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Concept for an Experimental Study of Dust Rim Formation on Chondrules

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Motivation

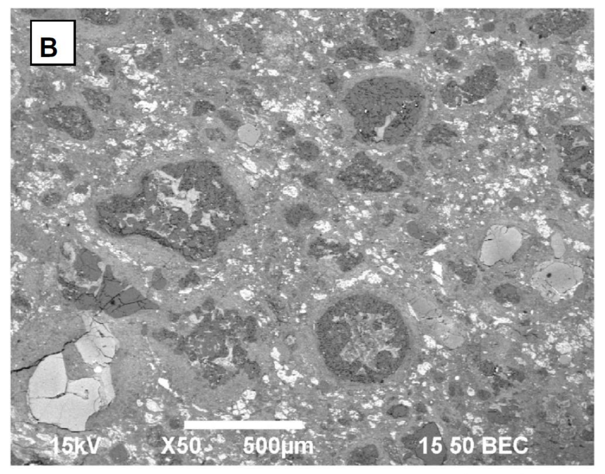

Figure 1: Backscatterd Electron (BSE) image of a rimmed chondule [10]

Chondrules are one of the primary components of chondritic meteorites. In carbonaceous chondrites, chondrules are commonly surrounded by fine-grained dust rims (FGRs) [1] as shown in Figure 1. Analysis of the physical characteristics of FGRs preserved in meteoritic samples [2] may be able to give insight into processes in the early solar nebula. We propose an experimental method to investigate rim growth to compare with previous experimental studies [3]. Fundamental processes affecting the formation of FGRs can be studied, allowing verification of numerical models which show that porosity and thickness of FGRs collected in a protoplanetary nebula depend on relative velocity and charge of the dust grains [4, 8, 9]. Comparison with rims observed in meteoritic samples may help elucidate the conditions and processes present in the solar nebula.

The IPG6-B Facility

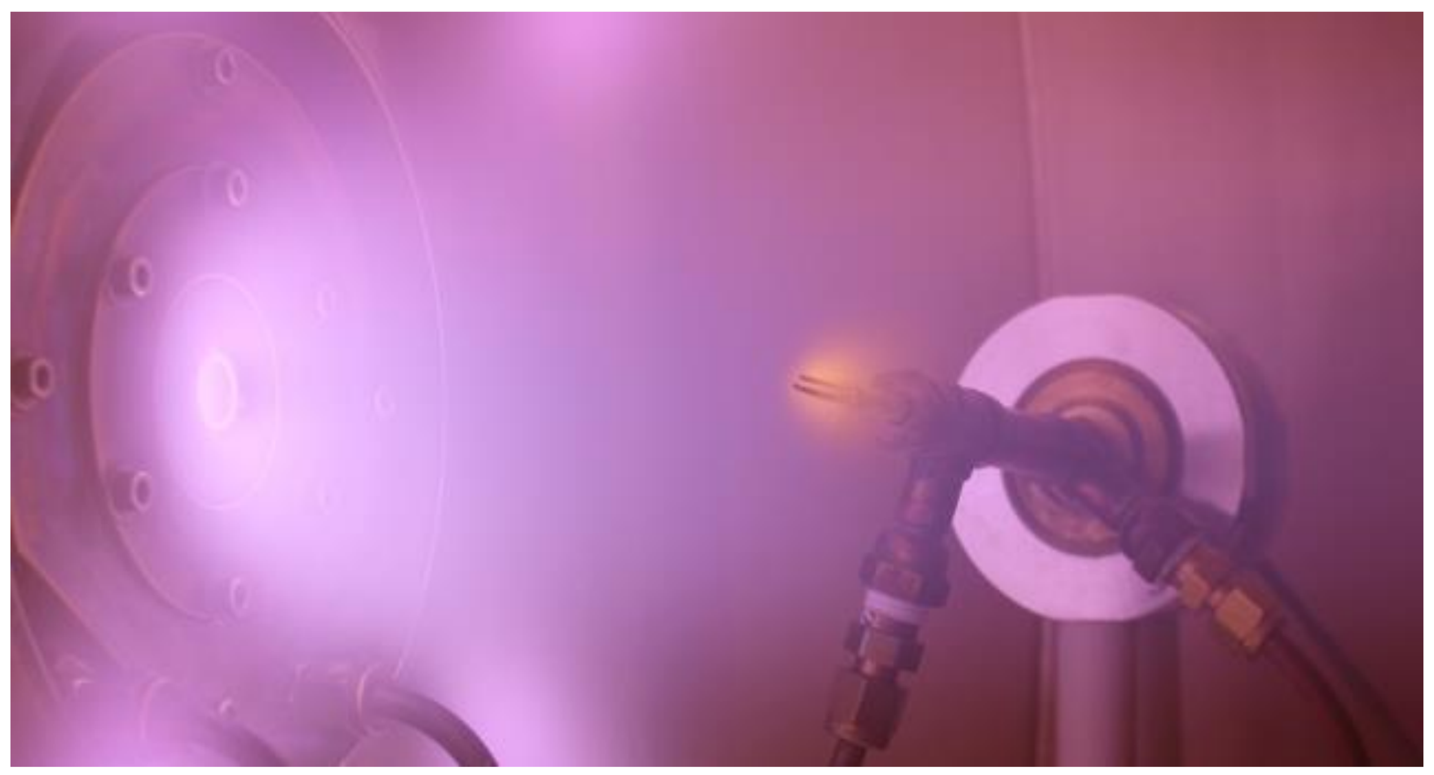

Figure 2: IPG6-B facility in operation with argon

Experiments will be conducted within the IPG6-B experimental facility at Baylor University [5]. The facility consists of a 1.2 m^3 vacuum tank connected to a vacuum system capable of maintaining a base pressure of 0.2 Pa. This vacuum tank is connected to an inductively-heated plasma generator (IPG), shown in operation in Figure 2, which is capable of producing an inductively coupled discharge with electrical powers between 150 and 15000 W in various gases. A light gas gun can be used to shoot dust into the facility as well as to create gas-dynamic shocks with a wide range of velocities [6].

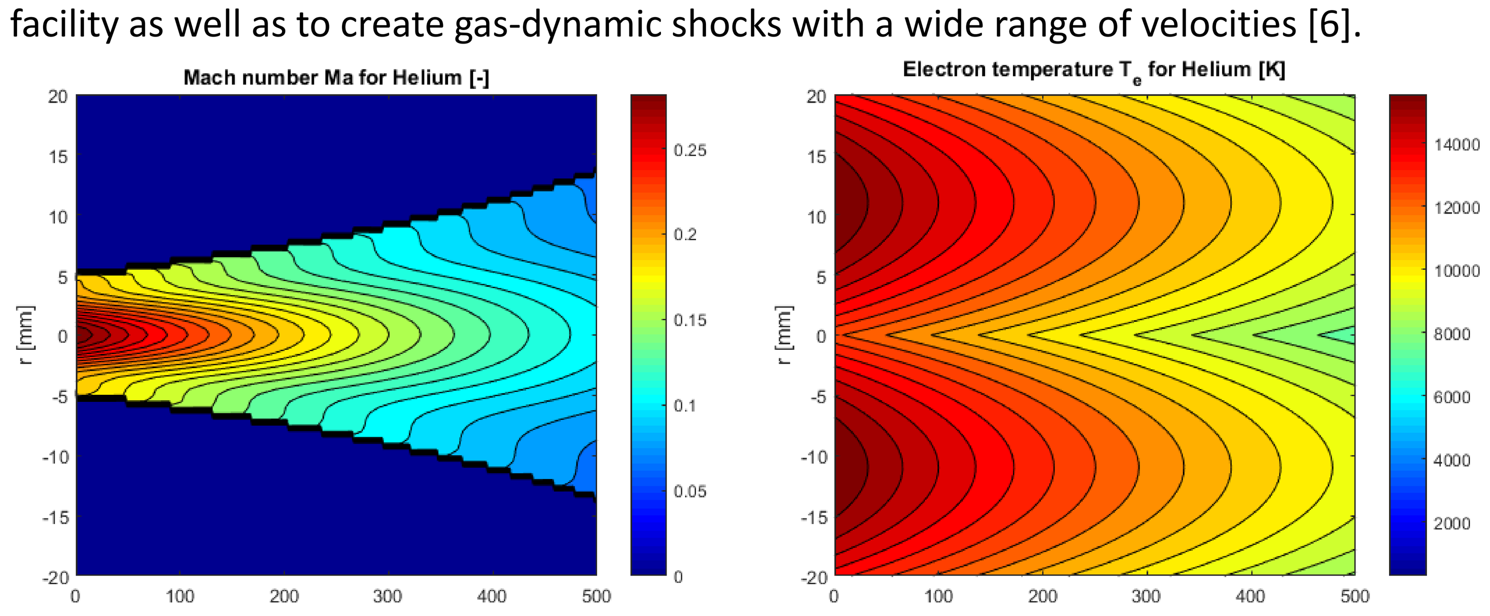

Figure 3: Mach number and electron temperature of a Helium Jet at vacuum pressure of 25 Pa as function of axial position z and radial position r

Experiment

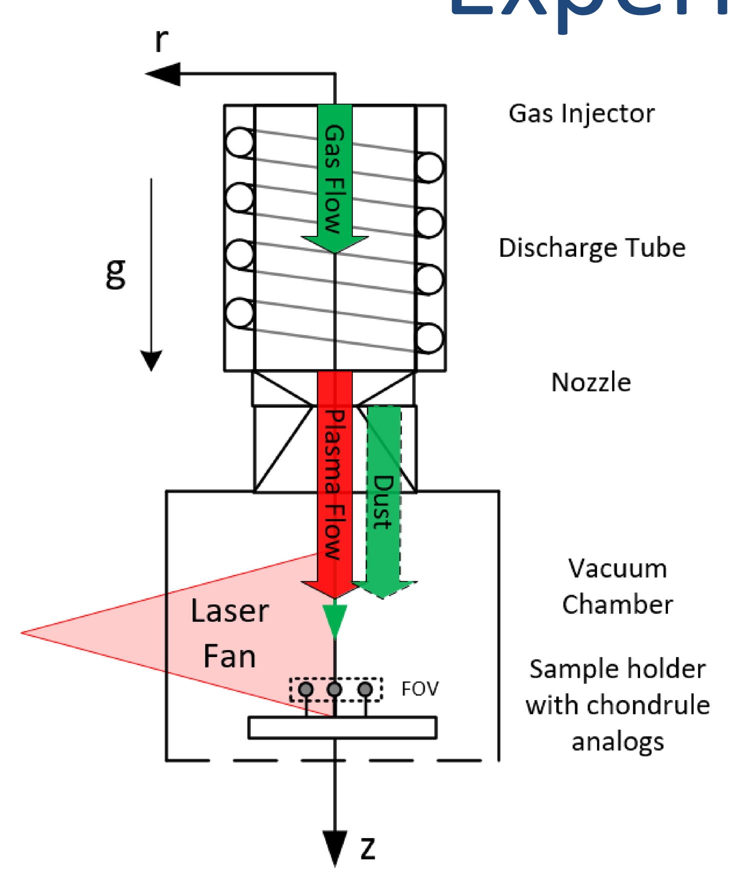

Figure 4: Scheme of the experiment (not to scale)

Chondrule analogs are mounted on a sample holder within the vacuum chamber by using very thin needles. As shown in Figure 4, the vacuum chamber is aligned vertically with the gas and particle injector head on top of the chamber. Micrometer-sized olivine dust is injected into the vacuum chamber and directed onto the sample holder. The velocity $v(z)$ of the dust at a distance z from the dust injection device can be calculated as velocity and temperature profiles of the gas flow are known (shown in Figure 3). The position of the sample holder is varied to achieve different velocities. For a dust particle with diameter d_p, density ρ_p and mass $m_p = (\pi/6)\, d_p^3\, \rho_p$, the equation of motion is

$$\boldsymbol{m_p \frac{dv_p}{dt} = m_p g + F_d}.$$

The resulting velocities for a particle with a diameter of 10 µm are shown in Figure 5. The dust flow and collisions with the chondrule analogs will be illuminated using a laser and tracked using particle image velocimetry (PIV). After dust rims are collected on the chondrule surface, the light gas gun can be used to induce gas-dynamic shocks which compact the dust. Samples of chondrules will be studied using optical and electron microscopy as well as computer tomography before and after treatment in the facility to observe differences in the collected dust rims.

Dust aggregation is studied for three different cases:

- *Low pressure.* In this condition, particles are dropped on the sample with no gas flow at very low pressure. The particles are not entrained in the gas and have very low-velocity collisions with the chondrule surface. This condition is similar to the environment in a minimum-mass solar nebula at a distance of 1 AU to the center of the nebula and serves also as a control condition for the two other cases.
- *Neutral dust in gas flow.* A small gas flow is introduced in the experimental chamber. This enables the influence of relative velocity between dust and gas on FGR growth to be investigated. Background gases used are Argon and Helium.
- *Charged dust in a plasma flow.* A special focus of this study is to investigate the difference in aggregation between neutral grains and charged grains. For this case, a low power inductive discharge is ignited, ionizing the gas flow and charging the dust grains. Electron temperature and density are known from prior characterization of the plasma generator.

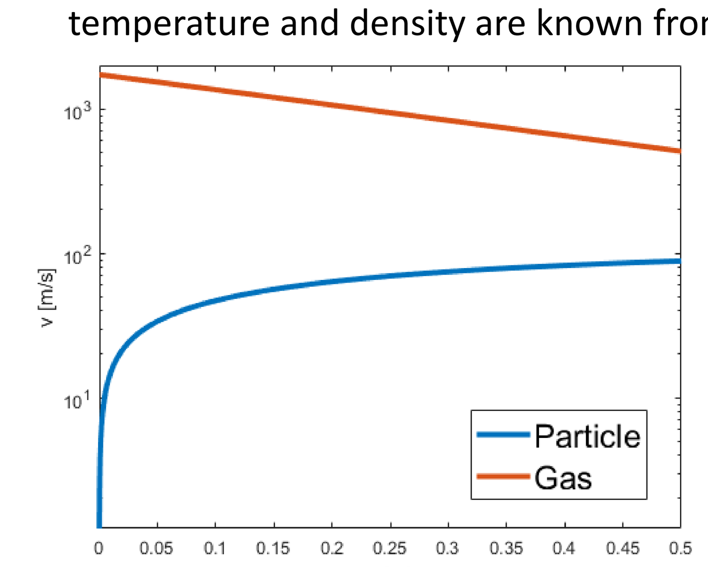

Figure 5: Gas and particle velociy v(z) as a function of distance z from nozzle exit for a 10 µm particle

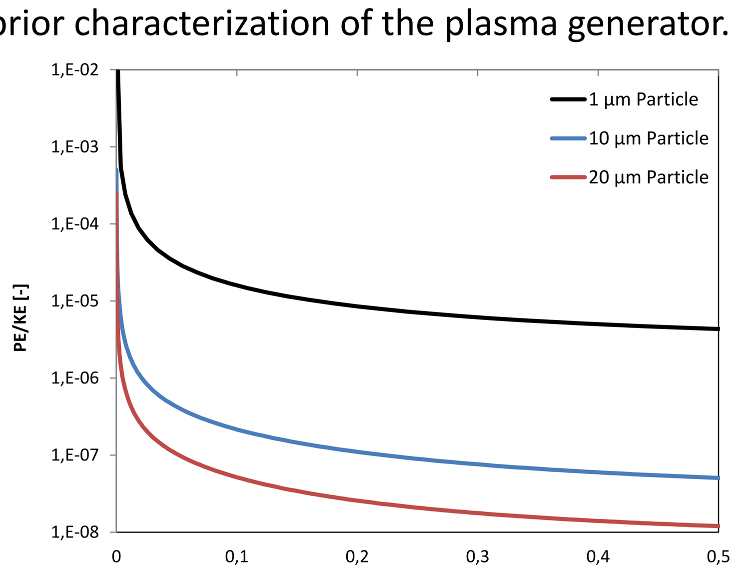

Figure 6: Ratio between potential energy PE and kinetic energy KE for a 1 µm-particle

Using electron temperature and density, the ratio between the potential energy and kinetic energy of a dust grain in the jet can be calculating, treating the dust as point charge. This ratio is shown in Figure and can be directly compared with numerical models [4, 9].

Scaling

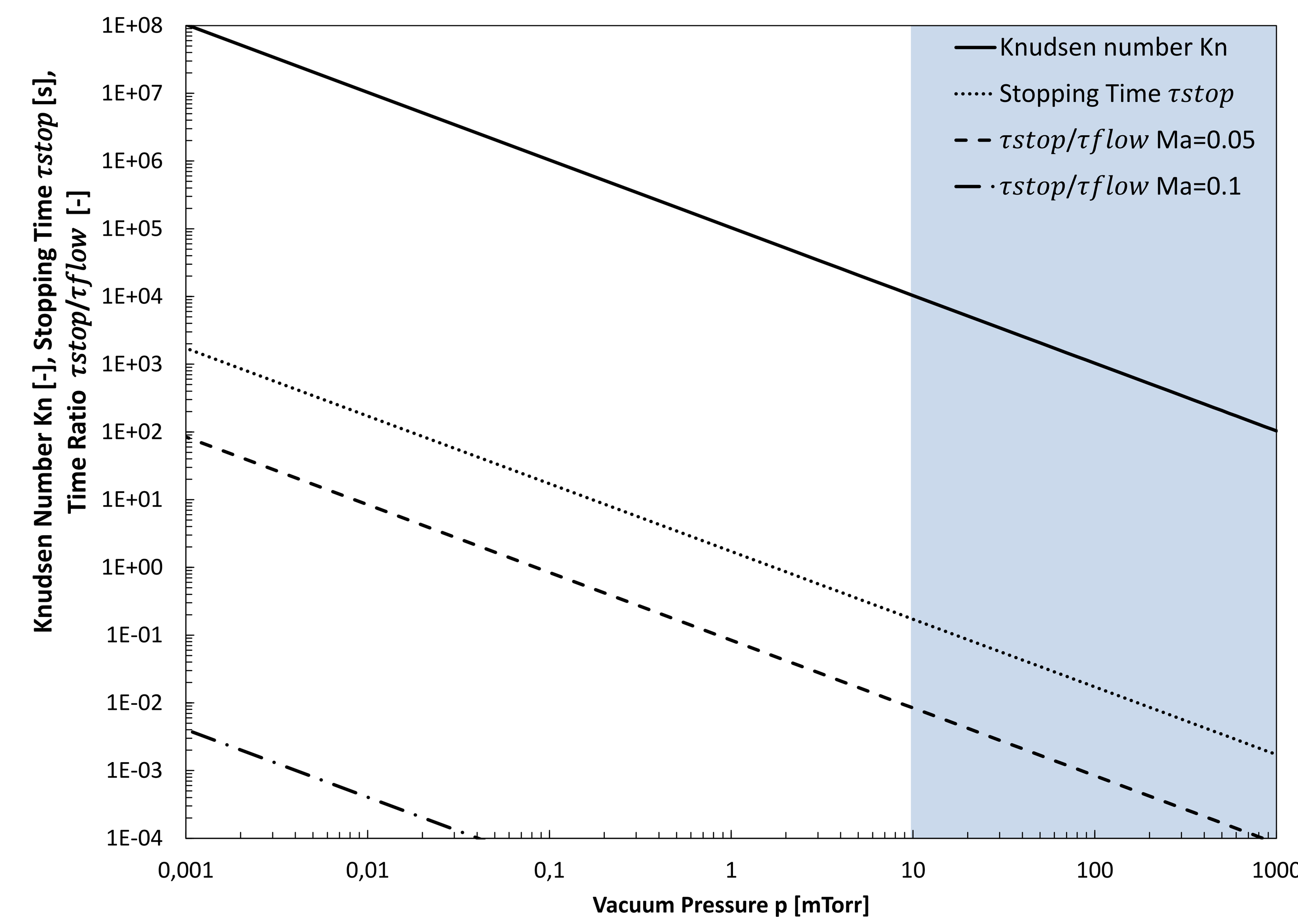

Figure 7: Knudsen number (solid line), stopping time (dotted line) and ratio between stopping time and characteristic timescale at Mach Numbers of 0.05 (dashed line) and 0.1 (dashed-dotted line) of 1-µm particles at T = 300K as function of vacuum pressure. Blue area indicates pressure range of the IPG6-B facility.

Reproducing the environment in the solar nebula at the time of FGR formation requires thoughtful experimental design. Some processes can be reproduced in the experiment, as relevant parameters (size of the chondrules and dust particles, dust velocity) are on the laboratory scale. The Knudsen number $Kn = \lambda/d_p$, ratio between the mean free path $\lambda = 1/(\sqrt{2}\, N\sigma)$ of the background gas (with number density N and collisional cross section σ) and dust diameter d_p, plays an important role in defining the interaction of the dust with the gas.

In Figure 7 it can be seen that for the pressure range of the experimental facility (indicated by the blue area) $Kn \gg 1$, leading to the conclusion that particle-gas interaction is in the Epstein regime. The neutral drag in a gas with velocity v_g is [7]

$$\boldsymbol{F_d = \frac{4\pi}{3} N m \bar{v}_{th} r_p{}^2 (v_p - v_g)}$$

for a particle of radius r_p and velocity v_p, where m and $\bar{v}_{th}$ are mass and mean thermal velocity of the gas particles. Dust couples to the gas flow (with the gas density ρ_g and mean thermal velocity v_{th}) within the characteristic time scale

$$\boldsymbol{\tau_{stop} = \frac{3}{4} \frac{m_p}{v_{th} \rho_g \pi d_p{}^2}}$$

The characteristic time for the gas to travel the distance L between nozzle and sample holder is $\tau_{flow} = v_g/L$. As shown in Figure 2, the stopping time is $\tau_1 \leq 10^{-1} s$ for the pressure regimes of the facility, while the ratio $\tau_{stop}/\tau_{flow} \ll 1$, leading to the conclusion that the particles reach gas velocity before interacting with the chondrules.

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