7th Spacecraft Charging Conference

INTERACTIONS OF PLASMA WITH SURFACES AND BODIES IN SPACE

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Introduction

There are numerous aspects to interaction of bodies in space with the plasma environment including • the charging of surfaces, • formation of sheaths and wakes, • transport of locally generated plasma, • plasma chemistry, • surface-plasma chemistry.

The transport of charge and collection of current is one of the fundamental problems in plasma physics. This lecture will address current collection with the theory of plasma probes and then show how these concepts may be applied to real interaction problems. With a beginning in early vacuum tube and lighting research, current collection is still an issue in many areas:

- Plasma processing
- Vacuum insulation
- Plasma diagnostics
- Electric propulsion
- Interstellar dust grain charging
- Spacecraft potential control (Low Voltage)
- Spacecraft Charging (High Voltage)
- Solar array arcing

Outline

- Review of basic probe theory
  - The Turning Point Method
  - Orbit Motion Limited theory
  - Space Charge Limited theory
  - Magnetic Field Limited theory
  - Presheath Theory
- Results of recent space flights
  - SPEAR Space Power Experiments Aboard Rockets
  - CHAWS Charge Hazards And Wake Studies
  - TSS-1R Tethered Satellite System

Debye Screening

- The Debye Length, λ_d, is an important normalizing parameter.
- Start with Poisson's equation: $\nabla^2 V = -\frac{Ne}{\varepsilon_o}(n_i - n_e)$
- Define: $\Phi = eV/kT$, $\lambda_d = \varepsilon_o kT/Ne^2$: $\nabla^2 \Phi = -\lambda_d^{-2}(n_i - n_e)$

For Debye screening, assume a small test charge, -Ze, uniform ion and equilibrium electron density,

$$\nabla^2 \Phi = -\lambda_d^{-2}\left(1 - e^{+\Phi} - \frac{Z}{N}\delta(\vec{r})\right)$$

Expanding the exponential gives,

$$\nabla^2 \Phi - \lambda_d^{-2}\Phi = -\lambda_d^{-2}\frac{Z}{N}\delta(\vec{r})$$

with solution:

$$\Phi = \frac{Z}{4\pi N r \lambda_d^2} e^{-r/\lambda_d}$$

Debye screening can be a useful approximate screening model. However, λ_d is *not* the sheath thickness for probes comparable to λ_d in size and/or greater than kT in potential.

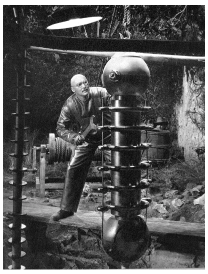
Plasma Probes

Plasma probes are spheres, cylinders, and plates, which are inserted into a plasma to diagnose parameters of the plasma, e.g. Temperature and Density.

Probes may be allowed to float to an equilibrium potential or the potential may be swept to generate a current-voltage, I-V, curve.

Ideally, probes are 'small' compared to the characteristic lengths of the plasma, but may in practice, be almost any size.

A 'probe' theory must be used to extract the plasma parameters from the probe data



Probe Theory

Plasma probe theory is based on a self-consistent combination of solutions to Poisson's equation,

^{2}

where $\Phi = eV/kT$, and $\rho = e(n_i - n_e)$

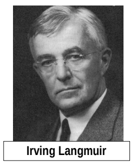
and an appropriate solution to the plasma kinetic problem, most generally described by the Boltzmann equation,

$$\frac{\partial f}{\partial t} + v \bullet \nabla_x f + a \bullet \nabla_v f = \frac{D_c f}{Dt}$$

where $f = f(x,v)$ is the velocity distribution function, and D_c is collision operator. For most space plasma problems, collisions may be ignored on the scale of a probe, and the Boltzmann eq. reduces to the Vlasov equation and a general conclusion from Liouville's theorem,

"*f(v)* is constant along trajectories".

Density and current are velocity space moments over *f(v)*.



Irving Langmuir

Katherine Blodgett

Turning Point Method

For an given potential solution, the turning point method, TPM, [L. Parker, 1981] can be used to compute particle density and currents from a collisionless isotropic plasma (no B) about a spherical or cylindrical probe.

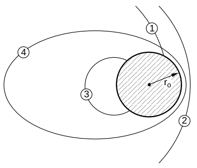
Density and current are velocity space moments over the distribution function, $f(v) = f(v_r, v_\theta)$. From Louisville's theorem, $f()$ is constant along trajectories. These are curves in $v_r\, v_\theta$ space and must be computed numerically.

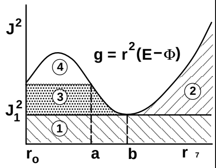
Transform to a E, J (energy and angular momentum) space by observing, $J^2 = r^2 v_\theta^2$, and,

$$E = \Phi + v^2 = \Phi + v_r^2 + J^2/r^2.$$

Trajectories are straight lines and the space may be sectored by observing that *real* trajectories have $v_r^2 > 0$ everywhere along the trajectory, or $J^2 < g = r^2(E - \Phi)$.

Moment integrals are still numerical, but over limits determined by inspection..





Orbit Limited Collection

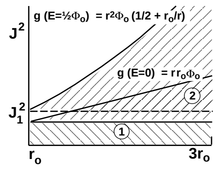
A special case of probe theory, valid for an isotropic (Maxwellian) plasma in the limit of large Debye length, is Orbit Motion Limited collection, OML, [Mott-Smith & Langmuir, 1926; Laframboise & Parker, 1973].

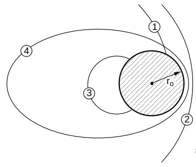
With negligible space charge, the potential is Laplacian or $\Phi = \Phi_o r_o/r$. The limiting J^2 for $v_r^2 > 0$, is given by the 'g' curves in the figure for two values of the particle energy.

By inspection, we see there exists only type 1 and type 2 orbits, i.e...., there are no J^2 barriers between any point and infinity.

At the limit, g, $v_r = 0$, and the trajectory is tangential, and at J = 0, $v_\theta = 0$. Thus all orbits connect to infinity, once for type 1, and on both ends for type 2.

At r_o we have only type 1, so we may return to velocity space and determine the current:





Orbit Limited Collection

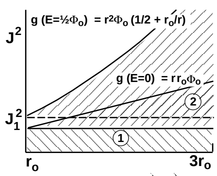
The current is the first moment of the normal velocity, v_r over the velocity distribution:

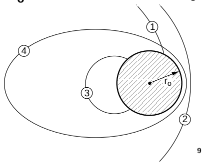
$$I = \int f(v) v_r\, d^3v$$

$$= n_\infty \pi^{-3/2} (2\pi) e^{-\Phi} \int_{(-\Phi)^{1/2}}^{\infty} e^{-v^2} v^3 dv = I_o(1+\Phi)$$

The 2π results from the full half space integral over polar angles, the Orbit Motion Limit.

The density in general still requires numerical integration because of the mix of orbit types, but approximations may be made for points near and far from the probe.





Space Charge Limited Collection

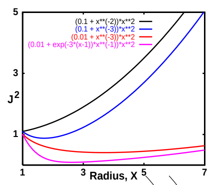
Another special case of probe theory, valid for an isotropic plasma in the limit of small Debye length, is Space Charge Limited collection, [Langmuir and Blodgett, 1924].

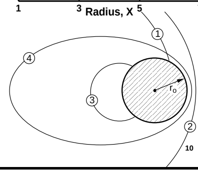
With non-negligible space charge, the potential must be determined by Poisson's equation self-consistently with the density. Simple forms for Φ are not generally available, however we may learn much from inspecting special cases.

For the case of $\Phi = \Phi_o(r_o/r)^2$, we may observe that '2' is the greatest power of radius that presents no J barrier.

For higher powers, as illustrated, we see that barriers begin to develop at some distance from the probe.

For large powers and high potential (negligible E), we may observe that the barrier is also an absorption radius. This is the Space Charge limited case and if the absorption radius, r_a, can be found, the current is just, $I = J_o 4\pi r_a^2$.





Space Charge Limited Collection

The absorption radius, or sheath edge may be determined by appealing to a space charge limited diode model.

For an infinitesimally thin sheath, we may integrate the 1D Poisson equation to derive the famous Child-Langmuir equation [Child, 1911; Langmuir, 1913]. For particles of mass *m*, a gap of thickness *D*, and a potential drop *V*, the current density *J* is.

$$J = (4/9)\,\varepsilon_o\,[2e/m]^{1/2}\, V^{3/2}/D^2$$

At the sheath edge, $J = J_o = Ne\sqrt{kT/2\pi m}$, the thermal current density. Substituting,

$$D = 1.26\,\lambda_D\,[eV/kT]^{3/4}$$

For a spherical sheath, the numerical procedure of Langmuir and Blodgett [1924] has been fitted to the semi-analytic equations of Parker [1981] and is further approximated here for conditions where $R_o/\lambda_D > 10$, and $D/R_o > 10$. The sheath radius R_{LB} , is,

$$R_{LB} = R_o\,[D/R_o]^{\alpha}, \quad 1/2 < \alpha < 4/7$$

The total current is, $PI = J_o P\, 4\pi R_{LB}^2$, where we have introduced the pre-sheath and its enhancement factor, P.

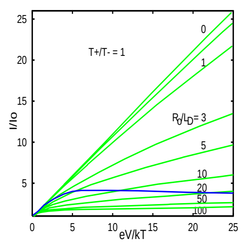
Current Collection Between the Limits

The Turning Point or Equivalent Potential methods, combined with a Poisson solution provide self-consistent solutions for both the charge density about a spherical probe and the probe current.

The plot shown here, [from Laframboise,1966] was computed with the Equivalent Potential method, for an isotropic unmagnetized Maxwellian plasma with equal ion and electron temperatures .

The $R_o/\lambda_D = 0$ curve represents the OML limit.

The 'other' crossing curve delimits the regime for the appearance of an absorption radius and thus the beginning of the Space Charge Limited collection,



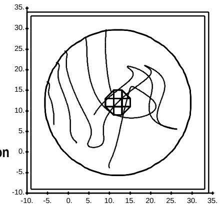
Magnetic Field Limited Collection
The Parker-Murphy Theory

Parker and Murphy [1967] derived a rigorous limit on the distance from which a charged particle may be collected across a magnetic field, B.

For a sheath that is symmetrical about the magnetic field, $B = B_z$, the *z* component of a charged particle's canonical angular momentum L_z, will be conserved.

The theory is a highly regarded standard for evaluation of both theoretical and experimental results.

It is also difficult to observe in space.



At $z = \infty$ and $\rho = R_{PM}$; $\dot{\rho} = 0,\ \dot{z} = 0,\ V = 0,\ \varphi = 0$, and $L_z^{\infty} = R_{PM}^2 eB/2$

At $z = 0$ and $\rho = R_o$; $\dot{\rho} = 0,\ \dot{z} = 0,\ V = V_o$, by conservation of energy,

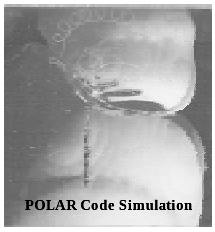
$$R_o\dot{\varphi} = \sqrt{2eV_o/m},\ \text{and}\ L_z^0 = R_o^2 eB/2 + mR_o\sqrt{2eV_o/m}.$$

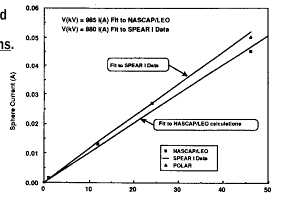
Equating $L_z^{\infty} = L_z^0$, we find ; $R_{PM}^2 = R_o^2\left[1 + \sqrt{8V_o m/eB^2R_o^2}\right]$

Magnetic Field Limited Collection
SPEAR I Results

The SPEAR I (Space Power Experiments Aboard Rockets) measured electron collection from a near stationary HV probe with no electron beams.

•Good agreement with 3D steady state simulations (classical magnetic limiting)





Katz, et al., JGR, February 1989

POLAR and NASCAP-LEO adhere to Parker-Murphy limit for symmetric collection

•No mystery with full geometry models

•Similar results from CHARGE-2B

•Agreement with no flux tube depletion!

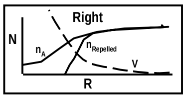
The Presheath and
Bohm Sheath Criterion

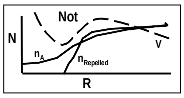
Consider an absorbing sheath.

The repelled species has a density given by a (very good) Boltzmann approx., $N_r(\Phi) = N_o \exp(\Phi)$.
If $\Phi_s = 0$ on the sheath edge, $N_r(\Phi_s) = 1$.

The attracted species has only the ingoing half of the distribution. If $\Phi = 0$ from the edge to ∞, $N_a(\Phi_s) = 1/2$.

Outside the sheath, we should have quasi-neutrality, $N_a \approx N_r$. So it must be that $\Phi_s \neq 0$.





Parrot et al. [1982] have developed a quasi-neutral iteration for Φ_s to determine:
$\Phi_s = 0.49$, $N_a = 0.61$, and $J_s = 1.49\ J_o$ in the limit of totally absorbing sheath.
- Assumes no magnetic field and Orbit Motion Limited, OML, collection.

The Bohm sheath criterion [Bohm,1949] states that throughout the sheath, $N_a > N_r$..
- Satisfied by the Parrot et al. theory.
- Must be satisfied by any presheath collection model [Riemann, 1991]

A Heated Pre-Sheath Model for
TSS Current Collection [Cooke & Katz, 1998]

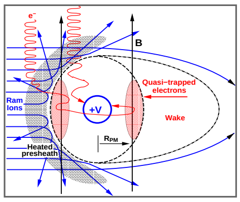
Reflecting ions create a mild density enhancement throughout the pre-sheath.

A Bohm stable pre-sheath requires a (nearly) matching electron density.

Strict magnetization of electrons leads to 1D continuity and an electron density reduction.

3D OML collection give an enhancement, but fluctuations are required for demagnetization.

Fluctuations heat a pre-sheath electron fluid.



Assuming a constant density in the presheath, and zero charge density allows analytic integration of the fluid equations.

We assume a well defined absorbing sheath at the Parker-Murphy radius, R_{PM} .

The presheath electron flux is integrated over the Ram side for an enhancement over the Parker-Murphy adiabatic limit.: $I = \frac{1}{2} I_{P\text{-}M} (1 + (1 + 2E_{Ram}/5T_o)^{1/2})$

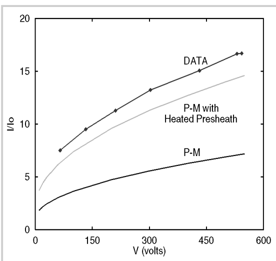
TSS Current Collection
during EGA Emission

The early results by Wright et al. [1997] are show in the figure.

Later collection of all similar data by Thompson et al., [1998] clusters well with the Wright results.

The Thompson enhancement factors over P-M theory range from 2.2 to 2.9.

The model presented here predicts an enhancement of 2.5.



$I = \frac{1}{2} I_{P\text{-}M} (1 + (1 + 2E_{Ram}/5T_o)^{1/2})$

Conclusion

•It's the Spacecharge; maybe an obvious conclusion, but if one wants to distinguish the interaction of bodies with plasma from the other effects of charged particles, the key feature is the spacecharge.

•The classical theories of probes are important tools for understanding plasma effects.

•However, classical probe theory as an analytical tool has its limitations and the scientist/engineer must know the limitations as well as the strengths.

•Numerical simulation is often required.

•There are still many interesting and unanswered problems which as always, will be best addressed by a balanced approach with theory, experiment, and models.