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

Shu T. Lai, MIT, Cambridge, MA, 02139, USA, and
Boston College, Newton, MA, 02457, USA

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 naïve 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 from the surface. 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 $E_1 < E < E_2$, where E_1 and E_2 are the crossing points [4-10]. For $E > E_2$, 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.

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

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

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

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.

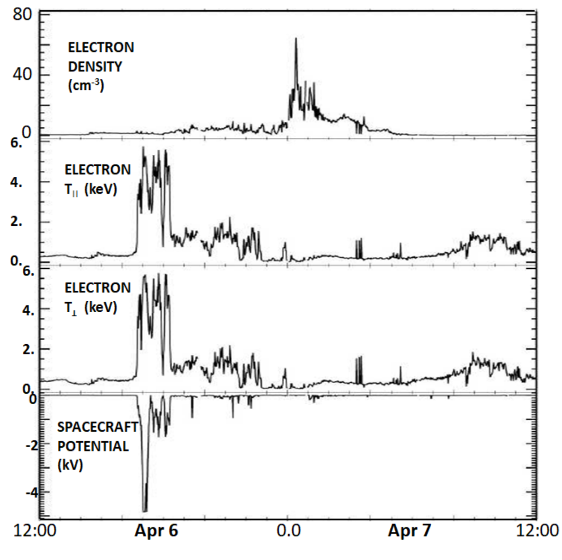

Figure 1 Spacecraft charging on the LANL 1994-084 satellite. The spacecraft potential rises to -5 kV at 17:00 UT, Apr 6, whereas the electron density rises to 65 cm^{-3} at 01:00 UT, Apr 7, 2000. Adapted from Ref.[23].

KAPPA DISTRIBUTION

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

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

where $T_\kappa = \dfrac{\kappa}{(\kappa-3/2)}T$ and $3/2 < \kappa < \infty$

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

$$\int_0^\infty dEEf_K(E) = \int_0^\infty dEEf_K(E)\left[\delta(E)+\eta(E)\right] \quad (4)$$

yielding the critical kappa temperature T_κ* [23].

Again, the density n on both sides of eq(4) cancels out [23]. There exists critical T_κ^*, but the values are different from those of T* 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]

$$\int_{E_L}^{E_U} dEEf(E) = \int_{E_L}^{E_U} dEEf(E)\ \delta(E)+\eta(E) \quad (5)$$

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_D(E) may happen if a plasma moves into the region of another plasma and it takes time to reach equilibrium.

$$f_D(E) = f_1(E)+f_2(E) \quad (6)$$

$$f_1(E) = n_1\left(m/2\pi kT_1\right)^{3/2}\exp\left(-E/kT_1\right) \quad (7)$$

$$f_2(E) = n_2\left(m/2\pi kT_2\right)^{3/2}\exp\left(-E/kT_2\right) \quad (8)$$

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 ϕ(>0) in sunlight depends on the ambient electron current $I_e(\phi)$. For a conducting sphere, the current balance equation is as follows.

$$I_e(0)\left(1-\frac{q_e\phi}{kT_e}\right)-I_i(0)\exp\left(-\frac{q_i\phi}{kT_i}\right) = I_{ph}(\phi) \quad (9)$$

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

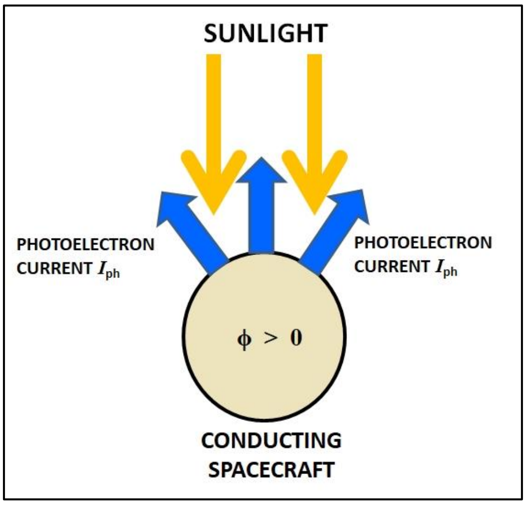

Figure 2. Low-level charging to positive potentials in sunlight.

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 ϕ. The spacecraft current balance equation is as follows.

$$\int_{E_L}^{E_U} dEEf(E) = \int_{E_L}^{E_U} dEEf(E)\ \delta(E)+\eta(E)\ +I_p \quad (10)$$

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, ϕ 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

$$\int_0^\infty dEE\,f(E) = \int_0^\infty dEE[\delta(E)+\eta(E)]f(E) + I_B(E_B)\Theta(E_B - q\phi) \quad (11)$$

where $I_B(E_B)$ is the current of the ion beam of energy E_B and Θ is a step function (= 1 if $E_B > q\phi$, and = 0 if $E_B < q\phi$). 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, ϕ 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.

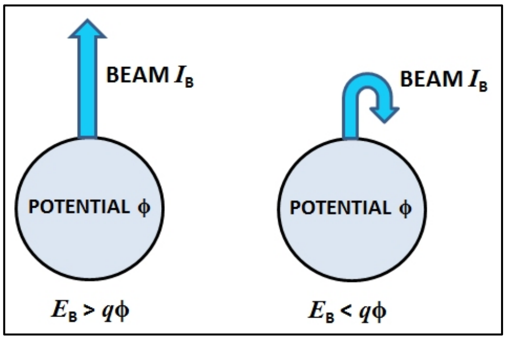

Figure 3. Charged particle beam emission. The beam returns if the beam energy is less than the spacecraft charging potential energy.

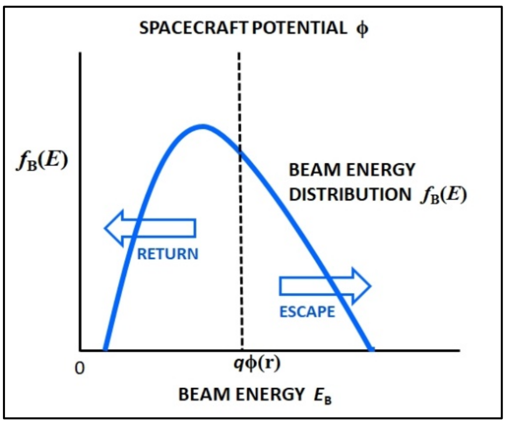

Figure 4. Partial return of a beam with an energy distribution. The partition is at the spacecraft charging potential energy at the location r.

SUMMARY AND DISCUSSION

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

Table 1: Facets of Spacecraft Charging

Situation	Electron Density	Critical Temperature
Maxwellian	Independent	T*
Double Maxwellian	Dependent	No
Kappa	Independent	T*
Cutoff Maxwellian	Independent	T*
Monopole-Dipole Model in Sunlight	Independent	T*
Low-Level Charging in Sunlight	Dependent	No
Plasma Probe on Spacecraft	Dependent	No
Charged Particle Beam Emission	Dependent	No

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 ϕ.

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 in the balance equation. Therefore, the property of density cancellation does not apply.

Beam emission is gaining attention not only for spacecraft charging mitigation but also for space propulsion. A beam emitted can partially return depending on the beam energy distribution and the spacecraft charging level. Again, 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.

ACKNOWLEDGMENT

The author thanks Dr. Roberto Cimino for inviting this paper. It was presented at MIT Space Propulsion Laboratory, May, 2018. The author thanks Professor Paulo Lozano for his encouragement.

REFERENCES

[1] DeForest, S.E., Spacecraft charging at synchronous orbit, *J. Geophys. Res.*, (1972), 77, 3587-3611.

[2] Hastings, D. and H. B. Garrett, Spacecraft-Environment Interactions, Cambridge Univ. Press, Cambridge, UK, (1997).

[3] Lai, S.T., Fundamentals of Spacecraft Charging, Princeton University Press, Princeton, NJ, USA. ISBN: 9780691129471, (2011).

[4] Sternglass, E. J., "Theory of secondary electron emission," Scientific Paper 1772, Westinghouse Research Laboratories, Pittsburgh, PA, (1954).

[5] Sanders, N.L. and G.T. Inouye, "Secondary emission effects on spacecraft charging: energy distribution consideration," in Spacecraft Charging Technology 1978, ed. R.C.Finke and C.P. Pike, NASA-2071, ADA 084626, (1978), pp.747-755.

[6] Scholtz, J. J., D. Dijkkamp, and R.W.A. Schmitz, *Philips J. Res*., (1996), 50(3-4), 375–389.

[7] Cazaux, J., *J. Phys. D: Appl. Phys*., (2005), 38, 2433-2441.

[8] Lin, Y. and D. G. Joy, *Surf. Interface Anal.,* (2005), 37: 895–900.

[9] Cimino, R., M. Commisso, D.R. Grosso, T. Demma, V. Baglin, R. Flammini, R. Laciprete, *Phys. Rev. Lett*., (2012), 109, 10.1103, doi: 109.064801.

[10] Larciprete, R., D.R. Grosso, M. Commisso, R. ammini, and R. Cimino, *Phys. Rev. Special Topics*, (2013), 16, 011002.

[11] Sternglass, E. J., *Phys. Rev.* (1954), 95: 345–358.

[12] Darlington, E. H., and V. E. Cosslett, *J. Phys. D: Applied Phys*. (1972), 5: 1969–1981.

[13] Jabonski, A., and P. Jiricek, *Surf. Interface Anal.*, (1996), 24: 781–785.

[14] Cazaux, J., *J. Applied Phys.*, (2012), 111, 064903.

[15] Lai, S.T., Spacecraft charging: Incoming and outgoing electrons, in Proceedings of ECLOUD'12: Joint INFN-CERN-EuCARD-AccNet Workshop on Electron-Cloud Effects, eds. R. Cimino, G. Rumolo, and F. Zimmermann, (CERN-2013-002, Geneva, 2013), pp.165-168, doi:10.5170/ CERN-2013-002.

[16] Lai, S.T., M.S. Gussenhoven, and H.A. Cohen, Range of electron energy spectrum responsible for spacecraft charging, presented at *AGU Spring Mtg*., Philadelphia, PA, May, (1982).

[17] Lai, S.T., M.S. Gussenhoven, and H.A. Cohen, The

concepts of critical temperature and energy cutoff of ambient electrons in high-voltage charging of spacecraft, in *Spacecraft/Plasma Interactions and Their Influence on Field and Particle Measurements*, eds. A. Pedersen, D. Guyenne and J. Hunt, European Space Agency (ESA), Noordwijk, the Netherlands (1983), pp.169-175.

[18] Laframboise, J.G., R. Godard, and M. Kamitsuma, Muliple floating potentials, threshold temperature effects, and barrier effects in high-voltage charging of exposed surfaces on spacecraft, in *Proceedings of Intn'l Symposium on Spacecraft Materials in Space Environment*, Toulouse, France, ESA Report ESA-178, ESA, Noordwijk, the Netherlands, (1982), pp.269-275.

[19] Laframboise, J. G., and M. Kamitsuma, "The threshold temperature effect in high voltage spacecraft charging," in *Proceedings of Air Force Geophysics Workshop on Natural Charging of Large Space Structures in Near Earth Polar Orbit*, eds. R. C. Sagalyn, D. E. Donatelli, and I. Michael, AFRL-TR-83-0046, ADA-134-894, Air Force Geophysics Laboratory, Hanscom AFB, MA, (1983), pp.293–308.

[20] Lai, S.T., *IEEE Trans. Nucl. Sci.*, Vol.19, pp.1629-1634, (1991).

[21] Lai, S.T. and D. Della-Rose, *J. Spacecraft & Rockets*, Vol.38, No.6, 922-928, (2001).

[22] Lai, S.T. and M. Tautz, *J. Geophys. Res*., Vol 111, A09201, doi:10.1029/2004JA010733, (2006).

[23] Lai, S.T., M. Martinez-Sanchez, K. Cahoy, M. Thomsen, Y. Shprits, W. Lohmeyer, and F. Wong, *IEEE Trans, Plasma Sci*., Vol.45(10), pp.2865-2884, (2017). doi:10.1109/TPS.2017.2751002.

[24] Vasyliunas, V.M., *J. Geophys. Res*., Vol. 73, pp. 2839-84, (1968).

[25] Meyer-Vernet, N., *Eur. J Phys*.,Vol.20, pp.167-176, (1999).

[26] Thomsen, M. F., H. Korth, and R. C. Elphic, *J. Geophys. Res*., 107(A10), 1331, doi:10.1029/2001JA000148, (2002).

[27] Lai, S.T., *J. Geophys. Res*.- *Space Phys.*, Vol.110, A01, pp.204-215, doi:10.1029/2002JA009447, (2005).

[28] Besse, A.L., *J. Geophys. Res*., (1981), Vol.86, pp.2443-2446.

[29] Lai, S.T., *J. Geophys. Res.*, (1991), 96, No.A11, pp.19269-19282.

[30] Lai, S.T. and M. Tautz, *J. Geophys. Res*., (2008), 113, A11211, doi:10.1029/2008JA01361.

[31] Huang, J.G., G.Q. Liu, and L.X. Jiang, *J. Geophys. Res*., 120, doi:10.1002/2015JA021173, (2015).

[32] Huang, J., G. Liu, and L. Jiang, *J. Geophys. Res.,* Vol.120, pp.10,404–10,414, doi: 10.1002/2015JA 021820, (2015).

[33] A. L. Besse and A. G. Rubin, *J. Geophys. Res.*, 85(A5), pp.2324–2328, (1980).

[34] Lai, S.T. and M. Tautz, *IEEE Trans. Plasma Sci*., Vol.34, No.5, 2053-2061, doi: 10.1109/TPS.2006 .883362, (2006).

[35] Lai, S.T. and K. Cahoy, *IEEE Trans. Plasma Sci*., Vol.43, No.9, pp.2856-2860, doi: 10.1109/TPS.2015 .2453370, (2015).

[36] Feuerbacher, B. and B. Fitton, *J. Appl. Phys.*, vol. 43, no. 4, (1972), pp.1563–1572.

[37] Knott, K., A. Korth, P. Décréau, A. Pedersen, and G. Wrenn, 'Observations of the GEOS Equilibrium Potential and its Relation to the Ambient Electron Energy Distribution', in *Spacecraft Plasma Interactions and Their Influence on Field and Particle Measurements, Proceedings of the 17th ESLAB Symposium*, ESA SP-198, (1983), p.19.

[38] Escoubet, C.P., A. Pedersen, R. Schmidt, and P.A. Lindquist, *J. Geophys. Res*., Vol.102, (1997), pp.17595-17609, doi:10.1029/97/JA00290

[39] Garnier, P., M.K.G. Holmberg, J.-E. Wahlund, G.R. Lewis, S. Rochel Grimald, M.F. Thomsen, D.A. Gurnett, A.J. Coates, F.J. Crary, and I. Dandouras, *J. Geophys. Res*., Vol.118, no.11, (2013), pp.7074-7073, doi: 10.1002/2013JA019114

[40] Kurth, W.S., S. De Pascuale, J.B. Faden, C.A. Kletzing, G.B. Hospodarsky, S. Thaller and J.R. Wygant, *J. Geophy. Res*., 120, (2004), pp.904-914, doi:10.1002/2004JA020857

[41] Lai, S.T., *IEEE Trans. Nuclear Sci.*, Vol.36, No.6, (1989), pp.2027-2032.

[42] Lai, S.T., *J. Geophys. Res.*, Vol.99, (1994), pp.459-468.