COLLISONAL GROWTH POSSIBILITY OF DUST AGGREGATES: A BOUNCING PROBLEM.

K. Wada[1], H. Tanaka[2], T. Suyama[3], H. Kimura[4], and T. Yamamoto[2], [1]Planetary Exploration Research Center, Chiba Institute of Technology (Chiba 275-0016, Japan, wada@perc.it-chiba.ac.jp), [2]Insitute of Low Temperature Science, Hokkaido Univ., Japan, [3]Niigata Science Museum, Japan, [4]Center for Planetary Science/Kobe Univ., Japan.

Introduction: Growth and disruption processes of dust aggregates through their mutual collisions play an important role in our understanding of planetesimal formation in protoplanetary disks. One of the main problems with planetesimal formation is the feasibility of dust growth through collisions at velocities up to several tens of m/s [e.g., 1, 2]. Recently, we performed numerical simulations of aggregate collisions using two kinds of aggregates of submicrometer-sized spheres: ballistic cluster-cluster aggregation (BCCA) clusters and ballistic particle-cluster aggregation (BPCA) clusters. BCCA clusters are fluffy (fractal dimension D < ~2) and BPCA clusters are relatively compact (D ~ 3). As a result, we find that BCCA clusters compressed at collisions still remain fluffy with D ~ 2.5 and BPCA clusters consisting of ice particles are able to grow at collision velocities up to ~50m/s [3-5]. These results support a scenario that very fluffy palnetesimals are formed through collisions of dust aggregates in protoplanetary disks. However, several experimental studies report that low-velocity (< ~1m/s) collisions for porous silicate aggregates often induce bouncing of colliding aggregates [6,7], while such colliding aggregates always result in sticking in our previous numerical studies. This "bouncing" problem is critical for dust growth and planetesimal formation through collisions of dust, because bouncing would prevent dust aggregates from sticking to each other [6].

Bouncing requires a mechanism inhibiting energy dissipation to leave sufficient energy after collisions. Since energy dissipation occurs through relative motions between particles in contact, we expect that bouncing is caused by immobility of particles consisting in aggregates, which is controlled by the number of contacts in the aggregates. If constituent particles in an aggregate are in contact with many neighbor particles, they cannot freely roll, slide and twist on the neighbors and thus energy cannot dissipates enough for the aggregates to stick to each other. The number of particles in contact with a particle is called as the coordination number. In this study, we perform numerical simulations of collisions between aggregates with various coordination numbers. Then we discuss the bouncing conditions of aggregates and the feasibility of dust growth through collisions.

Numerical Model: We perform 3D simulations of aggregate collisions by the use of the particle interaction model and the numerical code developed in [8,9]. We directly calculate the motion of each particle, taking into account all mechanical interactions between particles in contact. The contact theory of adhesive elastic spheres determines the interactions for each degree of motion (normal motion, sliding, rolling, and twisting). Energy dissipates at the moments of contact and separation of particles due to the excitation of elastic waves. When the displacements due to sliding, rolling, and twisting exceed their elastic limits, the mechanical energy is also dissipated. The amount of energy dissipation is proportional to the critical displacements. We consider aggregates composed of ~4,000 spherical particles with a radius of r_1= 0.1μm and made of ice (Young's modulus 7 GPa; Poisson's ratio 0.25; material density 1000 kg/m^3; surface energy 100 mJ/m^2).

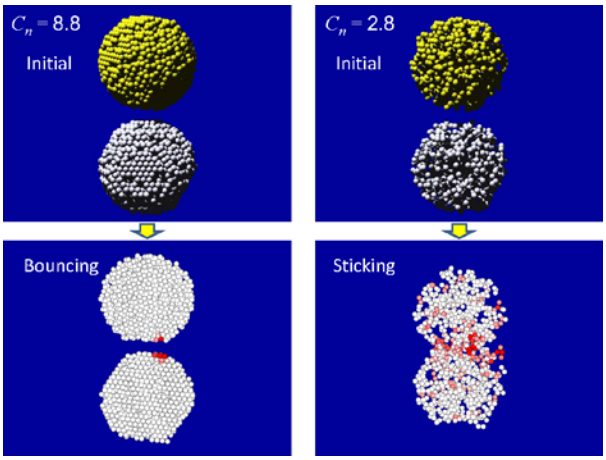

Figure 1: Examples of initial ice aggregates with C_n = 8.8 and 2.8 (upper panels) and their collisional outcomes (lower panels). The lower panels show cross sections of the aggregates and red-colored particles where energy dissipates. Collision velocity is 1.5 m/s for both cases.

Although we treat the coordination number C_n averaged over all particles of an aggregate as a parameter in our simulation, it is difficult to numerically produce aggregates with an arbitrary C_n. In this study, we prepare aggregates with various values of C_n by a simple procedure as follows: First, we numerically produce a hexagonal close-packed aggregate, which definitely has the maximum value of C_n = 12 (but actually C_n = 11 because of the finite size of aggregates we treat). Then

we randomly extract particles from the close-packed aggregate with a ratio *f*. Changing *f* from 0.05 to 0.75, we obtain aggregates with C_n from 10.5 to 2.8 (see Fig. 1, for example). BCCA and BPCA clusters have the theoretical minimum value of $C_n = 2$ and they did not bounce in our previous simulations. We simulate head-on collisions of two identical aggregates and examine whether colliding aggregates stick or bounce. For each case of C_n, we prepare three different types of aggregates by changing random seeds of particle extraction. The collision velocity u_{col} is changed from 0.1 to 22 m/s. The corresponding impact energy E_{imp} is given by $(1/2)Nm_1(u_{col}/2)^2$, where N is the total number of particles of colliding aggregates and m_1 is the mass of one particle.

Results on Bouncing Conditions: As shown in Fig. 1, energy dissipation occurs at various locations within aggregates with small C_n, indicating that effective dissipation leads to sticking of aggregates.

The numerical results are summarized in Fig. 2 showing the sticking cases by red circles and the bouncing cases by blue crosses under various parameter sets of C_n and E_{imp} (or u_{col}). E_{imp} is normalized by NE_{break} for scaling, where E_{break} is the energy needed to break a contact between particles. At E_{imp} small enough, aggregates stick to each other because it is possible to dissipate energy through a contact between monomers. With increasing E_{imp}, aggregates with large C_n tend to bounce and we do not see any bouncing cases for aggregates with $C_n < 6$. With larger E_{imp}, the probability of sticking again increases even for aggregates with $C_n > 6$. This is caused by a large amount of energy dissipation due to disruption of aggregates. This sticking mode accompanied by fragmentation is also reported in experimental studies[7]. The collision velocity at which this sticking mode emerges in the experiments is consistent with our numerical results by converting the size and the material property of particles used in the experiments (SiO_2 particles with $r_1 = 0.75\mu m$) to those in our simulation (ice particles with $r_1 = 0.1\mu m$), using scaling laws [3,8,9].

Discussion and Conclusion: The critical number of $C_n = 6$ is reasonable because particles with $C_n = 6$ is locked by contact particles in triaxial directions and their degrees of freedom of motion are greatly restricted. However, aggregates in laboratory experiments bounce although they are thought to have small $C_n \sim 2$ estimated from their preparing manner similar to BPCA[10]. It is difficult to interpret this contradiction. Possible explanation is that surface conditions of colliding aggregates could determine their collisional outcomes. That is, aggregates could bounce when particles located in the surface region have large coordination numbers. It is necessary to investigate the coordination number in the surface region of aggregates used in laboratory experiments.

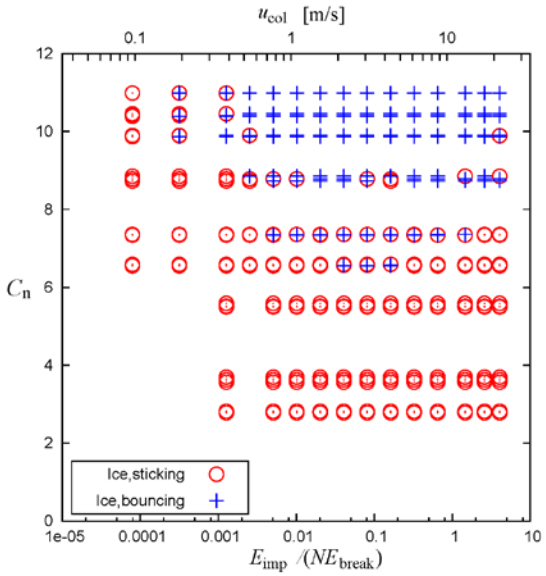

Figure 2: Diagram indicating the collisional outcomes (sticking or bouncing) of ice aggregates for parameter sets of C_n and $E_{imp}/(NE_{break})$. Corresponding u_{col} is indicated in the upper horizontal axis.

In our previous simulations, resultant aggregates generated through collisions of BPCA clusters have C_n less than 4. Such collision-generated aggregates are expected to stick and grow without any bouncing when our result that aggregates with $C_n < 6$ always stick is applied. Actually, we have simulated some cases of collisions between collision-generated aggregates with $C_n = 3.8$ and they result in sticking regardless of the collision velocity. Therefore, based on our numerical simulations, we conclude that dust aggregates in protoplanetary disks are able to grow through collisions without any bouncing.

References: [1] Weidenschilling and Cuzzi (1993) in *Protostars and Planets III*, 1031. [2] Adachi et al. (1976) *Prog. Theor. Phys. 56*, 1756. [3] Wada et al. (2008) *Astrophys. J. 677*, 1296. [4] Suyama et al. (2008) *Astrophys. J. 684*, 1310. [5] Wada et al. (2009) *Astrophys. J.* 702, 1490. [6] Blum and Wurm (2008) *Annu. Rev. Astron. Astrophys. 46*, 21. [7] Guettler et al. (2009) *Astron. Astrophys.* in press. [8] Dominik and Tielens (1997) *Astrophys. J. 480*, 647. [9] Wada et al. (2007) *Astrophys. J. 661*, 320. [10] Blum and Schrapler (2004) *Phys. Rev. Lett. 93*, 115503.