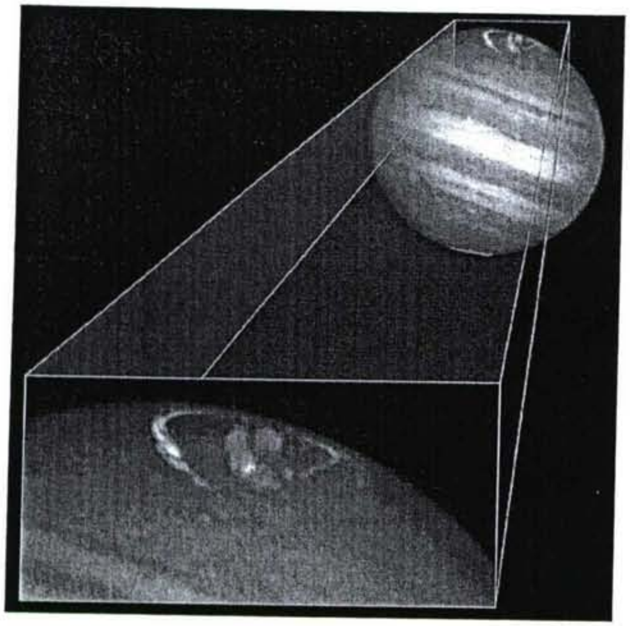

Figure 5. X-ray emissions observed on Jupiter. (http://www.jpl.nasa.gov/releases/2001/belts.html)

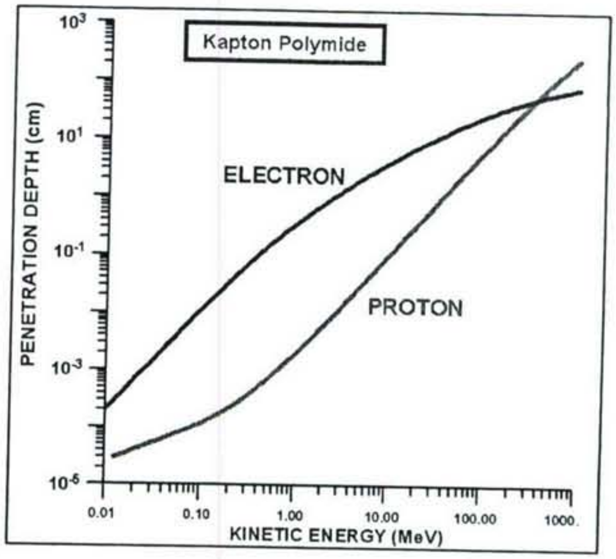

Figure 6. Different Electron and ion penetration depths into solid.

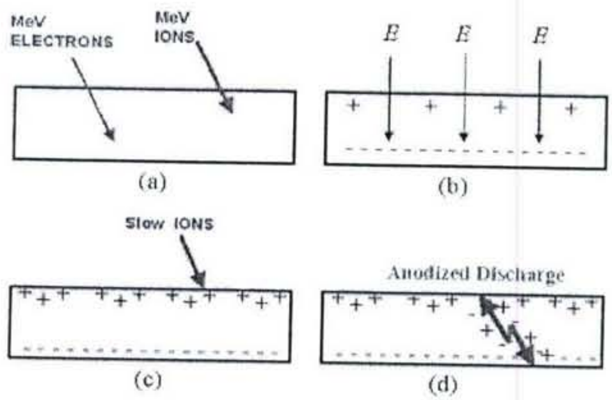

Figure 7. A consequence of high-energy electron bombardment in solids: formation of double layer. (Ref.36)

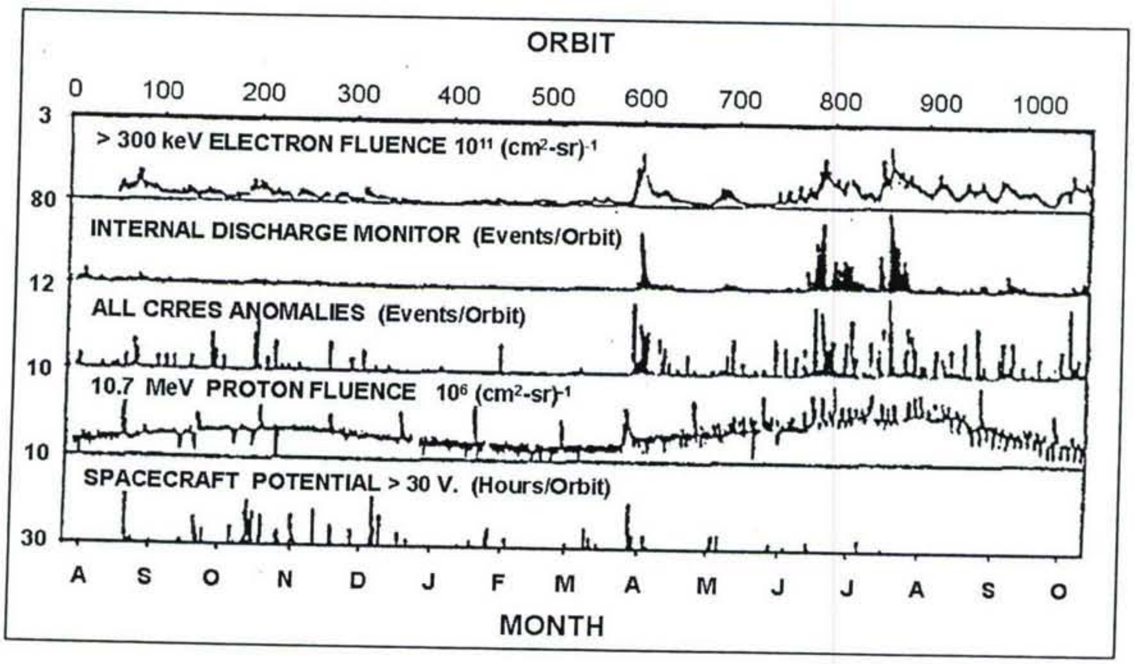

Figure 8. Charging and discharging observed on the CRRES satellite in the radiation belts. Surface charging and discharging do not correlate. (Ref.37)

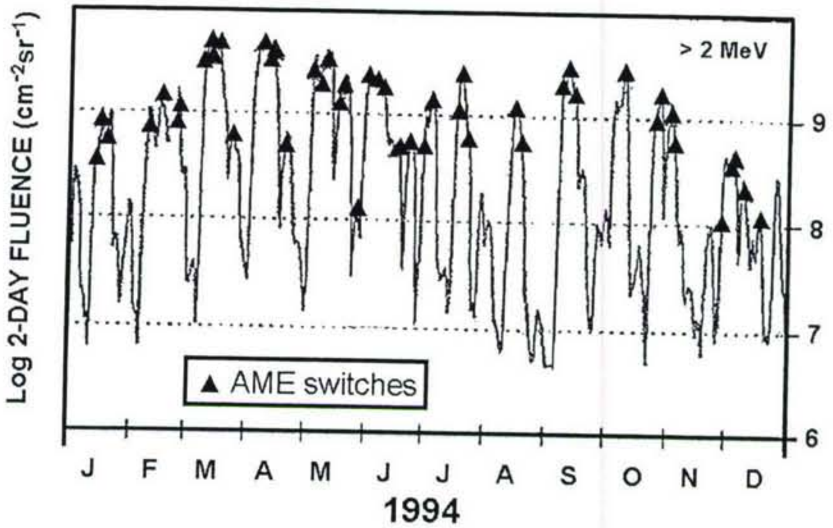

Figure 9. Correlation discharges and high electron fluences. Conclusive evidence of deep dielectric charging. (Ref.38)

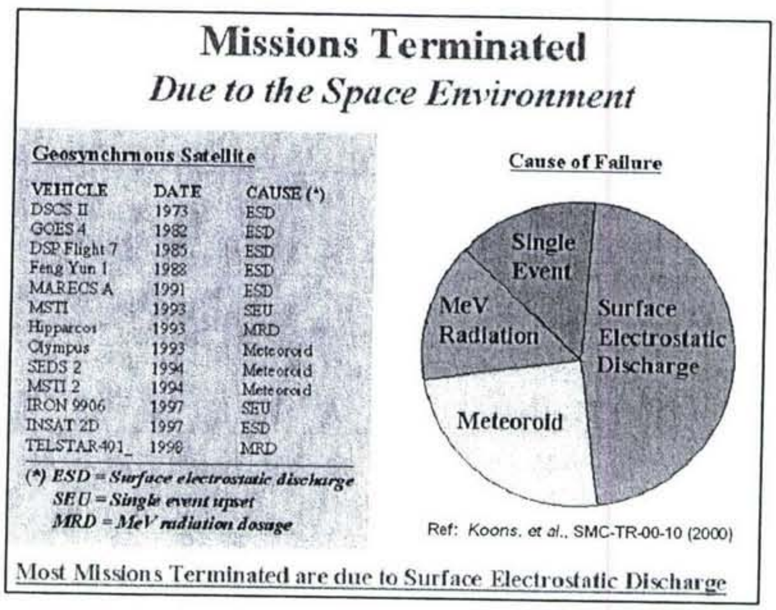

Figure 10. Missions terminated due to the space environment. Most missions terminated are due to surface electrostatic discharge.