Dust Grain Growth in a Protoplanetary Disk: Effects of Location on Charge and Size

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Introduction: Protoplanetary disks, the sites of planet formation, have their origins in the processes behind the birth of stars. Cold, dense molecular cloud cores within nebulae made up of dust and gas collapse due to gravitational instabilities. Young stellar objects (YSOs) form at the center of the core where the gas and dust are the most dense. During the collapse, the mass of gas and dust in the cloud transitions from being distributed over parsec (pc) scales to being confined within astronomical unit (AU) scales. Redistribution and conservation of angular momentum leads to the remaining gas and dust forming a disk-shaped structure which is referred to as the accretion disk. This disk then evolves into a more tenuous protoplanetary disk (PPD) [1]. It is in this structure that the first stages of planet formation begin. The growth of micrometer- and submicrometer-sized dust particles into kilometer-sized planetesimals is the initial stage of planet formation, with the first step being the aggregation of submicrometer-sized particles into highly porous fractal aggregates [2]. The collisions and sticking of dust monomers (single spherical particles) and aggregates (two or more monomers stuck together) is a complex process that requires an in-depth knowledge of both the properties of the dust grains as well as their environment. Dust grains in the disk couple to the gas and thus their motions are determined primarily by Brownian motion and turbulence [3]. However, because the gas is (weakly) ionized,n many regions of a protoplanetary disk, plasma is the dominant component. thus another another effect must be taken into consideration: dust grain charging. Although dust aggregation in planet formation is well-recognized, few have explored the role of charging in this process within the context of the PPD [4]. Some studies show that the charging of dust grains has a significant impact on the dust size distribution within the protoplanetary disk and can even lead to the formation of a so-called

"frozen zone" within the disk, where no aggregation takes place [2]. It has also been shown that the charge on an aggregate affects its size, mass, and "fluffiness" [3]. Thus, charging is clearly a key factor in grain growth within a PPD. Aggregation affected by grain charging within the PPD is investigated and initial conditions for radial distances $R = 2, 5$ AU at elevations of $Z = 0.8H, 0.9H, 1.0H$, where H is the vertical scale height, are calculated [2]. For each of these locations in the PPD, aggregates are constructed using a numerical model through particle-particle, particle-cluster, and cluster-cluster aggregation (PPA, PCA, and CCA, respectively) while self-consistently calculating the charge on the newly formed aggregates using the plasma parameters for that location. The impact of dust grain charging on aggregation and comparisons of the resultant aggregates at the different locations in the disk are shown.

Methods: To build dust aggregates, a modified *N*-body code is used that models collisions between two aggregates, coupled with an aggregate charging algorithim. The initial conditions for the charging and construction of the aggregates based on the location of the aggregate in the disk are taken into account. Turbulence in the disk is also considered in order to provide the necessary relative velocity between aggregates to achieve collisions.

Building Aggregates. To build aggregates, an initial monomer or an aggregate is placed at the origin. Then, a monomer (or an aggregate) is shot towards the target particle from a randomly selected direction. The monopole and dipole terms of each particle's charge distribution are used to calculate the electric fields at the other particle's location., which are then used to calculate the accelerations of each particle. The interaction of the dipole moment of each particle with the electric field of the other particle produces a torque about the particle's COM [5]. A fifth-order Runge-Kutta method is utilized to determine the resulting position, velocity and orientation of the target grain. An example of one such aggregate is seen in Figure 1.

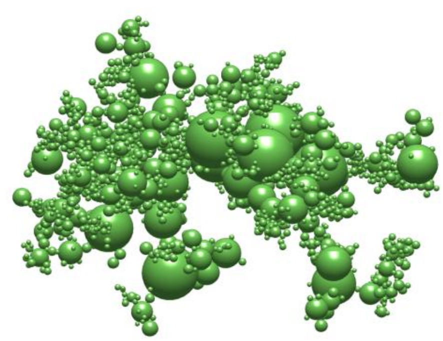

Figure 1. Aggregate with over 2000 monomers with radii chosen from an initial power law distribution.

Charging Aggregates. To simulate the charging of dust grains within the PPD, an aggregate charging code that relies on Orbital Motion Limited theory and a Line Of Sight approximation (OML_LOS) is employed. Because the dust grain is immersed in a plasma within the PPD environment, ions and electrons continuously bombard the grain, with electrons colliding more frequently. For a sphere with lines of sight that are completely unblocked, calculating the open solid angle is trivial. However, for an aggregate composed of more than one sphere where other spheres in the aggregate block lines of sight in other spheres, the solid angle must be computed for open lines of sight at each point on the surface. To determine this, the surface of the monomer is divided up into many small patches. Vectors are constructed that go from the center of the surface patch in many (>400) test directions. If these “lines of sight” intersect with any other monomer in the aggregate, the direction is considered blocked. Otherwise, it is unblocked. This determination then allows for the calculation of the LOS_factor, the numerical approximation of the open solid-angle [3].

Initial Conditions. A range of initial conditions are used to model aggregate growth at multiple locations in the disk. A Maxwellian distrubution is assumed for the plasma species [3]. The temperature, T, assumed to be constant in Z for this range of scale heights, and the gas density were estimated and calculated from [4]. Fractional ionization (X_e) estimations were made based on [6]. For all of the elevations at $R = 5$ AU, $X_e = 10^{-10}$ was assumed. The size of the dust within the PPD is assumed to be distributed according to a powerlaw distribution $n(a)\,da \propto a^{-3.5}\,da$ [7].

Results: The purpose of this study is to examine the charge on the aggregates and how this affects their morphology and coagulation rate. Figure 2(a) shows the relationship between Z_D, the charge number, and N, the number of monomers for $R = 2$ AU. The large spread in values for $N = 2$ is due to the large difference in size that the initial dimers may have. First generation aggregates at all heights and both disk radii show a very large spread in Z_D. Aggregates with $N > 20$ have a narrower distribution of charges. As can be seen by the fit lines for $Z/H = 0.9$, 1.0 in Fig. 2(a), the grains are more highly charged at the higher elevations.

Figure 2(b) shows the relationship between Z_D and the equivalent radius, R_σ, the radius of a circle with area equal to the average projected area of the aggregate. This is a better characteristic for the charge, as the charge is nearly linear with R_σ on a log-log scale, with the exception of the $N = 2$ aggregates which form their own group. Further results will show the difference in aggregate morphology and coagulation rates at the different disk locations.

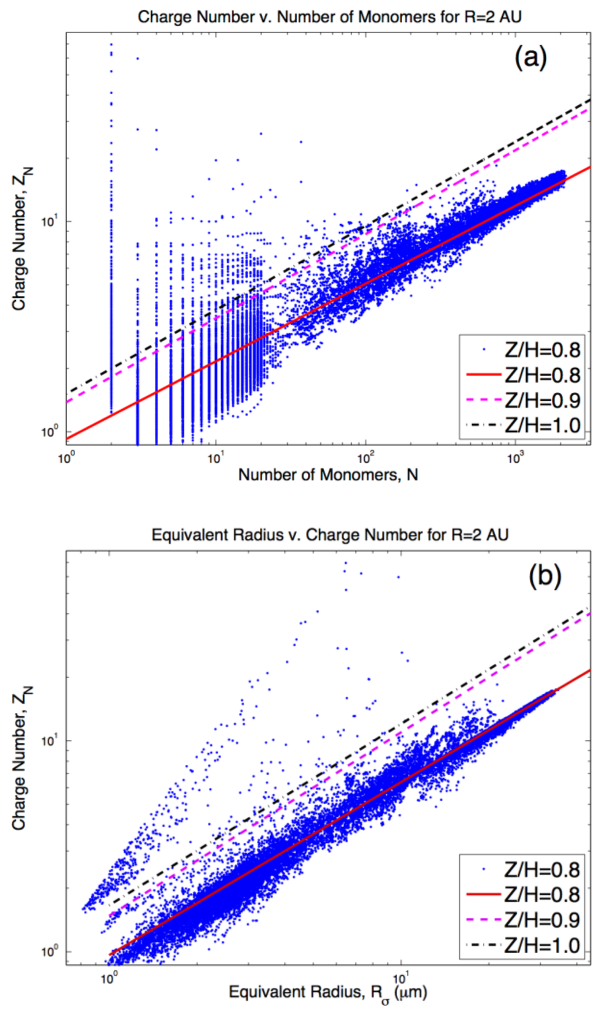

Figure 2. Log-log plot of (a) charge number versus number of monomers and (b) charge number versus equivalent radius for $R = 2$ AU with three different Z/H values shown for each.

References: [1] Apai, D., D. S. Lauretta (2010) *Protoplanetary Dust,* 1-26 [2] Okuzumi, S. et al. (2011) *Astrophys. J.,* 731 1-14 [3] Matthews, L. S., V. Land and T. W. Hyde (2012) *Astrophys. J.,* 744 1-12 [4] Okuzumi, S. (2009) *Astrophys. J.,* 698 1122-1135 [5] Matthews, L. S. et al. (2007) *IEEE Trans. Plasma Sci.,* 35 260-265 [6] Semenov, D., D. Wiebe and Th. Henning (2004) *Astron. Astrophys.* 417 93-106 [7] Mathis, J. S., W. Rumpl and K. H. Nordsieck (1977) *Astrophys. J.,* 217 425-433