

# Spacecraft Charging

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## Abstract

This entry is an overview of spacecraft surface charging in space plasmas. It occurs mostly at geosynchronous orbits where many communication satellites are located. Depending on the surface properties, spacecraft surface charging occurs when the ambient electron temperature is hot (kiloelectronvolts). Differential charging between spacecraft surfaces is the main cause for hazardous discharges, which may disturb scientific measurements onboard, damage instruments and even terminate missions. Several mitigation methods are discussed. Finally, spacecraft anomalies are discussed and some examples of spacecraft anomalies due to surface charging are given.

## OVERVIEWS OF SPACECRAFT CHARGING

### Historical Introduction

The first significant spacecraft-charging event (several negative kilovolts, kV) was observed by DeForest<sup>[1]</sup> on the National Aeronautics and Space Administration (NASA) Applications Technology Satellite, ATS-5, which launched to geosynchronous orbit in 1969. Olsen and Purvis<sup>[2]</sup> observed  $-17$  kV on ATS-6. Whipple<sup>[3]</sup> presented a historical account of the early charging studies before 1981.

The first and only satellite dedicated to the study of spacecraft charging was Spacecraft Charging at High Altitudes (SCATHA).<sup>[4]</sup> It was a geosynchronous satellite launched in 1979. Important spacecraft-charging data were obtained from it for the next several years. Other than SCATHA, several satellites and rockets equipped with instruments related to spacecraft charging have been launched, but they were not dedicated solely to the study of spacecraft charging. In the 1990s, several geosynchronous satellites were launched by Los Alamos National Laboratory (LANL) with instruments measuring the ambient electrons, ions, and magnetic fields together with spacecraft potential.<sup>[5]</sup> The coordinated data obtained on the LANL geosynchronous satellites enabled useful studies of spacecraft charging.

A series of spacecraft charging technology conferences tracks the evolution of this field over the years. The first four conferences in spacecraft charging technology were held at the U.S. Air Force Academy, Colorado Springs, Colorado.<sup>[6–9]</sup> In subsequent years, conferences in the series were held at the U.S. Naval Postgraduate School, Monterey, California; NASA Marshall Space Flight Center,

Huntsville, Alabama; U.S. Air Force Geophysics Laboratory, Hanscom AFB, Bedford, Massachusetts; European Space Agency, Noordwijk, the Netherlands; Tsukuba, Japan; Biarritz, France; U.S. Air Force Research Laboratory, Albuquerque, New Mexico; Kitakyushu, Japan; and Jet Propulsion Laboratory, Pasadena, California. The conference publications have been in the form of conference proceedings or as peer-reviewed papers in Special Issues of IEEE Transactions of Plasma Science.<sup>[10–13]</sup>

### What Is Spacecraft Charging?

Spacecraft charging is the condition that occurs when a spacecraft accumulates excess electrons or ions. For a conducting spacecraft, the excess charges are on the surface. The term spacecraft surface charging is used to clearly denote charging on the spacecraft surface as opposed to other charge distributions.

### What Causes Spacecraft Charging?

Space plasmas interact with spacecraft. The ambient electrons are much faster than the ambient ions because of their mass difference. The ambient electron flux received by a spacecraft exceeds that of the ambient ion flux by typically two orders of magnitude.

$$n_e q v_e \gg n_i q v_i \quad (1)$$

where  $q$  is the elementary charge, the electron and ion densities,  $n_e$  and  $n_i$ , respectively, are equal in a neutral plasma, the electron velocity  $v_e$  is much greater than the ion velocity  $v_i$ . As a result, an object placed in space plasmas intercepts

more electrons than ions. Excess of intercepted electrons charges the spacecraft to negative voltages. This property of electron-ion flux inequality is true not only in space plasmas but also in laboratory plasmas.

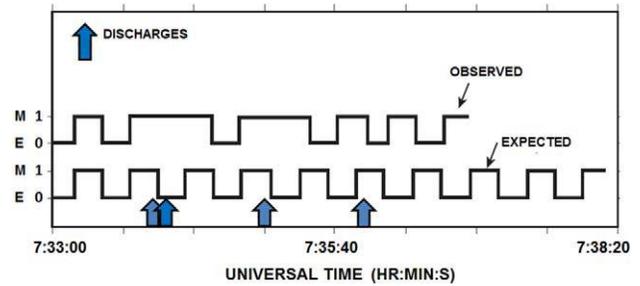
### Why Is Spacecraft Charging Important?

Spacecraft charging may cause electrostatic discharges and electromagnetic fields. It may interfere with the scientific measurements onboard (Figs. 1 and 2). It may cause spacecraft anomalies. Fredericks and Scarf<sup>[15]</sup> and Pike and Bunn<sup>[16]</sup> provided early reports on the correlation of spacecraft anomalies with spacecraft charging. In general, spacecraft charging may be harmful to the health of onboard electronics. In severe cases, it may damage the control or navigation systems and terminate the mission of the spacecraft. A compilation of spacecraft anomaly events with spacecraft charging has been given by Koons et al.<sup>[17]</sup> (Fig. 3).

### Where Does Spacecraft Charging Occur?

The most important region where spacecraft charging occurs is geosynchronous orbit. Geosynchronous orbit is a popular location for satellites used for communications, surveillance, or scientific measurements. The ambient plasma energy, or temperature, at geosynchronous orbit varies by large amplitudes from a few electronvolts to over ten thousand electronvolts over time periods of hours or minutes.<sup>[18]</sup>

Spacecraft charging can occur in the ionosphere, but the ionospheric electron energy is often so low (less than 1 eV) that the charging voltage is below 1V. However, large spacecraft traveling faster than the ambient thermal ion velocity ( $\text{km s}^{-1}$  in the ionosphere) can collect more positive



**Fig. 2** An anomaly on a spacecraft. The signal sequence observed behaves unexpectedly. The timing of the deviations coincides with that of discharges detected onboard.

**Source:** Data from Koons, Mizera, et al.<sup>[14]</sup> ©1988 AIAA. Reprinted with permission.

ions on surfaces facing the ram direction and fewer ions facing the wake region. Since ambient electrons are much more mobile than the ions, they can enter the wake region and cause negative voltage charging in the wake.<sup>[19–21]</sup>

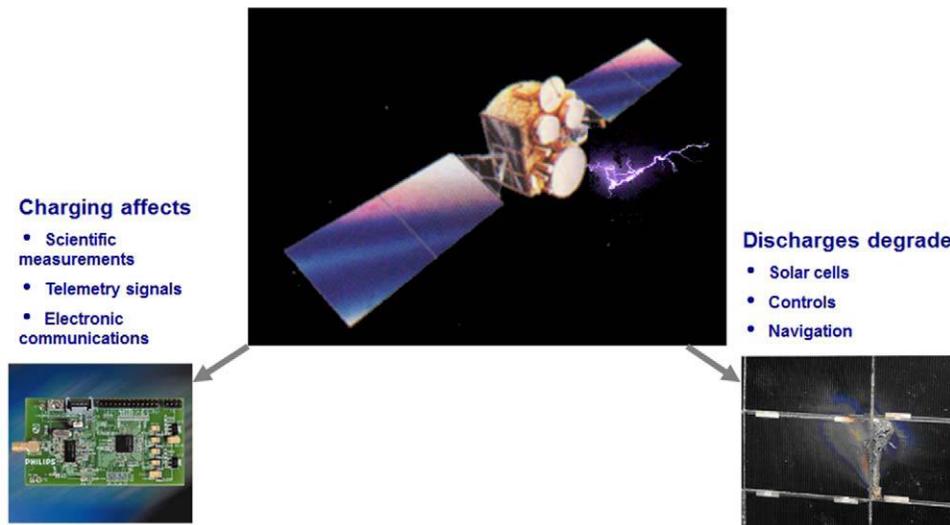
The auroral regions are also places where the ambient electrons are energetic (hundreds of electronvolts typically), and therefore, spacecraft charging can also occur there.<sup>[22–24]</sup> In the magnetospheres of the planets with high-energy electrons, spacecraft charging can also occur.<sup>[25]</sup>

### When Does Spacecraft Charging Occur?

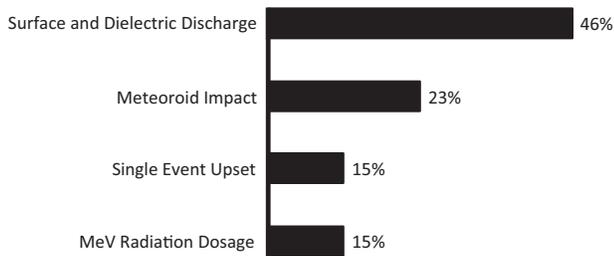
Spacecraft charging to a few volts is usually not harmful and is generally ignored. As a function of local time, spacecraft charging is mostly likely to occur during eclipse passage. This is because during eclipse there is no photoemission from the spacecraft to get rid of the excess electrons collected from the ambient plasma.

The Earth's magnetotail<sup>[26,27]</sup> often extends beyond 200 Earth radii. Substorms<sup>[26–28]</sup> occur when magnetic field

### Spacecraft Charging may be Harmful to Onboard Electronics



**Fig. 1** Spacecraft charging may be harmful to onboard electronics.

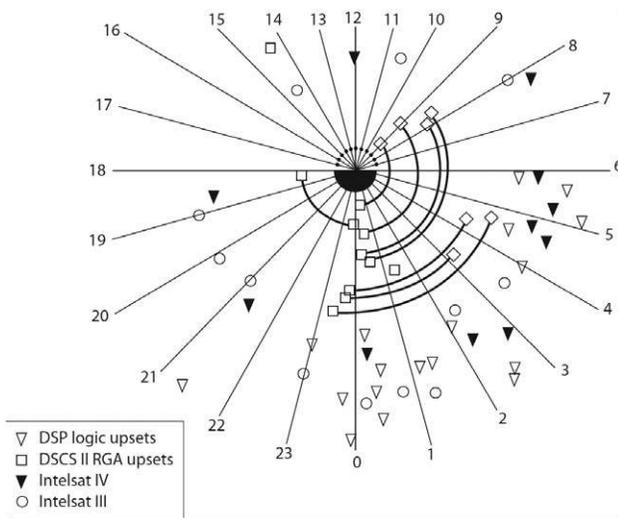


**Fig. 3** Causes of spacecraft missions terminated due to the space environment.

reconnection occurs (typically at about 30–40 Earth radii) in the magnetotail. Following the reconnection, the magnetic field lines confining the plasma within them snap back toward Earth. The process is analogous to the compression of plasma in a magnetic bottle in plasma fusion devices. As a result, the plasma moving toward Earth is heated up to keV or higher. In general, because the hot electrons at the geosynchronous altitudes tend to drift eastwards in the local morning hours, spacecraft charging is much more likely in the dawn sector than the noon and dusk sectors (Figs. 4–6).<sup>[31,32]</sup>

### How Does Space Weather Affect Spacecraft Charging?

When the space weather<sup>[26–28,33–37]</sup> is stormy with the ambient space plasma electrons going up to hundreds or thousands of electronvolts in energy, spacecraft charging to hundreds or thousands of negative volts (–V) may occur. The Sun is the major driver of space weather activity. During the solar maximum years in the 11-year solar cycle, the



**Fig. 4** Spacecraft anomalies as a function of local time. Most of them are in the morning sector. The Sun is in the noon direction. **Source:** From Vampola.<sup>[29]</sup> ©1987 Elsevier. Reprinted with permission.

Sun often has coronal mass ejections (CMEs).<sup>[26,27]</sup> CMEs carry neutral particles and energetic plasma. If a CME travels toward Earth, it takes about 2–3 days to reach Earth's magnetosphere. When it arrives, it severely disturbs the magnetosphere. Such disturbances are transient, lasting for hours or days. During the declining solar activity years of a solar cycle, the Sun sometimes ejects high-energy plasma streams from coronal holes. The streams are called corotating interaction regions (CIR).<sup>[38]</sup> The CIRs may interact with the magnetosphere every 27 days, the rotation period of the Sun. If the CMEs or CIRs hit Earth, the magnetosphere is energized and becomes stormy.

### How Fast Is the Response Time for Charging?

The ambient space plasma is the driving factor for natural spacecraft charging. How fast does the spacecraft potential respond to the driving factor? The response time depends on the surface capacitance, the ambient current, and the charging voltage. For a spacecraft of about 1 m radius, the surface capacitance is about  $10^{-10}$  Farads. Charging the spacecraft at geosynchronous altitudes to –1 kV takes about a few milliseconds. It takes a longer time to charge spacecraft surfaces that have higher capacitance.

### What Is Deep Dielectric Charging?

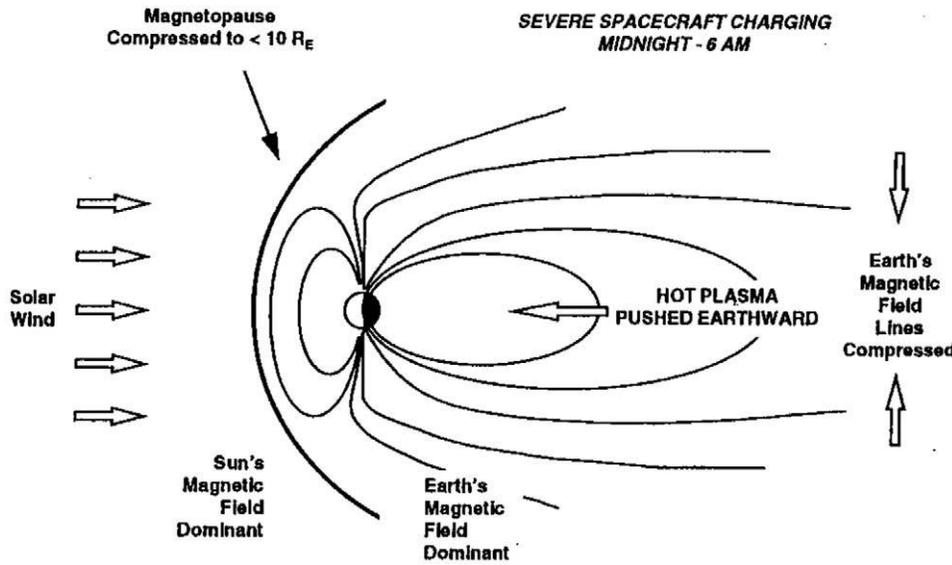
For a non-conducting (dielectric) spacecraft, the charges can deposit themselves on the surface or inside the dielectric materials.<sup>[29,39–42]</sup> High-energy ambient electrons can penetrate deep into dielectric materials and stay there for a long time (hours to months, depending on the material conductivity and the depth of accumulation). Both surface charging and deep dielectric charging can occur for non-conducting spacecraft.

## MEASUREMENT TECHNIQUE FOR SPACECRAFT POTENTIAL

### How Is the Potential of a Spacecraft Measured?

The commonly used method is to obtain the data of the spacecraft potential by the shift of the energy distribution. It is also called the ion line method. When a spacecraft is charged to a negative potential, an ambient positive ion arriving at the spacecraft surface gains an energy  $q\phi$  where  $q$  is the elementary charge and  $\phi$  is the spacecraft potential.<sup>[31]</sup> Even an ion of initially zero energy gains  $q\phi$  when it arrives. For a plasma at equilibrium, one needs to describe with a distribution function instead of single particles. It is often a good approximation to describe the ambient plasma at equilibrium with a Maxwellian distribution  $f(E)$ .

$$f(E) = n \left( \frac{m}{2\pi kT} \right)^{3/2} \exp \left( -\frac{E}{kT} \right) \quad (2)$$



**Fig. 5** The push and pull of the magnetosphere. The day side is pushed, while the night side is pulled to a long distance. Snap-back Earthward occurs in the night side. The plasma is energized.  
**Source:** From Tribble.<sup>[30]</sup> ©1995 Princeton. Reprinted with permission.

where  $E$  is the ion energy,  $n$  the density,  $m$  the mass,  $k$  the Boltzmann constant, and  $T$  the temperature. Plotting  $\log [f(E)]$  as a function of  $E$  gives a straight line. If every ion arriving at the surface gains an energy  $q\phi$ , the distribution measured on the surface shifts forward in energy (Fig. 7). As a result of the shift, the graph of the log of the Maxwellian plasma velocity distribution  $f$  as a function of ion energy  $E$  shows a straight line with a gap of  $q\phi$ . Since it is more practical to measure the ion energy  $E$  than the velocity, the velocity in the distribution  $f$  has been converted to  $E$  by  $(1/2)mv^2 = E$ .

If the distribution deviates from being Maxwellian, every particle attracted to the surface gains the same energy  $q\phi$ . Therefore, the gap of  $q\phi$  is unchanged (Fig. 8).

**The Ion Line**

In practice, it is better to use the differential flux  $j(E)$  instead of the distribution  $f(E)$ . Flux  $J$  is defined as  $J = nqv$ , where  $n$  is the charge density and  $v$  is the charge velocity. For charge

particles with a velocity distribution  $f$ , the flux  $J$  is given as:<sup>[31]</sup>

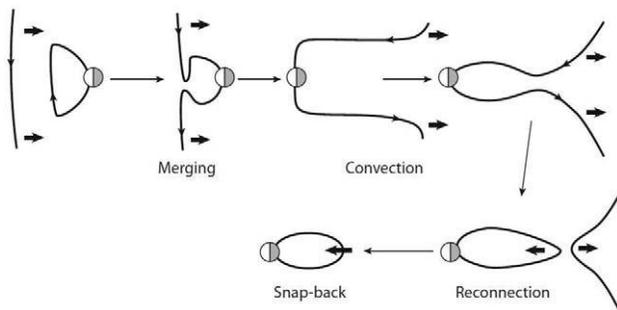
$$J = \int_0^\infty d^3v f(v)v \tag{3}$$

Converting the variable  $v$  to energy  $E$ , the flux can be written as:

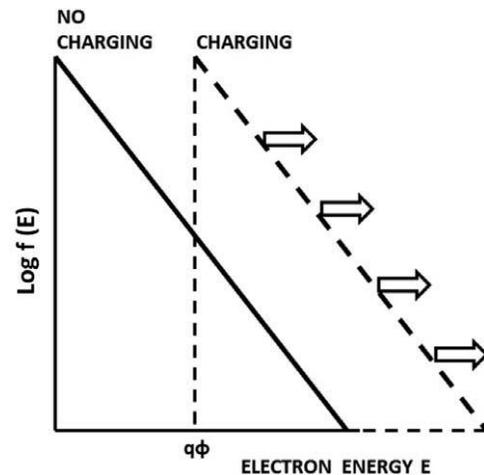
$$J = C \int_0^\infty dE E f(E) \tag{4}$$

where  $C$  is a constant. The equation can be written as:

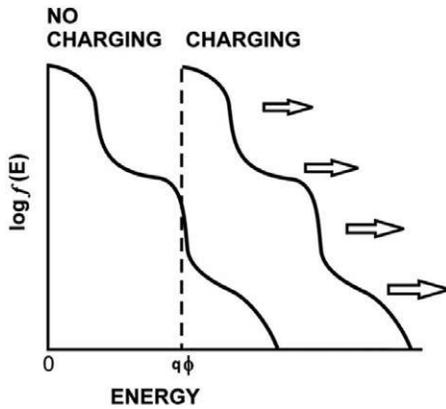
$$J = C \int_0^\infty dE \frac{dJ}{dE} \tag{5}$$



**Fig. 6** Sequence of push and pull of the magnetosphere. The Sun is on the left. We are looking at the noon-midnight plane.  
**Source:** Adapted from Lai.<sup>[31]</sup> ©2011 Princeton. Reprinted with permission.



**Fig. 7** Shift of an electron or ion distribution. For a Maxwellian distribution, the slope of the straight line is  $-1/kT$ . For a positive ion distribution, the gap between 0 and  $q\phi$  indicates the surface voltage,  $-\phi$ .



**Fig. 8** Shift of an electron or ion distribution. Suppose the distribution deviates from being Maxwellian, the line deviates from being straight. For the positive ion distribution, the gap between 0 and  $q\phi$  indicates the surface voltage,  $-\phi$ .

Therefore, the differential flux  $j(E)^{[43]}$  is given by:

$$j(E) = \frac{dJ}{dE} = Ef(E) \tag{6}$$

If one plots the graph,  $\log [Ef(E)]$  as a function of energy  $E$ , the gap is the same as in Fig. 6 or 7, but there is an advantage: the graph at energy  $E$  is amplified by an addition of  $\log E$ . With the amplification, it is easier to identify the peak of the  $\log [Ef(E)]$ . The peak is commonly called the ion line. The gap is the same as described above. The gap energy is then interpreted as the spacecraft potential. It takes time for the spacecraft potential to reach equilibrium because of the surface capacitance. The response by the plasma ions is faster.

Note that the spacecraft potential measured using the gap method is the absolute potential between the spacecraft and the ambient plasma.

**Other Measurement Methods**

One can measure the potential difference between the tip of a long boom (Fig. 11.4 in the study by Lai<sup>[31]</sup>) and the spacecraft body. One often assumes that the tip of the long boom is so far from the satellite body that the potential difference gives the satellite potential. This method has a disadvantage. Even if the boom tips are outside the potential sheath of the spacecraft body, the boom tips may not be at the plasma potential. The boom tips themselves may charge to finite potentials by the ambient electrons, which can be energetic. As a result, the potential difference measured in this way may be very misleading.

There are other measurement methods. For example, an instrument can be installed behind a surface for measuring the electric field between the surface and the spacecraft ground. The potential difference measured in this way is relative to the ground but not to the ambient plasma.

**SECONDARY AND BACKSCATTERED ELECTRONS**

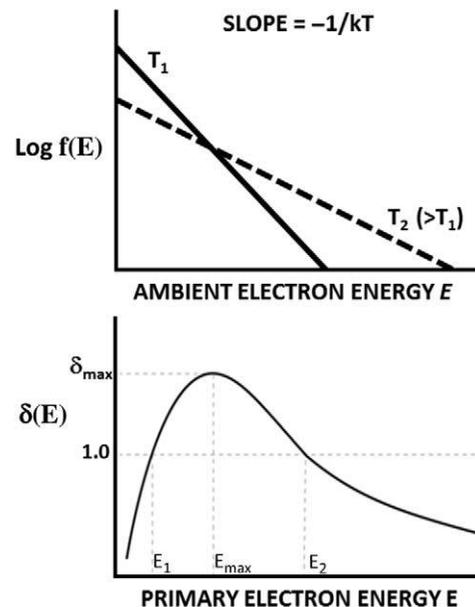
**Secondary Electron Yield (SEY) and Backscattered Electron Yield (BEY)**

Although a spacecraft generally collects more incoming electrons than ions in space plasmas, this property alone does not guarantee the spacecraft to charge to negative potential. For every incoming electron (also called primary electron) impacting a surface, there are  $\delta(E)$  secondary electrons<sup>[44-51]</sup> and  $\eta(E)$  backscattered electrons<sup>[52,53]</sup> generated from the surface. The probabilities  $\delta(E)$  and  $\eta(E)$  are also called SEY and BEY, respectively. Both SEY and BEY depend mainly on the primary electron energy  $E$  and the surface properties. They both depend also on the angle of incidence of the primary electrons.<sup>[53,54]</sup>

Fig. 9 shows  $\delta(E)$  and  $\eta(E)$  for a typical surface material with the primary electron in normal incidence.

In general, the  $\delta(E)$  curve starts with  $\delta(E) = 0$ . Below an energy called the “work function of the surface material,” no electron can leave the surface. It exceeds unity for an energy range from  $E_1$  to  $E_2$  for some materials. The two energies  $E_1$  to  $E_2$ , commonly called the unity crossing points, depend on the surface material properties, surface impurity, smoothness, and angle of electron incidence.

$$\delta(E) > 1 \quad \text{for } E_1 < E < E_2 \tag{7}$$



**Fig. 9** Secondary electron yield  $\delta(E)$  as a function of primary electron energy  $E$ . For typical surface materials, there are two crossing points  $E_1$  and  $E_2$ . Between the crossing points,  $\delta(E)$  exceeds unity. Beyond  $E_2$ ,  $\delta(E)$  decreases monotonically as  $E$  increases.

aded by [Shu Lai] at 21:46 26 February 2017

Semiconductor - Steam

Beyond  $E_2$ ,  $\delta(E)$  falls below unity and decreases slowly and monotonically toward zero at high energies (multiple kiloelectronvolts). Why does  $\delta(E)$  fall to lower values when  $E$  reaches higher energies? A physical reason is that the primary electrons of higher energies can penetrate deeper into the material so that the secondary electrons created may not be able to find their way out.

$$\delta(E) < 1 \quad \text{for } E > E_2 \quad (8)$$

The values of the crossing points are  $E_1 \approx 30\text{--}40$  eV and  $E_2 \approx 800\text{--}1800$  eV for typical spacecraft surface material. The energy of a secondary electron is typically only a few electronvolts.

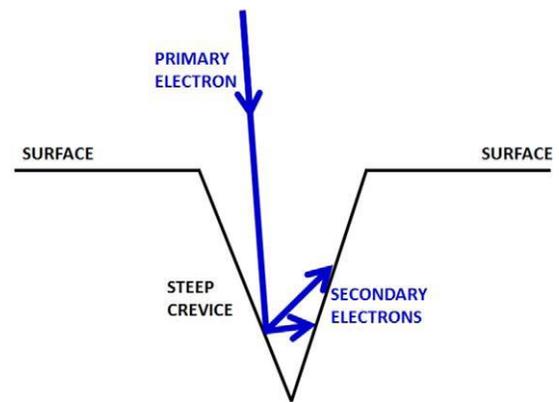
### What Does $\delta(E) > 1$ Imply for Spacecraft Charging?

If the ambient electron energies  $E$  are in the range  $E_1 < E < E_2$ , positive voltage charging occurs. This is because for every electron coming in, there are  $\delta(E)$  (more than one) secondary electrons going out. The positive charging level is up to a few volts only, because the secondary electrons have a few electronvolts in energy only. Beyond a few volts, the secondary electrons cannot leave.

### Importance of Surface Conditions

There has been increasing interest in the importance of surface conditions on SEY and photoelectron yield. Surface conditions such as roughness and contamination can affect the SEY.<sup>[55–65]</sup> For a simple physical explanation, let us consider first an initially flat surface. If the surface becomes undulating, its effective area increases and  $\delta(E)$  increases accordingly. In an opposite scenario, suppose the flat surface is deeply scratched resulting with crevices. Some secondary electrons generated from the deep valleys may hit the valley walls and are likely absorbed. Why absorbed? This is because the probability for generating a tertiary electron is low. The energy  $E$  of a secondary electron is typically only a few electronvolts. The energy  $E$  is below the work function of typical surfaces. Therefore, in this scenario,  $\delta(E)$  decreases (Fig. 10).<sup>[60,65]</sup> In other scenarios, high-energy electron bombardment<sup>[62]</sup> can change the surface roughness. Chemical contamination,<sup>[64]</sup> ultraviolet radiation,<sup>[66]</sup> and atomic oxygen bombardment<sup>[66]</sup> can also change the surface properties.

The discussion above suggests that prolonged exposure of surfaces in space can change the surface condition and thereby affect spacecraft charging. High-energy electron bombardment and ultraviolet radiation are more important at geosynchronous altitudes. This suggestion is significant, but it needs to be confirmed at geosynchronous altitudes. Chemical contamination and oxygen bombardment are more prone to happen in the ionosphere. For experiments on radiation damage to surface materials in the ionosphere,



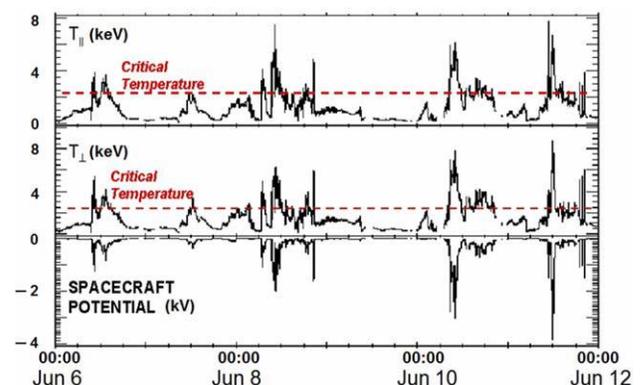
**Fig. 10** Reduction of SEY as a primary electron hits a steep crevice. The secondary electrons are likely absorbed by the crevice walls. The secondary electrons are of low energies and therefore unable to produce the next generation of secondaries (i.e., tertiaries).

e.g., see findings from the Materials International Space Station Experiment (MISSE).<sup>[67]</sup>

### Properties of Backscattered Electrons

A backscattered electron has nearly the same energy as the incoming electron.<sup>[52,53]</sup> The probability of backscattering is much smaller than secondary electron emission. Therefore, the graph of  $\eta(E)$  is much lower than that of  $\delta(E)$ . Some researchers simply neglect  $\eta(E)$  compared with  $\delta(E)$ . To be complete, it is better to include backscattering. The total probability of electrons generated from the surface by primary electron impact is then  $\delta(E) + \eta(E)$ .

There has been interest in the feature of electron reflection at  $E$  near 0. There,  $\eta(E)$  increases to near unity as  $E$  decreases to zero. This was discovered by both theory<sup>[61,63]</sup> and laboratory experiments.<sup>[58,62]</sup>



**Fig. 11** Ambient electron temperatures and spacecraft potential obtained on LANL Satellite 97A on June 6–11, 2000. The existence of critical temperature for the onset of spacecraft charging is displayed.

**Source:** From Lai & Della-Rose.<sup>[18]</sup> ©2001 AGU. Reprinted with permission.

## ONSET OF SPACECRAFT CHARGING

### Incoming and Outgoing Electron Currents

For an uncharged spacecraft, the ambient ion current received by the spacecraft can be ignored because it is two orders of magnitude smaller than that of the ambient electrons. The onset of spacecraft charging is therefore governed by the current balance between the incoming ambient electrons and outgoing secondary and backscattered electrons. The current balance equation is given as follows:<sup>[54,68,69]</sup>

$$\int_0^{\infty} d^3v v f(v) = \int_0^{\infty} d^3v v f(v) [\delta(E) + \eta(E)] \quad (9)$$

where  $f(E)$  is the electron velocity distribution with the velocity  $v$  related to the energy  $E$  by  $1/2 mv^2 = E$ ,  $\delta(E)$  the SEY,  $\eta(E)$  the BEY, and  $E$  the primary electron energy.

$$f(E) = n (m/2\pi kT)^{3/2} \exp(-E/kT) \quad (10)$$

If the primary electrons are coming in at various angles, one has to use the angle-dependent SEY and BEY functions,  $\delta(E, v)$  and  $\eta(E, v)$ , in the integral. For more details on these angle-dependent functions, see, e.g., Lai<sup>[31]</sup> and Laframboise and Kamitsuma.<sup>[54]</sup> For simplicity, the equation shown is for normal incidence only.

Converting the ambient electron velocity  $v$  to energy  $E$  and canceling the constant terms on both sides, the current balance equation becomes:<sup>[54,56,68,69]</sup>

$$\int_0^{\infty} dE E f(E) = \int_0^{\infty} dE E f(E) [\delta(E) + \eta(E)] \quad (11)$$

The above equation has two properties as follows:

1. The electron density  $n$ , which is a multiplicative factor in the distribution  $f(E)$ , is canceled on both sides. This cancellation property holds for any distribution that has  $n$  as a multiplicative factor. The Maxwellian and kappa distributions are such examples. A kappa distribution  $f_{\kappa}(E)$ <sup>[70,71]</sup> may give a better description when the space plasma is highly disturbed. The cancellation property implies that the onset of spacecraft charging is independent of the ambient electron density in a Maxwellian or kappa space environment.
2. The temperature  $T^*$  satisfying the equation is the critical temperature<sup>[18,54,68,69,72]</sup> for the onset of spacecraft charging to negative voltages (Fig. 11). Below  $T^*$ , the spacecraft potential is zero or slightly positive (up to a few volts only). Above  $T^*$ , the spacecraft potential is finite and negative; the magnitude of the spacecraft potential increases with the temperature (Table 1).

Note that one can introduce a short-hand notation  $\langle \delta + \eta \rangle$  for the current balance at the threshold as follows:

**Table 1** Table of critical temperatures (eV) for the onset of spacecraft charging.

Surface Material	Isotropic	Normal
Magnesium	400	—
Aluminum	600	—
Kapton	800	500
Aluminum oxide	2,000	1,200
Teflon	2,100	1,400
Copper–beryllium	2,100	1,400
Glass	2,200	1,400
Silicon oxide	2,600	1,700
Silver	2,700	1,200
Magnesium oxide	3,600	2,500
Indium oxide	3,600	2,000
Gold	4,900	2,900
Copper–beryllium (activated)	5,300	3,700
Magnesium fluoride	10,900	7,800

**Source:** Data from Lai.<sup>[31]</sup> ©2011 Princeton. Reprinted with permission.

$$\langle \delta + \eta \rangle = \frac{\int_0^{\infty} dE E f(E) [\delta(E) + \eta(E)]}{\int_0^{\infty} dE E f(E)} = 1 \quad (12)$$

If  $\eta(E) \ll \delta(E)$  depending on the surface material, one can neglect the former and simplify the short-hand notation as  $\langle \delta \rangle = 1$ .

$$\langle \delta \rangle = \frac{\int_0^{\infty} dE E f(E) \delta(E)}{\int_0^{\infty} dE E f(E)} = 1 \quad (13)$$

Note that the current balance equations (Eqs. 9–13) may yield a second root at a low temperature for some surface materials. It is called anticritical temperature.<sup>[72]</sup> Not many materials have this property. The rapid rise of the backscattered electron yield at low primary electron energies affects the existence of the second root.<sup>[72]</sup> Cassini Langmuir probe results<sup>[74]</sup> observed at Saturn have been interpreted in terms of critical and anticritical temperatures.

Note also that the Eqs. 9–13 can be used for non-Maxwellian distributions. For double Maxwellian distributions, the equations may yield triple roots<sup>[72,73,75,76]</sup> for the spacecraft potential. The roots may jump under suitable conditions.<sup>[76]</sup> The electron densities and temperatures define the domains of single and triple roots. The middle root is always unstable.<sup>[76]</sup> The instability of a root in a double Maxwellian distribution is further discussed in Huang et al.<sup>[77,78]</sup>

## BEYOND THE CRITICAL TEMPERATURE

Suppose the ambient electron temperature increases beyond  $T^*$ . The spacecraft potential ( $\phi < 0$ ) becomes finite

and negative. Because of the negative voltage, the ambient ions are attracted toward the spacecraft. The ion current becomes non-negligible; it is the additional chess piece in the current balance.

$$I_e(0)[1 - \langle \delta + \eta \rangle] \exp\left(-\frac{q_e \phi}{kT_e}\right) - I_i(0)\left(1 - \frac{q_i \phi}{kT_i}\right)^\alpha = 0 \quad (14)$$

where

$$\langle \delta + \eta \rangle = \frac{\int_0^\infty dE E f(E) [\delta(E) + \eta(E)]}{\int_0^\infty dE E f(E)} \neq 1 \quad (15)$$

The solution  $\phi$  ( $<0$ ) of the above equation is the spacecraft potential. In the equation,  $I_e(\phi)$  is the incoming electron current,  $I_i(\phi)$  the incoming ion current,  $T_e$  the electron temperature,  $T_i$  the ion temperature,  $k$  the Boltzmann constant,  $q_e < 0$  the electron charge, and  $q_i > 0$  the ion charge. In Eq. 14, the last term in parentheses with an exponent  $\alpha$  is called Langmuir's orbit-limited attraction factor ( $>1$ ). The exponent  $\alpha = 1$  for a sphere,  $1/2$  for a long cylinder, and 0 for a large plane, approximately. Using the electron beam emission method, the exponent for SCATHA was found to be about  $\alpha = 0.75$ .<sup>[79]</sup>

## SPACECRAFT CHARGING IN SUNLIGHT

To generate photoelectrons from a surface, it is necessary to have the photon energy exceed the work function of the surface materials.<sup>[80,81]</sup> The Lyman Alpha line is the most important spectral line in sunlight and has about 10.2 eV in energy that exceeds the work function (about 4 eV) of typical spacecraft surfaces. Sunlight generates photoelectrons from typical spacecraft surfaces at geosynchronous altitudes. There is an exception to this rule: if the surface has high reflectance, the efficiency of photoelectron generation is reduced.<sup>[82]</sup>

$$Y(\omega, \theta) = Y_0(\omega, \theta)[1 - R(\omega, \theta)] \quad (16)$$

where  $Y(\omega, \theta)$  is the photoelectron yield,  $Y_0(\omega, \theta)$  the photoelectron yield at zero reflectance,  $R(\omega, \theta)$  the reflectance,  $\omega$  the photon frequency, and  $\theta$  the incidence angle. In view of this property, one conjectures that a highly reflecting ( $R$  near unity) spacecraft surface can charge to high negative voltages as if in eclipse.<sup>[83]</sup> This important conjecture is subject to experimental verification in the laboratory and in space.

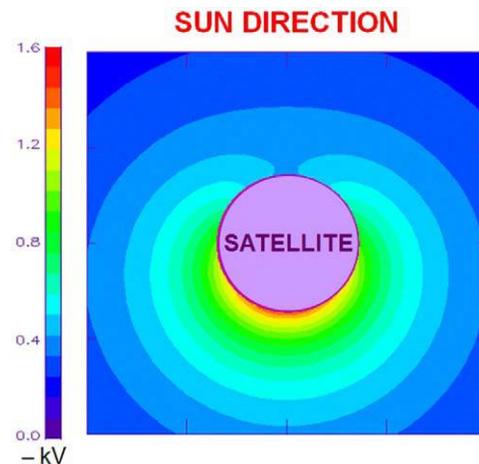
For typical spacecraft surfaces, the photoelectron current generated exceeds the ambient electron current at geosynchronous altitudes by typically an order of magnitude. Photoelectrons have only a few electronvolts in energy. If the positive charging level of the spacecraft surface exceeds a few volts, the photoelectrons cannot leave. Therefore, for a conducting spacecraft, the charging

voltage in sunlight is typically a few positive volts. Such a low level is not expected to cause any significant harm to the scientific measurements onboard or to the spacecraft electronics.

For a spacecraft with mostly dielectric surfaces, the surface voltages can be different. Spacecraft charging to negative voltages can occur in sunlight. This is because a spacecraft always has a dark side, where there is no photoemission. Without photoemission, the criterion for the onset of negative voltage charging on the dark side is given by the critical temperature  $T^*$ . Although the sunlit side may charge to low positive volts by photoemission, the dark side can charge to high negative voltages ( $-kV$ ) by ambient electrons. The high-voltage contours from the dark side can wrap to the sunlit side, blocking the photoelectrons, which have only a few electronvolts. As a result, the entire spacecraft may charge to negative voltages, even in sunlight (Fig. 12).<sup>[85-87]</sup>

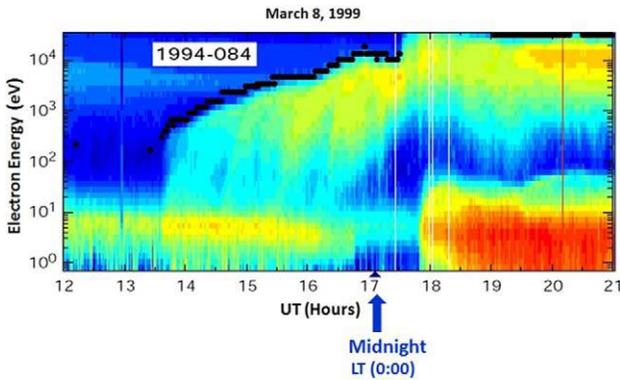
## POTENTIAL WELLS AND BARRIERS

Differential charging can form potential wells and barriers. Consider the sunlight charging situation for example. The high-negative-voltage contours wrapping to the sunlit side may form a potential barrier with a saddle point. The photoelectrons and secondary electrons emitted from the spacecraft surface are of low energy (a few electronvolts) and can be blocked by the barrier (Fig. 13). Some of these electrons can escape over the barrier, but the lower energy ones bounce back. The low-energy electrons trapped in the region behind the barrier enhance the total electron density



**Fig. 12** An example of monopole-dipole potential configuration for a spacecraft with dielectric surfaces in sunlight. The dark side can charge to high negative voltages ( $-kV$ ). The negative voltage contours can wrap to the sunlit side overwhelming the low positive potential. As a result, the entire spacecraft can charge to negative voltages in sunlight.

**Source:** Data from Lai.<sup>[84]</sup> ©2012 IEEE. Reprinted with permission.



**Fig. 13** Low-energy (below 20 eV) photoelectrons and secondary electrons trapped on the sunlit side of Los Alamos National Laboratory (LANL) Satellite 1994-084 on the morning side of March 8, 1999.

**Source:** From Thomsen, Korth, et al.<sup>[88]</sup> 2002, AGU. No copyright. Reprinted.

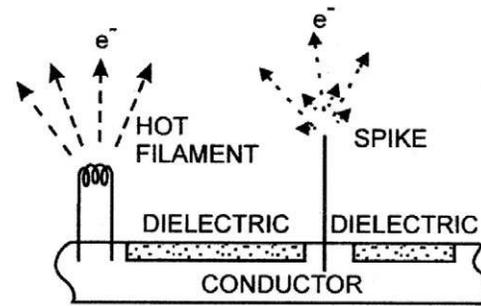
there.<sup>[87]</sup> External plasma waves disturbing the potential well may allow some of the trapped electrons to escape, affecting the current balance and resulting in variation of the spacecraft potential (Fig. 13).

## MITIGATION METHODS

There are several mitigation methods for spacecraft charging.<sup>[84,89]</sup> For example, 1) electron emission; 2) ion emission; 3) plasma emission; 4) partially conducting paint; 5) polar molecule emission; 6) mirror reflection; and 7) ultra-violet irradiation.

1. Electron emission is the most direct method for getting rid of excess electrons from a conducting spacecraft. Indeed, new electron emission devices with improved efficiency have been proposed from time to time. However, electron emission cannot rid of electrons from dielectric surfaces, which hardly conduct. As a result of electron emission, differential charging occurs (Fig. 14).<sup>[84,89]</sup>
2. Low-energy positive ion emission from a highly negatively charged spacecraft can produce an ion fountain. The returning ions can find their way to the most negatively charged spots on the spacecraft, thereby neutralizing the negative charge. This method is effective in mitigating differential charging.

If positive ions with more energy than the spacecraft potential energy are being emitted, they would leave. As a result, the spacecraft potential increases with negative voltage until the potential energy equals the ion beam energy. The negative potential is clamped by the ion beam emission. However, if there are thermal neutrals present, the potential level can decrease further because charge exchange between the emitted ions and the thermal neutrals can occur. As a result, the newborn



**Fig. 14** An example of mitigation by means of electron emission only. Suppose the initial surface voltages are about  $-4$  kV. The final voltages can be  $0$  V on the conducting surfaces but  $-4$  kV on the dielectric surfaces, resulting in a differential charging situation that is worse than the initial one.

**Source:** From Lai.<sup>[84]</sup> ©2012 IEEE. Reprinted with permission.

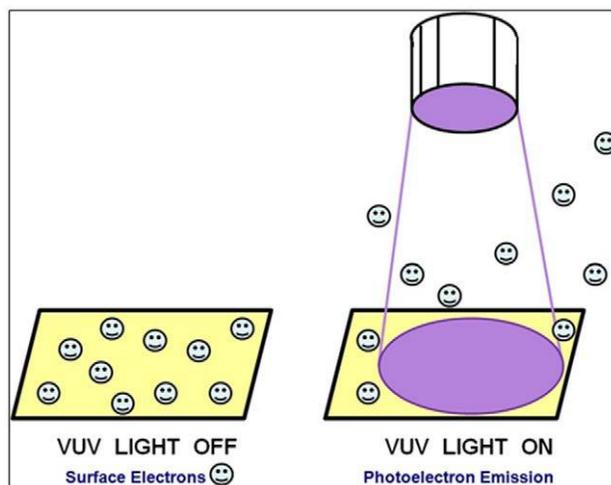
positive ions, being of the same energy as the neutrals, would return and contribute to three effects. They are: 1) neutralizing the negatively charged surfaces; 2) two stream instability between the fast beam ions and the slow ions newly born in the beam; and 3) surface contamination and electroplating of possibly the entire spacecraft.

3. Low-energy plasma emission is an effective method for spacecraft charging mitigation. It combines the advantages of methods 1 and 2 described above. In practice, such a system needs to have some kind of gas container with an abundant supply of neutral gas for ionization followed by ion extraction and then neutralization of the ions by electrons. It also needs to monitor the surface potential. When the potential is undesirably high, a command is sent to the plasma generator for carrying out the mitigation. Though this method is effective for mitigation, the stepwise controls may be inconvenient. The gas containers add weight. They only contain a limited supply of neutral gas.
4. Partially conducting paint, such as indium oxide, can reduce differential charging of spacecraft surfaces. The paint renders the surfaces conducting with each other to some extent. Since no excess electrons are expelled, the absolute potential relative to the ambient plasma is unchanged. If the partially conducting surface property is acceptable, this method is effective and convenient. It automatically prevents differential charging of the spacecraft surfaces, without the many steps required in the plasma emission method.
5. Spray of polar molecules, such as water, on conducting and non-conducting spacecraft surfaces can also get rid of the surface electrons. It does so by means of scavenging the surface electrons, thereby accumulating the electrons in the polar molecule droplets. When the droplet Coulomb repulsion force exceeds the surface tension, the droplet bursts into smaller ones. The droplets evaporate away. Unlike method 1, this method gets rid of electrons

without resulting in differential charging. However, this method may cause surface contamination.

- Spacecraft can charge in sunlight because the dark side can charge to negative volts without emission of photoelectrons. The high-negative-voltage contours from the dark side can wrap around to the sunlit side, blocking the photoelectrons. Sunlight reflected by mirrors can generate photoelectrons from the dark side, thereby mitigating the surface charging. Aluminum mirrors can have reflectivity around 88% for ultraviolet light. The mirrors have to be deployed at a distance from the spacecraft and, like solar panels, have to face the sun at an appropriate angle for reflection.<sup>[84]</sup> Unlike the plasma emission method, there is no need to operate a plasma discharge chamber attached to a finite gas supply.
- Light emitting diodes (LED) manufactured years ago used to emit low-frequency light only. Modern advances<sup>[90]</sup> have been successfully extending the frequency range toward the violet side. The method of using LEDs to generate photoelectrons from a spacecraft works similarly to the mirror reflection method 6, but the LED method works at all time, even in eclipse (Fig. 15).<sup>[84]</sup>

There are other safety measures. Most of them are for increasing reliability in general and not specifically intended to mitigate spacecraft charging. For example, it is always good to have redundant circuits. If a circuit fails for whatever reason, the backup comes to rescue. Another measure is not to expose wires and wire junctions to the space plasma. Do not let the solar cells be too close to each other, if the cell surfaces are of opposite polarity. Do not use



**Fig. 15** Photoemission removing electrons by using LED ultraviolet light. Spacecraft charges in sunlight because the shadowed side charges without photoemission. The high-negative-voltage contours can wrap to the sunlit side. Removing the electrons on the shadowed side mitigates the charging of the entire spacecraft. **Source:** Data from Lai.<sup>[84]</sup> 2012 IEEE. Reprinted with permission.

“unleaded” solder that is not conformally coated because tin whiskers may form and then they may short circuit. If an energetic magnetic storm is imminent, turn off any susceptible electronics if possible.

## SPACECRAFT ANOMALIES

Spacecraft charging may disturb scientific measurements onboard and may cause spacecraft anomalies for electronic instruments. In severe cases, it may terminate missions and permanently incapacitate the spacecraft. Broadly speaking, all of the adverse phenomena above can be termed spacecraft anomalies.

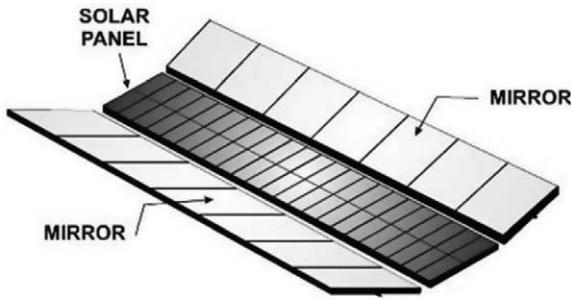
One may believe that anomalies are fairly predictable using the Kp index. We will explain why this is not the case.

The Kp index is a 3-hours average over measurements made on the ground around the globe.<sup>[26,27]</sup> It measures the magnetic disturbance induced in the ionosphere. Spacecraft anomalies, at least for those spacecrafts at geosynchronous orbits, occur far from the ionosphere and the ground. Most importantly, Kp is a 3-hours average, whereas spacecraft charging occurs at locations where the ambient electron temperature exceeds a critical value.<sup>[18,54,68–70,91]</sup> That is, spacecraft charging is very much a local event, both in time and in space. Since ambient electron temperature often changes quickly, spacecraft charging varies accordingly. Therefore, a 3-hours average, such as the Kp index, may not catch a significant spacecraft-charging event.<sup>[92]</sup> As a result, Kp may be far from being a reliable indicator of spacecraft anomalies.

The causes of spacecraft anomalies can, broadly speaking, fall into five categories. They are: 1) spacecraft surface charging; 2) deep dielectric charging; 3) hypervelocity impacts; 4) non-environmental causes; and 5) all others including unknown. The first two categories are the main ones, according to Koons et al.<sup>[17]</sup> Both of them are due to differential charging between surfaces, or inside dielectric materials, followed by discharges. Hypervelocity impacts<sup>[93]</sup> include impacts by meteoroids, asteroids, and space debris. The impacts may induce discharging if the surfaces, or dielectric materials inside, are charged *a priori*. Non-environmental causes include instrument design faults, workmanship, artificial beam emissions, command errors, and circuit overheating during operations. Unknown cases are abundant because, in general, spacecraft cannot be retrieved for forensic analysis and, besides, spacecraft manufacturers and operators usually do not publicly discuss anomalies.

We now discuss a few anomaly cases:

- Recoverable damage: An example of a spacecraft anomaly probably caused by surface charging is shown in Fig. 2. The event<sup>[14]</sup> occurred on the SCATHA satellite. In this type of anomaly, the measurements were affected by the anomaly, but the instrument recovered afterwards.



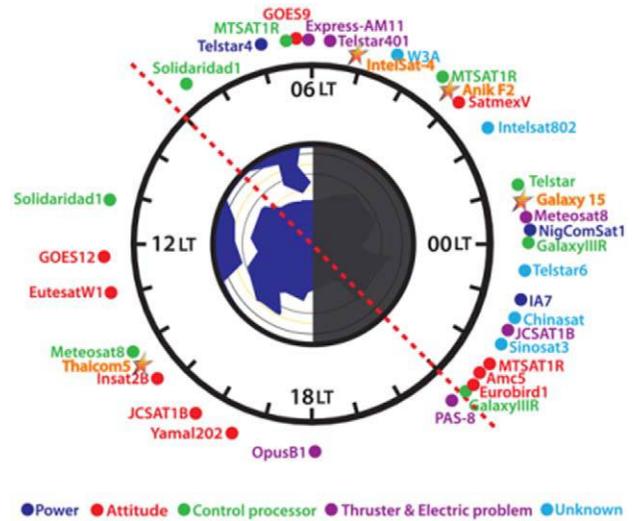
**Fig. 16** Mirrors flanking a solar panel on PAS-7. Differential voltage could have existed between the mirrors and the solar panel causing occasional discharges. Subsequently, Boeing discontinued this design.

**Source:** From Lai,<sup>[83]</sup> AGU 2005. No copyright. Reprinted.

2. Irreversible damage: Another interesting example is the stepwise degradation of the solar panels of Satellite PAS-7. The solar panels were flanked by mirrors for reflecting the sunlight onto the solar cells (Fig. 16). It has been conjectured<sup>[83]</sup> that highly reflecting surfaces do not generate photoelectrons because of energy considerations. Highly reflecting surfaces would charge during stormy periods in sunlight as if in eclipse, whereas the solar panel, which is not highly reflecting, would not charge in sunlight. As a result, there must be differential charging between the mirrors and the PAS-7 solar panel. The level of differential charging could be up to kV or more. Occasional discharges between the mirrors and the solar panel could provide physical explanation to the stepwise degradation. In this type of anomaly, the damage is gradual but irreversible.

3. Deep dielectric charging: Some anomalies occurred during or shortly after days of energetic events of space weather. For example, the Anik 1 and Anik 2 failures (Fig. 17) occurred within a few hours from each other during such an event.<sup>[94–96]</sup> Both failures are believed to be due to deep dielectric charging and discharging. The failures affected the television broadcasts in Canada. Baker<sup>[97,98]</sup> has compiled several spacecraft anomaly cases believed to be due to a similar scenario with days of high fluences of energetic (MeV or above) electrons. They are called “killer electrons.” These events are commonly considered to be caused by deep dielectric charging and discharging.

It is a debate<sup>[99,100]</sup> whether surface charging or deep dielectric charging is responsible for some cases of spacecraft anomalies. Together, surface charging and deep dielectric charging are generally believed to be responsible for many spacecraft anomalies including, the anomaly on Galaxy 15.<sup>[101]</sup> Choi et al.<sup>[99]</sup> studied a large data base of anomalies.<sup>[102]</sup> Statistically, more spacecraft anomalies at geosynchronous altitudes occur in the morning sector<sup>[99,103–105]</sup>



**Fig. 17** Local time occurrence of spacecraft anomalies. Most of them occur in the morning sector.

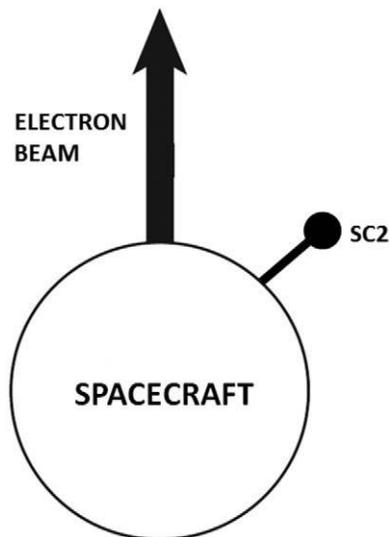
**Source:** From Choi, Lee, et al.<sup>[99]</sup> ©2011 AGU. Reprinted with permission.

compared with the noon to afternoon sector (Fig. 18). This local time property favors surface charging as a more common cause of spacecraft anomalies.<sup>[99,105]</sup> This is because following the onset of a geomagnetic substorm, hot (keV)



**Fig. 18** Panic in the sky. Failures of Anik E1, Anik E2, together with the PAS-7 anomalies caused panic in the sky news.

**Source:** From Allen & Lanzoretti.<sup>[106]</sup> ©2006. Reprinted with permission.



**Fig. 19** High-current electron beam emission from SCATHA. The high return current knocked out SC2 even though the probe was not in the path of the beam.

electrons injected from the midnight magnetosphere travel toward Earth and drift toward the morning sector. In comparison, fluences of very high-energy electrons responsible for deep dielectric charging are more abundant in the noon to afternoon sector.<sup>[105]</sup>

It is generally accepted that the presence of a southward interplanetary magnetic field results in more effective interaction with the magnetosphere when Earth's magnetic axis is perpendicular to the solar wind. There are more substorms and spacecraft anomalies in spring and autumn.<sup>[99]</sup>

As for non-environmental reasons for spacecraft anomalies, we cite an example of artificial beam emission from the SCATHA (P78-2) satellite.<sup>[107]</sup> A 3-keV 13-mA electron beam was emitted from SCATHA. It promptly knocked out an instrument (SC2 probe) on the surface of the spacecraft even though the instrument was not aimed at by the beam. The cause and effect were clearly identified in this example. In this type of anomaly, the damage is total and permanent (Fig. 19).

It is often necessary to better understand the instrument electronics that experience anomalies on spacecraft.<sup>[108]</sup> It would be beneficial to maintain and analyze information from large spacecraft anomaly databases in depth. Since this entry focuses on surface charging and not deep dielectric charging, we did not discuss dielectric charging in depth but instead refer the interested reader to Rodgers and Sørensen,<sup>[109]</sup> and the papers in this subject published in journals such as IEEE Transactions of Plasma Science.<sup>[10–13,110]</sup>

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