A surface physics inspired model for particle charging in plasmas

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Outline

Introduction

- qualitative discussion of the build-up of surface charges

Physisorption-inspired charging model

- surface states for electrons and ions
- "effective" electron and ion surface densities

Results

- criteria to determine $Z_p = Q_p/(-e)$
- power, pressure, and radius dependence of Z_p

Conclusions

- sum-up and to do's

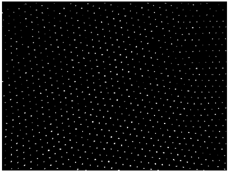
Introduction (1)

Macroscopic objects in an ionized gas acquire a charge

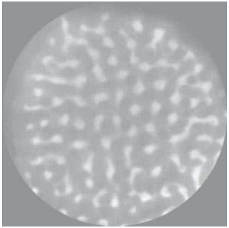
- plasma boundaries in general
- artificial satellites in the ionosphere of planets
- dust particles in the interstellar medium
- contaminants in processing discharges
- aerosols in the upper atmosphere
- grains in laboratory plasmas

Problem of plasma-boundary interaction

- solid state physics meets plasma physics
- quantum meets classical mechanics
  in a plasma context

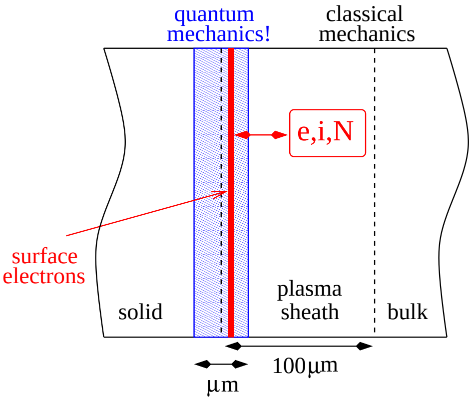


A. Piel *et al.* 2008



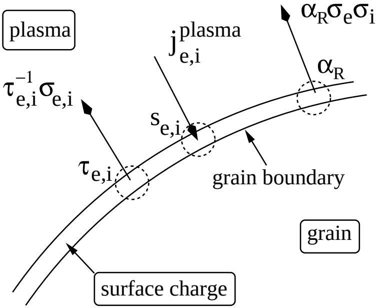
L. Stollenwerk *et al.* 2007

Introduction(2)



Introduction (3)

Lets consider a spherical grain with radius $R \ll \lambda_D$.



<u>Quasi-stationary surface charge density</u> (in units of $-e$)

$$0 = d\sigma_e/dt = s_e j_e^{\text{plasma}} - \tau_e^{-1}\sigma_e - \alpha_R\sigma_e\sigma_i$$
$$0 = d\sigma_i/dt = s_i j_i^{\text{plasma}} - \tau_i^{-1}\sigma_i - \alpha_R\sigma_e\sigma_i$$
$$\Longrightarrow \sigma_p = \sigma_e - \sigma_i$$

phenomenological!

Introduction (4)

TR 24 complex plasmas

Standard approach

- ions reach surface $\Longrightarrow \tau_i^{-1} = 0$
- $\tau_e^{-1} = 0$ or at least $\tau_e^{-1}\sigma_e \ll s_i j_i^{\mathrm{plasma}} = \alpha_R \sigma_e \sigma_i$.
- $s_e = s_i = 1$ or at least $s_e = s_i$

$\Longrightarrow$ grain $\hat{=}$ perfect absorber for e^- and A^+

$\Longrightarrow j_e^{\mathrm{plasma}}(\sigma_p) = j_i^{\mathrm{plasma}}(\sigma_p)$ at $r = R$

We challenge all 3 assumptions

- surface states $\Longrightarrow A^+$ & e^- spatially separated
- if A^+ & e^- spatially separated then $\alpha_R \sigma_i \sigma_e \ll \tau_{e,i}^{-1}\sigma_{e,i}$
- physisorption $\Longrightarrow s_e \ll s_i$

$\Longrightarrow \sigma_p = (s\tau)_e \cdot j_e^{\mathrm{plasma}}(\sigma_p)$ at $r_e = R$

$\sigma_i = (s\tau)_i \cdot j_i^{\mathrm{plasma}}(\sigma_p)$ at $r_i \gtrsim r_e$

Within our approach $(s\tau)_{e,i}$ important surface parameter!

phenomenology $\Longrightarrow (s\tau)_{e,i} \simeq (s\tau)_{e,i}^{\mathrm{LJD}} \equiv \frac{h}{kT_{p,g}} \exp\left[\frac{E_{e,i}^d}{kT_{p,g}}\right]$ with $T_g \sim 300K$

and T_p adjustable parameter $\rightarrow T_p$ measurement $\rightarrow$ H. Maurer *et al.* $\boxed{\text{P4.7}}$

Charging model (1)

Electron and ion surface states

grain $(R, Z_p, \epsilon) \Longrightarrow V_{e,i}(x) = [U_C(r) + U_p(r)]/U_f = \frac{1}{1+x}[\pm 1 - \frac{\xi}{x(1+x)(2+x)}]$,

$$U_f = e^2 Z_p/R,\ x = r/R - 1, \text{ and } \xi = (\epsilon - 1)/2(\epsilon + 1)Z_p$$

electrons: $x \ll 1,\ V_e(x) \simeq 1 - \xi/2x$ (image potential)
$\lambda_e^{dB}/R \simeq |V_e/V_e'| \simeq 10^{-4}$ @ $x \simeq 10^{-4} \Longrightarrow e^-$ quantum mechanical

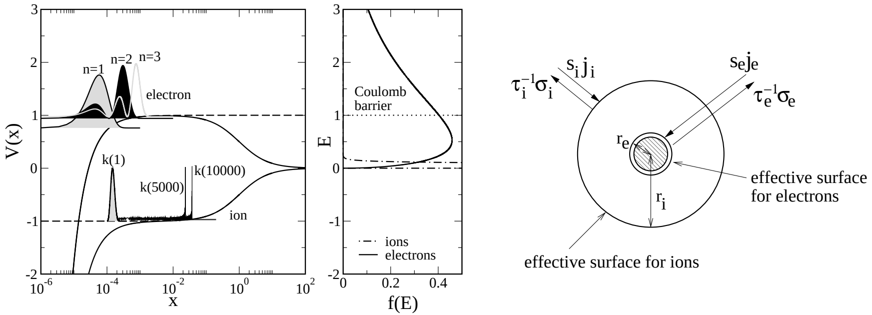
ions: $x_i^{size} \simeq 10^{-4},\ V_i(x) \simeq -1/(1+x)$ (Coulomb tail)
$\lambda_i^{dB}/R \ll |V_i/V_i'|$ @ $x \geq x_i^{size} \Longrightarrow A^+$ classical

Schrödinger equation ($E < 0 \Longrightarrow e^-$ and A^+ bound states)

$$\frac{d^2}{dx^2}u^{e,i} + \left[-\frac{\alpha_{e,i}^2}{k^2} + \tilde{V}_{e,i}(x) - \frac{l(l+1)}{(1+x)^2}\right]u^{e,i} = 0$$

with $\tilde{V}_e(x) = 2\alpha_e/x,\ \tilde{V}_i(x) = 2\alpha_i/(1+x)$, and BC @ $x \to \infty$ and $x = \begin{cases} x_b \simeq 0 \\ x_i^{size} \end{cases}$

Charging model (2)



$\underline{e^-}$: high energy, come close to the surface, inelastic scattering with grain

$$\Longrightarrow E_e^d = |U_C(R) - E_1| = \frac{1}{16}\left(\frac{\epsilon-1}{\epsilon+1}\right)^2 R_y \simeq 0.5\ eV \Longrightarrow (s\tau)_e^{\mathrm{LJD}}$$

$\underline{A^+}$: low energy & $x_i^{size} > 0$, already trapped in Coulomb tail, inelastic scattering with neutrals (CX)

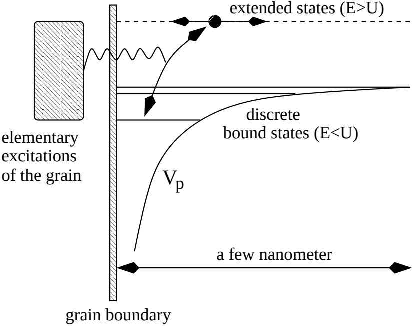
$$\Longrightarrow 2\pi r_i = l_{cx} = (\sigma_{cx} n_g)^{-1} \text{ (largest "stable" orbit)}$$

$$\Longrightarrow E_i^d = |U_C(r_i)| = 4\pi\sigma_{cx} a_B n_g Z_p R_y \simeq 0.37\ eV \Longrightarrow (s\tau)_i^{\mathrm{LJD}}$$

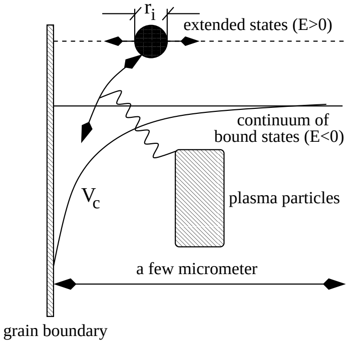
Charging model (3)

Energy relaxation at the grain boundary

a) e^-



b) A^+



$\Longrightarrow E^d_{e,i}$ and $(s\tau)^{\mathrm{LJD}}_e$

$\Longrightarrow s_{e,i}$ and $\tau_{e,i}$

Charging model (4)

"Effective" e^- and A^+ surface densities

quasi-stationary charge in the vicinity of the grain ($x_D = \lambda_D/R \gg 1$):

$$Z(x < x_D) = Q(x < x_D)/(-e) \simeq 4\pi R^3 \int_{x_b}^{x} dx' \left(1 + x'\right)^2 \left[n_e^b(x') - n_i^b(x') + \dots \right]$$

- effective surface density: $n_{e,i}^b(x) \simeq \sigma_{e,i}\delta(x - x_{e,i})/R$, with $x_e \simeq 0$ and $x_i \simeq 1 - 10$
- individual (!) quasi-stationarity of "surface densities "
  $\Longrightarrow \sigma_{e,i} = (s\tau)_{e,i} j_{e,i}^{\text{plasma}}$

final equations for particle charge and its partial screening due to trapped A^+:

$$Z_p \equiv Z(x_e < x < x_i) = 4\pi R^2 \cdot (s\tau)_e \cdot j_e^{\text{OML}}(Z_p, n_e, T_e)$$

$$Z_i \equiv Z_p - Z(x_i < x < x_D) = 4\pi R^2 (1 + x_i)^2 \cdot (s\tau)_i \cdot j_i^B$$

- Z_p resides on grain surface
- Z_i resides on effective surface where we subsume all trapped A^+

Results (1)

Criteria to determine Z_p

1. orbital motion limited charges: $j_e^{\mathrm{OML}} = j_i^{\mathrm{OML}} \Longrightarrow Z_p$

2. charge-exchange enhanced charges: $j_e^{\mathrm{OML}} = j_i^{\mathrm{OML}} + j_i^{\mathrm{CX}} \Longrightarrow Z_p$
(M. Lampe *et al.* (01 & 03), S. A. Khrapak *et al.* (05))

3. surface model: approximate $(s\tau)_e \simeq (s\tau)_e^{\mathrm{LJD}} = \frac{h}{kT_p} \exp\left[\frac{E_e^d}{kT_p}\right]$ and adjust T_p such that
$Z_p = 4\pi R^2 \cdot (s\tau)_e^{\mathrm{LJD}} \cdot j_e^{\mathrm{OML}} = Z_p^{\exp}$

where the fluxes are defined by

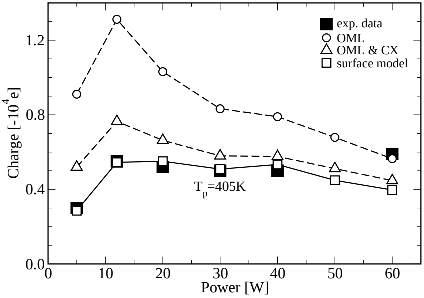
$$j_e^{\mathrm{OML}} = n_e \sqrt{\frac{k_B T_e}{2\pi m_e}} \exp[-\frac{Z_p e^2}{R k_B T_e}],\ j_i^{\mathrm{OML}} = n_i \sqrt{\frac{k_B T_i}{2\pi m_i}} [1 + \frac{Z_p e^2}{R k_B T_i}],$$

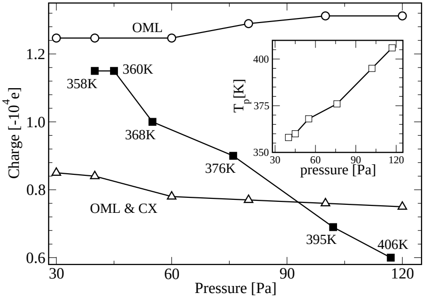
$$j_i^{\mathrm{CX}} = 0.1 n_i \frac{\lambda_i^D}{l_{\mathrm{cx}}} \sqrt{\frac{k_B T_i}{2\pi m_i}} \left(\frac{Z_p e^2}{R k_B T_i}\right)^2, \text{ and } j_i^{\mathrm{B}} = 0.6 n_i \sqrt{\frac{kT_e}{m_i}}$$

Results (2)

MF particle in He discharge (A. Melzer (97))

- $R = 4.7\ \mu m$
- $T_{e,i}$ and $n_{e,i}$ known, $\sigma_{\mathrm{cx}} = 0.32 \times 10^{-14} cm^2$

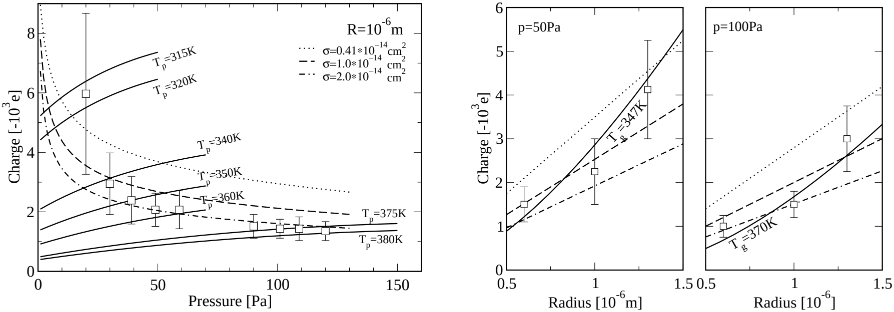




- our approach works, predicted T_p reasonable
- $Z_i \simeq 150$ (at $p = 102 Pa$) in accordance with MD simulations (S. J. Choi *et al.* (94))

Results (3)

MF particle in Ne discharge (S. A. Khrapak *et al.* (05))

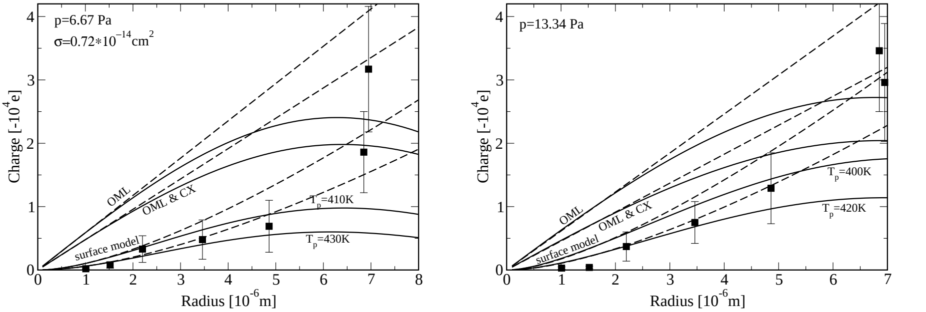


- our approach reproduces non-linear R-dependence of Z_p

Results (4)

MF particle in Ar discharge (E. B. Tomme *et al.* (2000))

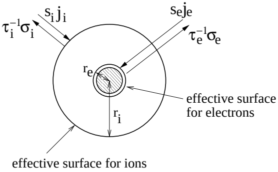
- particles confined in sheath $\Longrightarrow n_e(R) = n_e \exp[e\Phi(z_{\mathrm{eq}}(R))/kT_e]$



- our approach works particularly well for $R < 5\ \mu m$
- ad-hoc description of j_e^{plasma} perhaps too crude for $R > 5\ \mu m$ (secondary electron emission from electrode?)

Conclusions

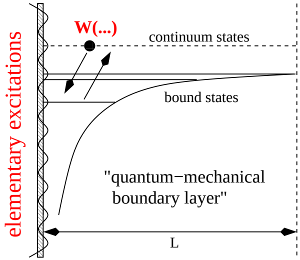
Sum-up and to do's

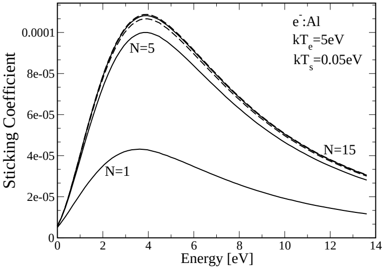


- We questioned the treatment of grains as perfect absorber for e^- and A^+
- and presented a surface physics inspired charging model (F. X. Bronold *et al*, PRL 101, 175002 (08)).
  charge of a dust particle $\longleftrightarrow$ microphysics at its surface
- Model based on two main hypotheses:
  1. ions get stuck in disturbed region of the grain
  2. electrons are bound in external surface states
- Using T_p as an adjustable parameter model works very well.
  $\Longrightarrow$ hypotheses have to be justified theoretically. Thats what we do now!
  $\Longrightarrow$ microscopic calculation of $s_{e,i}$ and $\tau_{e,i}$. Thats what we do now!
  $\Longrightarrow$ Z_p and T_p should be measured simultaneously.
- Diagnostics of electronic structure of grain surface would be very helpful (IPES etc.).

Sticking, desorption

e^- : metal surface





$\mathcal{W}(\ldots) \Rightarrow s_e \;\&\; \tau_e$

- internal electron-hole pairs
- golden rule & PT $\Rightarrow s_e, \tau_e$ (Bronold *et al.* submitted to EPJD 2009)

$\Rightarrow s_e \sim 10^{-4}$ very small; approximation?

$\Rightarrow \tau_e \sim 10^{-2}s$ very large; assumption of thermodynamical equilibrium?