Máster Universitario en Ingeniería Aeronáutica

The Space Environment

Space environment plasma effects, Solar wind

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Maretial y Página web de la Asignatura basada eb ka web del Prof. Dr. L. Conde:
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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 ($n_e \sim 10^{10} - 10^{11}\ \mathrm{part./m^3}$) 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 ($n_e \sim 10^{8} - 10^{9}\ \mathrm{part./m^3}$) 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 $\boldsymbol{\lambda_D < L_S}$ whereas $\boldsymbol{\lambda_D > L_S}$ 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 $v_o \sim 7\ \mathrm{km/s}$ 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)	$B = 0.14 \cdot 10^{-4}\ \mathrm{T}$	$E \sim 9.8 \cdot 10^{-2}\ \mathrm{V/m}$
ISS (500 km)	$B = 0.23 \cdot 10^{-4}\ \mathrm{T}$	$E \sim 16.0 \cdot 10^{-2}\ \mathrm{V/m}$

- 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.

Space enviroment effects

Name		Main ambient effects
Low Earth orbit Altitude 100-1000 km Inclination < 65º	**LEO**	• **Neutral** atmosphere • Ionospheric plasma (**cold and dense**) • Solar **UV, EUV (extreme UV) X-Rays** • Orbital **debris** • South Atlantic anomaly (inner radiation belt, weaken B field)
Polar Earth orbit Altitude > 100 km Inclination > 65º	**PEO**	• Neutral atmosphere • Ionospheric plasma (**cold and dense**) • High energy auroral particles • **Cosmic** rays • Solar UV, EUV radiation . Solar wind
Medium Earth orbit Altitude 1000-36000 km Inclination < 65º	**MEO**	• Plasmasphere • **Energetic particles** (Van Allen radiation belts) • Solar UV, EUV and X-Ray radiation. Solar wind
Geosynchronous orbit Altitude 36000 km Inclination 0	**GEO**	• **High energy** particles (magnetospheric plasmasheet) sensitive to marnetic storms • Substorm plasma. Solar wind • **Outer radiation belt** • **Cosmic** rays (low frequency waves)

Main effects and plasma models

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. (energy transpoted by Alvén waves affects all media)
- 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 in lower altitude orbits.
- Charged particle energy distributions **are not necessarily Maxwellian**, this complicates the physical models.
- *Sudden injections of* ***high energy particles*** ($\sim$ 10 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** ($> 65^{o}$) 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 eV − 10 KeV)** can increase the electron density by orders of magnitude.

Main effect: 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** (bias surface potential) that can produce adverse effects such as material **contamination or localized electric discharges**.

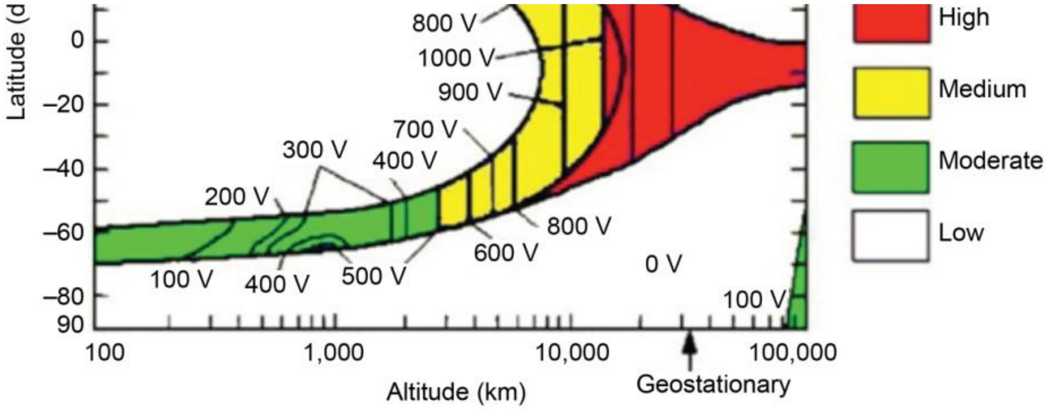
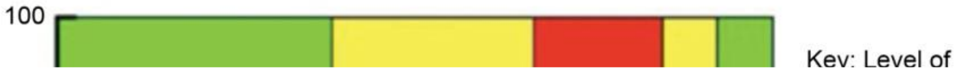


Fig. 1-1. Earth regimes of concern for on-orbit surface charging hazards for spacecraft passing through indicated latitude and altitude [8]. See Whittlesey et al. (1992) [9] for an alternate reference with the "wishbone" chart



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.

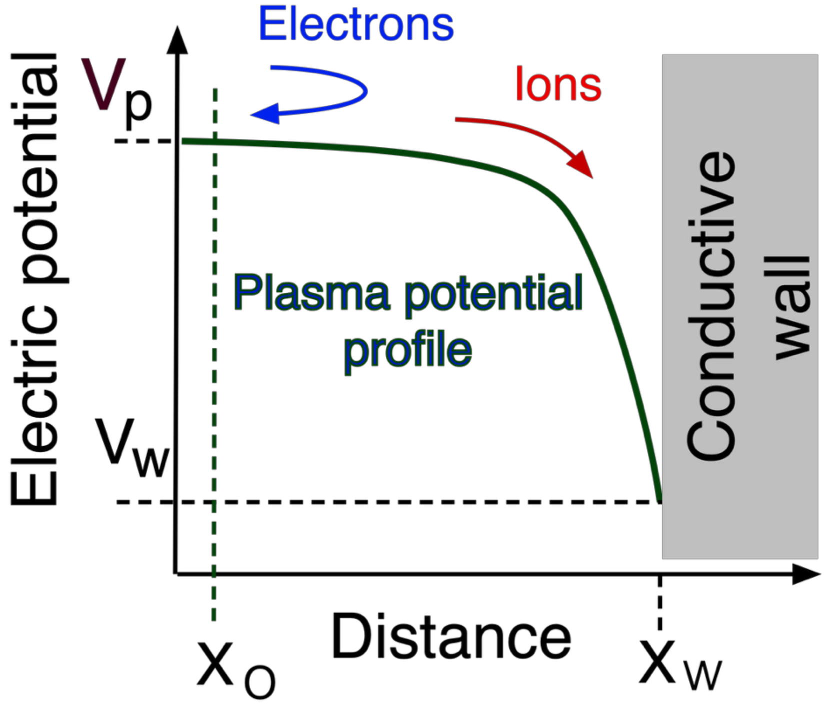
- Surface **charging by accumulation** of charged particles on surfaces.
- **High energy impact of electric charges** from cosmic rays and/or solar wind.
- **Internal charging by** penetration of energetic electrons inside the plasma exposed materials.
- Current leakage (losses) produce **power losses** 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 (**arcing**) 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.

- **The knowledge of these processes at each orbit is of capital importance for the mitigation of damages in human space technologies**

Review: Ion collection by metallic surfaces (Sheath)

- 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,



$$\Gamma_i = n_{io} u_{io} = n_i(x)\, u_i(x)$$

$$\left.\begin{array}{l}\frac{m_i}{2} u_i^2(x) + e\,V(x) = \frac{m_i}{2} u_{io}^2 + e\,V_p\end{array}\right\}$$

$$\varphi(x) = V(x) - V_p < 0$$

$$n_i\,(x) = \frac{n_{io}\, u_{io}}{\sqrt{u_{io}^2 - \frac{2e}{m_i}\varphi(x)}}$$

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

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

Main ideas: Floating Potential and its polarization (bias) with respect to the plasma potential.

In different orbits and daylight conditions a spacecraft can be positive or negatively grounded

Spacecraft charging (not only on surfaces)

- 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.

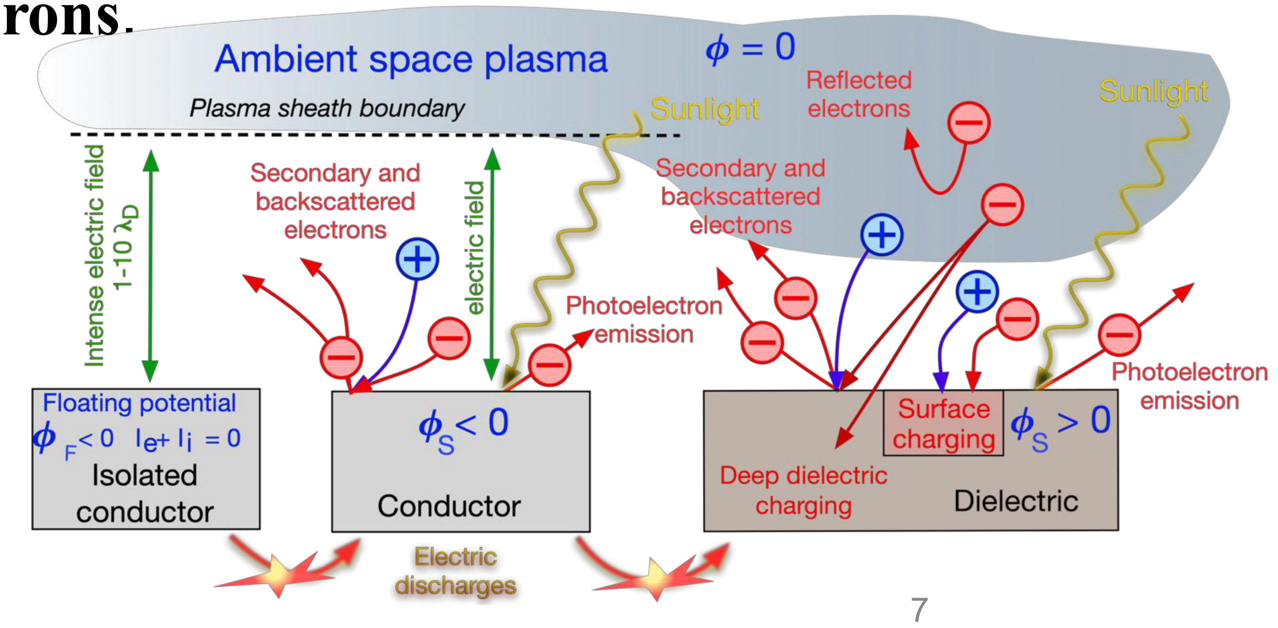
- In the **steady state** the current $I_T(\phi_s) = 0$ (**the surface FLOATS respect to the plasma**) and can be expressed as the sum of different contributions,

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

and these (among others) 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 (re-ionized ions)
- ○ $I_{se}(\phi_s)$ secondary electron current due to I_e (due to impact on metals)
- ○ $I_i(\phi_s)$ **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: **Solar wind and Van Allen belts** knowledge required



Magnetosphere inviroment

The Earth's magnetosphere is a complex physical system resulting fromthe interaction between the **planetary magnetic field and the solar wind.**

The Earth's magnetosphere acts as a **protective shield against cosmic** and solar radiation understanding its plasma dynamics is fundamental to capital issues as:

Evaluating **risks** (electrostatic potential and current densities):

- Surface Electrostatic Charging. **Current balance** on surfaces*: I=0*, the **surface is floating** with respect to the plasma and becomes **grounded (+ or -)** with respect to the plasma potential. *Poisson Maxwell* equation gives potential distribution.

- **Accumulation of energetic** electrons (> 1 MeV) in insulating (any **dielectric, like solar panels**) materials, A **continuity equation for electric current with sources** gives charging properties (risk of **arcing** and electronics damages in GEO, PEO).

- Atomic **Oxygen Corrosion** and erosion rates in LEO:

- The Earth's magnetosphere is a *dynamic and multifaceted environment* whose understanding requires to combine observations, theory, and modeling

- **Risks** for spacecraft are signiifcant and vary substantially in *all orbital regimes*.

- Effective **mitigation** of these implies **multidisciplinary approach** combining plasma physics, materials science, and *systems engineering*.

Magnetosphere Structure

External Boundaries:

- **Bow Shock**: Formed at 13-15 RE (Earth radii) in the solar direction, where the supersonic solar wind becomes subsonic (Parker model prediction)

- **Magnetopause**: boundary **separating magnetosphere plasma from the solar wind**, at 10-12 RE on the dayside.

Internal Regions

- Magnetotail: *Elongated structure on the* ***night side*** extending hundreds of RE,divided into north/south lobes separated by the plasma sheet.

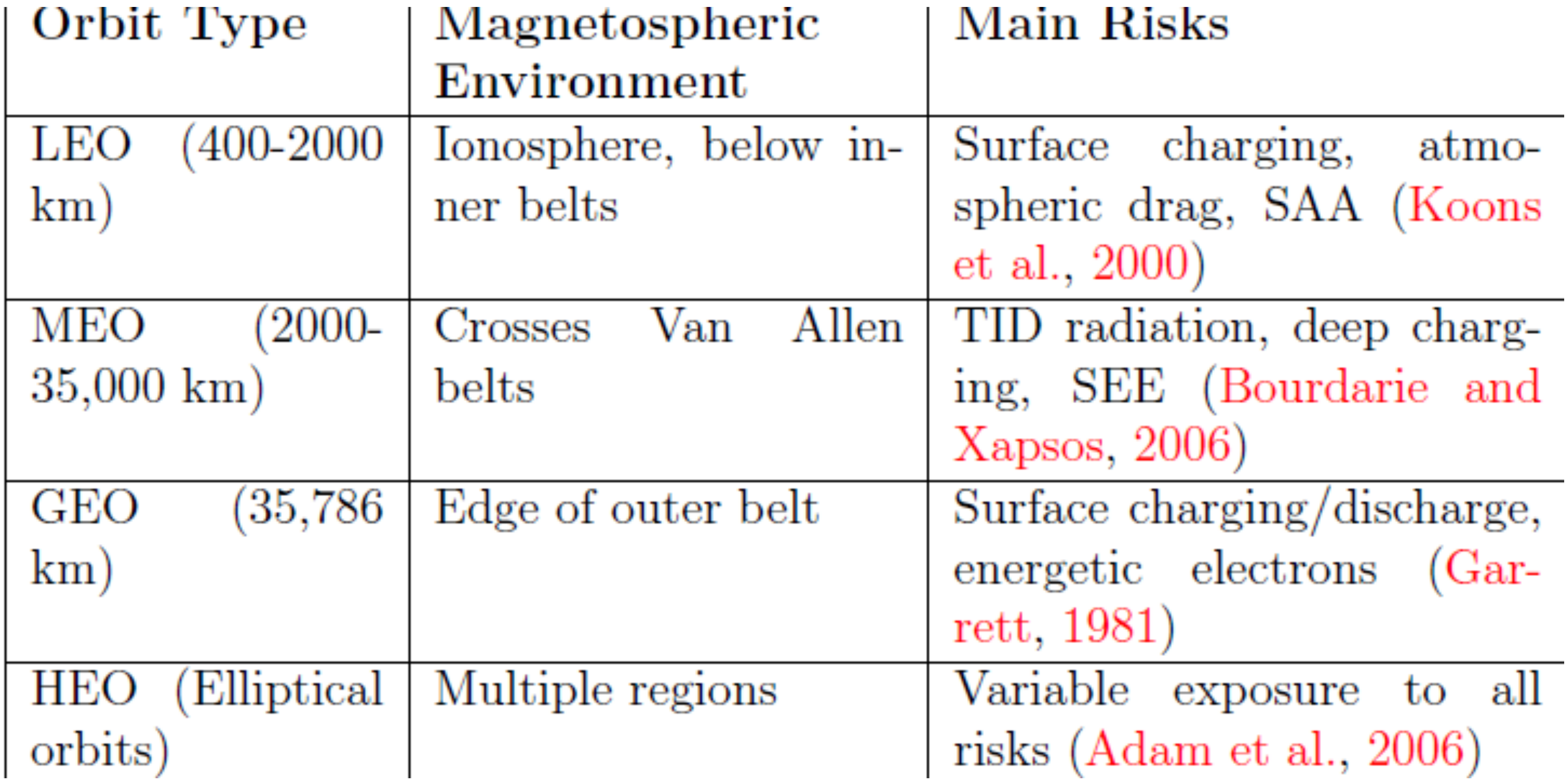
- Van Allen Belts: Toroidal regions of trapped particles: **Inner belt** (1-2 RE) with Energetic protons (10-100 MeV) and the **Outer belt** (3-7 RE) with Relativistic electrons (0.1-10 MeV)

- Ring Current: Toroidal current of energetic ions and electrons (1-300 keV) be tween 2-7 RE. *Sometimes , a third Van Allen Belt has been found, lasting months after solar magnetic storm*

Mathematical models: Dipole B Field and Chapman-Ferraro model (equilibrium between plasma pressure and thermal mechanical pressure :

$$\frac{1}{2}\rho v^2 = \frac{B^2}{2\mu_0}$$

Orbital and risk classification



Orbit Type	Magnetospheric Environment	Main Risks
LEO (400-2000 km)	Ionosphere, below inner belts	Surface charging, atmospheric drag, SAA (Koons et al., 2000)
MEO (2000-35,000 km)	Crosses Van Allen belts	TID radiation, deep charging, SEE (Bourdarie and Xapsos, 2006)
GEO (35,786 km)	Edge of outer belt	Surface charging/discharge, energetic electrons (Garrett, 1981)
HEO (Elliptical orbits)	Multiple regions	Variable exposure to all risks (Adam et al., 2006)

See RefChar in additional materials   and others like :

Koons, H. et al. (2000). Spacecraft charging observations on the dmsp satellite in leo.IEEE Transactions on Plasma Science, 28(6):2027{2034)

Responsible of charging: THE SOLAR WIND

All spacecraft charging processes are dominated by the Solar Wind dynamics

The solar wind is a *supersonic outflow of plasma from the Sun's corona*, originating from the high coronal temperatures (T ≈ 106 K) that drive therma expansion beyond the gravitational escape velocity

In **Low Earth Orbit** (LEO, 200–2000 km), charging is primarily due to **dense ionospheric plasma**, where electron densities are kown.The spacecraft potential φ_s is determined by the previous current balance equation.

In **Medium Earth Orbit** (MEO, 2000–35,786 km), exposure to **radiation belts increases deep dielectric charging**, where high-energy electrons (.1 MeV) penetrate materials, leading to **internal electric fields** that can **cause discharges**

In Geostationary Earth Orbit (GEO, 35,786 km**), charging huge during geomagnetic substorms**, with potentials reaching -10 kV.

Differential charging can occur when insulated surfaces charge differently, e.g. metal and dielectric ones, creating high volt arcs that damaging circuits or, even, the solar arrays or electronics onboard,

The solar wind modeling is needed to explore charging effects and to predict damages due to solar activity (storms, CME)

Main Characteristics (measures, SOHO, Parker… probes)

- *Composition: 95% protons and electrons,4% helium nuclei*
- *Veloci*ty: 250-800 km/s (slow to fast)
- Density: 1-10 particles/cm near Earth
- Temperature: 105 - 106 K
- Magnetic Field: Interplanetary Magnetic Field (IMF)

Magnetohydrodynamic (MHD) models if solar wind as a conducting fluid coupled with magnetic fields, solar and terrestrial, accounting for electromagnetic effects . The equations, with ρ is density, v velocity, P pressure, B magnetic field, total energy density, Φ gravitational potential

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad \text{(mass conservation)}$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla P + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nabla \Phi, \quad \text{(momentum)}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \quad \text{(induction)}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + P)\mathbf{v} + \frac{1}{\mu_0} \mathbf{B} \times (\mathbf{v} \times \mathbf{B}) \right] = -\rho \mathbf{v} \cdot \nabla \Phi, \quad \text{(energy)}$$

Solar Wind Parker Models

The foundational model by Parker [1958] describes solar wind as a supersonic expansion of the solar corona

MHD stationary radial coronal isothermal model, predicts a **critical radius** for transition from subsonic to supersonic flow.

Fails in capturing phenomena as the observed energetic charges and it does nor predict events due to solar transient activity (CME, solar storms…)

$$\frac{d}{dr}(\rho v r^2) = 0 \quad \text{(Mass conservation)}$$

$$\rho v \frac{dv}{dr} = -\frac{dp}{dr} - \frac{G M_\odot \rho}{r^2} \quad \text{(Momentum equation)}$$

$$p = \frac{2 k_B \rho T}{m_p} \quad \text{(Equation of state)}$$

Combining these equations yields the integral momentum equation:

$$\left(v - \frac{c_s^2}{v}\right)\frac{dv}{dr} = \frac{2c_s^2}{r} - \frac{G M_\odot}{r^2}$$

where $c_s = \sqrt{\frac{2k_B T}{m_p}}$ is the sound speed.
The critical point r_c where $v(r_c) = c_s$ is:

$$r_c = \frac{G M_\odot}{2c_s^2}$$

Other Magnetohydrodynamic Models describe the solar wind in 3D as a transient system that couples with measuremts of solar activity **(SOHO, Parker probe).**

Parker models (first and spiral magnetic field coupled to the fluis) are special cases.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad \text{(Mass conservation)}$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} \right) = -\nabla p + \mathbf{J} \times \mathbf{B} - \rho \frac{G M_\odot}{r^2} \hat{\mathbf{r}}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad \text{(Induction law)}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad \text{(Ampère's law)}$$

The B field structure is complex, even for non.resitive (ideal) MHD.

See Refs.

Kinetic models

Kinetic models go beyond the fluid approximation with **Vlasov and Boltzmann** equations for the distribution functions fs(r, v, t) of species s (protons, electrons, alpha particles).

This gives the probability of finding energetic particles with velocity v measured experimentally, finding **non-Maxwellian** distributions.

Observations show that solar wind protons and electrons exhibit temperature anisotropies (T⊥ differs from T∥) due to B field.

Capturing suprathermal tails and anisotropy (origin?, Alvén waves)

often modelled with bi-Maxwellian of even bi-kappa distributions, showing tails enlarged (high energy superthermal particle, more probable than for a Maxwellian). Kappa Distr. Isotropic and anisotropic cases become Maxwellian for κ → ∞

$$f(v) = \frac{n}{\pi^{3/2} v_{th}^3} \frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)} \left(1 + \frac{v^2}{\kappa v_{th}^2}\right)^{-\kappa-1}$$

$$f(v_{\|}, v_{\perp}) = \frac{n\Gamma(\kappa+1)}{\pi^{3/2}\kappa^{3/2} v_{th,\|} v_{th,\perp}^2 \Gamma(\kappa-1/2)} \left(1 + \frac{v_{\|}^2}{\kappa v_{th,\|}^2} + \frac{v_{\perp}^2}{\kappa v_{th,\perp}^2}\right)^{-}$$

Mitigation Methods and Optimization for Spacecraft Charging

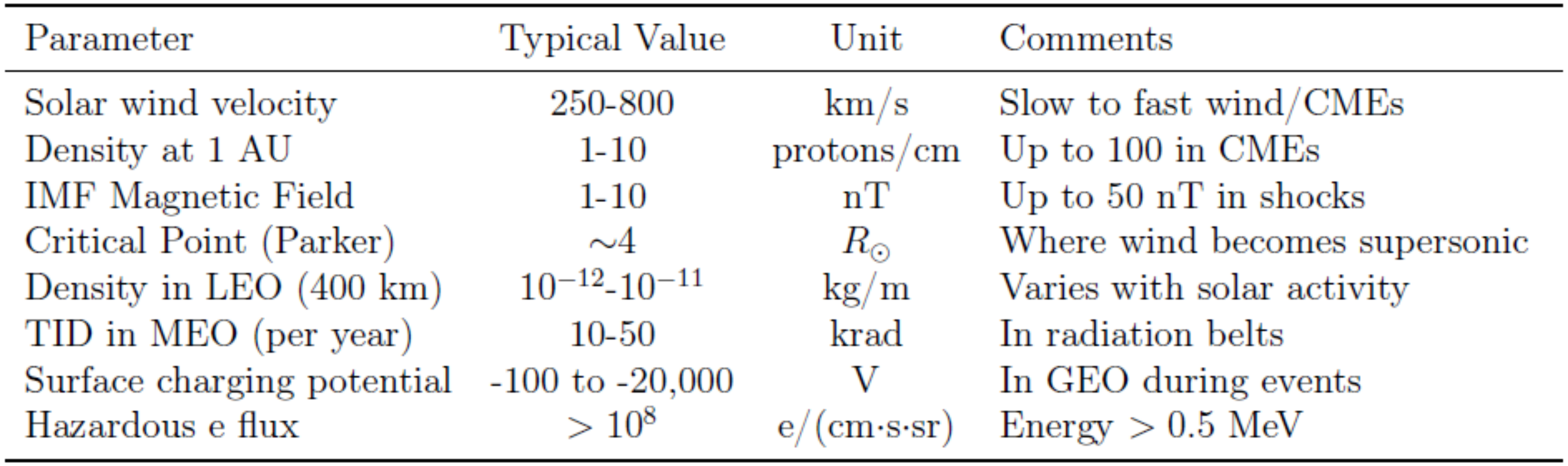
Mitigation Methods and Optimization for Spacecraft Charging due to solar wind and magnetic storms:

Desig of conductor-dielectric surface

Secundary electron emissive matherials or electrosn beams

Knowledge of orbital dynamics.

Potential grounding changes.



Parameter	Typical Value	Unit	Comments
Solar wind velocity	250-800	km/s	Slow to fast wind/CMEs
Density at 1 AU	1-10	protons/cm	Up to 100 in CMEs
IMF Magnetic Field	1-10	nT	Up to 50 nT in shocks
Critical Point (Parker)	~4	$R_\odot$	Where wind becomes supersonic
Density in LEO (400 km)	10^{-12}-10^{-11}	kg/m	Varies with solar activity
TID in MEO (per year)	10-50	krad	In radiation belts
Surface charging potential	-100 to -20,000	V	In GEO during events
Hazardous e flux	$> 10^8$	e/(cm·s·sr)	Energy > 0.5 MeV

Table 4: Summary of key solar wind parameters and effects

Application: Plasma wakes in mesothermal flow in LEO

Mesothermal flow conditions in LEO are

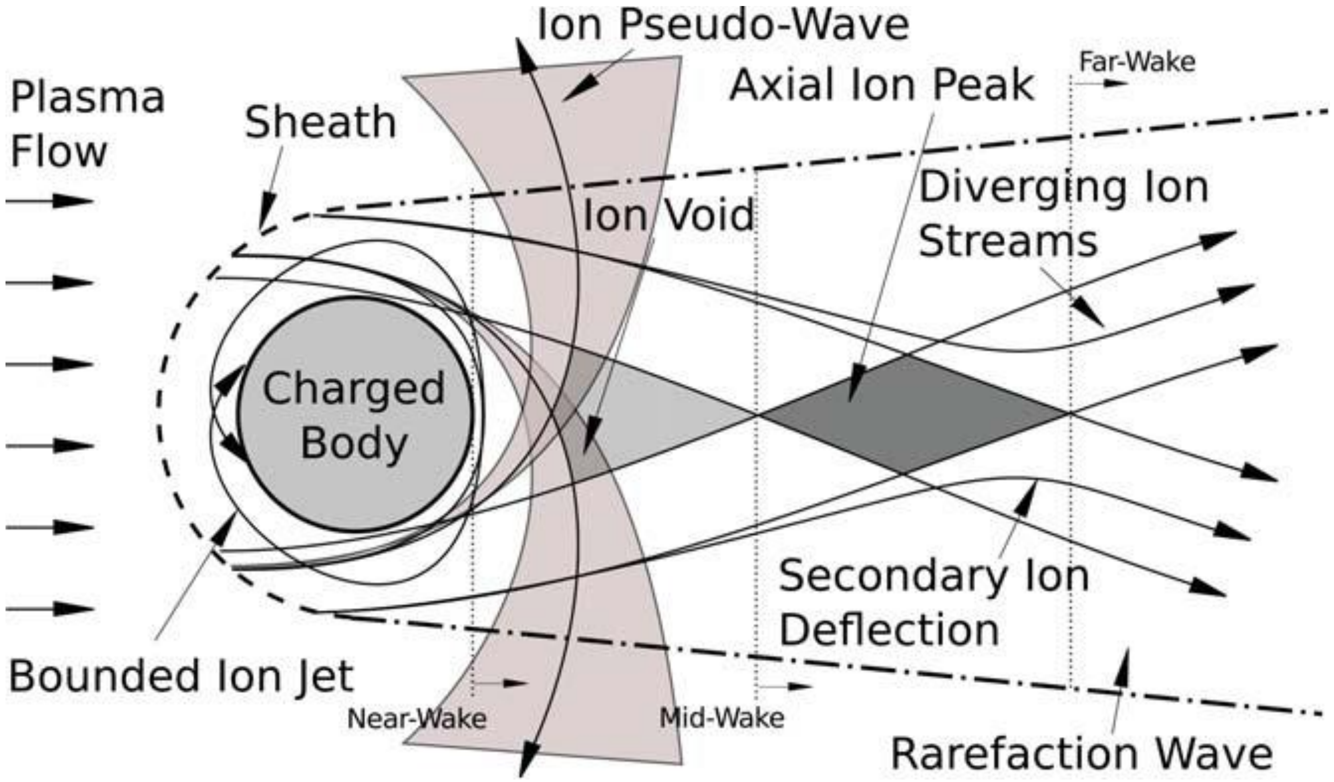
$$v_{th,e} \gg u_B \gg v_{th,i}$$

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

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

$$u_B \sim 7.5\ \mathrm{km/s\ \ LEO} \gg v_{th,i} = \sqrt{\frac{2k_B T_i}{m_i}} \simeq 1.25\ \mathrm{km/s}\ \ \mathrm{O}^+$$

$$u_B \sim 7.5\ \mathrm{km/s\ \ LEO} \ll v_{th,e} = \sqrt{\frac{2k_B T_e}{m_e}} \simeq 246\ \mathrm{km/s}$$

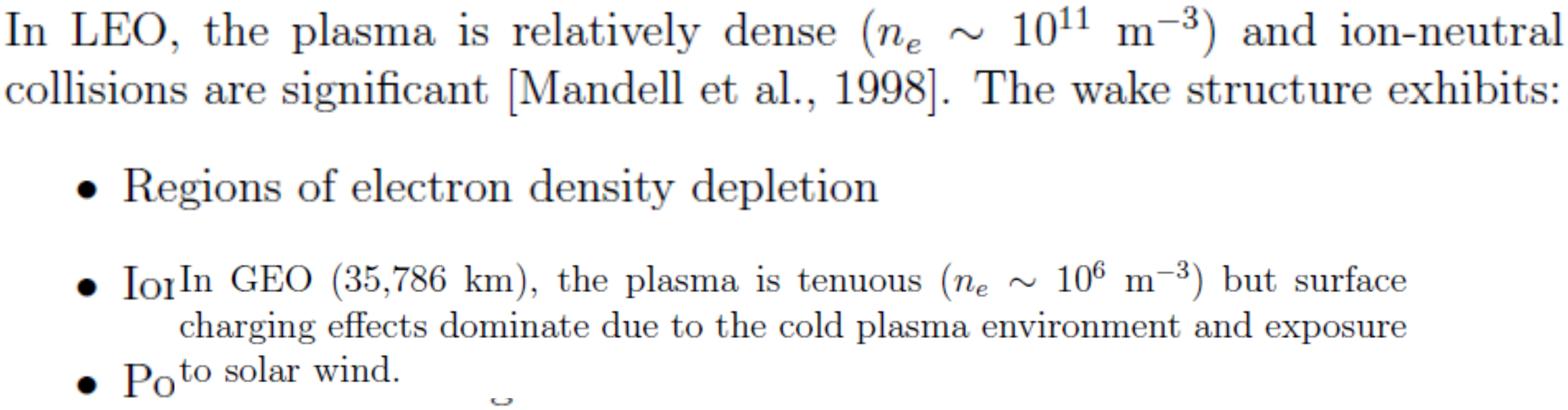


- Schematic cross-sectional structure of the plasma wake in the mesothermal flow around a spherical charged body in LEO. From L. Brown. *Rarefied plasma aerodynamics for LEO objects in the ionosphere*. Report AFL-AFOSR-JP-2018-0040 (2018).

Application: Plasma wakes in mesothermal flow in LEO

Plasma wakes form behind spacecraft due to supersonic motion through plasma creating density depletions. In LEO, the ram velocity (8 km/s) exceeds ion thermal speed, forming an ion void.

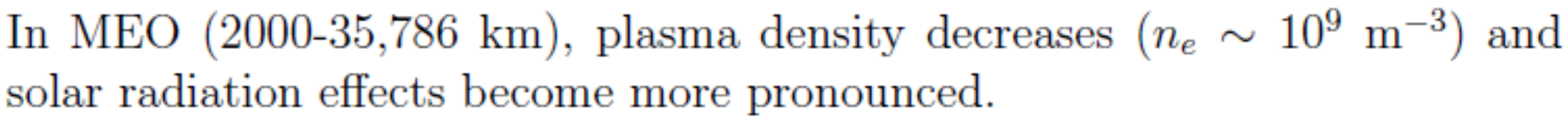
The wake structure includes: on focus region (enhanced density),
Expansion rarefaction, Ambipolar region.



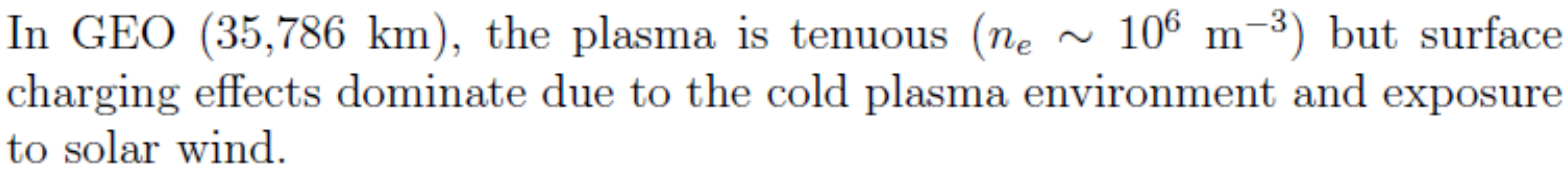
In LEO, the plasma is relatively dense ($n_e \sim 10^{11}$ m^{-3}) and ion-neutral collisions are significant [Mandell et al., 1998]. The wake structure exhibits:

- Regions of electron density depletion
- Io
- Po

In GEO (35,786 km), the plasma is tenuous ($n_e \sim 10^6$ m^{-3}) but surface charging effects dominate due to the cold plasma environment and exposure to solar wind.



In MEO (2000-35,786 km), plasma density decreases ($n_e \sim 10^9$ m^{-3}) and solar radiation effects become more pronounced.



In GEO (35,786 km), the plasma is tenuous ($n_e \sim 10^6$ m^{-3}) but surface charging effects dominate due to the cold plasma environment and exposure to solar wind.