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Observation of Real Time Transport of ROS/RNS From the Liquid Interface in 2-D Plasma Bubble Apparatus

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The interaction of plasma with liquid water lies at the heart of a range of applications extending from water purification to plasma medicine. This interaction takes place at the plasma-liquid interface. Plasma produced ions and neutral reactive species and energy are deposited into the interfacial region, producing a wide array of active species in the liquid that ultimately diffuse into the bulk solution. The nature of the production of reactive species in this region and their subsequent transport into solution are not well understood. Conventional electrical and optical diagnostics are not generally applicable in this region. In an effort to understand the plasma-liquid interfacial region, developed a 2-dimensional bubble apparatus (2DBA) that simulates a tomographical slice of the plasma-liquid interfacial region. A bubble in water is trapped between two glass plates, with one electrode inserted into the bubble and the second surrounding the bubble. A discharge is produced in the bubble that propagates into the bubble-liquid interface. The 2-D nature of the apparatus enables the interfacial region to be imaged and studied.

We doped the water trapped between the two glass plates of the 2DBA with chemical probes sensitive to specific reactive species. The goal is to observe the propagation of reactive species produced by the plasma such as reactive nitrogen species (RNS) and reactive oxygen species (ROS) from the interfacial region into the bulk. Such studies give insight into transport rates and mechanisms. We used methyl orange to track the transport of RNS into the solution as these species lead to acidification. Methyl orange turns red when the pH drops below 4.4. We used a KI-starch solution to track the reacting front driven by the propagation of ROS from the interface into the bulk. The KI-starch solution turns dark purple in the presence of ROS.

The 2DBA was operated in two modes: DBD/microdischarge mode and streamer mode. Propagation of plasma produced reactive species in the microdischarge mode was slow and uniform. Here radicals from the discharge within the bubble diffuse to the interface, generating longer-lived species, leading to slow diffusion into the bulk. In the streamer mode, large-scale convection cells are produced from the impulsive interaction of the streamer with the liquid interface, as shown in Fig. 1. This forced convection greatly enhances radical transport from the interface into the bulk solution. These results highlight the importance of fluid dynamical effects in the transport of plasma produced reactive species into the bulk solution.

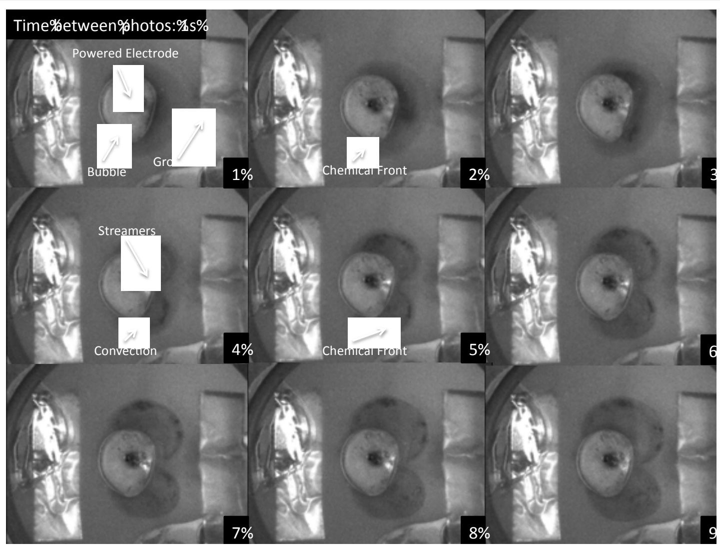
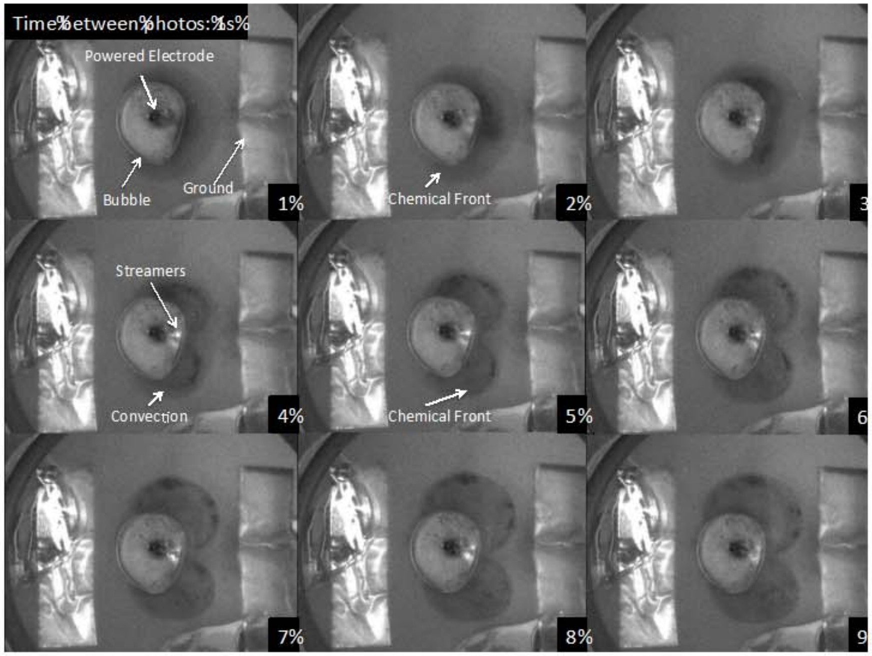


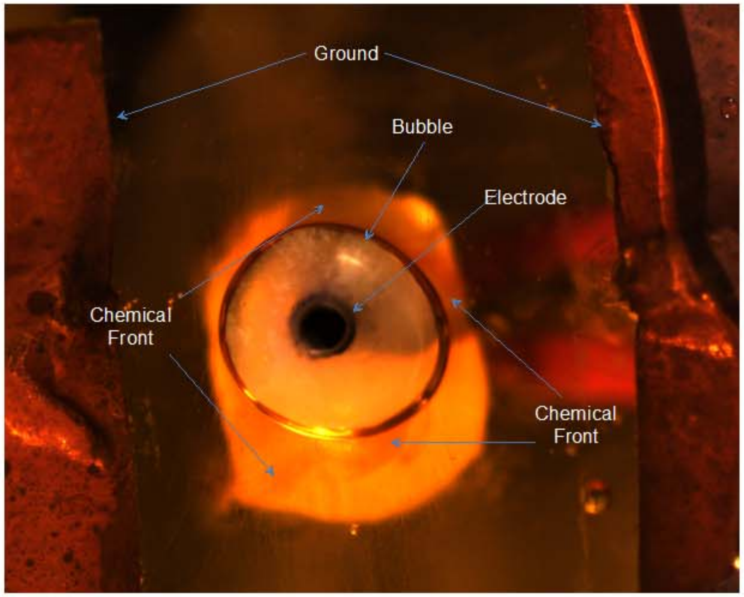
Figure 1 – Propagation of an acidified front associated with RNS driven by streamers at the plasma-liquid interface. Notice the induced circulation pattern.

REAL TIME TRANSPORT OF ROS/RNS FROM THE PLASMA-LIQUID INTERFACE

- **Using a 2-D plasma bubble apparatus, we observe transport of active species (chemical fronts) from the plasma liquid interface into the bulk solution.**
- **Strong circulation in the bulk solution induced by plasma streamers interacting with the interface suggests a fast transport mechanism from the interface.**
- **Reactive species transport from the interface into the bulk solution driven by DBD-like discharge at the interface was found to be considerably slower.**



- **Streamer induced convection**



- **Acidified chemical front produced by plasma RNS.**

Effect of Particle Charge Limits on Particle Charge Distributions in Dusty Plasmas

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A well-established theory has existed for about twenty years that predicts stationary particle charge distributions in dusty plasmas [1,2]. However, this theory does not take into account that the amount of charge a single dust particle can hold is limited. In a recently submitted paper [3], we developed an analytical expression for stationary particle charge distributions that accounts for the existence of charge limits, and we validated the analytical expression by showing agreement with Monte Carlo numerical simulations of particle charging. The existence of charge limits can significantly affect the particle charge distribution. We proposed a simple criterion for determining whether one is in the particle-charge-limited regime.

For cases where electron depletion by attachment to dust particles causes the ratio of electron-to-ion density to become small, we find that the existence of charge limits becomes relatively less important (Fig. 1) since the scarcity of free electrons relative to ions can cause particles to become much less negatively charged than their charge limit allows. We also found that ion mass plays an important role in the relative importance of charge limits, as lighter ions cause the charge distribution to shift toward less negative values.

We also examined the effect of charge limits on the temporal behavior of the charge distribution. We found that the existence of charge limits can have a strong effect on the time required to achieve a steady-state charge distribution. Smaller charge limits promote a more rapid approach to a steady state. Examination of the power spectrum of charge fluctuations indicates that the existence of charge limits increases the relative importance of high-frequency versus low-frequency charge fluctuations.

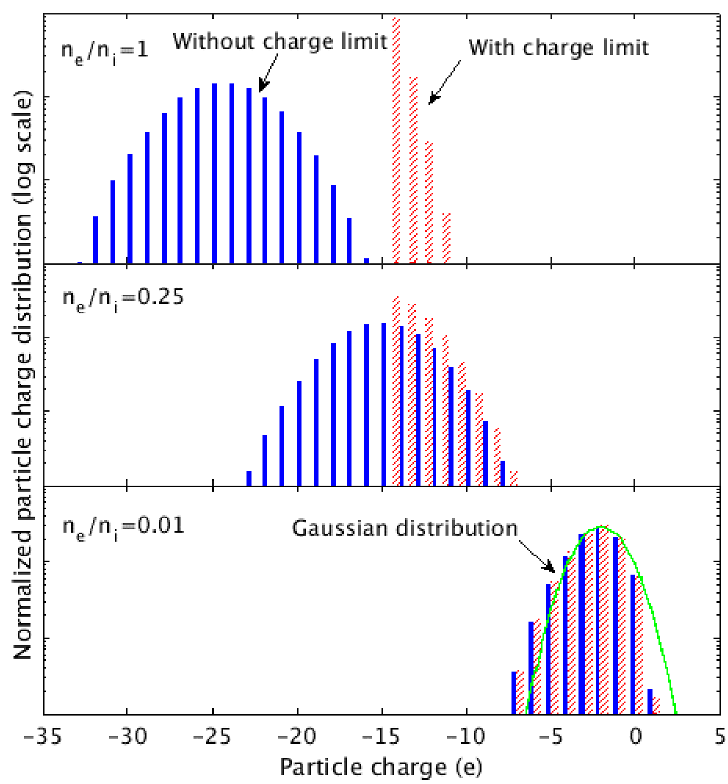


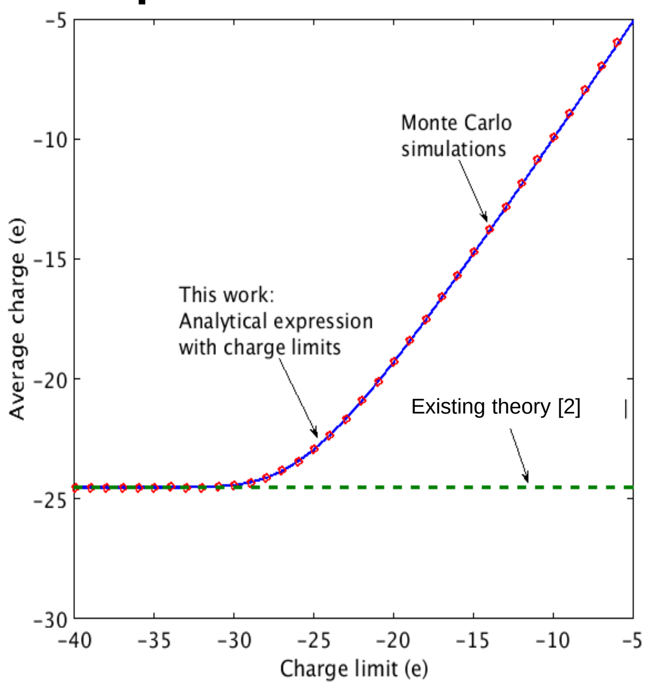
Figure 1 – Results of Monte Carlo simulations for 10-nm-diameter silicon particles in an argon plasma, with or without charge limits. Conditions: T_e = 3 eV, T_i = 300 K, and with various values of n_e / n_i.

References

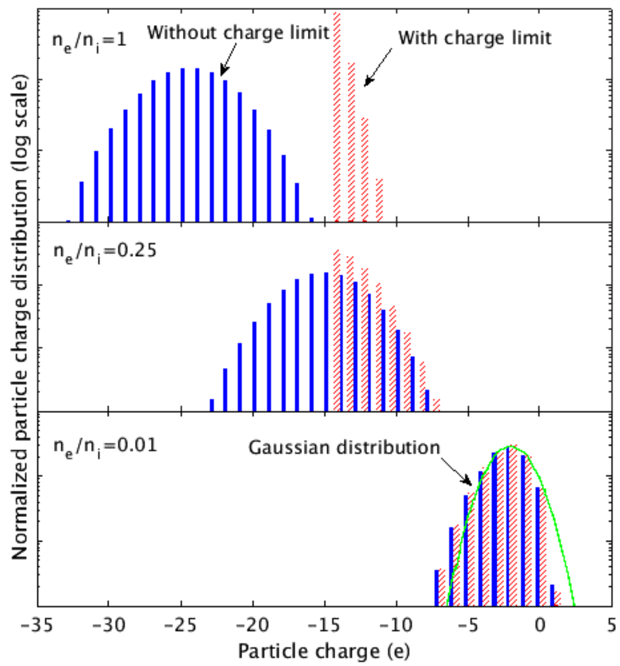
[1] T. Matsoukas and M. Russell, J. Appl. Phys. **77**, 4285 (1995).
[2] T. Matsoukas and M. Russell, Phys. Rev. E **55**, 991 (1997).
[3] R. Le Picard and S. L. Girshick, submitted (2015).

EFFECT OF SINGLE-PARTICLE CHARGE LIMITS ON PARTICLE CHARGE DISTRIBUTIONS IN DUSTY PLASMAS

- **Previous theoretical work on particle charge distributions in dusty plasmas neglect that the amount of charge a dust particle can hold is limited.**
- **We developed new analytical expression for stationary charge distributions that for accounts for existence of charge limits.[1] The theory was validated by comparison to Monte Carlo simulations.**



- **Effect of charge limits on average dust particle charge**



- **Effect of n_e / n_i with/without charge limits**

- **Conditions: 10 nm diameter Si particles in Ar plasma, T_e = 3 eV, T_i = 300 K (Left: n_e / n_i = 1)**

[1] R. Le Picard & S. L. Girshick, submitted (2015).

[2] T. Matsoukas & M. Russell, J. Appl. Phys. 77, 4285 (1995).