Dipole-Dipole Interactions of Charged-Magnetic Grains. Jonathan Perry, Lorin S. Matthews and Truell W. Hyde, Center for Astrophysics, Space Physics and Engineering Research (CASPER), Baylor University, One Bear Place 97310, Waco, Texas 76798-7310, USA (Jonathan_Perry@baylor.edu, Lorin_Matthews@baylor.edu, Truell_Hyde@baylor.edu)

Introduction: Astronomical observations have shown the coagulation of dust to be an initial stage of particle growth in early solar nebula [1] and that grains often grow in size through formation of fluffy fractal aggregates [2, 3]. Understanding the physics underlying the formation of these aggregates is a key component of being able to accurately model early stages of planetary formation [4, 5].

The ambient dust environment can have a significant effect on grain coagulation: grains immersed in plasma can become charged, which can either retard or enhance coagulation rates depending on charging conditions [6, 7]. In like manner, grain composition can also influence the coagulation rate; both numerical simulations and experimental date have shown that nanometer-sized iron grains often coagulate rapidly into small aggregates due to the alignment of their magnetic dipoles [8, 9, 10].

This study examines the behavior of charged-magnetic grains by comparing four specific cases: magnetized grains, charged grains, charged-magnetic grains and neutral grains. The results from numerical simulations are compared to previous studies on the growth of charged grains [6] and magnetic grains [8].

Method: In this study, aggregates were created by numerically modeling the interactions between colliding particle pairs [11]. Work was done in the center of mass (COM) frame of an initial seed particle; a second monomer or aggregate was chosen to approach the COM plus an offset from a random direction. Incoming charged grains were given velocities of a few times the thermal velocity to overcome Coulomb repulsion, while magnetic grains were given velocities that were fractions of the thermal velocity.

The forces acting on particle i from the electric or magnetic field of particle j are calculated along with the electric and magnetic torques. The charge on an aggregate is approximated using both the monopole and dipole moments [11], while the magnetic dipole moment is calculated as the vector sum of the dipole moments of the individual monomers. The electrostatic and magnetic dipole moments also create a torque on each particle inducing a rotation for the aggregate altering its orientation during collision which can affect the resulting structure.

Collisions are detected when monomers within each aggregate physically overlap. Colliding aggregates are assumed to stick at the point of contact with orientation being preserved. Fragmentation during collisions is not considered due to the low velocities imposed on incoming grains [12]. For charged aggregates, the charge and dipole moment are determined by the use of a heuristic charging scheme [11].

Aggregate populations were grown in three stages. The first generation aggregates were created by addition of single monomers until the number of monomers N = 20. Second generation aggregates grew though collisions between 1st generation aggregates up to a size N = 200. Third generation aggregates were grown by addition of 1st or 2nd generation aggregates up to a size of N = 2500.

For each population of aggregates assembled, iron grains were modeled with a radius of r = 20 nm and mass $m = 2.66 \times 10^{-19}$ kg. A magnetization of $\mu = 7 \times 10^{-18}$ A·m^2 and an initial surface potential V = -0.0707 eV were used for magnetic, charged or charged-magnetic grains as appropriate.

Results: Collision statistics for each potential interaction were collected including collision outcome, initial velocity, impact parameter, and the number of monomers (N) in the resulting aggregate. These statistics were used to determing the probability of interaction and coagulation between particles under various initial conditions for each dust population.

Magnetic dipole grains tended to align as they approached each other; upon collision the dipole moment was assumed to be "frozen in" contributing to the total magnetic dipole moment of the aggregate. The behavior of the magnetic population was in good agreement with previously published results [8].

Collision probability statistics for relative velocities between particles were considered for each population. Incoming magnetic aggregates have a high probability of colliding with the target aggregate for all velocities modeled. As expected, missed collisions occur at the highest velocities which allows for the least alignment of the magnetic dipole between the particles.

The minimum collisional velocity of charged grains was determined to be approximately $3v_{th}$. Below this threshold both charged and charged-magnetic grains have nearly the same probability of collision. From Fig. 1 it can be seen that charged-magnetic grains exhibit a higher probability of coagulation at speeds above this threshold, with a maximum difference of 12% at speeds between $3v_{th}$ and $4v_{th}$. At the highest speeds examined the collision probabilities approach the limiting value of one where the collisions between grains resemble ballistic collisions.

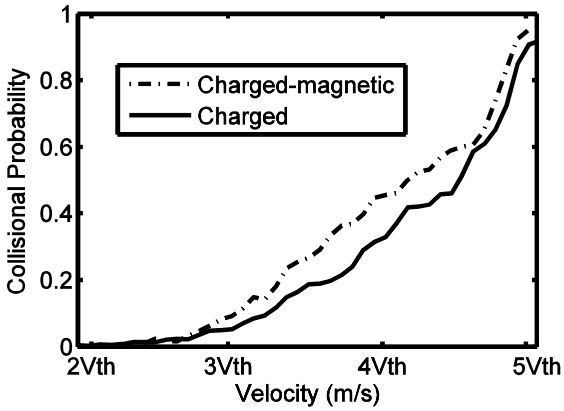

Figure 1. Probability of collision for charged and charged-magnetic aggregates having an initial speed of $2v_{th} \leq v \leq 5v_{th}$.

The difference in collision probability as a function of impact parameter for charged and charged-magnetic grains is less pronounced. Charged-magnetic grains appear to always have a slightly higher probability of collision when the impact parameter is less than the grazing distance.

The fractal dimension provides a measure of the openness or porosity of a structure. This value ranges from nearly one for a linear structure, to three for a compact sphere. Aggregates with a lower fractal dimension will have a higher collisional cross-section but can also become more entrained in the gas in their environment, reducing the likelihood of collisions.

The fractal dimension for each aggregate, F_d, is calculated using the Hausdorff method [13]. Aggregates assembled from a magnetic material tend to form filamentary structures consisting of many linear chains. Charged monomers tend to form a denser, more compact structure. Charged-magnetic grains exhibit behavior intermediate to both purely magnetic or purely charged grain populations. Examples of small and large aggregates from each population are shown in Figure 2.

The relative time for aggregates to grow to large size was also considered. As expected, magnetized grain populations aggregate more quickly than do simple charged populations. If an appreciable amount of magnetic material were in a protoplanetary disk it would increase the rate of coagulation for small particles.

The results of this study imply that the characteristics of aggregate growth for a given environment are controlled by both the material properties as well as the plasma parameters determining the charging of individual monomers. This can have a significant impact on the early stages of planetesimal formation depend

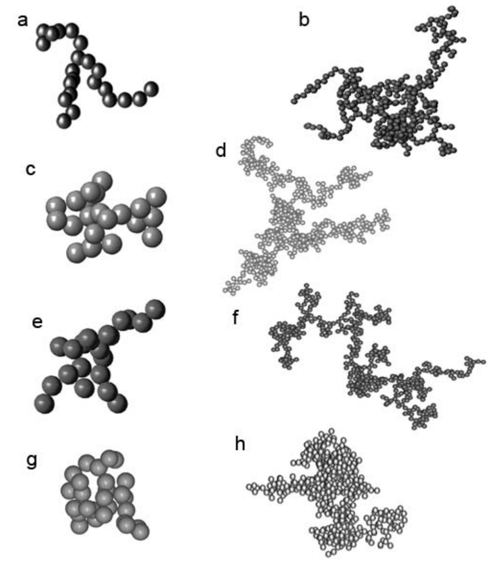

Figure 2. Comparison of aggregates formed from the following populations: Magnetic aggregates a) $N = 22$, $F_d = 2.159$, b) $N = 334$, $F_d = 1.789$; Charged aggregates c) $N = 21$, $F_d = 2.333$, d) $N = 595$, $F_d = 1.907$; Charged-magnetic aggregates e) $N = 21$, $F_d = 2.359$, f) $N = 504$, $F_d = 1.819$; and Neutral aggregates g) $N = 25$, $F_d = 2.403$, h) $N = 589$, $F_d = 1.976$.

ent upon the local conditions within a protoplanetary disk.

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