**Modeling the growth of chondrule dust rims under various plasma conditions.** C. Xiang, L. S. Matthews, A. Carballido, and T. W. Hyde, Center for Astrophysics, Space Physics and Engineering Research, One Bear Place #97283, Baylor University, Waco, TX, 76798-7283, USA.

**Introduction:** Dust mantles or rims around chondrules encode important information regarding processes in the solar nebula. Such rims are generally considered to have an accretionary origin, that is, they are thought to have been acquired through collisions between free-floating chondrules and dust particles in the nebular gas. In environments where the dust is charged, the deflection and deceleration due to the electrostatic force acting between the dust particles and chondrules can cause the dust particles to miss the chondrule, affecting the coagulation probability and resulting in different distributions of monomer sizes as well as time scales of rim formation. In addition, the charge also affects the porosity of the rim as the decreased relative velocity between the dust particles and chondrules can reduce restructuring. If the nebular hypothesis is correct, the structure of chondrule rims could ultimately be used to place constraints on the environmental conditions such as values of gas velocities, turbulent viscosity, and ionization state [1, 2].

In this work, we use a molecular dynamics code to model the growth of fine-grained chondrule rims through the collection of micron-sized dust grains in protoplanetary disks with different turbulence strengths and different plasma conditions.

**Method:** The accretion of the chondrule rims was modeled using the conditions in a MMSN turbulent protoplanetary disk at the midplane at a distance of 1 AU. The initial dust population is silicate spheres with radii $0.5 \le a \le 10$ μm with a power law size distribution $n(a)\mathrm{d}a \propto a^{-3.5}\,\mathrm{d}a$. The plasma environment is assumed to be singly-ionized hydrogen with equal electron and ion temperature, $T_e = T_i = 280$ K. The number density of free electrons and free ions in the gas varies as at higher dust densities a large percentage of electrons may reside on the dust grains. In this work, we consider three ratios of free electrons to free ions $n_e/n_i$ =1, 0.5, and 0.1, corresponding to dust surface potentials of -0.061 V, -0.048 V, and -0.020 V respectively [3].

We use a combination of a Monte Carlo method and a N-body code, Aggregate_Builder (AB), to model the collision between the chondrule, which is represented by a (sub) millimeter-sized spherical body, and the dust. The Monte Carlo algorithm is used to randomly select dust particles from the dust population to collide with the chondrule, as well as determine the elapsed time interval between collisions [4, 5]. The detailed collision process is modeled using AB, which takes into account the morphology of the dust rim and the trajectory of the incoming particle [6,7]. The distribution of charge on the aggregate surface is calculated by the Orbital Motion Limited Line of Sight (OML-LOS) method, where the monomer surfaces in the aggregate are divided into patches and the electric currents due to incoming electrons and ions are calculated for each patch. The total charge of the aggregate is calculated by summing the charge collected on each patch at equilibrium.

In each iteration, the chondrule is placed with its center of mass at the origin, and a dust particle is shot towards its COM plus an offset, with the relative velocity between the dust particle and chondrule determined by coupling of the particles to the turbulent gas environment [8, 9]. The possible collision outcomes are sticking at the point of contact, bouncing, or rolling on the surface, which results in compaction. These outcomes are determined by the critical bouncing velocity and the critical rolling energy [10, 11]. For computational expediency, we restrict dust aggregates to accumulate on a small patch of the chondrule surface, measuring approximately 100 $\mu$m by 100 $\mu$m.

**Results:** The distribution of dust grain sizes collected by chondrules in charged and neutral environments is different. When the dust is uncharged, the distribution of dust radii follows the distribution of dust in the surrounding environment (Fig 1a, b), while the size distribution of charged dust collected within the rim varies, depending not only on the magnitude of the charge, but also on the relative velocities between the dust and chondrule. In a weakly turbulent environment (characterized by a small value of the dimensionless turbulent viscosity parameter α) only the largest dust grains have enough energy to overcome the Coulomb repulsion barrier (Fig 1c). In a highly turbulent region where the relative velocities are large, the distribution of dust grain sizes is similar to that for the neutral environment (Fig 1d). Dust rims comprised of large monomers are more porous, due to the lack of small monomers filling in the gaps within the rims. The charge can affect the porosity of the dust rim in two additional ways: 1) The decreased relative velocity due to the electric repulsion can reduce the restructuring, which increases the porosity; 2) Dust particles are repelled from the extremities of the rims and rotate to an orientation which minimizes the potential energy of the configuration, decreasing porosity. In the case of strong turbulence ($\alpha \geq 10^{-3}$), the main effect of the charge is a reduction of the restructuring, and the FGR porosity has similar ranges for neutral and charged rims, with a value of 51-63% for $\alpha \geq 10^{-2}$, and a value of 57-70% for $\alpha = 10^{-3}$. In the case of weak turbulence ($\alpha \leq 10^{-4}$), the main effect of the charge is the repulsion of small dust grains, and the charged rims have a porosity of 65-85%, while the porosity of neutral rims ranges from 60% to 74%.

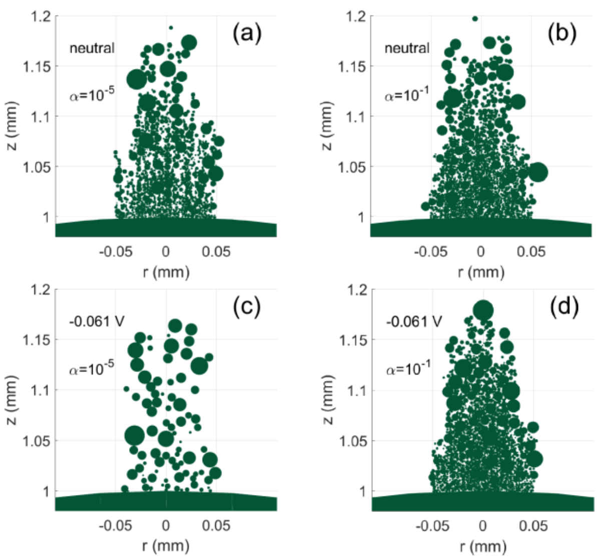


Figure 1: Monomer distributions within a vertical plane cutting through the center of the dust piles on a 100 $\mu$m-diameter patch on the surface of a chondrule with a radius of 1000 µm. Top row: neutral grains, Bottom row: charged grains. Left column: Weak turbulence, Right column: strong turbulence.

In general, dust rims grow more rapidly in highly turbulent environments than in weakly turbulent environments. The higher the charge and the weaker the turbulence, the more the growth rates of charged rims lag behind those of neutral rims, due to repulsion of small particles. In low turbulence ($\alpha < 10^{-4}$), the presence of charge not only slows the growth rate, but can also stop the rim growth.

**Conclusion**: The effects of charged dust on chondrule rim growth depends on both the plasma environment and the turbulence level, which can be characterized by the ratio of the grains' electrostatic potential energy at the point of the collision to the kinetic energy at large distances (PE/KE). This ratio determines the structure of dust rims (e.g., porosity, monomer size distribution) to a certain degree. Figure 2 shows an approximately linear relationship between the porosity of dust rims and PE/KE. Chondrules with PE/KE ≈ 1 stop collecting dust particles after growing to a thickness of ~100-150 µm. However, the freezing of chondrule growth could be prevented by several mechanisms: chondrules traveling through locations with different turbulence levels and different plasma conditions during the dust rim formation; vertical mixing of dust particles; and positive charging of dust grains caused by photoelectric emission or photoelectric charging.

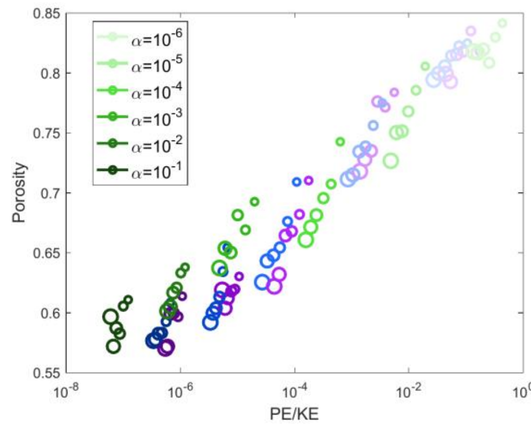


Figure 2: Porosity of dust rims as a function of the ratio of the grains' electrostatic potential energy to the kinetic energy, for different plasma conditions (dust surface potential indicated by purple: -0.061 V; blue: -0.048 V; green: -0.020 V) and different turbulence levels (in order of increasing color shades). The size of circles represents different chondrule sizes (500-1000 $\mu$m, in 100 $\mu$m increments).

It is important to note that this study models the initial stages of dust rim growth. The effects of post-processing of the rims, such as thermal/aqueous alternation and nebular shock waves that lead to compaction of dust rims should also be considered before comparing these results to measurements of rim characteristics in meteoritic samples [12].


**References:** [1] Ormel, C. W. et al. (2008) ApJ, 679:1588–1610. [2] Carballido, A. (2011) Icarus, 211, 876. [3] Matthews, L. S. et al. (2012) ApJ, 744 (1): 8. [4] Ormel, C. W. et al. (2007), A&A 461, 215-232. [5] Gillespie, D. T. (1975) AMS 32 (10): 1977-1989. [6] Ma, Q. et al. (2013) ApJ 763 (2): 77. [7] Matthews, L. S. et al. (2016) IEEE 44 (4): 519–24 [8] Carballido, A. et al. (2010) MNRAS 405 (4): 2339–44. [9] Carballido, A. et al. (2016) ApJ 823 (2): 80. [10] Chokshi, A. et al. (1993) ApJ, 407: 806-819. [11] Dominik, C. and Tielens, A. G. G. M. (1997) ApJ, 480: 647-673. [12] Hanna R. D. and Ketcham R. A. (2018) EPSL 481: 201-211.