Distribution of the electric potential arounf a small absorbing body in plasmas: Effect of ion-neutral collisions

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Motivation I

- Electric interaction is one of the main mechanisms of interparticle interactions in complex (dusty) plasmas (although other effects, e.g. ion and neutral shadowing, wake formation can be also important under certain conditions)

- Electric potential in isotropic plasma is often modeled by Debye-Hückel (Yukawa) short-range potential

$$\boxed{\phi(r) = -(Ze/r)\exp(-r/\lambda)}$$

where $Z>0$ is the particle charge number, λ is the plasma screening length, and the charge is negative

- This potential can be obtained by linearizing Poisson equation with the assumption that plasma electrons and ions obey Boltzmann distributions

Motivation II

- ✓ Two important features of complex plasmas are system openness and strong ion-grain coupling

- ✓ In collisionless plasmas Debye-Hückel potential with "effective" λ can be a good approximation up to several λ (Daugherty et al., 1992; Klumov 2006). At larger distances the potential is not exponentially screened, but decays as r^{-2} due to plasma absorption on the grain (Al'pert et al., 1965)

- ✓ Ion-neutral collisions affect grain charge and potential even when ions are weakly collisional ($l_i > \lambda$) (Zobnin et al., 2000; Lampe et al., 2003; Khrapak et al., 2005). In the continuum limit the potential is not screened at all, and decays as r^{-1} (Bystrenko and Zagorodny 2003; Khrapak et al., 2006).

- ✓ This motivated us to perform an analytical analysis of the combined effect of plasma absorption and ion-neutral collisions on the electric potential distribution using a simple kinetic model

Electric potential: Model

- Small individual grain of (negative) charge Q immersed in an isotropic stationary weakly ionized plasma
- The plasma sources and sinks are absent, except at the grain surface which is fully absorbing
- Electrons obey Boltzmann distribution

$$\mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \frac{e\mathbf{E}}{m_i}\frac{\partial f}{\partial \mathbf{v}} = \underbrace{\boxed{-\nu(f - nf_M)}}_{\text{collisions}} \underbrace{\boxed{-\delta(\mathbf{r})v\sigma(v)f,}}_{\text{absorption}}$$

$$n_e \approx n_0 \exp(e\phi / T_e),$$

$$\Delta\phi = -4\pi e(n_i - n_e) - 4\pi Q\delta(\mathbf{r}).$$

Here $\sigma(v)$ is the effective collection cross-section related to the actual ion flux, $J_i = n_0 \int v\, \sigma(v) f_M(v) d^3 v$

[Filippov et al., JETP 104, 147 (2007)]

Electric potential: Result

$$\boxed{\phi(R) = \frac{Q}{R}\exp\left(-\frac{R}{\lambda}\right) - \frac{8}{\pi^{3/2}}\frac{en_0\lambda^2}{R}\int\frac{\sin(kR)F(\xi)dk}{1+k^2\lambda^2},}$$

where

$$F(\xi) = \frac{\int x^2\sigma(x)\exp(-x^2)\arctan(x/\xi)dx}{1-\sqrt{\pi}\xi\exp(\xi^2)[1-\mathrm{erf}(\xi)]},$$

$$x = \left(v/\sqrt{2}v_{Ti}\right),\ \text{and}\ \ \xi = \left(\nu/\sqrt{2}kv_{Ti}\right) = 1/kl_i$$

1) No absorption ($\sigma(v)$=0) ➔ Yukawa (Debye-Hueckel potential), collisions do not play any role

2) No collisions (ν=0) ➔ $\phi(R) \approx \pi en_0\lambda^2(1+2z\tau)(a^2/R^2)$ at $R\to\infty$ (with OML collection cross section)

Weakly collisional regime: Charging

Collision enhanced plasma collection (CEC) model

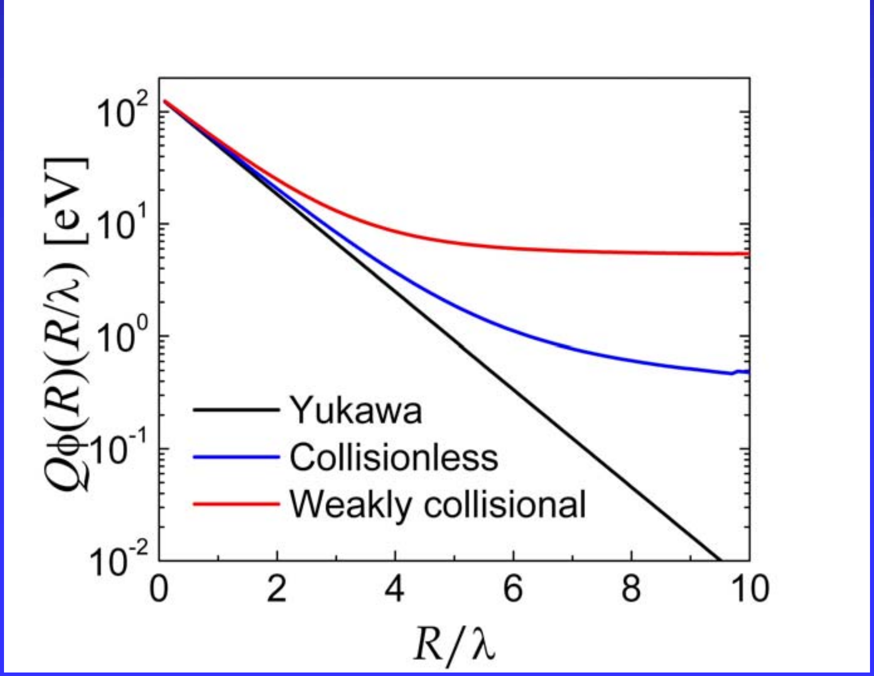
Collisional enhancement of the ion flux

Weakly collisional regime: Electric potential

$$\phi(R)=\frac{Q}{R}\exp\left(-\frac{R}{\lambda}\right)$$
$$-\frac{\sqrt{\pi}}{4\sqrt{2}}\frac{eJ_i\lambda}{Rv_{Ti}}\left\{\exp\left(-\frac{R}{\lambda}\right)\mathrm{Ei}\left(\frac{R}{\lambda}\right)-\exp\left(\frac{R}{\lambda}\right)\mathrm{Ei}\left(-\frac{R}{\lambda}\right)+\pi^{3/2}\frac{\lambda}{l_i}\left[1-\exp\left(-\frac{R}{\lambda}\right)\right]\right\}$$

PLASMA PARAMETERS

Ar gas at p~12 Pa, n_0~3×10^8 cm^{-3}, T_e~4 eV, T_i~0.03 eV, a = 1 μm → λ~ 70 μm, l_i~ 200 μm, Z ~3000.



Highly collisional regime

$$\boxed{\phi(R)=\frac{Q}{R}\exp\left(-\frac{R}{\lambda}\right)-\frac{e}{R}\frac{J_i\lambda^2}{l_i v_{Ti}}\left[1-\exp\left(-\frac{R}{\lambda}\right)\right]}$$

- ✓ This expression coincides with that recently obtained using hydrodynamic approach [Khrapak et al., PRL 99, 055003 (2007)]

- ✓ In the limit of point-like grain ($a/\lambda << 1$) we have $J_i \approx 4\pi n_i l_i v_{Ti}(Ze^2/T_i)$ and the potential at $R > \lambda$ has a Coulomb-like form

$$\boxed{\phi(r)=(Q/r)(1+T_i/T_e)^{-1}}$$

i.e., partial plasma screening reduces the magnitude of the effective grain charge compared to the actual value

Consequences

- ✓ Crystallization and melting of complex plasma, crystal structures, phase diagrams of complex plasma
- ✓ Occurrence of liquid-vapor critical point in complex plasma
- ✓ Possibility to adjust the strength of interparticle electrostatic coupling by varying neutral gas pressure
- ✓ Transport properties of complex plasmas (diffusion, viscosity, etc.)
- ✓ Ion drag force in complex plasmas
- ✓ Low-frequency waves in strongly coupled complex plasmas
- ✓ etc.

Summary

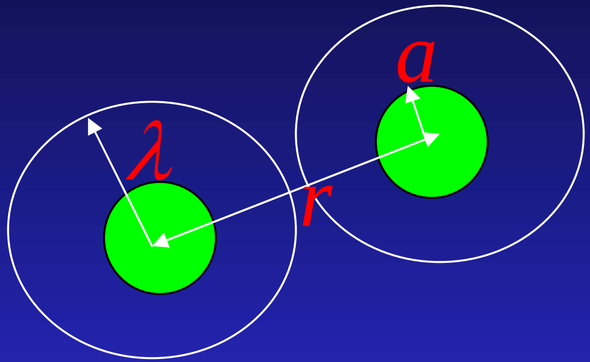
- ✓ The combined effect of plasma absorption and ion-neutral collisions on the distribution of electric potential around an individual grain in plasmas has been investigated using a simple kinetic model.
- ✓ Collection of collisional ions considerably enhances the absolute magnitude of the potential
- ✓ The long-range asymptote of the potential is Coulomb-like with the effective charge depending on the strength of collisionality
- ✓ Some consequences of these results have been discussed and problems requiring further study have been formulated

Thank you for your attention

Interaction

- Debye-Hückel (Yukawa) short range potential (Daugherty et al., 1992; Konopka et al., 2000)

$$\boxed{U(r) = (Z^2 e^2 / r)\exp(-r/\lambda)}$$



- Two dimensionless parameters
  - Coupling parameter, $\Gamma = \dfrac{Z^2 e^2}{\Delta T_d}$
  - Structure (lattice) parameter, $\kappa = \Delta / \lambda$
- "Screened" coupling parameter, $\Gamma_{ES} = \Gamma \exp(-\kappa)$

$$\Gamma \exp(-\kappa)(1+\kappa+\kappa^2/2) \approx 106$$