

Spacecraft Charging as an Asset to Interplanetary Small Spacecraft

INTERPLANETARY SMALL SATELLITE CONFERENCE PRESENTATION D.4

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Motivation – Small Satellites in Deep Space

- Nanosatellites as client spacecraft to large spacecraft
 - › Telemetry relays (**MarCO**)
 - › Distributed sensing of outer planetary magnetospheres (**proposed**)
- Spacecraft are power starved in the outer solar system
 - › Large solar array required
 - › RTGs not powerful relative to size/mass
- Can we harness the **space environment** for spacecraft operations?

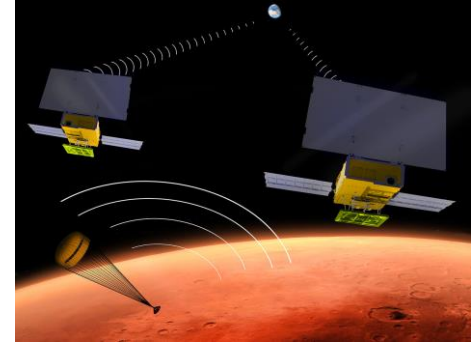


Image Credit: NASA



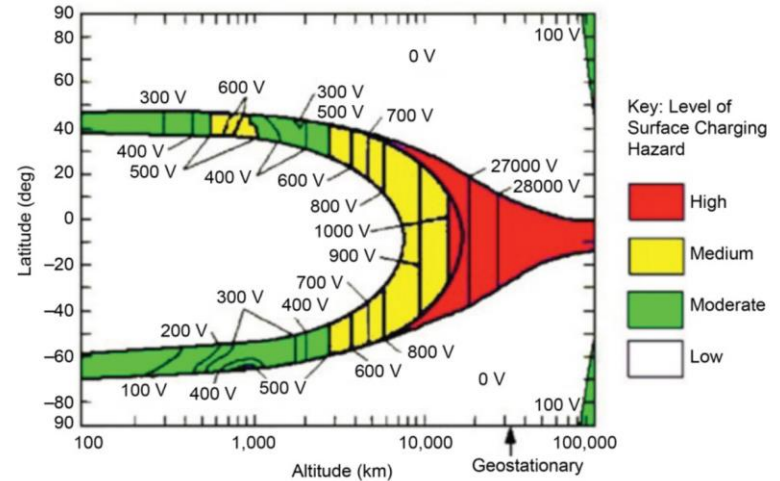
"The Giant Planets: Local Laboratories and Ground Truth for Planets Beyond," *Vision and Voyages for Planetary Science in the Decade 2013-2022*, National Academy of Sciences, 2013, pp. 175–216.

Space Plasmas

- Solar system not empty – permeated by plasma
 - › Solar wind
 - › Radiation belts
 - › Magnetospheres
- Energetic – damage to spacecraft

$$P \propto n_e T_e^{3/2}$$

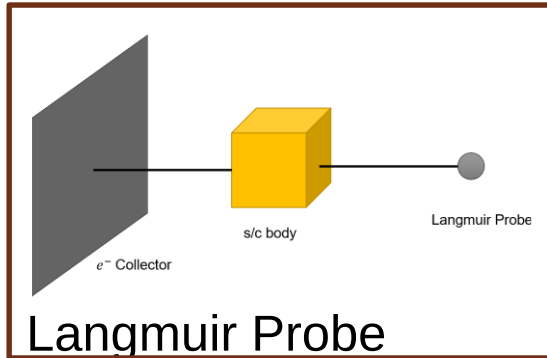
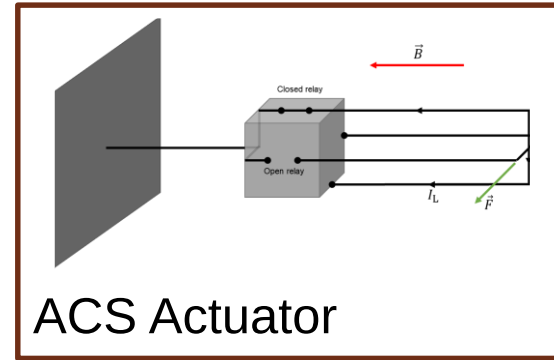
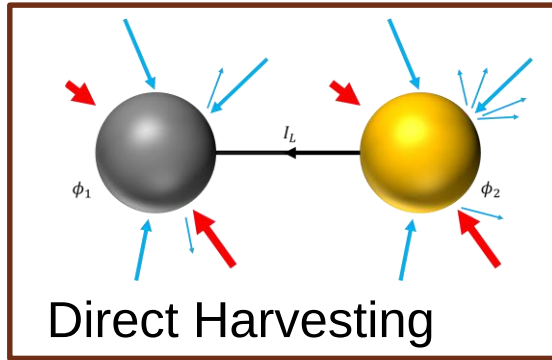
- Can we harness the damaging potential to do useful work?



Hazards from Space Plasmas

Garrett, H.B., Whittlesey, A.C., "Guide to Mitigating Spacecraft Charging Effects," JPL Space Science and Technology Series, pp .2, 2012, https://descanso.jpl.nasa.gov/SciTechBook/st_series3_chapter.html

Proposed Space Plasma Applications



Spacecraft Charging – Overview

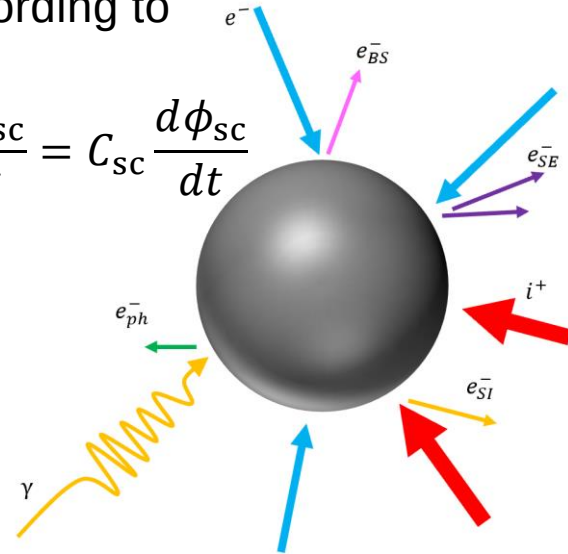
The charge Q_{sc} on the spacecraft surface evolves according to

$$I_T = \underbrace{I_e}_{\text{Electron current}} + \underbrace{I_i}_{\text{Ion current}} + \underbrace{I_{se} + I_{si}}_{\text{Secondary electron current}} + \underbrace{I_{bs}}_{\text{Backscattered electron current}} + \underbrace{I_{ph}}_{\text{Photoelectron current}} + \underbrace{I_o}_{\text{Other current}} = \frac{dQ_{sc}}{dt} = C_{sc} \frac{d\phi_{sc}}{dt}$$

All dependent on:

- Spacecraft potential ϕ_{sc}
- Constituent species j and properties (n_j, T_j, κ_j)
- Material properties
- Lighting conditions
- Surface Geometry

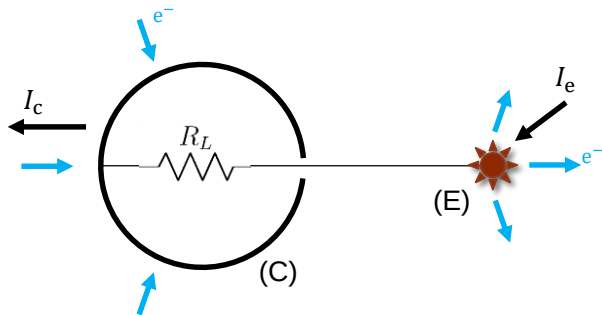
Characteristic curve $I_T(\phi_{sc})$ determines equilibrium potential and harvesting capabilities



Spacecraft Charging – Prior Work on Energy Harvesting

Field Effect Emitter

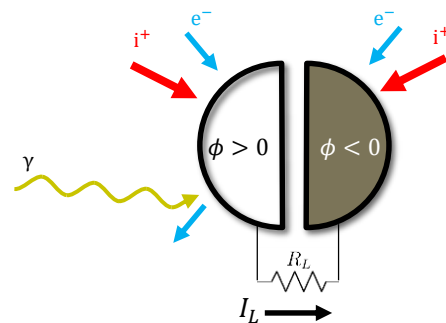
- Spacecraft Chassis as electron collector (C)
- Field effect electron emitter (E)



Grard, R. J. L., "The magnetospheric plasma as a source of energy for space instrumentation," Planetary and Space Science, Vol. 25, No. 7, 1977, pp. 615–620. [https://doi.org/10.1016/0032-0633\(77\)90100-3](https://doi.org/10.1016/0032-0633(77)90100-3).

Photoemission

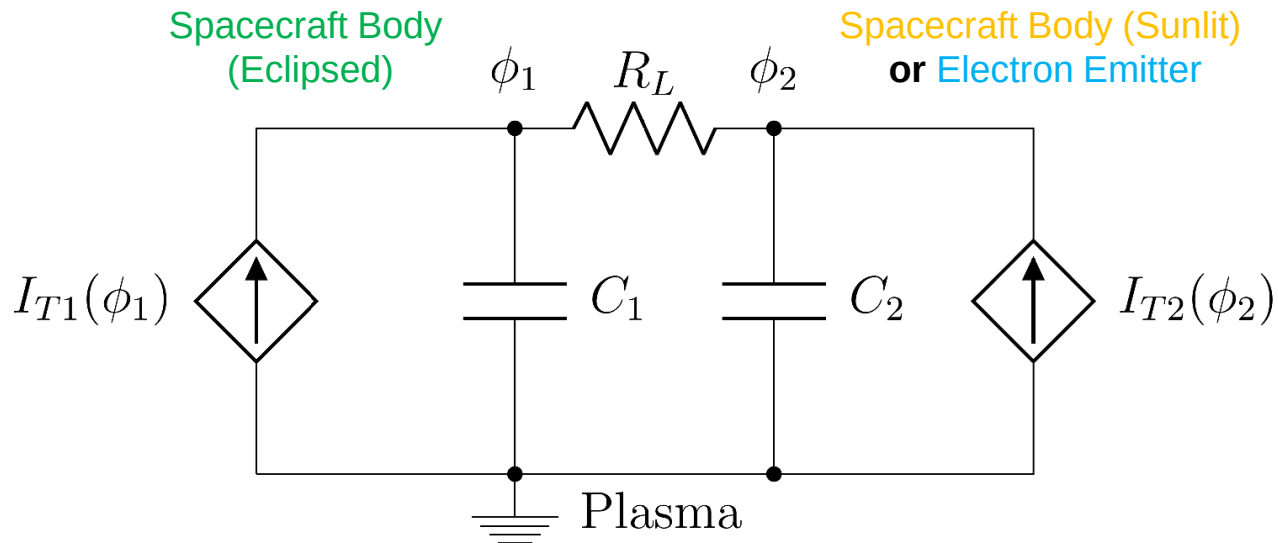
- Eclipsed anode
- Sunlit cathode
- $\Delta\phi$ from illumination



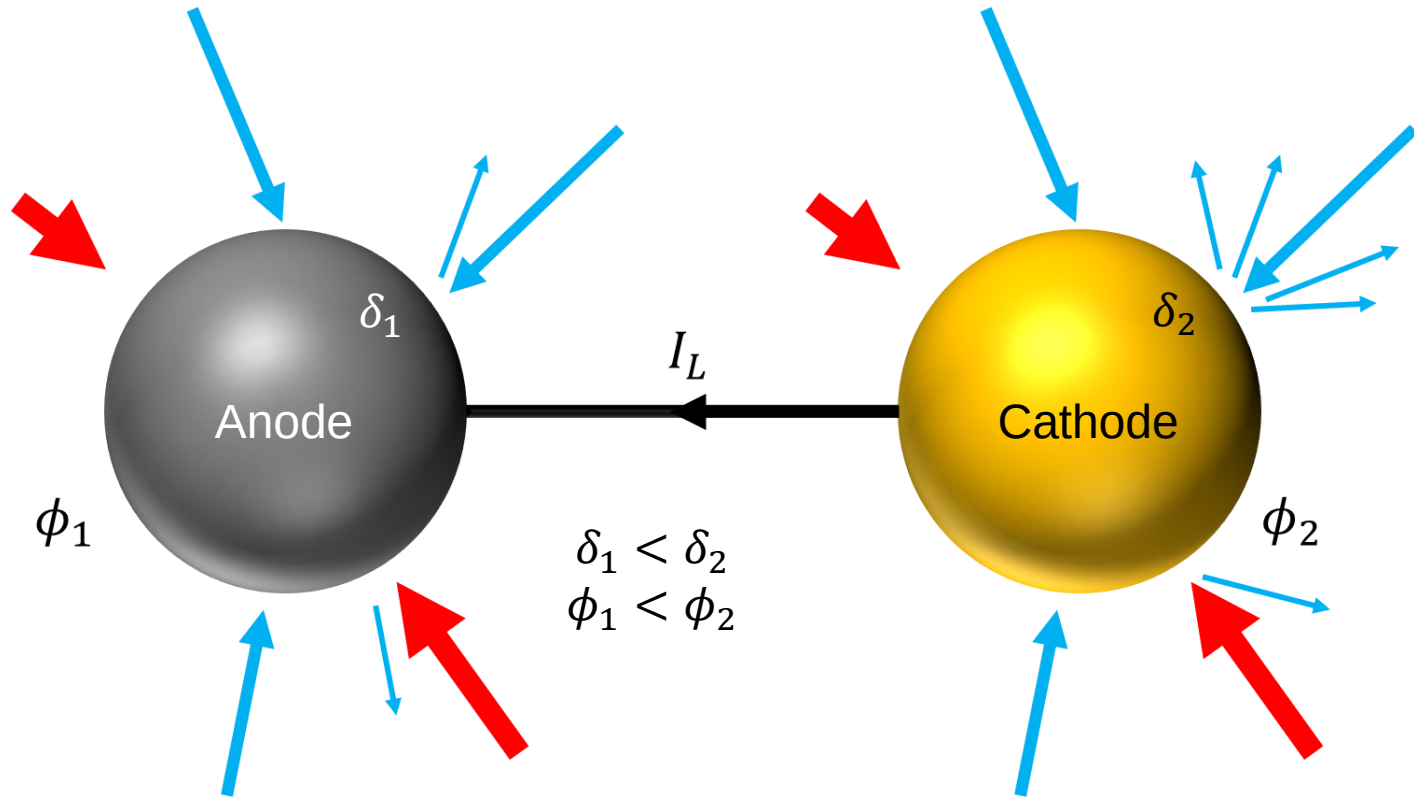
Gale, W., "Spacecraft Charge as a Source of Electrical Power for Spacecraft," Masters Thesis, Air Force Institute of Technology, 1988. <https://doi.org/10.1063/1.460797>.

Both rely on differences in $I_T(\phi)$

Spacecraft Charging – Equivalent Circuit Model



Implementation – Exploit Material Properties



Implementation – Exploit Material Properties

- Current balance

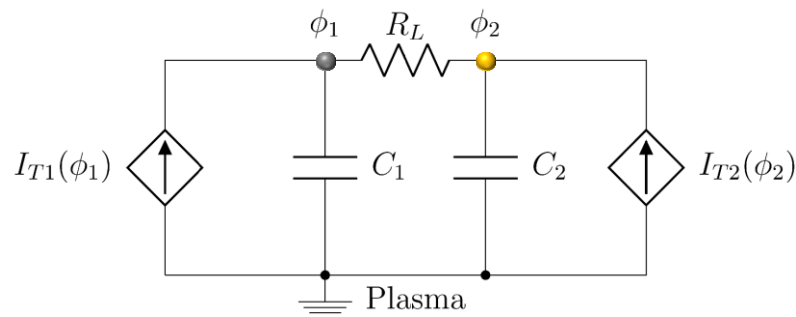


$$I_{T1}(\phi_1) + \frac{\phi_2 - \phi_1}{R_L} = C_1 \frac{d\phi_1}{dt}$$



$$I_{T2}(\phi_2) - \frac{\phi_2 - \phi_1}{R_L} = C_2 \frac{d\phi_2}{dt}$$

- Equivalent circuit:



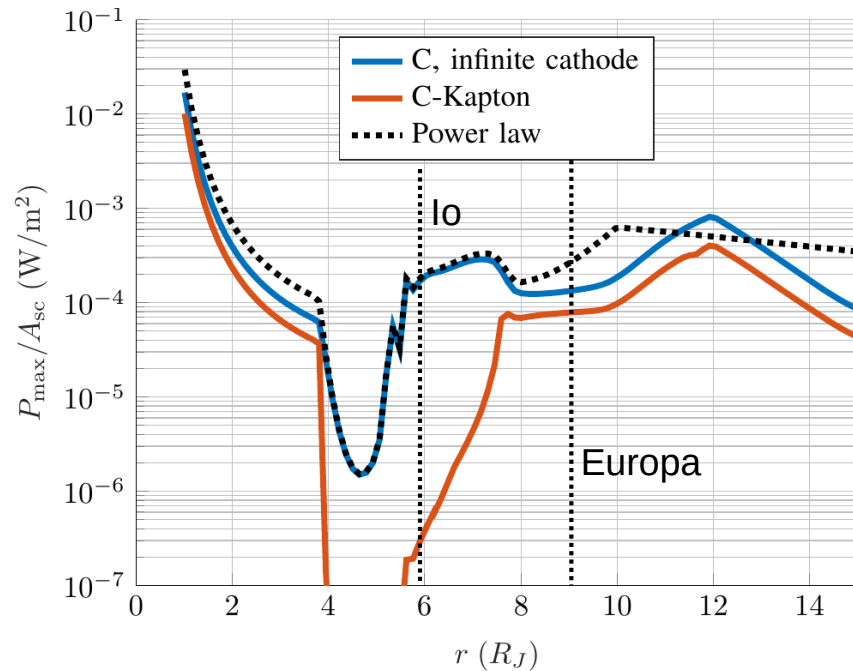
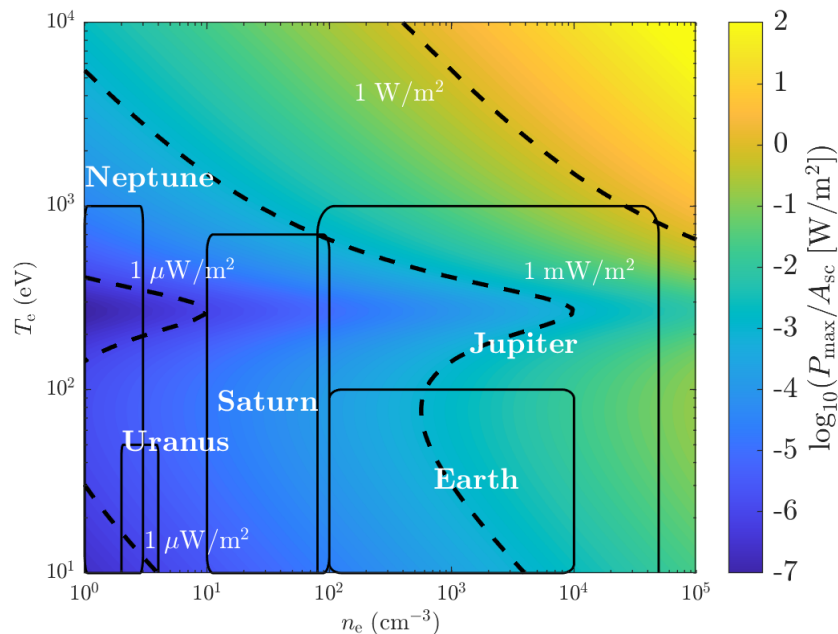
- Harvested power

$$P_L = \frac{(\phi_2 - \phi_1)^2}{R_L}$$

- Optimize design for maximum power

- › Resistance R_L^* – impedance match
- › Area ratio A_2/A_1 – minimize input impedance
- › Material selection – maximize difference in secondary electron yield

Harvesting in Relevant Space Environments



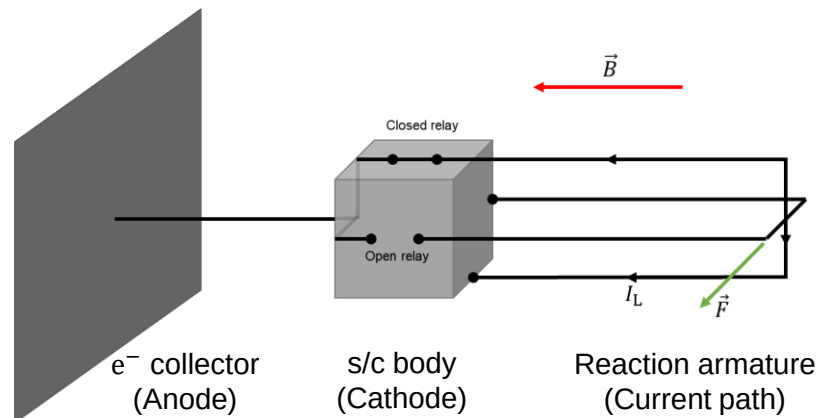
Attitude Control System (ACS) Actuator

- Current reaction with magnetic fields

- Force on a wire

$$\vec{F} = \int_C d\vec{s} \times \vec{B} I(\vec{s}) \propto I_L$$

- Deployable surfaces as charge reservoirs
- Maximize current to maximize force
- Several armatures for different field orientations



Example actuator geometry

ACS Actuator Implementation

- Current balance

$$I_{T1}(\phi_1) + I_L = C_1 \frac{d\phi_1}{dt}$$

$$I_{T2}(\phi_2) - I_L = C_2 \frac{d\phi_2}{dt}$$

- Equivalent circuit:

- Current balance

$$I_{T1}(\phi_1) + I_L = C_1 \frac{d\phi_1}{dt}$$

$$I_{T2}(\phi_2) - I_L = C_2 \frac{d\phi_2}{dt}$$

- Equivalent circuit:

- Load current

$$I_L = \frac{\phi_2 - \phi_1}{R_L}$$

- Optimize design for maximum current

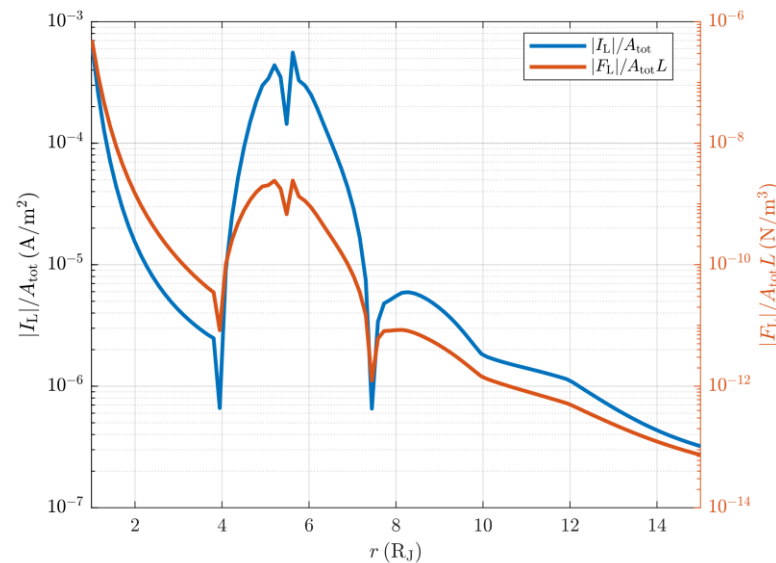
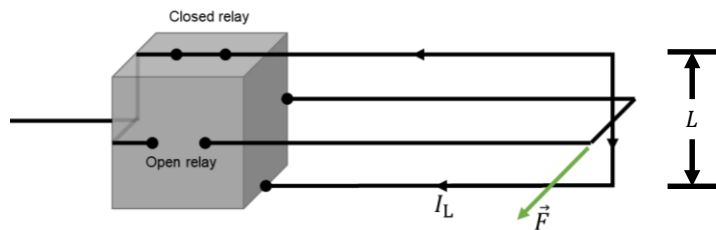
- › Resistance $R_L^* \rightarrow 0$
- › Area ratio A_2/A_1 – choose such that $\phi \approx 0$
- › Material selection:
 - $I_{T1}(0) < 0 < I_{T2}(0)$
 - $\delta_1 \rightarrow 0, \delta_2 \geq 1$

• Load current
 $I_L = \frac{\phi_2 - \phi_1}{R_L}$
 • Optimize design for maximum current
 Resistance $R_L^* \rightarrow 0$
 Area ratio A_2/A_1 – choose such that $\phi \approx 0$
 Material selection:
 • $I_{T1}(0) < 0 < I_{T2}(0)$
 • $\delta_1 \rightarrow 0, \delta_2 \geq 1$



ACS Actuator Results

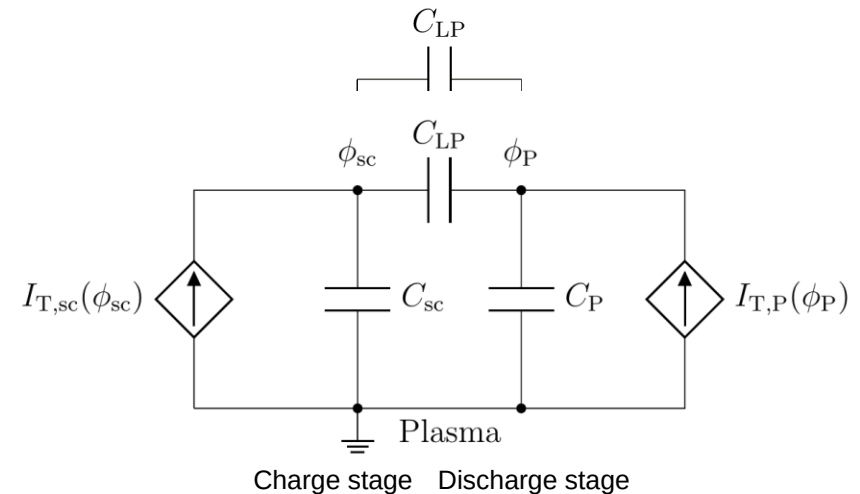
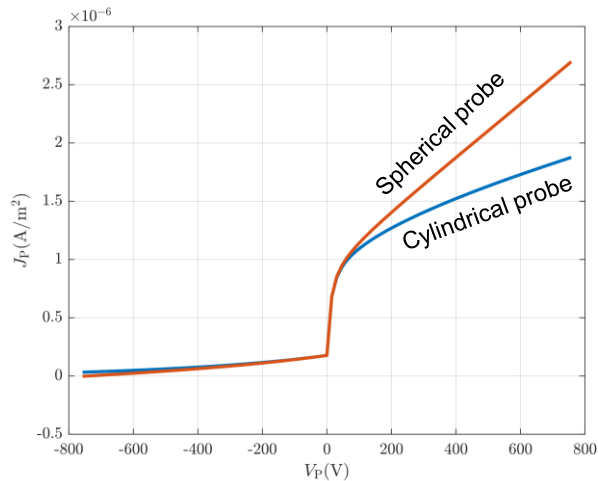
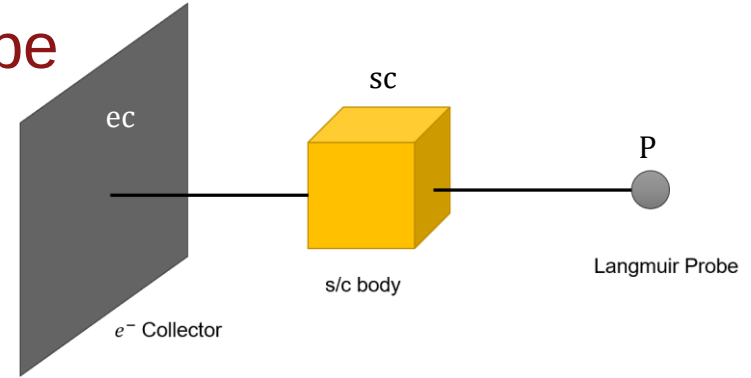
- Currents significant in Inner magnetosphere, Io torus
- Force is small
 - › Large moment arm
 - › Passive station keeping
- Transient currents are larger, more useful
- Future work: stability, control requirements



Plasma from Divine-Garrett model,
spherical anode/cathode, $\theta = \pi/2$

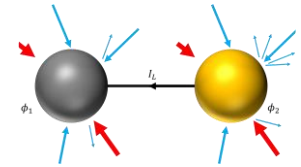
Plasma Powered Langmuir Probe

- Use collector/body to charge C_{LP} to desired bias
- Relays switch anode from collector to probe
- Measure current $I_P(\phi_P)$

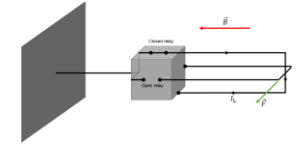


Conclusions

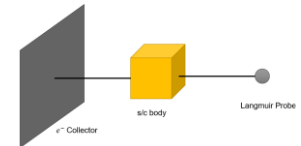
- Space plasmas contain energy that can be useful for the spacecraft
- Three ways to harness
 - › **Direct energy harvesting** – usable of power at Jupiter
 - › **Attitude control** – can react against magnetic field, use for passive station keeping
 - › **Plasma sensor** – capacitor charged with plasma to make plasma measurements



Direct
Harvesting



ACS Actuation



Langmuir
Probe

Questions?

Contact: saqyoung@stanford.edu

<https://sess.stanford.edu>

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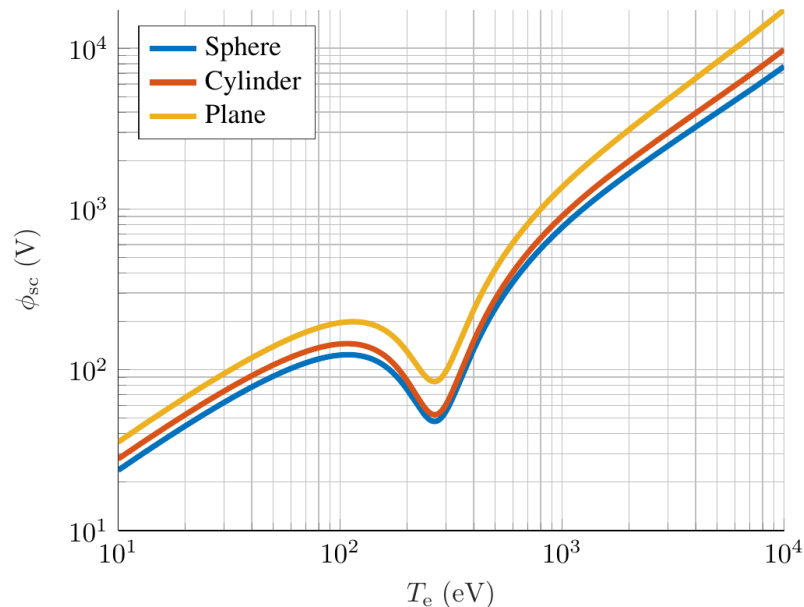
Backup

Motivation (cont.)

- Lab Mission: use the space environment for the benefit of the spacecraft.
 - › Enable new missions, new space science
- Approaches:
 - › Hypervelocity impacts
 - to probe asteroid composition (MIDEA, NIAC 2018)
 - › Space plasmas
 - Spacecraft power through spacecraft charging
 - Novel actuation/sensing

Implementation – Broken Symmetries

- Many options, including
 - › Passive electron emitter
 - › Photoemission
 - › Geometry
 - › Secondary electron emission (SEE)
- Develop general theory for harvesting from two surfaces
- Choose SEE in particular



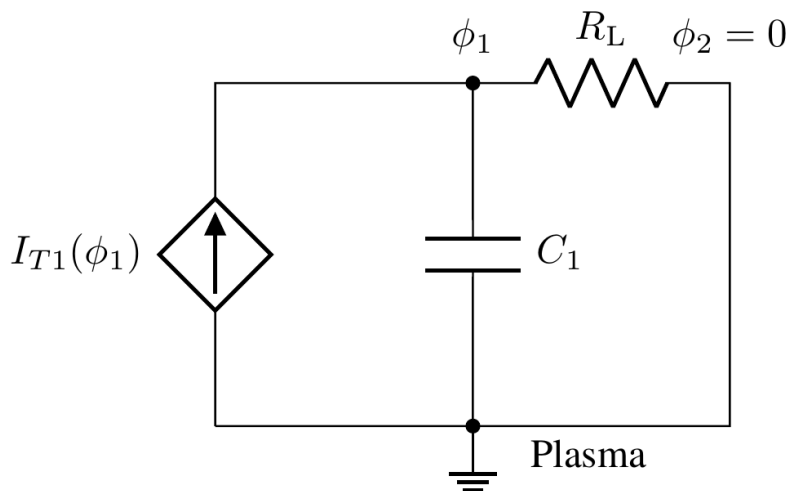
Solid Curves $\phi < 0$
Dashed Curves $\phi > 0$

Implementation – Fixed Cathode

- Current balance

$$I_{T1}(\phi_1) - \frac{\phi_1}{R_L} = C_1 \frac{d\phi_1}{dt}$$

- Equivalent circuit:



- Design parameters: R_L , anode material/geometry
- Power harvested in steady state is

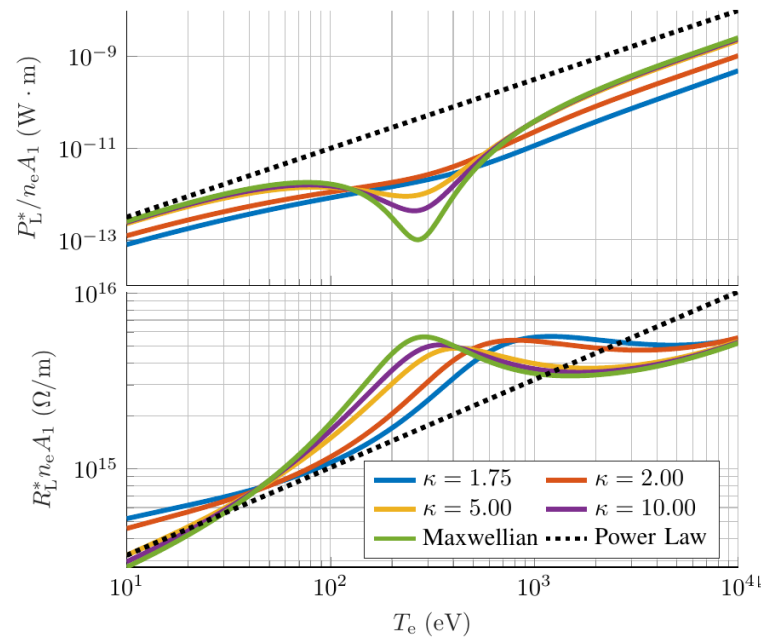
$$P_L = \frac{\phi_1^2}{R_L} = \phi_1 I_{T1}(\phi_1)$$

- Maximum when $R_L = -\left(\frac{\partial I_{T1}}{\partial \phi_1}\right)^{-1}$
- Influenced by:
 - Anode material
 - Anode geometry, and
 - Environmental condition

Optimal Power/Load Trends

Parameter	$P_L^*/n_e A_1$	$R_L^* n_e A_1$
$\langle \delta_e \rangle \uparrow$	$\downarrow$	$\downarrow$
Anode geometry (DoF) $\uparrow$	$\downarrow$	$\downarrow$
$\xi = I_{ph}/I_e \uparrow$	$\downarrow$	$\downarrow$
$\kappa \uparrow$	$\uparrow$	$\downarrow$

- Numerical solution using Orbit-Motion-Limited (OML) model
- Hydrogen-electron plasma, $T_e = T_H$
- $R_L = R_L^*$



Analytic Expression – Potential

Dimensionless **potential**

$$\theta = \frac{\mathcal{I} + 1}{\mathcal{G}} - W_0 \left(\frac{1}{\mathcal{G}} e^{(\mathcal{I}+1)/\mathcal{G}} \right)$$

Dimensionless **current** at $\theta = 0$

$$\mathcal{I} = -1 + \xi + \sum_{i=1}^N g_i Z_i \frac{\rho_i}{\rho_e} \sqrt{\frac{\tau_i}{\mu_i}}$$

Dimensionless **conductance**

$$\mathcal{G} = \begin{cases} \frac{1}{\mathcal{R}} & \text{planes} \\ \frac{1}{\mathcal{R}} + \underbrace{\sum_{i=1}^N \frac{g_i Z_i^2 \rho_i}{\sqrt{\mu_i \tau_i} \rho_e}}_{\mathcal{G}'} & \text{spheres} \end{cases}$$

$W_k(z)$ = Lambert-W function

$$z = W_k(z) e^{W_k(z)}$$

Parameter Definitions

Dimensionless potential: $\theta = \frac{q_e \phi}{k_B T_e}$

Temperature ratio: $\tau_i = \frac{T_i}{T_e}$

Mass ratio: $\mu_i = \frac{m_i}{m_e}$

Density ratio: $g_i = \frac{n_i}{n}$

Ion charge: $Z_i = \frac{q_i}{q_e}$

SEE modifier: $\rho_j = 1 + \frac{q_j}{|q_j|} \langle \delta_j \rangle$

Dimensionless load resistance: $\mathcal{R} = \frac{I_{e0} R_L}{k_B T_e / q_e}$

Photoemission factor: $\xi = \frac{I_{ph}}{I_{e0}}$

Net electron current at $\phi = 0$: $I_{e0} = \frac{1}{2} n q_e A \rho_e \sqrt{\frac{2 k_B T_e}{\pi m_e}}$

Analytic Expression – Optimum Power

Maximize $\mathcal{P} = \theta^2/\mathcal{R}$, where

$$\theta = \frac{\mathcal{I} + 1}{\mathcal{G}} - W_0 \left(\frac{1}{\mathcal{G}} e^{(\mathcal{I}+1)/\mathcal{G}} \right)$$

Planar solution

$$\theta^* = W_0(e(1 + \mathcal{I})) - 1$$

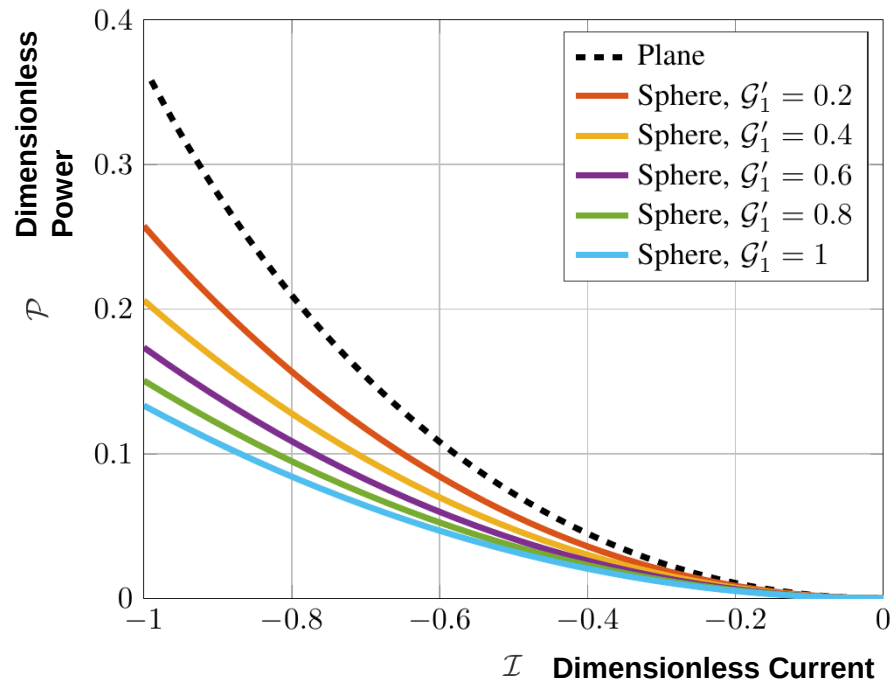
$$\mathcal{P} = (1 + \mathcal{I}) \frac{(W_0(e(1 + \mathcal{I})) - 1)^2}{W_0(e(1 + \mathcal{I}))}$$

Maximized when $\mathcal{I} \rightarrow -1$

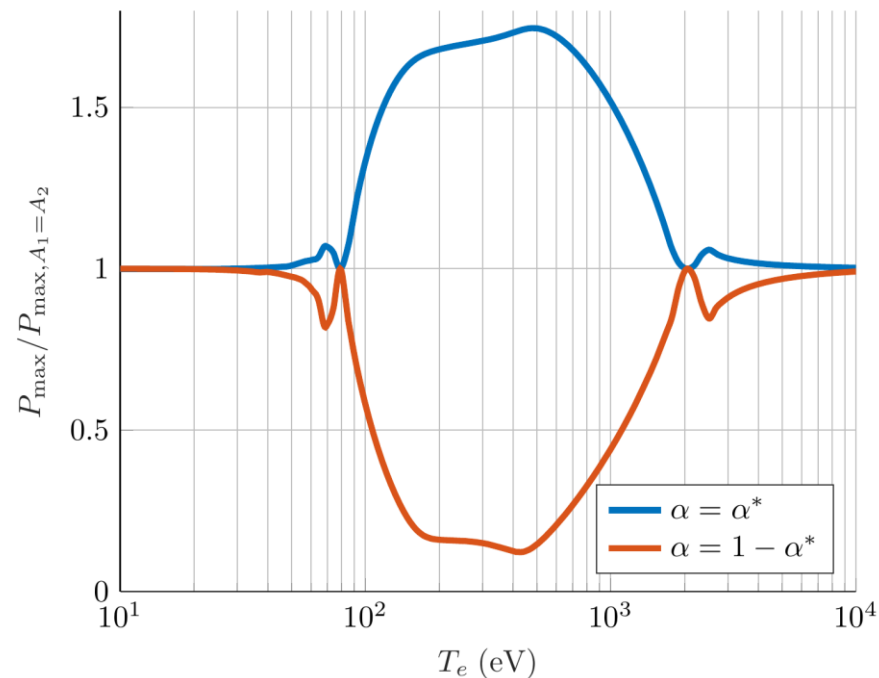
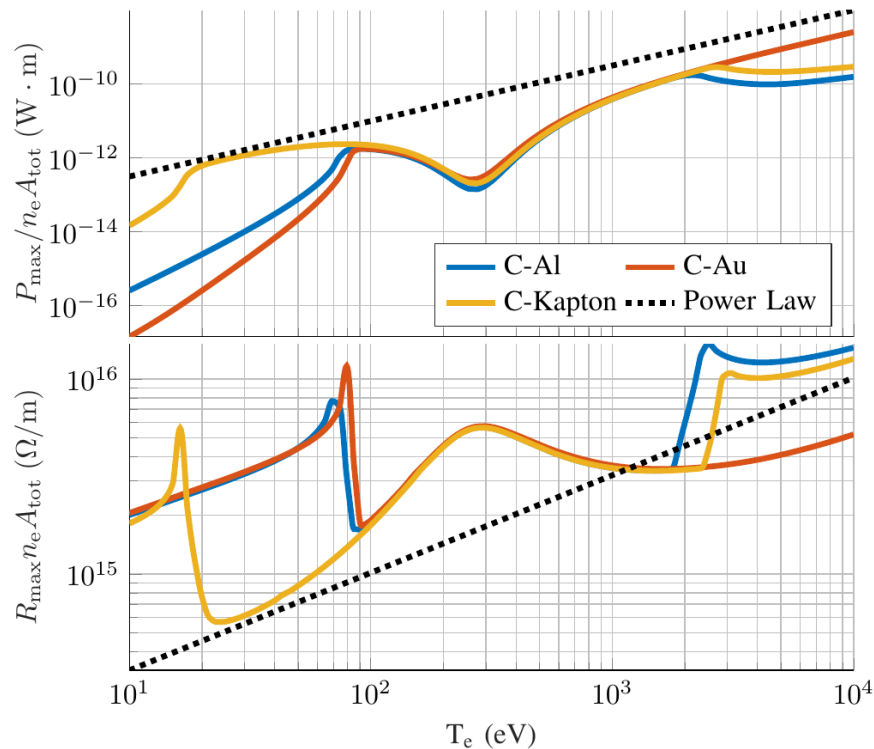
$$\theta^* \rightarrow -1, \quad \mathcal{P} \rightarrow \frac{1}{e}, \quad \mathcal{R} \rightarrow e$$

$$\frac{P_{\max}}{A} [\text{W/m}^2] \approx 10^{-8} n_e [\text{cm}^{-3}] T_e^{3/2} [\text{eV}]$$

$$R_{\max} A [\Omega \text{m}^2] \approx 10^8 \sqrt{T_e} [\text{eV}] / n_e [\text{cm}^{-3}]$$



Free Cathode – Material/ α Dependence



Hydrogen/electron plasma, Maxwellian, $T_e = T_H$, spherical cathode/anode