Máster Universitario en Ingeniería Aeronáutica

The Space Environment

Plasma-Wall Interaction

Jorge Gonzalez
Based on the work by Luis Conde
Personal website: http://plasmalab.aero.upm.es/~lcl/
Departamento de Física Aplicada

POLITÉCNICA

UPM PlasmaLab

Plasmas at main Earth orbits

The plasma environment affects spacecrafts in any orbit that can be roughly divided in:

- LEO (Low Earth Orbit): the plasma is cold and dense ($n_e \sim 10^{10} - 10^{11}\ \text{part./m}^3$) in the plasmasphere (altitudes below 2000 km) and can be approximated by a Maxwellian energy distribution.
- PEO (Polar Earth Orbit): in addition to dense plasma at low altitudes exist fluxes of energetic particles from the solar activity transported by the geomagnetic field.
- GEO (Geostationary Orbit): the plasma density drops ($n_e \sim 10^{8} - 10^{9}\ \text{part./m}^3$) and energy distributions are not Maxwellian with higher mean energy.

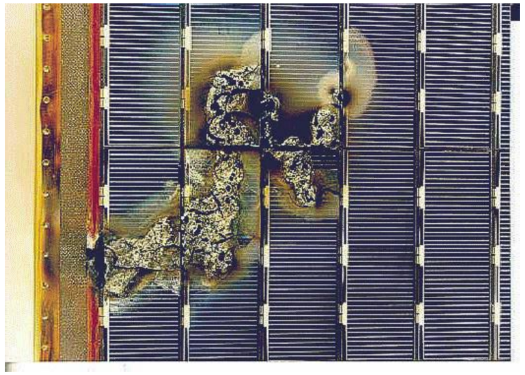
- Spacecrafts (typical dimension L_S) interact with plasmas (natural and/or artificial, created by the vehicle itself) in many ways and in LEO $\lambda_D < L_S$ whereas $\lambda_D > L_S$ in GEO orbits.
- Dielectric and metallic component are immersed in an electrically active medium where orbital speed also induces potential differences.
- For the typical orbital velocity $v_o \sim 7\ \text{km/s}$ in LEO the induced electric field is $\boldsymbol{E} = \boldsymbol{v_o} \times \boldsymbol{B}$ we can estimate, $E \sim v_o B$

EOS (700 km)	$B = 0.14 \cdot 10^{-4}\ \text{T}$	$E \sim 9.8 \cdot 10^{-2}\ {}^{\text{V}}/_{\text{m}}$
ISS (500 km)	$B = 0.23 \cdot 10^{-4}\ \text{T}$	$E \sim 16.0 \cdot 10^{-2}\ {}^{\text{V}}/_{\text{m}}$

- Along the 109 m length of the ISS solar array, we have a voltage drop of:

$$\Delta V = 16 \cdot 10^{-2} \times 1.09 \cdot 10^{2} = 17.4\, V$$

this medium is thus electrically active.



ESA EURECA solar array sustained arc damage (ESA)

Definitions

Flux: Number of particles (energy, radiation, etc.) crossing a surface by time unit (ECSS)

Fluence: time-integration of the flux (ECSS)

- Distribution function $f(\boldsymbol{v},\boldsymbol{r},t)$ in phase space (r,v) is,

$$f(\boldsymbol{v},\boldsymbol{r},t)=\frac{dN}{d^3r\,d^3v}$$ and gives the particle density $$n(\boldsymbol{r},t)=\int_{-\infty}^{+\infty}f(\boldsymbol{v},\boldsymbol{r},t)d^3v$$

Gives the *particle flux*, $d\boldsymbol{J}=\boldsymbol{v}\,dn=\boldsymbol{v}\,f(\boldsymbol{v},\boldsymbol{r},t)d^3v$ and,

$$\boldsymbol{J}(\boldsymbol{r},t)=n(\boldsymbol{r},t)\,\boldsymbol{u}(\boldsymbol{r},t)=\int_{-\infty}^{+\infty}\boldsymbol{v}\,dn=\int_{-\infty}^{+\infty}\boldsymbol{v}\,f(\boldsymbol{v},\boldsymbol{r},t)d^3v$$ with units of $$\frac{particles}{m^2\times sec.}$$

- The *differential particle fluxes* are,

$$\frac{d\boldsymbol{J}}{dE}\qquad\frac{\text{particles}}{\text{m}^2\times\text{sec.}\times\text{ energy}}\qquad;\qquad\frac{d\boldsymbol{J}}{dE\,d\Omega}\qquad\frac{\text{particles}}{\text{m}^2\times\text{sec.}\times\text{ energy}\times\text{Sr}}$$

- The energy flux $d\boldsymbol{Q}=(\boldsymbol{v}\,E)dn=(\boldsymbol{v}E)\,f(\boldsymbol{v},\boldsymbol{r},t)d^3v$

$$\boldsymbol{Q}(\boldsymbol{r},t)=\int_{-\infty}^{+\infty}(\boldsymbol{v}E)\,dn=\int_{-\infty}^{+\infty}(\boldsymbol{v}E)\,f(\boldsymbol{v},\boldsymbol{r},t)d^3v$$

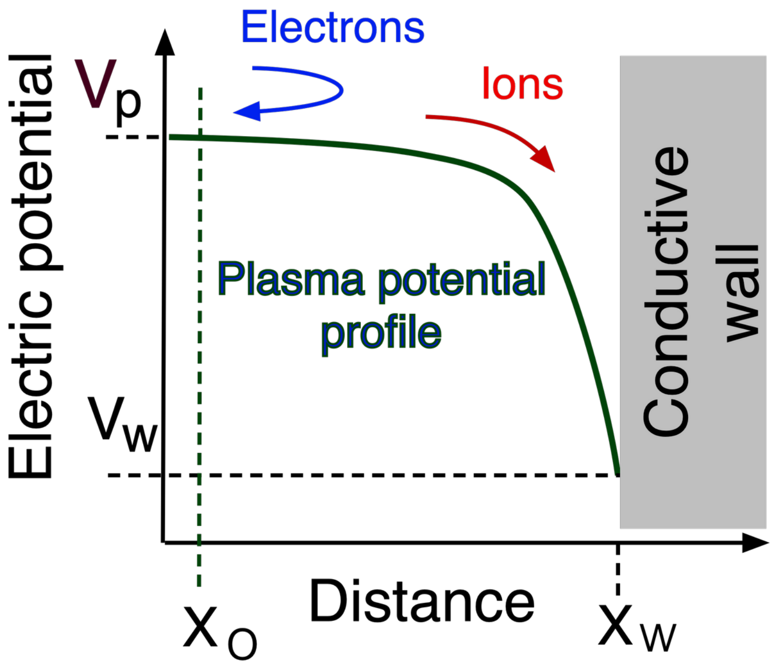
- and gives the *differential energy fluxes* are,

$$\frac{d\boldsymbol{Q}}{dE}\qquad\frac{\text{energy}}{\text{m}^2\times\text{sec.}\times\text{ energy}}\qquad;\qquad\frac{d\boldsymbol{Q}}{dE\,d\Omega}\qquad\frac{\text{energy}}{\text{m}^2\times\text{sec.}\times\text{ energy}\times\text{Sr}}$$

Ion collection by metallic surfaces

- Metallic surfaces interact with the ambient plasma through an electric potential profile called *plasma sheath*. For the evaluation of the ion current to a conductive surface we consider in the steady state a one-dimension model under the following assumptions,
  - The distant plasma $x < x_o$ is quasineutral $n_{eo} \simeq n_{io} = n_o$ and V_p is uniform in space.
  - The electric potential $V_p > V(x) > V_w$ with respect to the ambient plasma is negative.
  - The ions are attracted and Maxwellian electrons are repelled by the wall.

The flow of ions is $\Gamma_i = n_i(x)\, u_i(x)$ and continuity equation and energy conservation gives,



$$\left.\begin{aligned} \Gamma_i = n_{io}u_{io} &= n_i(x)\, u_i(x) \\ \frac{m_i}{2}u_i^2(x) + e\,V(x) &= \frac{m_i}{2}u_{io}^2 + e\,V_p \end{aligned}\right\} \qquad \begin{aligned} \varphi(x) &= V(x) - V_p < 0 \\ n_i(x) &= \frac{n_{io}\,u_{io}}{\sqrt{u_{io}^2 - \dfrac{2e}{m_i}\varphi(x)}} \end{aligned}$$

The electrons have a Maxwellian distribution and $n_e(x)$ decreases along the plasma potential profile as $V(x) > V_w$ becomes more negative,

$$n_e(V) = n_{eo}\exp\left(\frac{e\left(V - V_p\right)}{k_B T_e}\right) \qquad \text{equivalently,} \qquad n_e(\varphi) = n_{eo}\exp\left(\frac{e\,\varphi}{k_B T_e}\right)$$

The heavy ions move driven by the electric field whereas the more mobile electrons are distributed by the electric potential profile.

The plasma potential profile $\phi(x)$ is the solution of the 1-D Poisson equation, $\nabla\cdot\boldsymbol{E} = {}^{\rho_c}/_{\varepsilon_o}$ $\boldsymbol{E} = -\nabla\varphi$

$$\frac{dE}{dx} = \frac{e}{\epsilon_o}[n_i(x) - n_e(x)]$$

gives,

$$-\frac{d^2\phi}{dx^2} = \frac{e\,n_o}{\varepsilon_o}\left[\left(1-\frac{2e}{m_i u_{io}^2}\varphi(x)\right)^{-1/2} - e^{e\phi/k_BT_e}\right]$$

This equation can be made dimensionless using the ion sound speed $c_{is} = \sqrt{k_BT_e/m_i}$ and the following scaled variables,

$$U_{io} = \frac{u_{io}}{c_{is}} \qquad \phi = -\frac{e\varphi}{k_BT_e} > 0 \qquad N_e = \frac{n_e}{n_o} \quad \text{and,} \quad N_i = \frac{n_i}{n_o}$$

$$\frac{d^2}{dx^2}\left(-\frac{e\phi}{k_BT_e}\right) = -\frac{e^2\,n_o}{\varepsilon_o k_BT_e}\left[e^{e\phi/k_BT_e} - \left(1+\frac{2e\phi/k_BT_e}{u_{io}^2/c_{is}^2}\varphi(x)\right)^{-1/2}\right]$$

Here appears the plasma electron Debye length λ_{De} as the dimensionless scale $s = x/\lambda_D$ for the longitudes.

$$\frac{d^2\phi}{dx^2} = -\frac{1}{\lambda_{De}^2}\left[e^{-\phi} - \frac{1}{\sqrt{1+2\phi/U_{io}^2}}\right]$$

Finally, the differential equation for the scaled electric potential profile $\phi(s)$ is:

$$\frac{d^2\phi}{ds^2} = \frac{1}{\sqrt{1+2\phi/U_{io}^2}} - e^{-\phi}$$

We multiply both sides by $d\phi/ds$ and integrating between the distant plasma located at $s_o = x_o/\lambda_{De}$ and any point $s = x/\lambda_{De}$ within the plasma sheath,

$$\int_{s_o}^{s} \frac{d^2\phi}{ds^2}\frac{d\phi}{ds}\,ds = \int_{s_o}^{s}\left(1+\frac{2\phi}{U_i^2}\right)^{-1/2}\frac{d\phi}{ds}\,ds - \int_{s_o}^{s} e^{-\phi}\frac{d\phi}{ds}\,ds$$

integrating,

$$\frac{1}{2}\left(\frac{d\phi}{ds}\right)^2\Bigg]_{s_o}^{s} = U_i^2\sqrt{1+\frac{2\phi}{U_{io}^2}}\,\Bigg]_{s_o}^{s} + e^{-\phi}\Big]_{s_o}^{s}$$

The normalized potential $\phi(s) > 0$ and its derivative $\mathcal{E} = d\phi/ds > 0$ are positive along the potential profile and null in the distant plasma.

$$\frac{1}{2}\left(\frac{d\phi}{ds}\right)^2 = \frac{1}{2}\mathcal{E}^2(s) = U_{io}^2\left[\sqrt{1+\frac{2\phi}{U_{io}^2}}-1\right] + \left(e^{-\phi}-1\right)$$

We arrive a to a non-linear differential equation for the electric potential profile $\phi(s)$ that has no analytic solution.

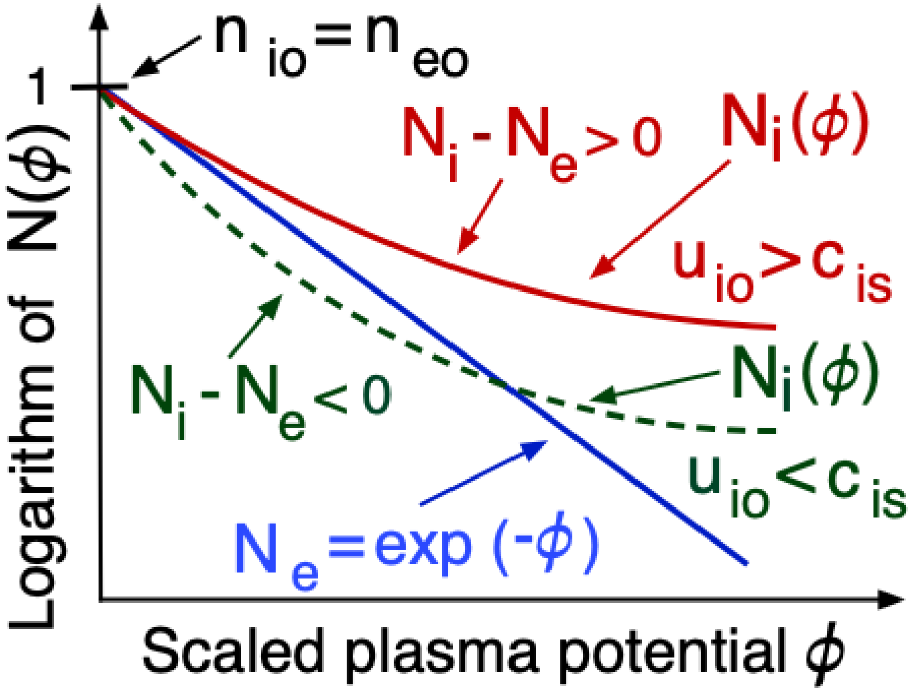
For a weakly coupled plasma $|e\varphi/k_B T_e| = |\phi| \ll 1$ where the kinetic energy of electrons is higher than their electrostatic energy and the power expansion gives,

$$\frac{1}{2}\left(\frac{d\phi}{ds}\right)^2 = U_i^2\left[\left(1+\frac{\phi}{U_{io}^2}-\frac{\phi^2}{2U_{io}^4}+\cdots\right)-1\right] + \left[\left(1-\phi+\frac{\phi^2}{2}+\cdots\right)-1\right] > 0$$

$$\frac{1}{2}\left(\frac{d\phi}{ds}\right)^2 \simeq U_i^2\left(\frac{\phi}{U_{io}^2}-\frac{\phi^2}{2U_{io}^4}\right) - \phi + \frac{\phi^2}{2} > 0 \qquad \frac{1}{2}\left(\frac{d\phi}{ds}\right)^2 \simeq \frac{\phi^2}{2}\left(1-\frac{1}{U_{io}^2}\right) > 0$$

$$\frac{1}{2}\left(\frac{d\phi}{ds}\right)^2 \simeq \frac{\phi^2}{2}\left(1-\frac{1}{U_{io}^2}\right) > 0 \quad \text{requires,} \quad U_{io} = \frac{u_{io}}{c_{is}} > 1$$

- Supersonic ion speeds ($u_{io} > c_{is}$) at the edge of the plasma sheath are required (Bohm criterion).
- Thus, the plasma sheath $\phi(s)$ is not a monotonic function and a pre-sheath must accelerate the ions.



$$\begin{cases} N_e = \exp(-\phi) & \ln N_e = \ln n_{eo} - \phi \\ N_i = \left(1+\frac{2\phi}{U_{io}^2}\right)^{-1/2} & \ln N_i = \ln n_{io} - \frac{1}{2}\ln\left(1+\frac{2\phi}{U_{io}^2}\right) \end{cases}$$

$$\frac{d}{d\phi}\left[-\frac{1}{2}\ln\left(1+\frac{2\phi}{U_{io}^2}\right)\right] = -\frac{1}{U_{io}^2+2\phi}$$

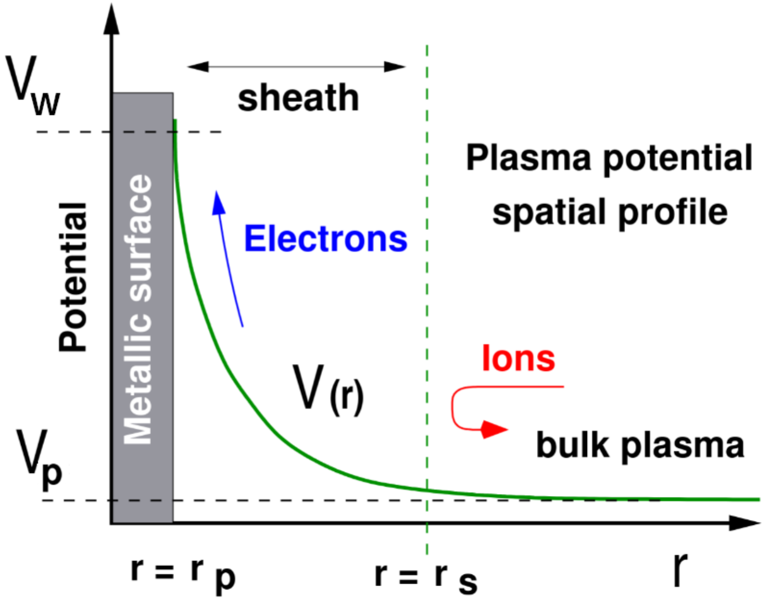
in the limit $\phi \to 0$ we find , $\frac{dN_i}{d\phi} \simeq -\frac{1}{U_{io}^2} < -1$

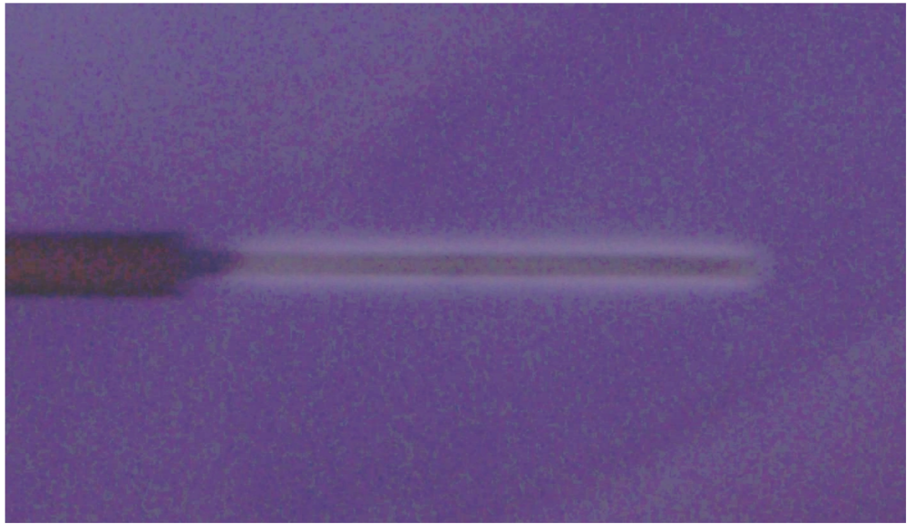
- For the ion density $N_i(\phi) > N_e(\phi)$ the slope of $\ln N_i(\phi)$ below the unity $1/U_{io}^2 < 1$ at $\phi = 0$ for this to happen $u_{io} > c_{is}$
- Consequently, the ions are accelerated by a smooth potential drop ΔV called pre-sheath, such as,

$$\frac{m_i}{2}c_{is}^2 = k_B T_e \sim \mathrm{e}\,\Delta V \qquad \text{then,} \qquad \Delta V \sim {}^{k_B T_e}\!/_{e}$$

Positive potential respect to ambient plasma

- Surface is biased positively with respect to plasma $V_w >> V_p$
- Electrons are attracted to the surface while ions are repelled back to the bulk plasma
  - Not all ions are repelled due to their larger mass (higher potential is required for this)
- Electrons might gain extra energy and interact with the neutrals (excitation and emission of light)





Electric probe biased positive accelerates electrons and these interact with the neutrals (Ar), emitting light.

Floating surface

- A metallic surface in contact with a plasma that is **not** polarized to a potential will be *floating*
- This means that the ion and electron current balance so the total charge reaching the surface is 0
- The surface reaches a potential that is called the *floating potential*
- **WARNING:** This does **not** mean that the plasma and the surface are at the same potential!
  - The floating potential is typically lower than the plasma potential

$$I = I_e + I_i = 0$$

$$\phi \simeq \frac{1}{2} \ln\left(\frac{m_i}{2m_e}\right)$$

We will see more about surfaces and biasing when we study plasma diagnostics with Langmuir probes on Nov 17th (theory) and Nov 19th (lab practice)

Electron emission by electron impact

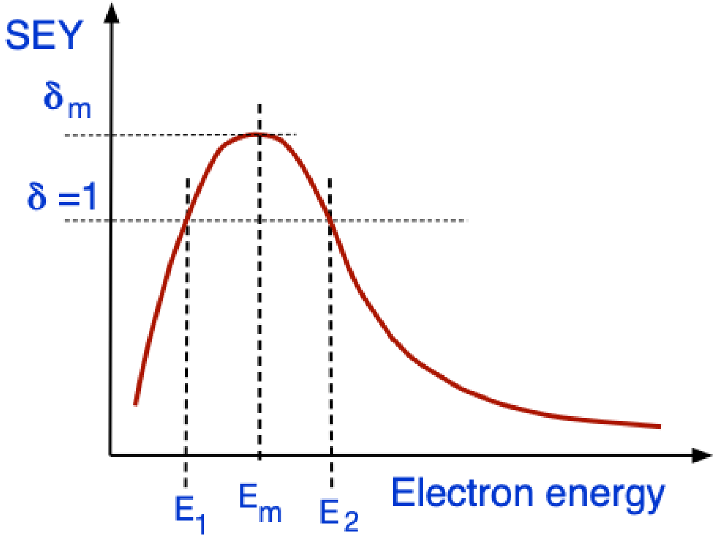
- The SEE emission rate is strongly material-dependent, as well as the physical state of the surfaces, etc.
- The $\delta(E)$ secondary emission yield (SEY) characterizes the electron emission current.

$$\delta \equiv \frac{\text{Number of secondary electron released}}{\text{1 impacting electron}} = \frac{I_{se}(\phi_s)}{I_e(\phi_s)}$$

Vaugham empirical model

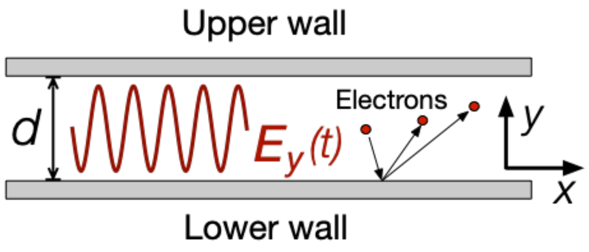
$$\delta(E) = \delta_{Max}\,(\nu \exp[1-\nu])^k$$

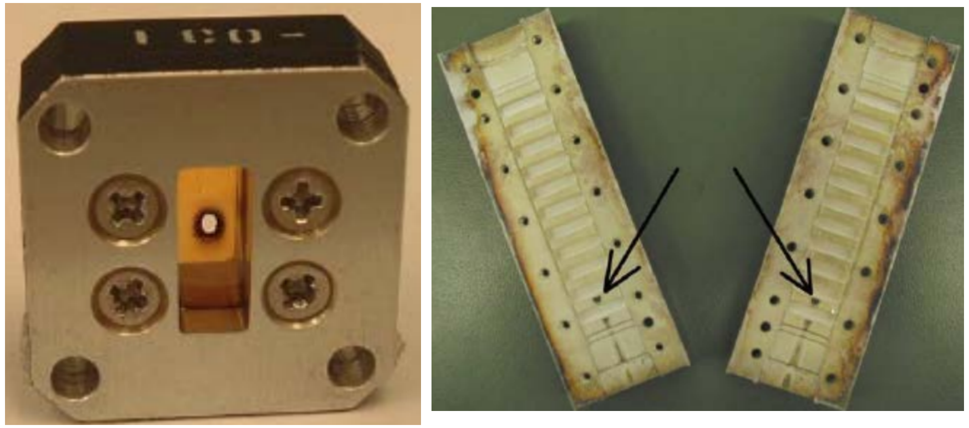
$$\nu = \frac{E-E_1}{E_m-E_1} \quad \text{the exponent is,} \quad k = \begin{cases} 0.62 & \nu < 1 \\ 0.25 & \nu > 1 \end{cases}$$



	Electron energy (eV)		
Material	E_1	E_2	E_m
Gold	150	4000	1000
Silver	30	5000	165
Aluminum	30	5000	805
Alodine	41	5000	180
Copper	25	5000	175

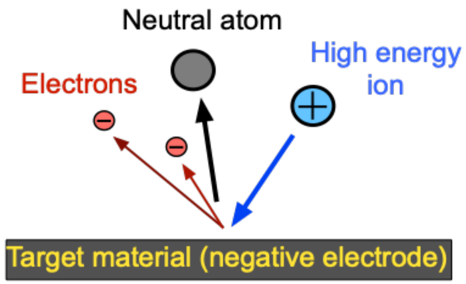
- Scheme of a RF waveguide



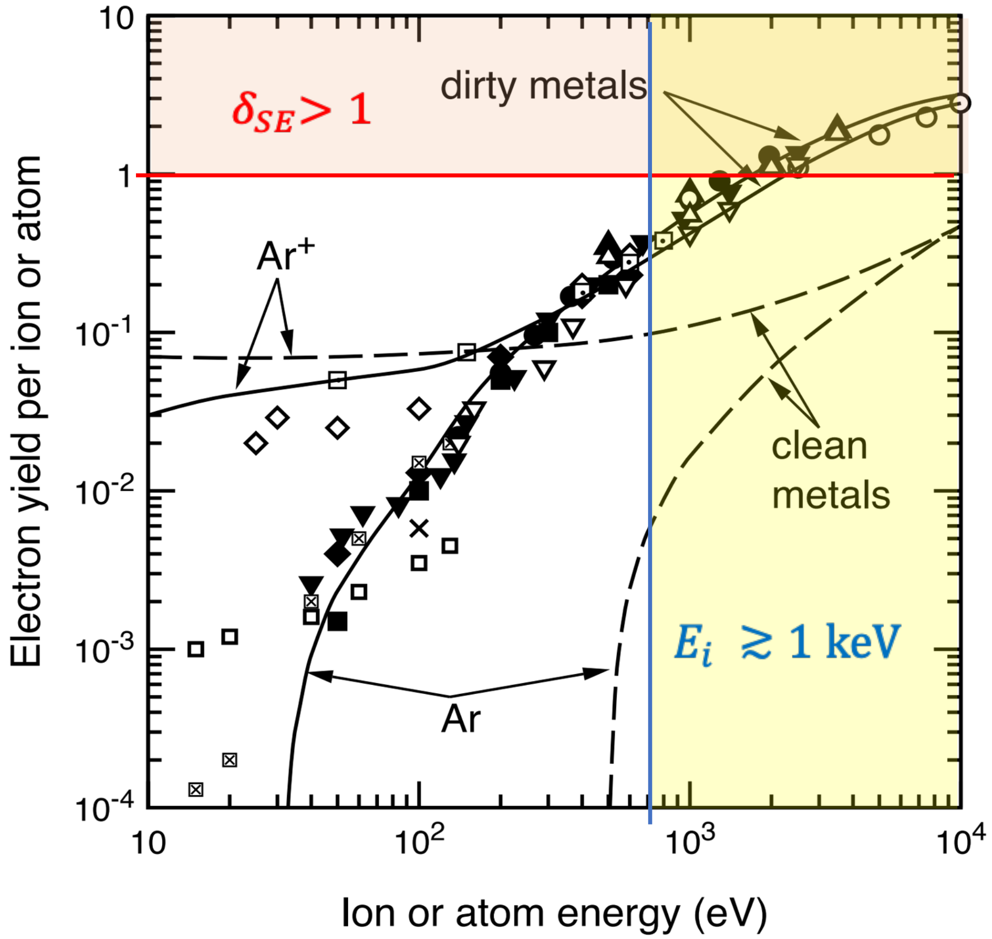


Harmful effects of secondary electron multiplication (multipactor) within RF communication equipment. Photographs courtesy of ESA.

Electron emission by ion/neutral impact



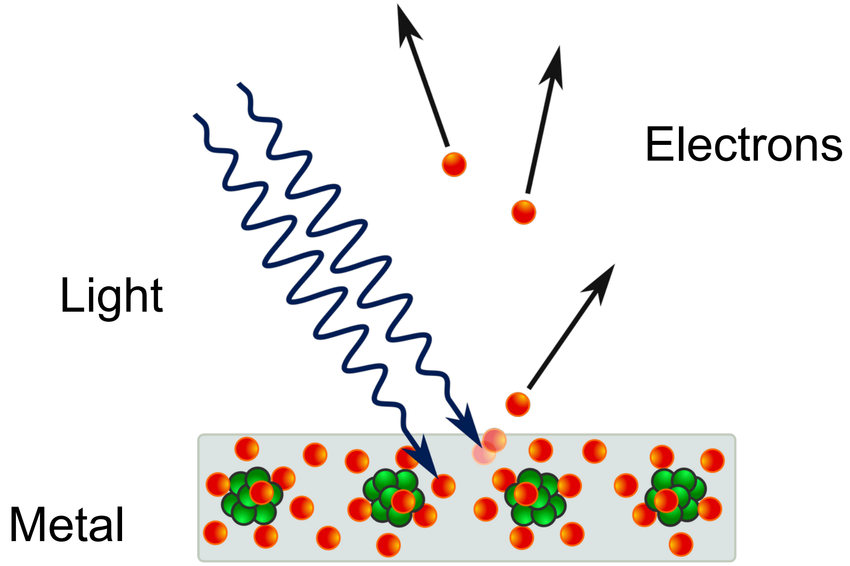
- The production of electrons is driven by the kinetic energy of the ions impacting a target electrode. Symbols in figure indicate different target materials of cited reference.
- The yield of electrons per ion δ_{SE} is a statistical concept that characterizes the average number of emitted electrons produced by the impact of one ion or neutral
- The electron emission needs of a group of ions with energies in the KeV range to obtain $\delta_{SE} > 1$ or production of more electrons than ions are lost.
- Energetic ions from radiation belts and/or particle flows in high inclination polar orbits can give rise to SEE electron emissions.
- However, SEE electron currents are much lower than in other electron emission processes.



- From A.V. Phelps and Z. Lj. Petrovic. *Cold-cathode discharges and breakdown in Argon: surface and gas phase production of secondary electrons.* Plasma Sources Sci. Technol. **8** (3) R21-R44 (1999). https://doi.org/10.1088/0963-0252/8/3/201

Photoelectric emission

- Energy of photons: $h\nu$
- Electrons are removed from the atomic binding by absorbing a photon $K_{max} = h\nu - W$
- $W = h\nu_0$ is the minimum energy required to remove an electron
- K_{max} is the maximum kinetic energy achieved by the electron
- The Sun is a huge source of radiation in multiple wavelengths



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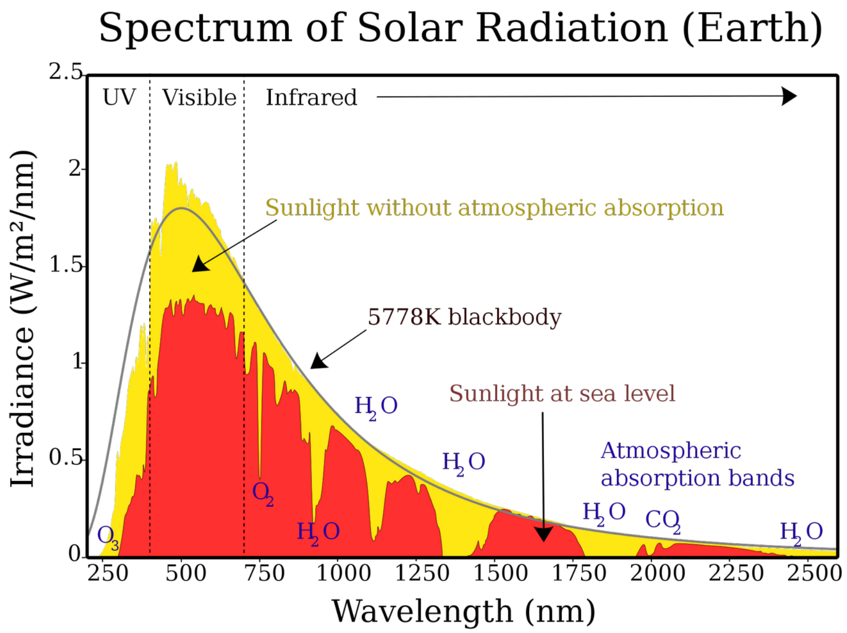

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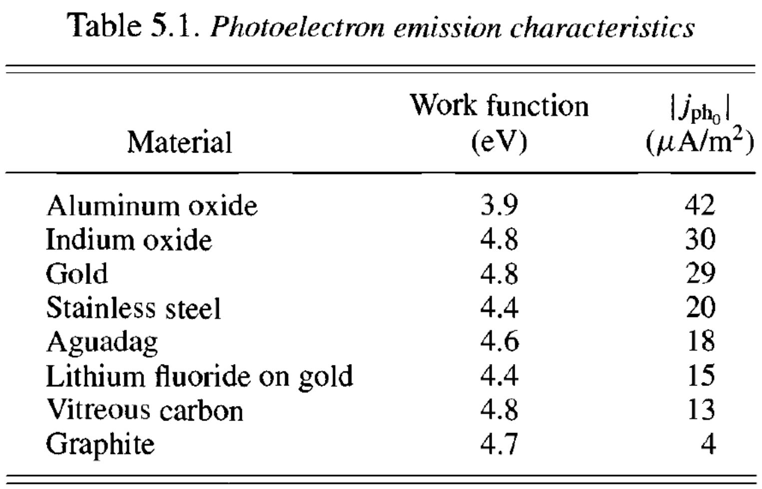


Table 5.1. *Photoelectron emission characteristics*

Material	Work function (eV)	$\|j_{ph_0}\|$ (μA/m^2)
Aluminum oxide	3.9	42
Indium oxide	4.8	30
Gold	4.8	29
Stainless steel	4.4	20
Aguadag	4.6	18
Lithium fluoride on gold	4.4	15
Vitreous carbon	4.8	13
Graphite	4.7	4

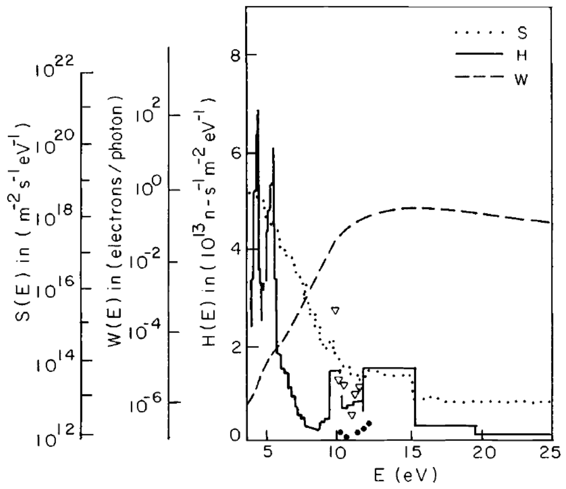


Figure 5.1. Composite Plot of the Electron Yield per Photon $W(E)$, the Solar Flux $S(E)$, and Their Product, the Total Photoelectron Yield, as Functions of Energy, E, for Aluminum Oxide.

LEO

- In sunlit hemisphere plasma density increases as EUV, EU X-Ray penetrate the neutral atmosphere giving rise the formation of ionization layers. Density depends on the solar activity and/or sunspot cycle.
- The accepted model for calculations is the International Reference Ionosphere Model (IRI) which
- The IRI software gives the electron density and ion composition $(O^+, O_2^+\ H^+, He^+, N^+, NO^+, \ldots)$, the equatorial vertical ion drift, vertical ionospheric electron content. Results are based on a huge database of observations.

GEO

- This region at the edge of the plasmapause and the plasma is collisionless with lower densities than in LEO or lower altitude orbits.
- Charged particle energy distributions are not necessarily Maxwellian, this complicates the physical models.
- Sudden injections of high energy particles ($\sim 10\ \mathrm{keV}$) associated with substorms are believed to be the major source of spacecraft charging in GEO.

PEO

- Polar orbits crossing the auroral oval region located at high equatorial latitudes (> 65°) and below 1000 km of altitude.
- Geomagnetic field confines energetic particles that give rise to an energetic plasma component not present in low inclination LEO orbits. Ionization by energetic auroral electrons $(100\ \mathrm{eV} - 10\ \mathrm{KeV})$ can increase the electron density by orders of magnitude.
- The two aurora regimes that have been identified are,

  - *Continuous* (bright bands): drifting Maxwellian electrons electrons of 1 keV. The Maxwellian differential electron number flux as a function of the energy E is,

$$\phi(E) = \frac{Q_M}{3\,E_M^3} E \exp\left(-\frac{E}{E_M}\right) \quad \text{with units of} \quad \frac{\mathrm{electrons}}{\mathrm{m}^2 \times \mathrm{sec.} \times \mathrm{eV}}$$

Where Q_M is the energy flux ($eV/(m^2 \times sec.)$ and $E_M = k_B T$ the characteristic temperature.

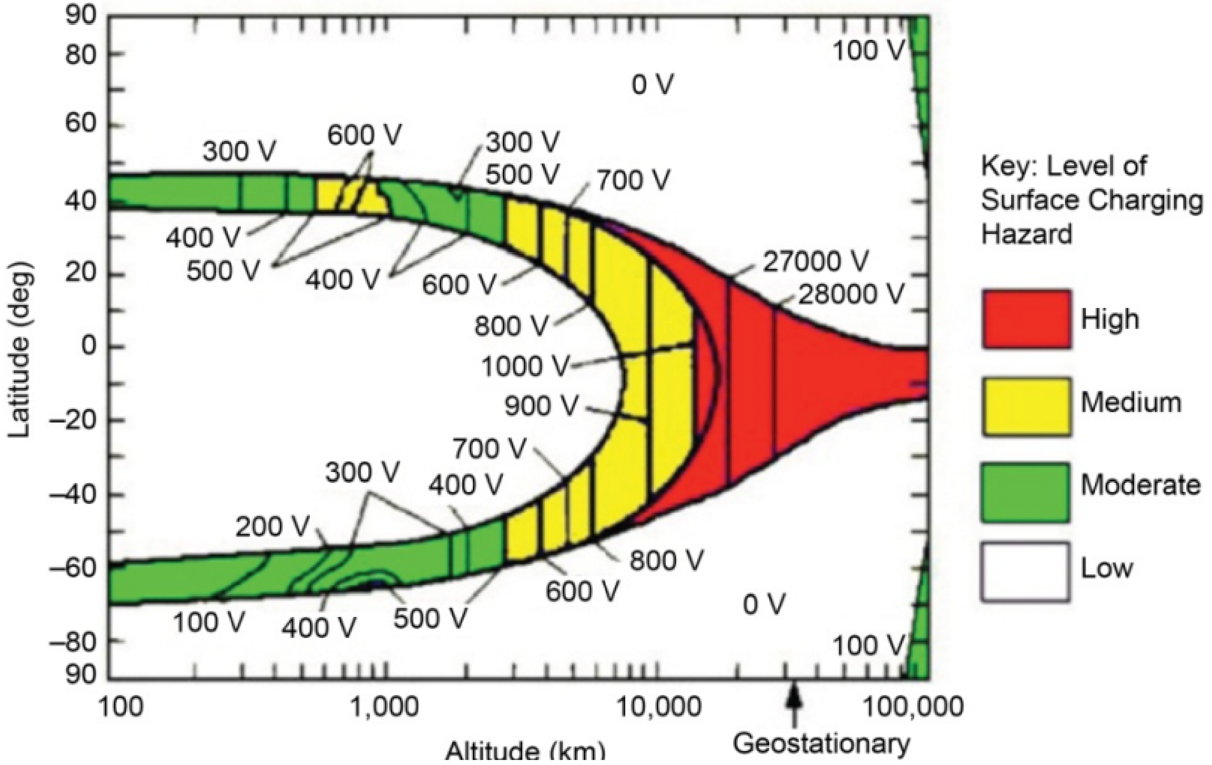
  - *Diffuse* (barely visible): isotropic precipitation of Maxwellian electrons of few keV, the number-flux distribution of precipitating electrons is approximated by a Gaussian function,

$$\phi(E) = \frac{Q_G}{\pi\,\sigma\,E_G} \exp\left[-\left(\frac{E-E_G}{\sigma}\right)^2\right] \quad \text{with units of} \quad \frac{\mathrm{electrons}}{\mathrm{m}^2 \times \mathrm{sec.} \times \mathrm{eV}}$$

Here E_G is the maximum energy in eV, parameter $\sigma \simeq 0.2 \times E_G$ and Q_G the energy flux of electrons.

Spacecraft charging

A major effect of the plasma environment is the accumulation of charged particles on the exposed surfaces of vehicles. This process creates local electrostatic fields that can produce adverse effects such as material contamination or localized electric discharges.



Nominal worst-case regimes of on-orbit surface charging hazards passing through indicated latitude and altitude. From H.B. Garrett and A.C. Whittlesey. *Guide to mitigating spacecraft charging effects*. JPL Space Science and Technology Series (2011).

Effects of plasma interaction.

- Surface charging by accumulation of charged particles on surfaces.
- High energy impact of electric charges from cosmic rays and/or solar wind.
- Internal charging by penetration of energetic electrons inside the plasma exposed materials.
- Current leakage produce power losses by power systems produced by the continuous flow of charge from the vehicle surfaces.
- Electric propulsion systems that create a denser local plasma and modify the current balance on the satellite.
- Differential charge accumulation that can trigger an electric breakdown when two spacecrafts come into contact and/or in EVA activities of astronauts.
- The plasma wake of satellites create electric fields that accelerate charged particles.

Spacecraft charging

- The total current I_T towards the surface with the electric potential $\phi_s = V_s - V_{sp}$ (V_{sp} is the local plasma potential) results from the collection of ions and electrons from the ambient plasma and the production of charges by their interaction with the surface materials.

- In the steady state the current $I_T(\phi_s) = 0$ and can be expressed as the sum of different contributions,

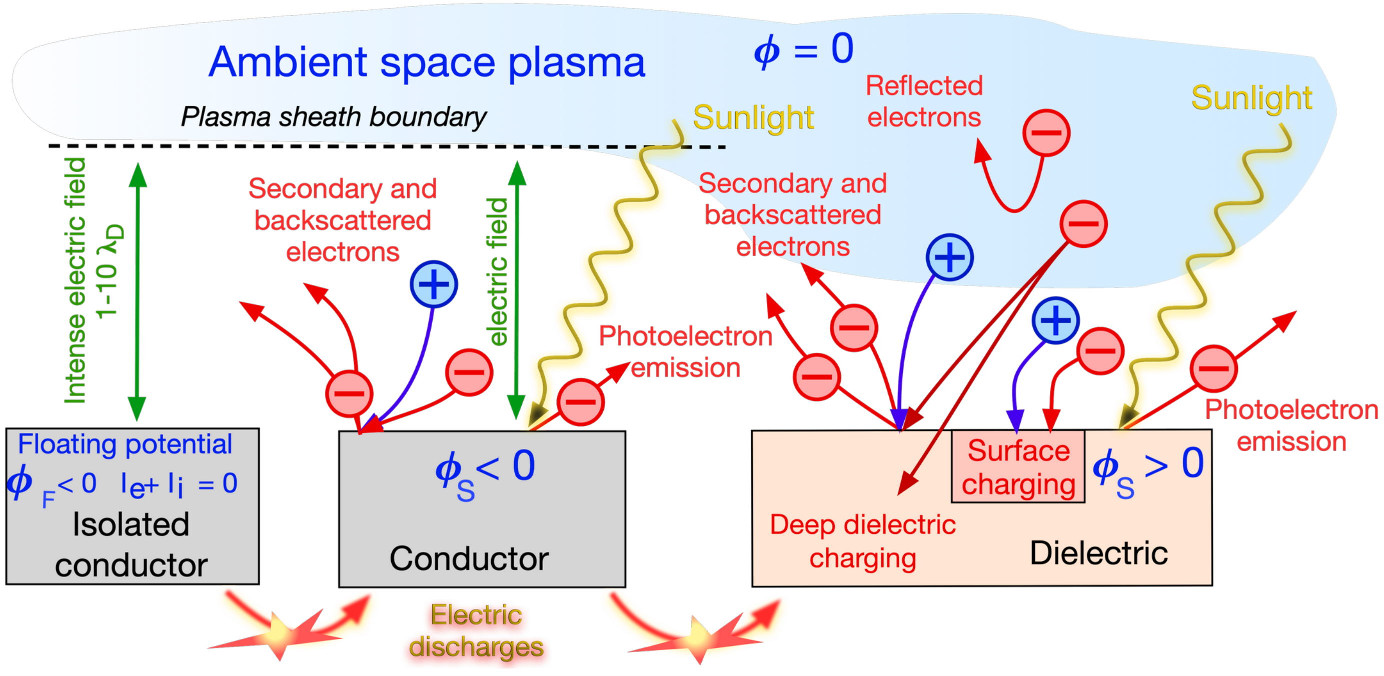
$$\frac{\partial Q_T}{\partial t} = I_T \text{ and, } \quad I_T = I_e(\phi_s) - \left[I_i(\phi_s) + I_{se}(\phi_s) + I_{si}(\phi_s) + I_{be}(\phi_s) + I_{ph}(\phi_s) + I_b(\phi_s)\right] = 0$$

and these are,

  - $I_b(\phi_s)$ active emission of charges by plasma thrusters or beams.
  - I_{ph} photoelectrons produced by sunlight.
  - $I_{be}(\phi_s)$ backscattered electrons due to I_e.
  - $I_{si}(\phi_s)$ secondary electron current due to I_i.
  - $I_{se}(\phi_s)$ secondary electron current due to I_e
  - $I_i(\phi_s)$ current of ambient plasma ions.
  - $I_e(\phi_s)$ current of ambient plasma electrons.

- The surface potential ϕ_s is usually self-consistently determined by the emitted and collected currents or intentionally fixed in active experiments.

- The interaction of ambient charges depends on their energy spectra and the physical nature (dielectric or conductor) of the spacecraft surface.



Application: Charge control at the ISS

Mesothermal flow conditions in LEO are

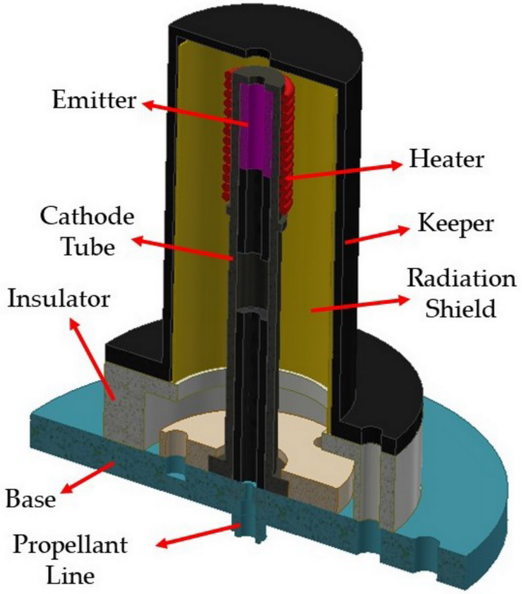
$$v_{th,e} \gg u_B \gg v_{th,i}$$

As $T_e \gg T_i$ the ion sound speed is higher than the ion thermal velocity,

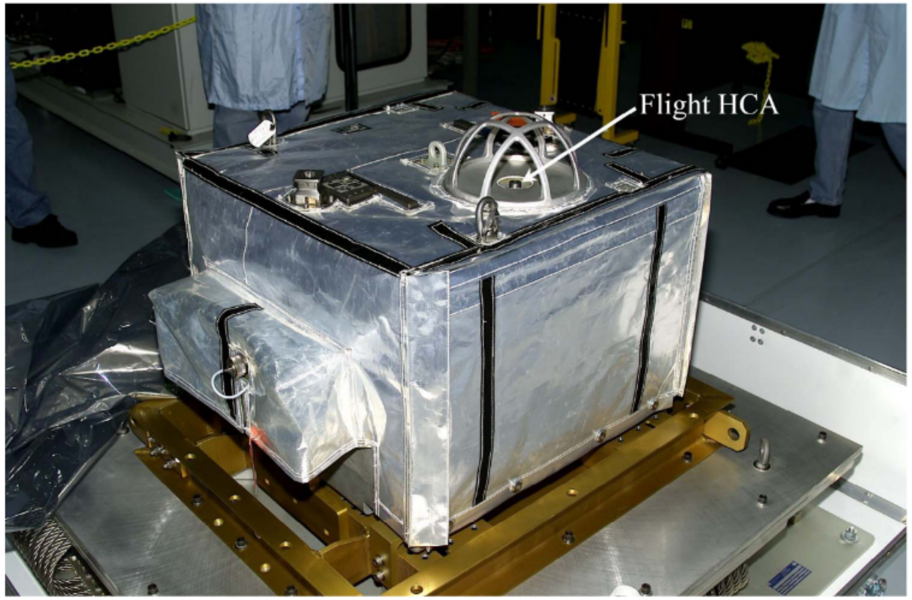
$$c_{is} = \sqrt{\frac{\gamma\, k_B T_e}{m_i}} \gg v_{th,i} = \sqrt{\frac{2\, k_B T_i}{m_i}}$$

$$\begin{cases} u_B \sim 7.5\ \mathrm{km/s}\ \ \mathrm{LEO} \gg v_{th,i} = \sqrt{\dfrac{2k_BT_i}{m_i}} \simeq 1.25\ \mathrm{km/s}\ \ \mathrm{O}^+ \\ u_B \sim 7.5\ \mathrm{km/s}\ \ \mathrm{LEO} \ll v_{th,e} = \sqrt{\dfrac{2k_BT_e}{m_e}} \simeq 246\ \mathrm{km/s} \end{cases}$$

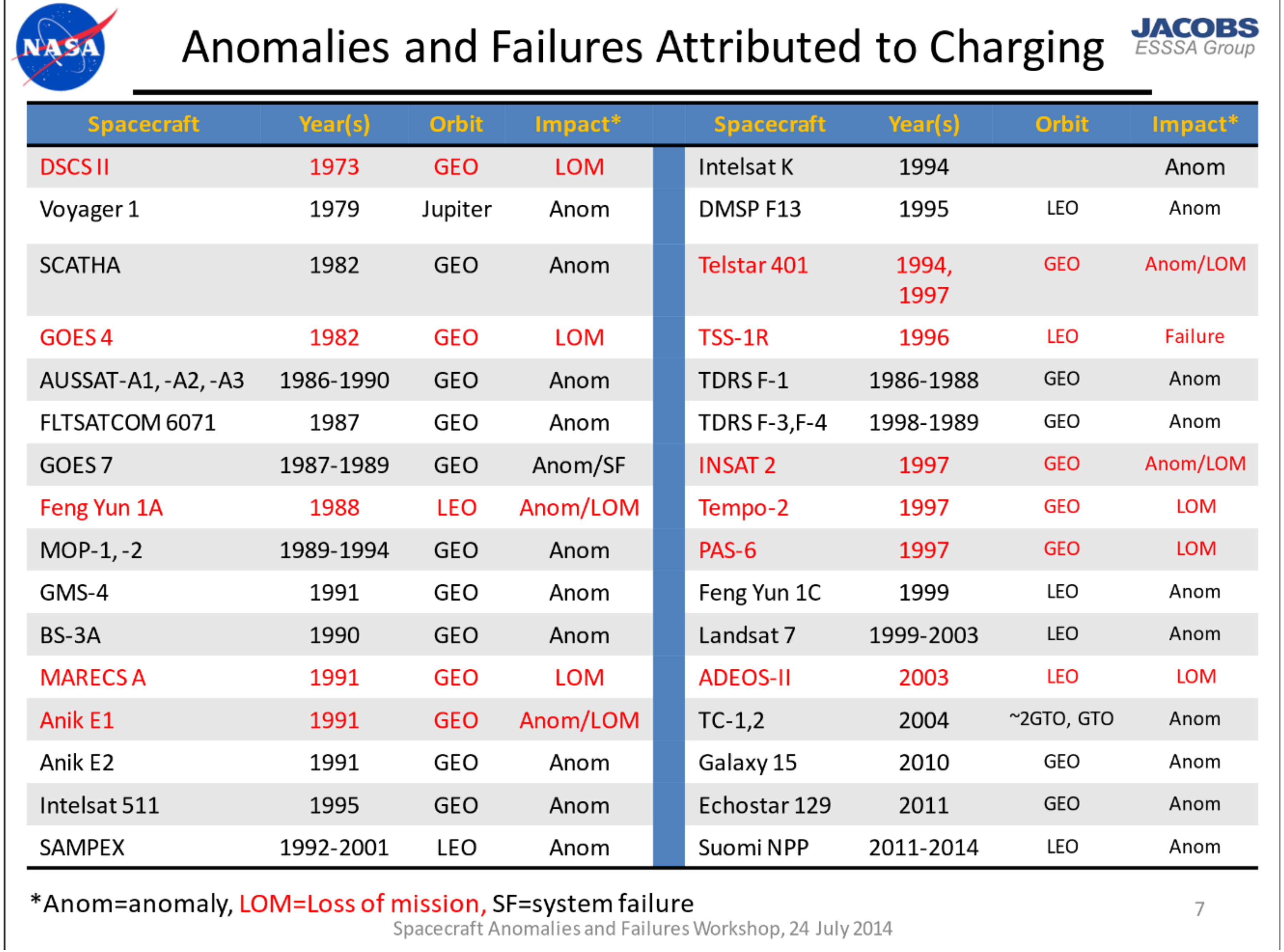
Use of a Hollow Cathode to avoid charging of ISS: Plasma Contactor Unit (PCU)



Kokal, Ugur, Nazli Turan, and Murat Celik. "Thermal analysis and testing of different designs of lab6 hollow cathodes to be used in electric propulsion applications." Aerospace 8.8 (2021): 215.



Carpenter, Christian. "On the operational status of the ISS plasma contactor hollow cathodes." 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 2004.



Anomalies and Failures Attributed to Charging

Spacecraft	Year(s)	Orbit	Impact*
DSCS II	1973	GEO	LOM
Voyager 1	1979	Jupiter	Anom
SCATHA	1982	GEO	Anom
GOES 4	1982	GEO	LOM
AUSSAT-A1, -A2, -A3	1986-1990	GEO	Anom
FLTSATCOM 6071	1987	GEO	Anom
GOES 7	1987-1989	GEO	Anom/SF
Feng Yun 1A	1988	LEO	Anom/LOM
MOP-1, -2	1989-1994	GEO	Anom
GMS-4	1991	GEO	Anom
BS-3A	1990	GEO	Anom
MARECS A	1991	GEO	LOM
Anik E1	1991	GEO	Anom/LOM
Anik E2	1991	GEO	Anom
Intelsat 511	1995	GEO	Anom
SAMPEX	1992-2001	LEO	Anom
Intelsat K	1994		Anom
DMSP F13	1995	LEO	Anom
Telstar 401	1994, 1997	GEO	Anom/LOM
TSS-1R	1996	LEO	Failure
TDRS F-1	1986-1988	GEO	Anom
TDRS F-3,F-4	1998-1989	GEO	Anom
INSAT 2	1997	GEO	Anom/LOM
Tempo-2	1997	GEO	LOM
PAS-6	1997	GEO	LOM
Feng Yun 1C	1999	LEO	Anom
Landsat 7	1999-2003	LEO	Anom
ADEOS-II	2003	LEO	LOM
TC-1,2	2004	~2GTO, GTO	Anom
Galaxy 15	2010	GEO	Anom
Echostar 129	2011	GEO	Anom
Suomi NPP	2011-2014	LEO	Anom

*Anom=anomaly, LOM=Loss of mission, SF=system failure

Minow, Joseph I., and Linda Neergaard Parker. "Spacecraft charging: Anomaly and failure mechanisms." Spacecraft Anomalies and Failures Workshop. No. M14-3884. 2014.