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Introduction to Spacecraft Charging

We begin by asking four fundamental questions: What is spacecraft charging? What are the effects of spacecraft charging? How does spacecraft charging occur? Where and when does spacecraft charging occur?

1.1 What Is Spacecraft Charging?

When a spacecraft has a net charge, positive or negative, the net charge generates an electric field according to Gauss's law. Space plasmas are assumed neutral. Although the plasma densities may fluctuate, their time scales (inverse of plasma frequencies) are much faster than spacecraft potential variations. Spacecraft charging takes a longer time than the ambient plasma fluctuations because it takes time to fill up capacitances. In the spacecraft charging community, the potential, ϕ_p, of the ambient space plasma is traditionally defined as zero:

$$\phi_p = 0 \tag{1.1}$$

Since potential is not absolute but relative, it is not surprising that in some other plasma sciences, the plasma potential is sometimes defined relative to that of a surface. In the field of spacecraft charging, the spacecraft potential is relative to the space plasma potential, which is defined as zero. The spacecraft potential is *floating* relative to the ambient plasma potential (figure 1.1). When a spacecraft potential, ϕ_s, is nonzero relative to that of the ambient plasma, the spacecraft is charged:

$$\phi_s \neq 0 \tag{1.2}$$

The basic terminology of spacecraft charging is introduced here:

- For a conducting spacecraft, the charges are on the surfaces. This charging situation is called *surface charging*.
- A uniformly charged spacecraft has only one potential, ϕ_s. This situation is called *uniform charging* or *absolute charging*.
- For a spacecraft composed of electrically separated surfaces, the potentials may be different on different surfaces. The potentials depend on the surface properties and on the environment, which may be nonisotropic. In this case, we have *differential charging*.
- If a spacecraft is covered with connected conducting surfaces (i.e., spacecraft ground or frame) and some unconnected or nonconducting surfaces, the charging of the frame is called *frame charging*.
- When the ambient electrons and ions are very energetic (MeV or higher), they can penetrate deep into dielectrics, which are nonconductors. This situation is called *deep dielectric charging*, or *bulk charging*.*

*For a conducting material, an electron penetrating into it moves to the surface because of Coulomb repulsion. Therefore, for conductors, surface charging can occur, but deep conductor charging does not

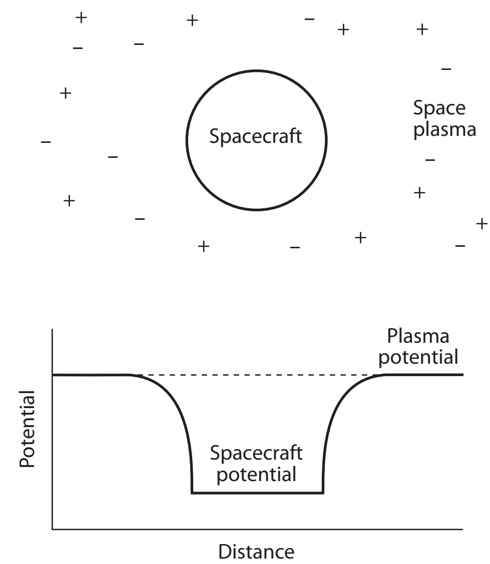

Figure 1.1 Floating potential of a spacecraft. The space plasma potential is defined as zero. A potential sheath is formed around the spacecraft.

1.2 What Are Some Effects of Spacecraft Charging?

Spacecraft charging manifests itself in two types of effects: (1) damage to onboard electronic instruments and (2) interference with scientific measurements. The first type is very rare but may be harmful. The second type is very common. These effects are discussed in the following sections,

1.2.1 Damage to Onboard Electronic Instruments

Spacecraft charging affects telemetry and electronics on spacecraft. Logical circuits and computer chips are becoming smaller and less power consuming but are more delicate. Delicate electronics are susceptible to charging, anomalies, damage, or catastrophes. Undesirable currents entering circuits by conduction, through pinholes, or via electromagnetic waves through inadequate shielding may cause disturbances. Such disturbances often cause anomalies in the telemetry of the data of the measurements.

If neighboring surfaces are at very different potentials, there is a tendency for a sudden discharge to occur. A discharge may be small, large, frequent, or rare. The size of a discharge depends on the amount of charge built up in the electrostatic capacitances, and on the amount of neutral materials, such as gas, which may be ionized when a discharge is initiated. An avalanche ionization can lead to a large current. A small discharge may be simply a spark, generating electromagnetic waves that may disturb telemetry signals. A large discharge may cause damage. Damage to electronics may, in turn, affect operations, navigation, or even survivability of a spacecraft.

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occur. For dielectrics (insulators), both surface charging and deep dielectric charging can occur. Surface charging can occur in dielectrics if the incoming electrons are below about 70 to 100 keV in energy; deep dielectric charging can occur if they are of higher energy. There is no sharp demarcation line between the two charging regimes. In general, MeV electrons are responsible for deep dielectric charging, while electrons of energy in the keV range are responsible for surface charging of dielectrics. The penetration depth depends on the electron energy and the material density. For kapton polymide, for example, an electron of 100 keV penetrates to about 0.007 cm. The ability to hold charges inside depends on the conductivity of the material. More will be discussed in chapter 16.

Two remarks: (1) A discharge on a spacecraft is often called an *electrostatic discharge* (ESD), because magnetic fields are almost not involved. In this context, *discharge* refers a harmful discharge. (2) The word *discharge* sometimes means "reduce the charging level." For example, suppose that a spacecraft charges to −10 kV, and the person in control suggests discharging the spacecraft to a lower voltage. In this context, to discharge means to mitigate.

If the incoming electrons or ions are of high energies (MeV or higher), they may be able to penetrate, pass through, or deposit inside materials. These high-energy electrons may stay inside nonconductors—i.e., dielectrics—for a long time. After a prolonged period of high-energy electron bombardment, the electrons inside may build up a high electric field. If the field is high enough, it may be sufficient to cause a local dielectric breakdown. When a local breakdown occurs, ionization channels develop extremely rapidly inside the dielectric, allowing currents to flow, which in turn generate more ionization and heat. As a result, internal instruments may be damaged. Fortunately, the densities of high-energy (MeV or higher) electrons and ions in space are low. Internal damage events are rare. However, when they occur, they may, in extreme cases, cause the loss of spacecraft.

1.2.2 Interference with Scientific Measurements

Spacecraft charging may affect scientific measurements on spacecraft. For example, when scientific measurements of space plasma properties such as the plasma density, mean energy, plasma distribution function, and electric fields are needed onboard, the measurements may be affected. The effects on each of these measurements are explained here.

We first examine the basic mechanism of how a charged object disturbs the ambient plasma. A charged spacecraft repels the plasma charges of the same sign and attracts those of the opposite sign (figure 1.1). As a result, a plasma sheath is formed in which the density of the repelled species is lower than that of the attracted species. The plasma density inside the sheath is different from that outside. The plasma in a sheath is nonneutral. Sheath formation occurs not only in space but also for charged objects in laboratory plasma.

Since the mean energy of the charged particles is shifted by repulsion or attraction, the mean energy of the electrons and that of the ions inside the sheath are different from their respective values outside. The amount of shift depends on the magnitude of repulsion or attraction.

The electron and ion energies of a plasma in equilibrium are in Maxwellian distributions:

$$f(E) = n(m/2\pi kT)^{3/2}\exp(-E/kT) \tag{1.3}$$

A graph of the logarithm of the distribution, $f(E)$, versus E would be a straight line with a slope equal to $-1/kT$, if $f(E)$ is Maxwellian (figure 1.2).

$$\log f(E) = \log n + \frac{3}{2}\log\left(\frac{m}{2\pi kT}\right) - \frac{1}{kT}E \tag{1.4}$$

If the distribution $f(E)$ is measured on the surface of a spacecraft charged to a potential, ϕ_s, the distribution measured would be shifted from that of the ambient plasma by an amount of energy $e\phi_s$. If the distribution is not Maxwellian, the graph $f(E)$ will not be a straight line. No matter what the distribution is, the energy shift will be $e\phi_s$. In the following, we will examine Maxwellian distribution only.

For the attracted species, the energy shift is $e\phi_s$, forming a gap from 0 to $e\phi_s$ in the distribution (figure 1.2). Physically, a charged particle initially at rest is attracted and would gain an energy $e\phi_s$ when it arrives at the spacecraft surface. This size of the gap, which can be clearly identified, gives a measure of the spacecraft potential, ϕ_s. The historical discovery[1] of

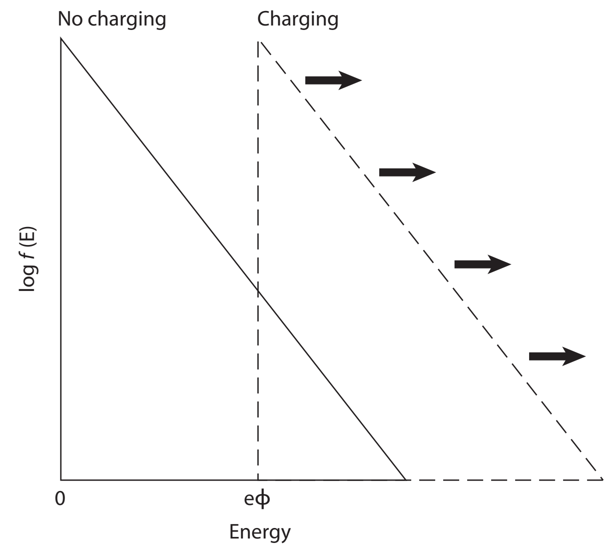

Figure 1.2 Shift of Maxwellian distribution plotted against energy. The amount of shift indicates the spacecraft charging potential. (Adapted from reference 4.)

kilovolt-level charging of a spacecraft (ATS-5) at geosynchronous altitudes at night was made by using a method related to the idea described in this paragraph.

For the repelled species, the shift is $-e\phi_s$. This forms no gap but results in the loss of the negative energy portion of the distribution (figure 1.2). Physically, the repelled ambient species of energy between 0 and $e\phi_s$ are repelled by the charged spacecraft. They cannot reach the spacecraft surface and the instrument on the surface and therefore cannot be measured.

Electric fields are important in governing the flow of electrons and ions in space plasmas. Measurements of electric fields in space are commonly carried out by means of the double probe method. The addition of an artificial potential gradient by a charged spacecraft may affect the measurements. Typical electric fields[2] measured in the ionosphere are of the order of mV/m, which is easily overwhelmed by strong electric fields near the spacecraft surfaces charged to, for example, hundreds of volts.

Spacecraft charging may also affect measurements of magnetic pitch angles of incoming charged particles since charged particles drift in the presence of both electric and magnetic fields. The trajectories of the charged particles are disturbed and therefore are different from those without spacecraft charging.

1.3 How Does Spacecraft Charging Occur?

The cause of surface charging is due to the difference between ambient electron and ion fluxes. Electrons are faster than (all kinds of) ions because of their mass difference. As a result, we have the following theorem:

Theorem: The ambient electron flux is much greater than that of the ambient ions.

To illustrate this point, let us consider hydrogen ions whose mass m_i is about $1837m_e$, where m_e is the electron mass. The electron and ion number densities are equal. Equipartition of energy gives the equality:

$$\frac{1}{2}m_i v_i^2 = \frac{1}{2}m_e v_e^2 \tag{1.5}$$

where the ion energy kT_i equals the electron energy kT_e, where k is the Boltzmann constant. Equation (1.5) yields a ratio of the electron to ion velocities: $v_e \approx 43v_i$.

The equality, equation (1.5), is only approximately valid. If the ion energy kT_i fluctuates and deviates, equation (1.5) would change accordingly. As long as the energies, kT_i and kT_e, are of the same order of magnitude, the preceding equality remains valid as a good approximation, viz, the ambient electron flux is much greater than that of the ambient ions. If some of the ions are heavier than H^+, the velocity difference would be greater.

Therefore, the electron flux, $n_e e v_e$, is greater than the ion flux, $n_e e v_i$. As a corollary of this property of relative velocities, we conclude that surface charging is usually negative, because the surface intercepts more electrons than ions.

It takes a finite time to charge a surface because its capacitance is finite. For typical surfaces at geosynchronous altitudes, it takes a few milliseconds to come to a charging equilibrium. At equilibrium, Kirchhoff's circuital law applies because the surface is a node in a circuit in space.

Kirchhoff's law states that at every node in equilibrium, the sum of all currents coming in equals the sum of all currents going out. Therefore, the surface potential, ϕ, must be such that the sum of all currents must add up to zero. These currents, $I_1, I_2, \dots, I_k$, account for incoming electrons, incoming ions, outgoing secondary electrons, outgoing backscattered electrons, and other currents if present. The current balance equation, equation (1.6), determines the surface potential ϕ at equilibrium:

$$\sum_k J_k(\phi) = 0 \tag{1.6}$$

1.4 Capacitance Charging

With a steady ambient current, I, the time, τ, for charging a surface is given by

$$\tau I = C\phi \tag{1.7}$$

where C is the capacitance, and ϕ is the surface potential. For a simple example, the surface capacitance C of a spherical object of radius $R = 1$ m is given by $C = \varepsilon_o 4\pi R \approx 10^{-10}$ farad/m. Let us take the ambient current $I = J\pi R^2$, where J is the ambient flux. The object in a space environment of flux density $J = 0.5$ nA/cm^2 would charge from 0 to 1 kV in $\tau \approx 2$ ms, which is a short time for many applications.[3] The charging time, τ, increases directly with the charging level, ϕ, and inversely with the radius, R, and the current density, J:

$$\tau \propto \frac{\phi}{RJ} \tag{1.8}$$

Capacitance charging is analogous to the filling of a tub with water; the water flow rate and the hose size (the cross section of flow) control the time of filling (figure 1.3). During filling, the water level is rising, and therefore the incoming current exceeds the outgoing current. This means that Kirchhoff's law, viz, steady state current balance, is not applicable during capacitance charging; one needs to include a time-dependent term. Once the tub is filled, the water level remains constant, and therefore the incoming and outgoing currents balance each other. The current balance equation, equation (1.6), is not applicable for our simple example during the first 2 ms but is a valid approximation thereafter. (Note that it takes infinite time to charge a capacitance asymptotically, but, for our purpose, we do not need exact values because the space plasma is not measured with high accuracy and varies very much in space and time.)

Note that coupled capacitances take a longer time to charge and thin dielectric layers have larger capacitances than surfaces. For simplicity, we will not consider these complications.

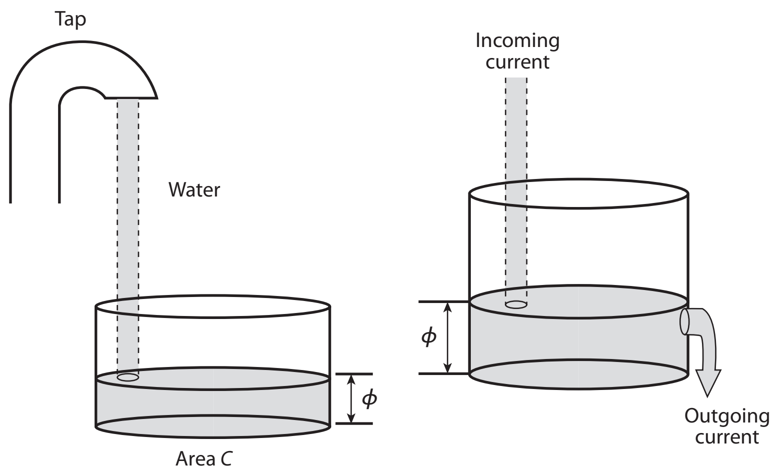

Figure 1.3 Charging of a capacitance. (Left) The water flux J received in a period τ equals the volume of water given by $C\phi$. The level ϕ is changing in time. (Right) At equilibrium, the incoming flux equals the outgoing flux. The level ϕ is constant.

1.5 Other Currents

In sunlight, the photoemission current emitted from a spacecraft surface has to be taken into account. In quiet periods (without severe magnetic storms), the photoemission current often exceeds the ambient currents, thus charging a typical spacecraft surface positively. Since photoelectrons generated by sunlight in the geosynchronous environment have typically a few eV in energy, they cannot leave if the surface potential exceeds a few volts positive. Thus, sunlight charging is typically at only a few volts positive.

Secondary and backscattered electrons are of central importance in spacecraft charging. They will be discussed in detail in chapter 4.

For spacecraft charging induced by charged beam emission, the beam current must be included in the current balance equation. Depending on the properties of the beam and the charging condition of the spacecraft, a fraction f of the beam may leave the spacecraft, while the rest of the beam current returns to the spacecraft. The net current leaving the spacecraft may be very different from that leaving the exit point of the beam,—i.e., the fraction f may be $\ll 1$. If the net beam current leaving the spacecraft exceeds the ambient current arriving at the spacecraft, the beam controls the spacecraft potential.

1.6 Where Does Spacecraft Charging Occur?

Natural surface charging depends on the location of the spacecraft, the material of the surface, the local time, and the space weather. It is customary to delineate four types of locations: geosynchronous altitudes, low Earth orbit altitudes, the auroral latitudes, and the radiation belts.

1.6.1 Geosynchronous Altitudes

The most important region of surface charging is at or near geosynchronous altitudes. This region is important for two reasons: (1) Even though the plasma density is often low, the energy is sometimes high. (2) There are many communication satellites in this region.

The geosynchronous region is sometimes inside the plasmasphere (figure 1.4). During very quiet days, the entire region can be inside the plasmasphere, while during extremely disturbed days, the entire region can be outside it. Most often, the dusk side is inside while the rest of the region is outside. Although the plasmasphere corotates to some extent with the

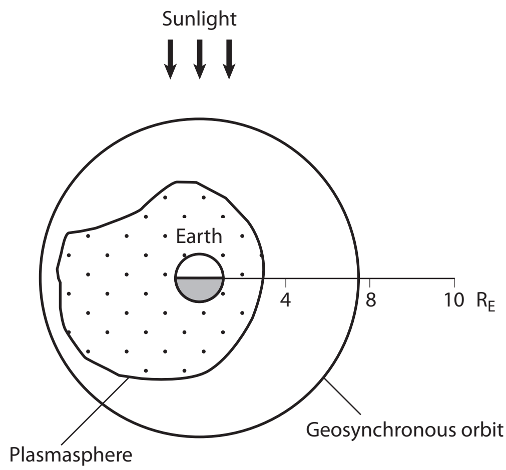

Figure 1.4 The plasmasphere is a dense region of low-energy plasma (about 100/cc, 10 to 30 eV). It sometimes expands into the geosynchronous region on the dusk side. (Adapted from reference 4.)

Earth, the protruding part on the dusk side often persists. The shape of the plasmasphere is not corotating. The plasmasphere usually has relatively high plasma density (> 1 cm^{-3}) and low plasma energy (< 100 eV). Within the plasmasphere, charging of spacecraft surfaces is at zero or low level (usually a few eV negative without sunlight) and is not of concern. In sunlight, the level is at most a few eV positive, which is also not of concern. Occasionally, the spacecraft is outside the plasmasphere and in a low-density (< 1 cm^{-3}), high-energy (keV) plasma region. There, high-level spacecraft surface charging may occur if there is a surge of high-energy electrons and the surface is in eclipse. The high-energy (many keVs and higher) electron cloud typically arrives sunward from the geomagnetic tail.

The initial disturbance usually comes from the Sun in the form of solar wind, high-energy electron and ion clouds, and also x rays. The electrons and ions, upon arrival, compress the dayside magnetosphere and then elongate the nightside magnetosphere to hundreds of Earth radii, forming a long magnetospheric tail (figure 1.5). The elongation is analogous to the stretching of a rubber band. An elongated rubber band eventually snaps back. After hours of stretching, magnetic reconnection occurs somewhere in the geomagnetic tail followed by a snap-back. As a result, an energized electron and ion cloud travels toward the Earth from the tail. This describes the process of a geomagnetic substorm, or simply substorm. It can occur more than once in a night—that is, a storm may consist of a series of substorms.

The energetic electrons and ions enter the Earth's geosynchronous altitudes at about midnight. There, the energetic electrons travel eastward due to the Earth's magnetic field curvature, while the energetic ions travel westward (appendix 1). Since the high-energy electrons are often the cause of spacecraft charging, spacecraft charging at or near the geosynchronous altitude region occurs most probably near midnight and the morning hours. Typically, the charging levels in this region reach hundreds of volts or even several kV, if the spacecraft surface is not in sunlight.

The exact charging level, of course, is determined by current balance. The currents of ambient electrons, ambient ions, and secondary and backscattered electrons have to be taken into account. Photoelectron current is important in sunlight. If there are different neighboring surfaces, currents flowing from one surface to another have to be considered. If electron or ion beams are emitted, the net beam currents leaving the spacecraft have to be taken into account also. The higher the beam-induced potentials are, the more significant are the current flows from surfaces to surfaces. The net beam currents can increase or decrease the surface potentials depending on the nature of the beam flows and the signs of the beam charges leaving or returning.

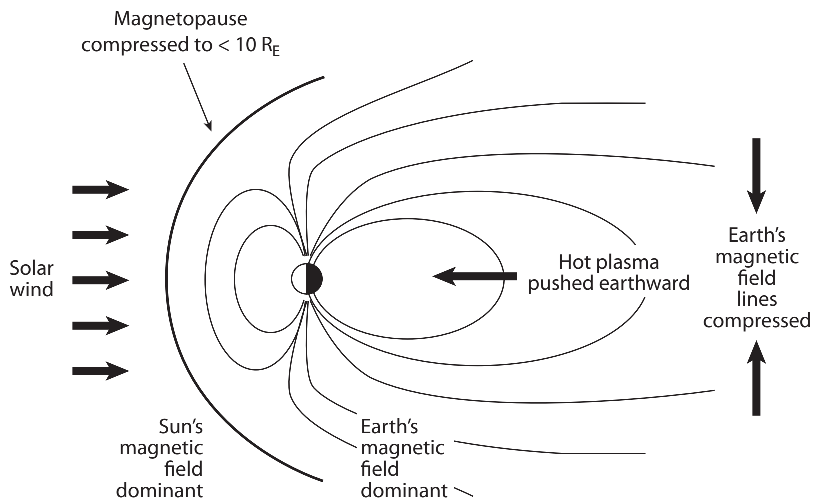

Figure 1.5 Solar plasma disturbance to the Earth's magnetosphere. Solar wind and solar plasma clouds energize the magnetosphere and pull the magnetic field lines to form a long tail. Hot plasma is injected from the tail during substorms and storms. Spacecraft charging is often due to the hot plasma injected around midnight.

1.6.2 Low Earth Orbits

The charging level at low Earth orbits (up to a few hundred km) is usually not of concern. At these altitudes, the space plasma is typically of low energy (about 0.1 eV) and high density (10^5 cm^{-3} or higher). Electrons of 0.1 eV can charge surfaces to 0.1 V at most. If a spacecraft surface is charged to one sign, abundant charges (10^5 cm^{-3}) of the opposite sign can quickly arrive from the vicinity of the charged surface to neutralize it. Charging at low altitudes is not of concern, except (1) when a high-current charged beam is being emitted from the spacecraft, (2) if differentially charged surfaces of solar, or nuclear, batteries are exposed, (3) when a long tether attached to the spacecraft is moving across the Earth's magnetic field lines, (4) in the wake behind a spacecraft moving with an orbiting velocity faster than the ambient ion velocity, or (5) when the spacecraft is at the auroral latitudes during auroral activities. High-current charged beams[4,5] are outside the scope of the introductory part of this course. Exposed battery surfaces are artificial high-voltage devices. Tethers generate electric fields by means of the $\mathbf{V} \times \mathbf{B}$ effect. Natural charging at auroral latitudes will be described briefly in the next section.

1.6.3 Auroral Latitudes

At about 60° to 70° (auroral) latitudes, there are occasionally "inverted V events" during which high-energy (keV) electrons precipitate downward in a beam-like fashion. The events are so called because of the shape of the energy flux plotted as a function of time. During the events, the density of the low-energy plasma component often becomes low, while the the energy distribution of the high-energy electrons (5 to 10 keV typically at 1000 to 1500 km) become beam-like. High-level (hundreds of kV typically) surface charging can occur at these latitudes, and even at fairly low altitudes (approximately 300 km or above). Low-latitude charging in this region is more common than previously thought.

1.6.4 Radiation Belts

Very high energy (MeV or higher) and low flux electrons and ions are in the radiation belts. Spacecraft normally avoid this region because the very high energy radiation (i.e., electrons and ions) may cause internal damage to electronic instruments onboard. The Combined Release and Radiation Effects Satellite (CRRES) flew through this region and collected some interesting data before it suddenly ceased functioning. In this region, spacecraft surface charging is not an important issue, but deep dielectric charging is. Surface charging occurs, but not to very high levels. Deep dielectric charging is due to the very high energy electrons and ions. They can penetrate into and deposit inside nonconducting materials, or even pass through thin insulations. If they enter the electrical wires, they can disturb the circuits, causing anomalies in the electronics, telemetry, and computers. Charge accumulation inside dielectrics may build up a very high electric field, which, if high enough, may lead to a sudden big discharge or dielectric breakdown, damaging instruments onboard.

Very high energy electrons and ions also exist in the geosynchronous region, but with much less intensity and lower fluxes. During the passage of solar coronal mass ejection clouds, very high energy electrons and ions appear in the geosynchronous region and, of course, in the radiation belts.

1.7 Exercises

1. What is spacecraft charging? What are absolute charging, differential charging, spacecraft ground, frame charging, deep dielectric charging, and bulk charging? Is it wrong to think of a spacecraft as at zero potential while the ambient plasma is at a nonzero potential?
2. Spacecraft charging is due to accumulation of charges on spacecraft surfaces. The cause of electron accumulation is often due to the higher flux of electrons than that of ions. In a neutral plasma of density 100 cm^{-3} and average energy 1 eV, calculate the ion and electron velocities and fluxes.
3. Consider a sphere in a vacuum. What is the surface capacitance of a sphere with respect to infinity? How long does it take for a spherical spacecraft of 1-m radius to charge to −1 kV, assuming that the dielectric constant of the ambient plasma is almost that of a vacuum? Calculate the charging time for the sphere as a function of radius, plasma density, and plasma energy.
4. Spacecraft charging may affect some measurements on the spacecraft. How does it affect the plasma density in the vicinity of the spacecraft? How does it affect the plasma electron distribution $f(E)$ measured on the surface of the spacecraft?
5. How does one use the electron or ion energy distribution to measure the level of spacecraft charging? In practice, the energy gap is sometimes partially filled. Why?
6. In the following ion distribution (figure 1.6) plotted as a function of time, the energy scale (left) is in keV, and the flux scale (right) is in #/(cm^2 sec eV). What is the charging voltage?

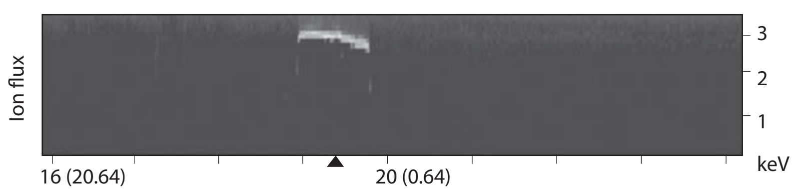

Figure 1.6 A plot of the ion flux measured on a spacecraft surface as a function of time. This figure shows the shift of ion flux during a typical spacecraft charging event. The time given is in universal time (UT), and the time in parentheses is in local time (LT). The triangle indicates midnight in local time.

7. Suggest your own example of measurement that can be affected by spacecraft charging.
8. Why does spacecraft charging not occur at low altitudes—for example, below 5 km?
9. A spacecraft orbit is governed by the balance of the centrifugal force and the gravitational attraction force. Calculate the radius of the geosynchronous orbit.
10. Why is the geosynchronous region important for spacecraft charging? What is the plasmasphere? Do you expect high-level charging when a spacecraft is inside the plasmasphere?
11. At what local time sector in the geosynchronous region is spacecraft charging most likely?
12. At about what latitude at 800 km is spacecraft charging important?
13. Where does deep dielectric charging occur?

1.8 References

For a general reference on the space environment, see, for example, reference 6. For a tutorial on geomagnetic storms and substorms, see, for example, reference 7. For a comprehensive text on space weather and its effects, see, for example, reference 8.

For chapters on spacecraft charging in textbooks, see references 9 and 10. Research papers on spacecraft charging are usually published in *J. Geophys. Res.*, *IEEE Trans. Plasma Sci.*, *IEEE Trans. Nucl. Sci.*, *J. Spacecraft and Rockets*, and *J. Appl. Phys.* There have been Spacecraft Charging Technology Conferences every few years in the past three decades (see, for example, *IEEE Trans. Plasma Sci.,* October 2006 and November 2008).

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