ONSET OF SPACECRAFT CHARGING IN SINGLE AND DOUBLE MAXWELLIAN PLASMAS IN SPACE: A PEDAGOGICAL REVIEW

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Abstract

This paper reviews some recent advances in the onset of spacecraft charging. Current balance determines the spacecraft potential. The electron flux intercepted by an object in a plasma exceeds that of ions by orders of magnitude because of the ion-electron mass difference. Negative voltage charging occurs when the incoming electron flux exceeds the outgoing secondary and backscattered electron flux. The secondary electron emission coefficient depends on the surface material, typically exceeds unity at about 40 to 1800 eV of primary electron energy, and falls below unity at higher energies. Beyond a critical temperature T*, the incoming electron flux exceeds that of the secondary electrons, thereby negative charging occurs. Scarce evidence of T* was observed on ATS-5 and ATS-6 satellites. Recently, abundant evidence was observed on the Los Alamos National Laboratory geosynchronous satellites. The existence of T* enables accurate prediction of spacecraft charging onset. In double Maxwellian plasmas, the onset of spacecraft charging depends on the density and temperature of both distributions. We explain pedagogically the onset of charging in double Maxwellian plasmas. Triple-root jumps in spacecraft potential can occur.

Physical Reason of Critical Temperature

The spacecraft potential is governed by current balance. When the incoming electron flux exceeds the fluxes of the incoming ions and outgoing secondary electrons, negative charging occurs. In the geosynchronous environment, the electron flux exceeds that of the ions by nearly two orders of magnitude, because of their mass difference [Figure 1]. Negative charging is important at geosynchronous altitudes. However, the ambient flux difference alone is insufficient to obtain negative charging because the secondary electrons play an important role in the current balance.

Plotting the log of a Maxwellian electron distribution f(E) as a function of electron energy E gives a straight line. The inverse of its slope gives the temperature T. Higher temperature corresponds to more abundant higher energy electrons [Figure 2 Upper]. The secondary electron coefficient *(E) exceeds unity, meaning more outgoing secondary electrons than incoming primary electrons, in the energy E range of about E_1=40 to E_2=1800eV of primary electron energy, depending on the surface material. [Figure 2 Lower]

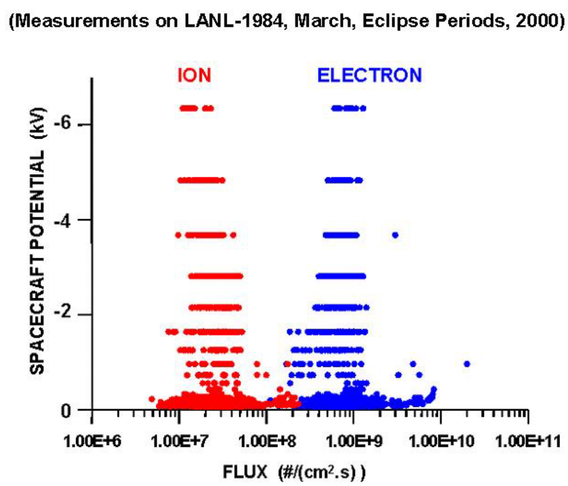

Figure 1. Electron and ion fluxes measured at geosynchronous altitudes.

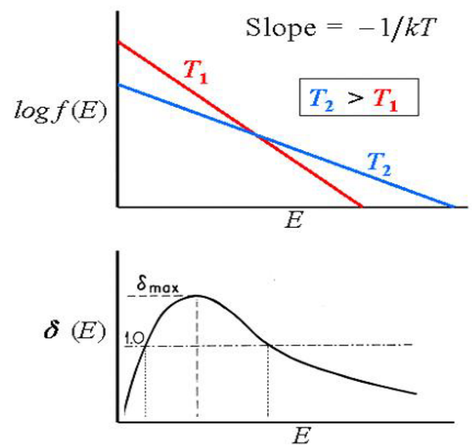

Figure 2. (Upper) Temperature T of Maxwellian distribition. (Lower) Secondary electron emission coefficient as a function of primary electron energy.

Combining the two concepts of $f(E)$ and $*(E)$, the temperature T controls the competition between the two camps of electrons, viz., the low energy camp generating more outgoing secondary electrons and the high energy camp generating less secondary electrons than primary electrons. A spacecraft put in an initially low T plasma would not charge negatively, because there are more low energy electrons. As the temperature reaches a critical value T*, the population of higher energy electrons begins to dominate, suppressing the secondary electron emission.

Maxwellian Space Plasma Environment

We now consider a mathematical formulation of the onset of charging to negative potentials. At equilibrium, the spacecraft potential N is determined by current balance. At the threshold of charging onset, the potential N is zero. For uniform charging, it is sufficient to consider balance of fluxes — the incoming flux equals the outgoing flux:

$$\int_0^\infty dEEf(E) = \int_0^\infty dEE\,f(E)[\delta(E)+\eta(E)] \qquad (1)$$

where f (E) is the distribution function of the incoming electrons, ∗(E) and 0(E) are the secondary and backscattered electron emission coefficients. To calculate eq(1), one needs the functional forms of f (E), ∗(E) and 0(E). For a Maxwellian plasma,

$$f(E) = n(m/2\pi kT)^{1/2}\exp(-E/kT) \qquad (2)$$

Simple analytical forms of *(E) and 0(E) for normal incidence has been given by Sanders and Inouye [1979] and Prokopenko and Laframboise [1980] respectively.

$$\delta(E) = c[\exp(-E/a) - \exp(-E/b)] \tag{3}$$

and

$$\eta(E) = A - B\exp(-CE) \tag{4}$$

Substituting eqs(2,3,4) into eq(1), one obtains:

$$c\left[\left(1+kT/a\right)^{-2} - \left(1+kT/b\right)^{-2}\right] + A - B\left(CkT+1\right)^{-2} = 1 \tag{5}$$

The Maxwellian distribution *f* (E) is a function of electron energy E, electron density n and electron temperature T. The energy variable E in eq(1) has been integrated out in the definite integral. Since the density *n* is multiplicative, it cancels out on both sides of eq(1). Therefore, the onset condition (eq.1) for charging is independent of the plasma density *n.* In other words, the condition for the onset of charging is a function of T only. The solution to eq(5) is the critical temperature T* for the onset of spacecraft charging.

Angular Dependence

The angular dependent forms of secondary and backscattered electron emission coefficients have been given by [*Darlington and Cosslett*, 1972] as follows:

$$\delta(E,\phi) = \delta(E,0)\exp\left[\beta_S(E).(1-\cos\phi)\right] \tag{6}$$

and

$$\eta(E,\phi) = \eta(E,0)\exp\left[\beta_b(E).(1-\cos\phi)\right] \tag{7}$$

where *N* is the angle of incidence of the primary electrons. $\exists_S$ and $\exists_b$ are empirical factors. By fitting experimental data, *Laframboise et al.* [1982] have obtained the forms of $\exists_S$ and $\exists_b$:

$$\beta_S(E) = \exp(\zeta) \tag{8}$$

and

$$\beta_b(E) = 7.37Z^{-0.56875} \tag{9}$$

where

$$\zeta = 0.2755(\xi - 1.658) - \left\{\left[0.2755(\xi - 1.658)\right]^2 + 0.0228\right\}^{1/2} \tag{10}$$

and

$$\xi = \ln(E/E_{\max}) \tag{11}$$

In eq(9), Z is the atomic number of the surface material. E_{max} in eq(11) is the primary electron energy where the secondary emission is maximum. Substituting eqs(3,4,6-11) into eq(1), one obtains the critical temperature T* for given surface materials [Table 1].

Table 1. Critical Temperatures

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

Evidences of Critical Temperature

Early evidences of the existence of T* were given by Rubin et al. [1980]. The Los Alamos National Laboratory (LANL) geosynchronous satellites provide abundant co-ordinated data of spacecraft charging and the space environment. The data span over several years and are available on the CDCWeb. Using these data, we have found abundant evidences of the existence

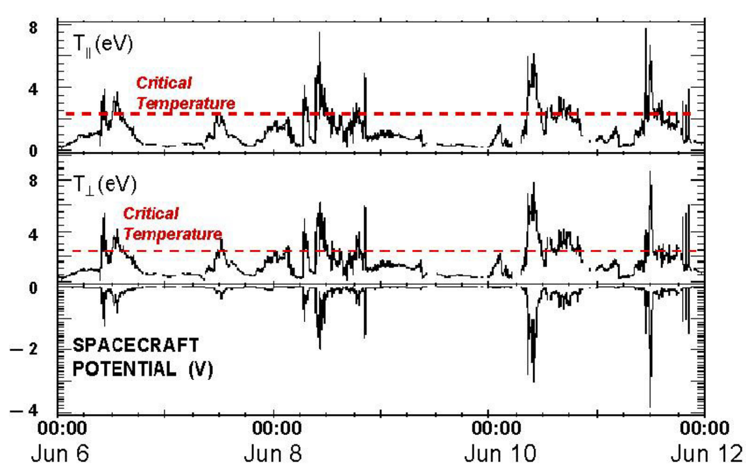

Figure 3. Evidence of critical temperature. Measurements obtained on LANL-97A.

of critical temperature, not only on one LANL satellite but on all of them, and not only in one year but in all years. Abundant observational evidences have been reported in Lai and Della-Rose [2001] and in Lai and Tautz [2003]. Figure 3 shows an example of the existence of critical temperature T*. Below T*, no charging occurs; above T*, the charging level increases almost

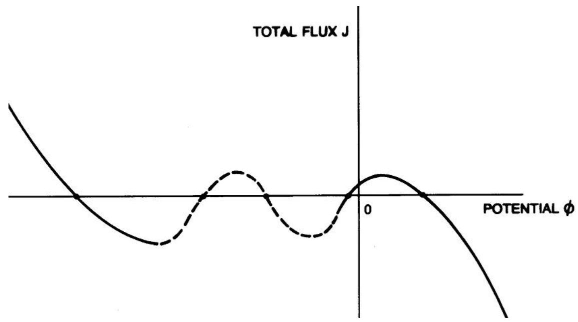

Figure 4. A triple-root situation. The even roots are unstable.

linearly with T. Using several years of data, we now know without a doubt the existence of critical temperature for the onset of spacecraft charging. More details are given in Lai and Tautz [2003].

Double Maxwellian Plasma Environment

In general, the current balance equation is of the form J(*N*) = 0 where J is the total (or net) flux. It is possible that the equation has multiple roots, i.e. solutions [Whipple, 1981; Besse, 1980; Laframboise, et al., 1982, 1983; Meyer-Vernat, 1982; Lai, 1991a, 1991b; Garrett and Hastings, 1996]. If it has three roots, the J(*N*) curve as a function of N is a “triple-root curve”. The spacecraft potential is at one of the roots. As the ambient plasma condition changes in time, a “triple-root jump” may occur. That is, the spacecraft potential may jump from one root to another. This behavior will be explained in the double Maxwellian plasma model.

A General Theorem on Multiple Roots

Our sign convention is that incoming flux of positive ion is positive, and so is outgoing electron flux. In a general curve of flux-voltage [Figure 4], there exists at least one root, J(*N*) = 0, where J is the total flux. This is because at high positive potential *N*> 0, incoming electron flux must dominate and therefore J < 0. At high negative potential *N*< 0, incoming ion flux must dominate and therefore J > 0. In between these two extremes, there must exist at least one or an odd number of zero crossings, J(*N*) = 0.

Therefore, we have a **general theorem: The number of roots, J(*N*) = 0, must be odd**.

The even roots are unstable, because their slopes, dJ/dN, have the wrong sign, corresponding to negative resistance. Only the odd roots are stable. Since the spacecraft potential cannot be multiple valued at the same time, it is at one of the odd roots only.

As the space plasma environment changes, it may happen that two neighboring roots, including the spacecraft potential, disappear together [Figure 5]. The spacecraft potential would jump to the next neighboring (the third) root. When the space plasma parameters reverse their course, the two lost roots may appear again. Yet, the spacecraft potential may remain at the new root. A return to its first root may occur but at different values of plasma parameters. This is a hysteresis behavior.

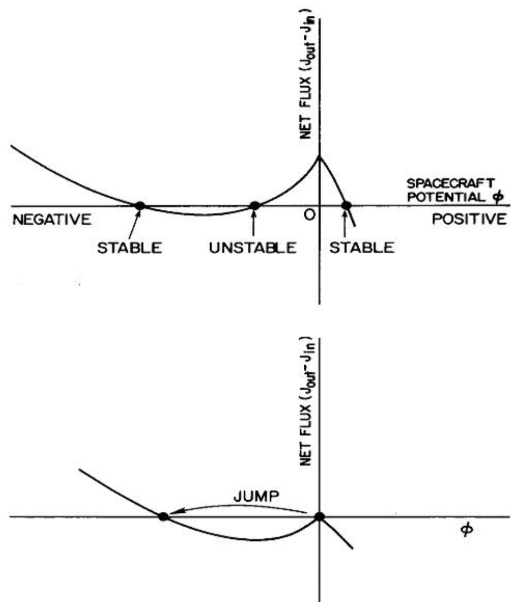

Figure 5. A triple-root jump in spacecraft potential.

Double Maxwellian Space Plasma

The space plasma environment varies in time. In the outer region of the geosynchronous orbit, energetic plasma clouds from the magnetotail may come in at about midnight hours. Due to the curvature of the magnetic field, the energetic electrons tend to drift eastwards and the energetic ions westwards. As they move nearer the Earth, the co-rotation effect tends to move everything eastwards. This describes what usually happens during a 'substorm injection', which may occur from once in many days to a few times a night.

In quiet time, it is often a good approximation to describe the energy distribution of the space plasma at geosynchronous altitudes as a Maxwellian $f_1(E)$. When a new plasma cloud arrives, the plasma distribution changes. It is often convenient to describe the distribution, f, as a double

Maxwellian, which is a sum of a low temperature, T_1, component and a high temperature, T_2, component.

$$f_e = f_{e,1} + f_{e,2} \tag{12}$$

and

$$f_i = f_{i,1} + f_{i,2} \tag{13}$$

By convention, the first Maxwellian f_1 is the one that has the lower electron temperature $T_{e,1}$. The density of f_1 is greater than that of f_2, otherwise the population is called ‘inverted’ which is rare.

$$T_{e,1} < T_{e,2} \tag{14}$$

$$n_{e,1} > n_{e,2} \tag{15}$$

The Triple-Root Situation of Spacecraft Potential

Firstly, at very high positive surface potential N, the flux must be predominantly that of incoming electrons (total J<0). Secondly, at very high negative surface potential, the flux must be predominantly that of incoming ions (total J>0). Consider the potential N as a variable. Let N decreases from the J<0 region. If $J(N)$ climbs above 0 and then decreases to below 0, we have a triple-root situation (Figure 7).

In a double Maxwellian plasma, the total (or net) flux J is given by

$$J = J_1 + J_2 \tag{16}$$

J_1 and J_2 must have opposite signs at roots of $J(N) = 0$ where the potentials are moderate, i.e. small enough for ion currents to be negligible. In order for J_1 and J_2 to have opposite signs, T_1 must be below T*, while T_2 above T*.

$$T_2 > T^* > T_1 \tag{17}$$

which gives $J_1 > 0$ while $J_2 < 0$.

The condition for the existence of a positive flux J(N) >0 is

$$|J_1| > |J_2| \tag{18}$$

where, neglecting the ions, the net fluxes are given by

$$J_1 = \int_0^\infty dEE\, f_1(E)\left[1-(\delta(E)+\eta(E))\right]\exp\left(-\frac{e\phi}{kT_1}\right) \tag{19}$$

and

$$J_2 = \int_0^\infty dEE\, f_2(E)\left[1-(\delta(E)+\eta(E))\right]\exp\left(-\frac{e\phi}{kT_2}\right) \tag{20}$$

Since $T_2 > T_1$, $J_1(N)$ decreases faster than $|J_2(N)|$ as the magnitude of (negative) N increases (i.e. to the left side in Fig.7). At a sufficiently large magnitude of (negative) N, $J_1(N)$ decreases to a value so small that the equality (18) is not satisfied, rendering the total J negative. Whether the inequality (18) is violated depends mainly on the relative densities n_1 and n_2. If n_1 decreases, J_1 decreases accordingly. Eventually, when $J_1 = J_2$ in magnitude, the total flux $J(N) = J_1(N) + J_2(N) = 0$. A root is at this value of N. As the magnitude of (negative) N increases to very large values, eventually the ambient ions must take over. That is, eventually, at such high magnitude of (negative) N, the curve $J(N)$ must have negative slope, crossing the $J(N) = 0$ again. Counting the roots, we already have one at positive N, now one at negative N, and eventually there must be one at a high magnitude of negative N. Thus, a triple-root situation is formed. A triple-root jump occurs when two of the adjacent roots coalesce and disappear.

A Potential Adverse Effect of High Secondary Electron Emission

As a corollary, the use of spacecraft surface materials with high secondary electron emission coefficient * poses a potential adverse effect, viz., triple-root jump in spacecraft potential. High * value makes J positive (because of outgoing electron) at or near $N = 0$. This property prevents the surface from onset of charging until the ambient electron temperature is high. However, in a double Maxwellian plasma (Figure 7), high J_1 at $N = 0$ may increase the likelihood of a triple-

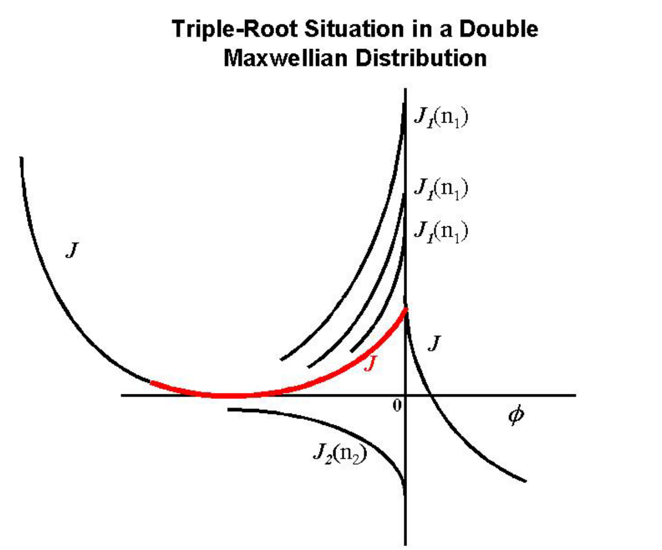

Figure 7. Formation of triple-root situation in a double Maxwellian space plasma. Sign convention: *J* is positive for incoming ion flux. The red line shows $J = J_1 + J_2$ in the low N values before the ions take over at very high negative N.

root situation with a high negative root. If the space weather changes in such a manner that n_1 decreases rapidly, the sum J of J_1 and J_2 may decrease to zero at $N = 0$. If so, a triple-root jump in spacecraft potential occurs. The amplitude of the jump may be very large. The time of jump may be very short, depending on the surface capacitances involved. For example, the jump in Day 114 of SCATHA occurred on the copper-beryllium surface, which has $* = 4$ approximately. It occurred when n_1 was dropping rapidly, while the other space environment parameters stayed relatively constant in the period of the event.

Summary and Conclusion

When an object is placed in a plasma, whether in space or in the laboratory, the object intercepts more electrons than ions, because the electrons are lighter than ions and therefore the electron flux is higher. When electrons impact on a surface, secondary and backscattered electrons are emitted from the surface. Secondary electrons are much more abundant and therefore more important than backscattered electrons. At a range of primary electron energy, typically between 50 to 1500 eV depending on the surface material, the outgoing electron flux exceeds the incoming primary electron flux. This property prevents negative-voltage charging of the surface for incoming electrons in this range of energy.

However, primary electrons from space plasma are not mono-energetic but form a distribution in energy. At equilibrium, the distribution is Maxwellian, which is characterized by the electron density and electron temperature. Because of the secondary-emission property of a given surface material, the electrons in a Maxwellian distribution can be thought of falling into two camps. The low energy camp generates more outgoing (secondary) electrons than incoming electrons and therefore tends to drive the surface potential positive. The high-energy camp generates less outgoing electrons than incoming electrons. Therefore this camp tends to drive the surface potential negative. The competition between these two camps determines the onset of spacecraft charging. As the electron temperature increases, the number of electrons in the high-energy camp increases. Eventually, at sufficiently high temperature (the critical temperature), the two camps are even, meaning onset of charging. At higher temperatures, the high-energy camp wins and therefore the surface potential is negative. Abundant evidences have been observed on the LANL geosynchronous satellites confirming, without a doubt, the existence of critical temperature for the onset of spacecraft charging.

In general, a spacecraft surface flux-voltage curve (or equation) can yield an odd number of roots. The even roots are unstable because they are opposite to Ohm's law. A triple-root situation does not necessarily imply a triple-root jump in potential. To have a jump, two of the adjacent roots have to coalesce and disappear together. The amplitude of a jump can be very large, kV, for example. The time of jump, being limited mainly by surface capacitances, can be extremely fast.

A double Maxwellian distribution is often a good approximation for describing the space plasma, especially when a new plasma cloud has arrived and an equilibrium has not achieved. Conventionally, the first Maxwellian $f_1(E)$ is the one with the lower temperature. Although the concept of critical temperature T* was developed for single Maxwellian plasmas, surprisingly the concept plays an important role in double Maxwellians and triple-roots. When the temperatures of f_1 and f_2 are both less than T*, no negative voltage charging occurs. When the temperatures of f_1 and f_2 both exceed T*, there must be negative charging. If T_1 < T*, while T > T*, the fluxes J_1 and J_2 of the two Maxwellians must be of opposite signs. Therefore J_1 and J_2 compete with each other. At low negative potentials, the ions can be legitimately neglected. If J_1 greatly exceeds J_2, their sum J exceeds 0. A triple-root situation may form. If the density n_1 of J_1 decreases, J_1 decreases accordingly. When J_1 decreases to below J_2, J falls below 0, allowing a triple-root jump to occur.

As a corollary, spacecraft surfaces of high secondary emission coefficient $*_{max}$ are more likely to suffer from triple-root jump. It has been a common belief that using surfaces of high $*_{max}$ is a good mitigation method. Not so! When the space plasma environment becomes hot while the first Maxwellian density is dropping steadily, there is danger for a triple-root jump to occur for such surfaces. With this corollary, we close this paper by bringing this important message to the attention of the community of spacecraft charging and space vehicle designs.

Acknowledgment

The Los Alamos Magnetospheric Plasma Analyzer (MPA) measurements were obtained from the CDAWeb data service at NASA Goddard Space Flight Center. We thank M. Thomsen for permission to use the MPA data.

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