Effects of Heliosphere Plasma on the Properties of Astrophysical Dust Grains

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Introduction

Solar phenomena, including ionizing electromagnetic radiation and an influx of charged particles in the solar wind, maintain an ionized environment throughout the heliosphere. Planetary environments are typically colder, dominated by neutral molecules and dust grains.

At the interface between these two regimes, hot plasma interacts with cold heavy molecules and astrophysical dust, creating a novel *dusty plasma* environment.

- A dusty plasma is a weakly-ionized plasma that contains small particles, typically on the order of nanometers to microns in diameter.
- "Dust" can have a variety of compositions, including rock particulates, ices, and large molecules.
- Examples of dusty plasmas in the space environment include planetary rings, comet tails, and the planetary ionospheres.

Fig 1: Examples of dusty plasmas. From left to right: comet outgassing, Saturn's rings, ice plumes of Enceladus, Earth's noctilucent clouds

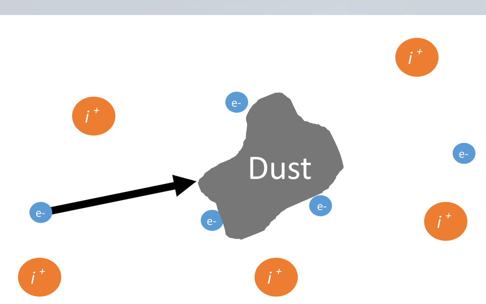
- Thermal motion of ions and electrodes cause a current flux to the dust grain surface, accumulating charge
- Dust grains act like a new species of ion, with charge numbers of 10^2 to 10^5 in magnitude, fundamentally changing dynamics of dust-plasma system

A simple charge balance

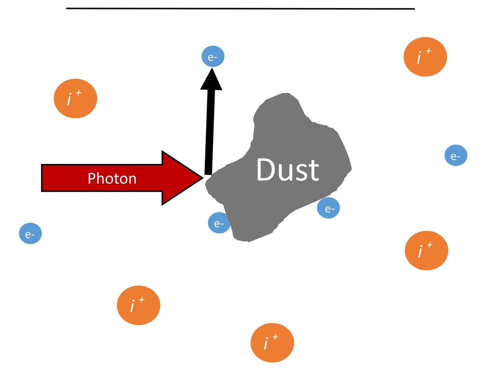
By charge conservation, all charge must sum to zero. In terms of charge densities,

$$n_i = n_e + Z_d n_d$$

n_σ is the charge density of ions, electrons, or dust particles. Z_d is the charge number on each dust grain.



Electron flux causes dust charge to be more *negative* ($Z_d > 0$)



Photoionization causes dust charge to be more *positive* ($Z_d < 0$)

- Dust charge changes at the expense of the free electrons.
- The equilibrium charge distribution depends on dust and plasma conditions
- Electron flux typically dominates, and dust builds large negative charges.

Effects of a bimodal electron energy distribution

If incoming electrons are not at a uniform temperature, equilibrium dust charge becomes more difficult to predict. Dynamical processes are highly dependent on the ion and electron energy distributions, which are driven by solar conditions in the heliosphere.

If a some small percentage δ are at a higher temperature, charge conservation can be written:

$$n_i = n_{e,H} + n_{e,C} + Z_d n_d \qquad \begin{aligned} n_{e,H} &= \delta\, n_e \\ n_{e,C} &= (1-\delta) n_e \end{aligned}$$

The effect of such an *energy* distribution on the equilibrium *charge* distribution is calculated. Define two nondimensional quantities:

- let α be the fraction of electrons bound to the dust grain
- Let ψ_d be the ratio of potential energy at the dust surface to its kinetic energy

$$\alpha = \frac{Z_d n_{d0}}{n_{i0}} = 1 - \frac{n_{e0}}{n_{i0}}$$

$$\psi_d = -\frac{e\varphi_d}{kT_i}$$

In equilibrium, ion and electron currents to the dust surface sum to zero. Therefore:

$$0 = n_i(1+\psi_d) - \delta n_{e0}\sqrt{\frac{m_i}{m_e}}\sqrt{\frac{T_{e,H}}{T_i}}\exp\left(-\psi_d\frac{T_i}{T_{e,H}}\right) - (1-\delta)n_{e0}\sqrt{\frac{m_i}{m_e}}\sqrt{\frac{T_{e,C}}{T_i}}\exp\left(-\psi_d\frac{T_i}{T_{e,C}}\right)$$

This is rewritten in terms of α and solved:

$$\boxed{\alpha(\psi) = 1 - \frac{(1+\psi_d)\sqrt{\frac{m_e}{m_i}}}{\delta\sqrt{\frac{T_{e,H}}{T_i}}\exp\left(-\psi_d\frac{T_i}{T_{e,H}}\right) + (1-\delta)\sqrt{\frac{T_{e,C}}{T_i}}\exp\left(-\psi_d\frac{T_i}{T_{e,C}}\right)}}$$

Results

The boxed equation is plotted in Figure 3 for three different values of δ. It is seen that just 1% of electrons at a hot temperature (red curve) has large effects, compared to the δ=0 case (blue curve).

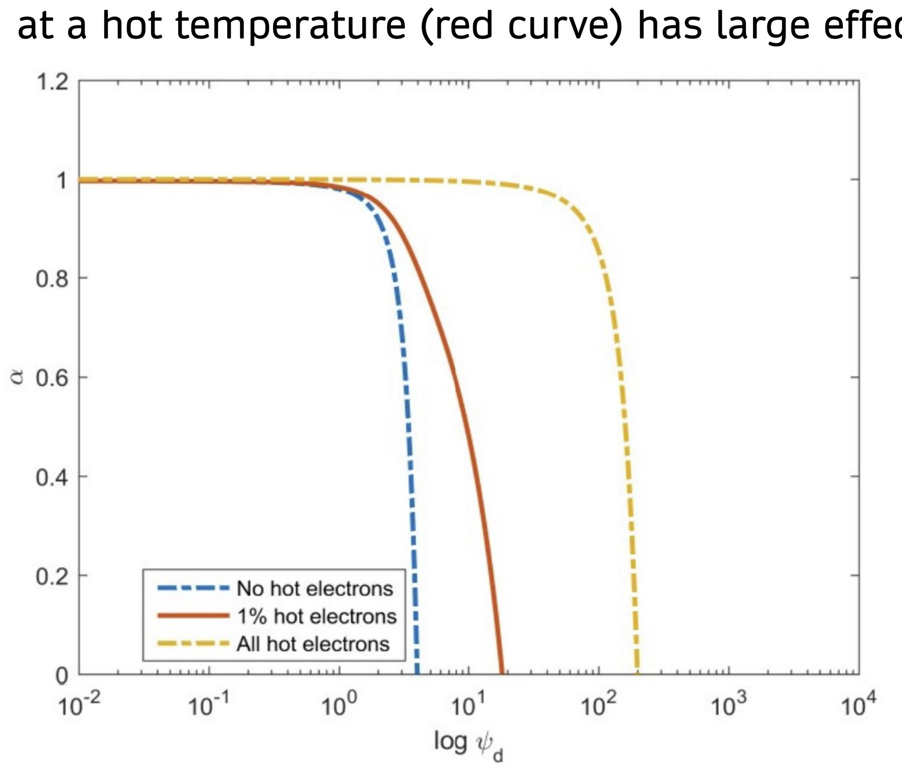


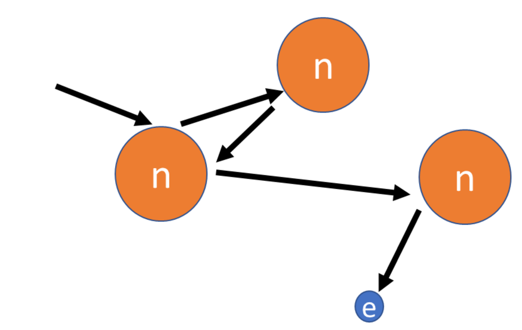
Fig 2: α - ψ curves for δ = 0, 0.01, and 1. $T_{e,C}/T_i$ = 1, $T_{e,H}/T_{e,C}$ = 80.

- When α = 1, dust absorbs all electrons from the plasma.
- In the α < 1 regime, dust charge is limited by electric repulsion of free electrons by the dust.
- Hot electrons can continue to reach the dust surface while all cold electrons are repulsed.
- The δ = 0 and the δ = 0.01 curve leave the α = 1 regime around the same ψ_d. However, the small amount of hot electrons allow dust to reach higher ψ_d for the same α.

This treatment assumes the ratio δ is held constant during the charging process. In environments where creation of hot electrons is slower than the collision time, a dip in hot electron density may occur.

Heliosphere environments

The exact electron distribution depends on the dominant mechanisms of ionization, cooling, and recombination in specific situations.



- Electrons cool through collisions with neutrals.
- If neutral temperature << energy of electrons at ionization, energy loss is:

$$\Delta w = \frac{1}{2}m_e v_e^2 \frac{4M/m_e}{(1+M/m_e)^2} \approx 2 m_e v_e^2 m_e/M$$

- The energy distribution will have two humps: one near the ionization energy, and one near the neutron temperature.
- This situation is common, as solar lyman-α radiation ionizes gas while neutrals and dust stay cold.

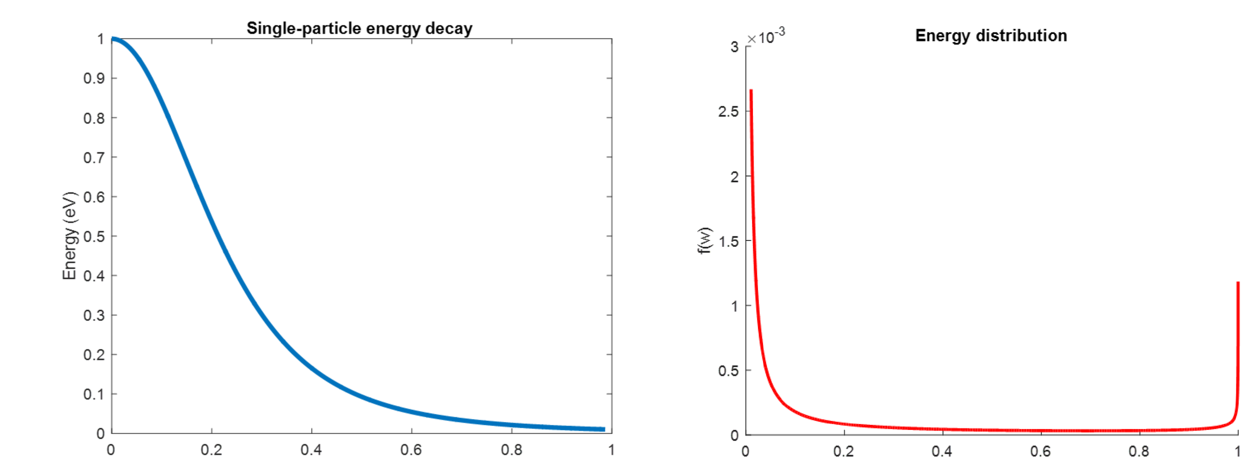


Fig 3: Energy decay of a single electron with time (left) and corresponding energy distribution of bulk electron population (right)

- When solar wind interacts with a dusty plasma, inflows and outflows of charge must be considered in charge conservation.
- Dust can absorb energetic solar wind particles, altering both charge and velocity
- This becomes important for atmospheres of planetary bodies without a magnetic field.

Summary + References

- Dusty plasma physics are relevant at the interface between the hot plasma of the heliosphere and cold planetary environments
- The charge on dust and particulates in interplanetary space and upper atmospheres is dependent on the electron distribution, and governs dynamics and behavior
- Hot electrons, due to radiation and the solar wind within the heliosphere, can dramatically increase dust charging

[1] P.M. Bellan, *Fundamentals of Plasma* Physics, Cambridge: Cambridge university press, 2006

[2] J.L. Fox et al., *Energy Deposition in Planetary Atmospheres by Charged Particles and Solar Photons.* Space Science Review, 2008

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