FACETS OF SPACECRAFT CHARGING; CRITICAL TEMPERATURE AND DEPENDENCE ON AMBIENT ELECTRON DENSITY

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Abstract

Spacecraft charging is important. Space plasmas, secondary and backscattered electrons, and surface conditions, are some of the main factors controlling spacecraft charging. At geosynchronous altitudes with Maxwellian space plasma, there are two properties for the onset of spacecraft charging. They are (1) existence of critical ambient electron temperature, and (2) independence of the ambient electron density. In space plasmas of Kappa or cut-off Maxwellian distributions, the two properties persist. In monopole-dipole configuration of dielectric spacecraft charging in sunlight, the high-level potential contours on the dark side wrap to the sunlit side and, as a result, the two properties also persist. However, the two properties do not apply to the following situations. They are charging by double-Maxwellian plasmas, charging by charged particle beam emissions, charging of plasma probes on spacecraft, low-level charging in the ionosphere, and low-level positive voltage charging of spacecraft in sunlight. We will summarize the various facets in a table, which, hopefully, will be very useful.

INTRODUCTION

Spacecraft charging [1,2,3] is caused by spacecraft-plasma interactions. High-level spacecraft charging at hundreds of electron volts (eV) or more, may affect scientific measurements onboard and, in severe cases, may terminate the mission.

When an object is put in space plasmas, or even laboratory plasmas, it intercepts more electrons than ions because electrons are much lighter and faster. This property alone leads to a naive belief: - (1) not only a spacecraft must charge to negative potentials, but also (2) the magnitude of the spacecraft potential increases with the ambient electron density.

But, nature is not so naïve. For every incoming electron of energy E, there are δ(E) secondary electrons [4-10] and η(E) electrons [11-14] going out at these energy levels. Here, δ(E) and η(E) are the secondary electron yield (SEY) and backscattered electron yield (BEY) respectively. Depending on the surface properties, the SEY δ(E) > 1 for E1 < E < E2, where E1 and E2 are the crossing points [4-10]. For E > E2, δ(E) < 1. This property suggests that, at sufficiently high energies E, there are more incoming electrons than outgoing secondary electrons.

The BEY η(E) < 1 at all E, except when E is very small [11-14] and therefore BEY does not an important role for spacecraft charging at high levels.

ONSET OF CHARGING

At equilibrium, the incoming and outgoing electron currents balance each other. The current balance equation determines the spacecraft potential φ.

For normal incidence, the current balance equation [Appendix in Ref.15] is as follows.

\[ \int_{0}^{\infty} dE e^{-(E/E_0)^{1/2}} \exp(-E/\kappa T) = \int_{0}^{\infty} dE f(E)[\delta(E) + \eta(E)] \quad (1) \]

At equilibrium, the Maxwellian distribution function f(E) is given by

\[ f(E) = n(m / 2\pi k T)^{3/2} \exp(-E/\kappa T) \quad (2) \]

Substituting eq(2) into eq(1), one finds that the electron density n cancels out on both sides. For more electrons coming in, more secondary and backscattered electrons are going out. Eq(1) yields the solution T = T*.

When the electron temperature exceeds the critical temperature T*, spacecraft charging occurs [16-22] and the occurrence is independent of the electron density n [21-23]. For a table of T* for various surface materials, see, for example, Ref.[3].

We have therefore obtained two important properties. Property I: The onset of charging is independent of the electron density n. Property II: For a given surface material, the solution T* of eq(1) is the critical electron temperature for the onset of spacecraft charging.
KAPPA DISTRIBUTION

The kappa distribution is often a good description of the ambient plasma in non-equilibrium [24,25]. The Kappa temperature $T_\kappa$ is related to the usual temperature $T$ as

$$f_\kappa(E) = \frac{\Gamma(\kappa+1)}{\Gamma(3/2)\Gamma(\kappa-1/2)} \left(\frac{3}{2} T_\kappa\right)^{\kappa-3/2} \frac{1+E}{(k-3/2)T_\kappa}^{-\kappa+3/2}$$

where $T_\kappa = \frac{3}{2} T$ and $3/2 < \kappa < \infty$

For onset of spacecraft charging, the current balance equation is solved by using $f_\kappa(E)$.

$$\int_{E_L}^{E_U} dE f_\kappa(E) = \int_{E_L}^{E_U} dE f_{\kappa}(E) \left[\delta(E) + \eta(E)\right]$$

yielding the critical kappa temperature $T_c^* [23]$. Again, the density $n$ on both sides of eq(4) cancels out [23]. There exists critical $T_c^*$, but the values are different from those of $T_c$ of the Maxwellian distribution.

CUT-OFF DISTRIBUTION

If the distribution $f(E)$ has cut-offs at $E_L$ and $E_U$. The current balance eq(1) becomes [17]

$$\int_{E_L}^{E_U} dE f(E) = \int_{E_L}^{E_U} dE f(E) \delta(E) + \eta(E)$$

where $E_L$ and $E_U$ are the lower and upper cutoff energies respectively [26]. The solution $T=T^*$ of the current eq(6) is the critical temperature for the onset of spacecraft charging. The values of $T^*$ [17,27] are different from those for the Maxwellian case. Again, the density $n$ is cancelled on both sides in eq(5).

DOUBLE MAXWELLIAN DISTRIBUTION

Sometimes a double Maxwellian distribution $f_\kappa(E)$ may happen if a plasma moves into the region of another plasma and it takes time to reach equilibrium.

$$f_\kappa(E) = f_1(E) + f_2(E)$$

$$f_1(E) = n_1 (m/2\pi kT_1)^{3/2} \exp(-E/kT_1)$$

$$f_2(E) = n_2 (m/2\pi kT_2)^{3/2} \exp(-E/kT_2)$$

In eq(6), there are two densities ($n_1$ and $n_2$) and two temperatures ($T_1$ and $T_2$). The spacecraft potential depends on all of them. They form parametric domains in which there exist single and triple roots of spacecraft potential. The resulting critical temperatures are not simple, as triple roots can suddenly change to single root [28-32].

MONOPOLE-DIPOLE POTENTIAL

For spacecraft with dielectric surfaces, the surface potentials can be different at different positions. Photoemission occurs on the sunlit side but not on the dark side. At geosynchronous altitudes, although the photoelectron current exceeds the ambient electron current, the photoelectron energy is typically a few eV only. The dark side can charge to hundreds of negative volts or more, because there is no photoelectron current involved. The high negative voltage contour can wrap to the sunlit side and block the photoelectrons, resulting in a monopole-dipole potential configuration [33-35]. The charging of the spacecraft is controlled by the charging of the dark side, where properties I and II apply.

LOW-LEVEL CHARGING IN SUNLIGHT

Photoelectron current $I_{ph}$ from spacecraft at geosynchronous altitudes exceeds the ambient electron current [33-36]. The main solar ultraviolet line is at about 10.2eV in energy. There are some higher energy spectral lines. The work function of typical surface materials is 3 to 4 eV. The charging level $\phi(>0)$ in sunlight depends on the ambient electron current $I_d(\phi)$. For a conducting sphere, the current balance equation is as follows.

$$I_d(0) - \frac{q\phi}{kT_e} I_{ph}(\phi) = I_{ph}(\phi)$$

For $\phi > 0$, the ambient ion current $I_d(\phi)$ is small and so are the secondary electron currents. As $I_d(0)$ varies, the potential $\phi$ varies accordingly [37,38]. In this case, $\phi$ depends on the ambient electron density $n$. The charging level is low because of the low energies of the solar spectral lines.

PLASMA PROBES ON SATELLITE

Plasma probes are sometimes used on spacecraft [39,40]. In this case, does the spacecraft potential depend on the ambient electron density? Take, for example, the current balance equation for a spacecraft charged to a negative potential $\phi$. The spacecraft current balance equation is as follows.

$$\int_{E_L}^{E_U} dE f(E) = \int_{E_L}^{E_U} dE f(E) \delta(E) + \eta(E) + I_p$$

where $I_p$ is the current applied to the plasma probe.
With the addition of the applied current $I_p$, the density $n$ of the incoming and outgoing electron current terms cannot be cancelled on both sides of eq(10). Therefore, $\phi$ depends on $n$. The onset of charging depends not only on the ambient currents but also the applied current. The above argument also applies to a positively charged spacecraft with a plasma probe on it.

**CHARGED PARTICLE BEAM FROM SPACECRAFT**

For a positive ion beam emitting from a negatively charged spacecraft, the current balance equation is

$$\int dEE f(E) = \int dEE [\delta(E)+\eta(E)] f(E) + I_p(E_p) \Theta(E_u - q\phi)$$

where $I_p(E_u)$ is the current of the ion beam of energy $E_u$ and $\Theta$ is a step function ($= 1$ if $E_u > q\phi$, and $= 0$ if $E_u < q\phi$). If the beam has an energy distribution, one has to integrate over the beam energy [41]. If the returning beam generates secondary and backscattered electron currents, they should be included in the balance. The electron density terms do not cancel in eq(11). Thus, $\phi$ depends on the electron density. The critical temperature is more complicated. It depends on beam energy, beam current, and other parameters. For electron beam emissions [42], the charge signs are changed.

![Figure 3. Charged particle beam emission. The beam returns if the beam energy is less than the spacecraft charging potential energy.](image1)

![Figure 4. Partial return of a beam with an energy distribution. The partition is at the spacecraft charging potential energy at the location r.](image2)

**SUMMARY AND DISCUSSION**

We summarize the facets of spacecraft charging discussed above in Table 1 as follows.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Electron Density</th>
<th>Critical Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwellian</td>
<td>Independent</td>
<td>$T^*$</td>
</tr>
<tr>
<td>Double Maxwellian</td>
<td>Dependent</td>
<td>No</td>
</tr>
<tr>
<td>Kappa</td>
<td>Independent</td>
<td>$T^*$</td>
</tr>
<tr>
<td>Cutoff Maxwellian</td>
<td>Independent</td>
<td>No</td>
</tr>
<tr>
<td>Monopole-Dipole Model in Sunlight</td>
<td>Independent</td>
<td>$T^*$</td>
</tr>
<tr>
<td>Low-Level Charging in Sunlight</td>
<td>Dependent</td>
<td>No</td>
</tr>
<tr>
<td>Plasma Probe on Spacecraft</td>
<td>Dependent</td>
<td>No</td>
</tr>
<tr>
<td>Charged Particle Beam Emission</td>
<td>Dependent</td>
<td>No</td>
</tr>
</tbody>
</table>

High-level spacecraft charging is important because it may affect the electronics and scientific measurements onboard. The natural cause of spacecraft charging is the result of spacecraft/plasma interaction.

Electrons are faster than ions because of the mass difference. An object put in plasmas would intercept more electrons than ions. It does not mean that the object must charge to negative volts, because the outgoing secondary and backscattered electrons play important roles in the current balance.

Since secondary electrons are of low energy (a few eV) and backscattered electrons are nearly negligible in most circumstances, high-level negative charging does not occur unless the energy $E$ of the incoming electrons exceeds the second crossing point, $\delta(E)=1$, which depends on the material properties. With an energy distribution, one has to integrate over the energies in eq(1). As a result, two properties I and II emerge. They are (I) existence of critical temperature for the onset of spacecraft charging, and (II) independence of ambient electron density. The physics of (I) is that there are more high energy electrons in a high-temperature plasma, and therefore high temperature favours charging to negative voltages. The physics of (II) is that as more electrons are coming in, more secondary electrons are going out proportionally. These two important properties have been observed easily and repeatedly on the LANL geosynchronous satellites.

It is necessary to know that under certain conditions, these two properties do not apply. In this paper, we have discussed various situations. For example, in a double Maxwellian distribution, there are two densities and two temperatures. One needs to use parametric domains to delineate the properties of charging, and the results are not simple.
Sometimes, a kappa distribution is more appropriate to describe the space plasma deviating from equilibrium. In this situation, the critical temperature $T^*$ still exists but the values are not the same as those for the Maxwellian case. Since the electron density $n$ is cancelled on both sides of eq(4), property II is valid.

Some other times, the distribution can be modelled as a cut-off Maxwellian. In this case, the critical temperature still exists but the values of $T^*$ are different. Again, property II also holds.

For a dielectric spacecraft in sunlight, the potential on the sunlit side is affected by photoemission while the dark side can charge to high levels by the energetic ambient electrons without photoemission. The high-level potential contours can wrap to the sunlit side blocking the photoelectrons. The charging of the sunlit side is greatly influenced by the charging of the dark side. The charging of the dark side is governed by both properties I and II.

Despite the persistence of property I and II in the above cases and the successful confirmations on all the LANL geosynchronous satellites, one must bear in mind that there are cases where these two properties do not apply. For example, if one has a conducting spacecraft charging by photoemission in sunlight. Although the charging level is low (10 V or less usually) because the sunlight spectral lines have low energies, the photoemission current exceeds the ambient electron current and therefore controls the spacecraft charging. Although low-level charging does practically no harm to the electronics onboard, we should discuss it because it is very common. In this case, the current balance is essentially between the photoelectrons and the ambient electrons, because most of the secondary electrons cannot leave and the ambient ions are repelled. Obviously, as the ambient electron density $n$ varies in eq(9), so do the ambient electron current $I_e$ and the spacecraft potential $\phi$.

Another common case is using plasma probes on spacecraft. In this case, one applies an artificial sweeping current to a probe. As a result, the current balance is no longer between the incoming electrons and the outgoing electrons only. In similar modern physics language, the symmetry between the natural currents is broken by the artificial beam current, rendering the property of density cancellation invalid. With the broken symmetry, a simple critical temperature is impossible because it depends on beam current, beam energy distribution, and other parameters.

Finally, we stress that both properties I and II are important. They have been derived theoretically and confirmed by space observation. One must be careful that there are situations where I and II do not apply.

A note added in proof: in the literature, there are other charging onset indicators such those without using SEY or with electron energies well above the second crossing point of SEY. Such approaches are outside the scope here and will not be discussed at this time.

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